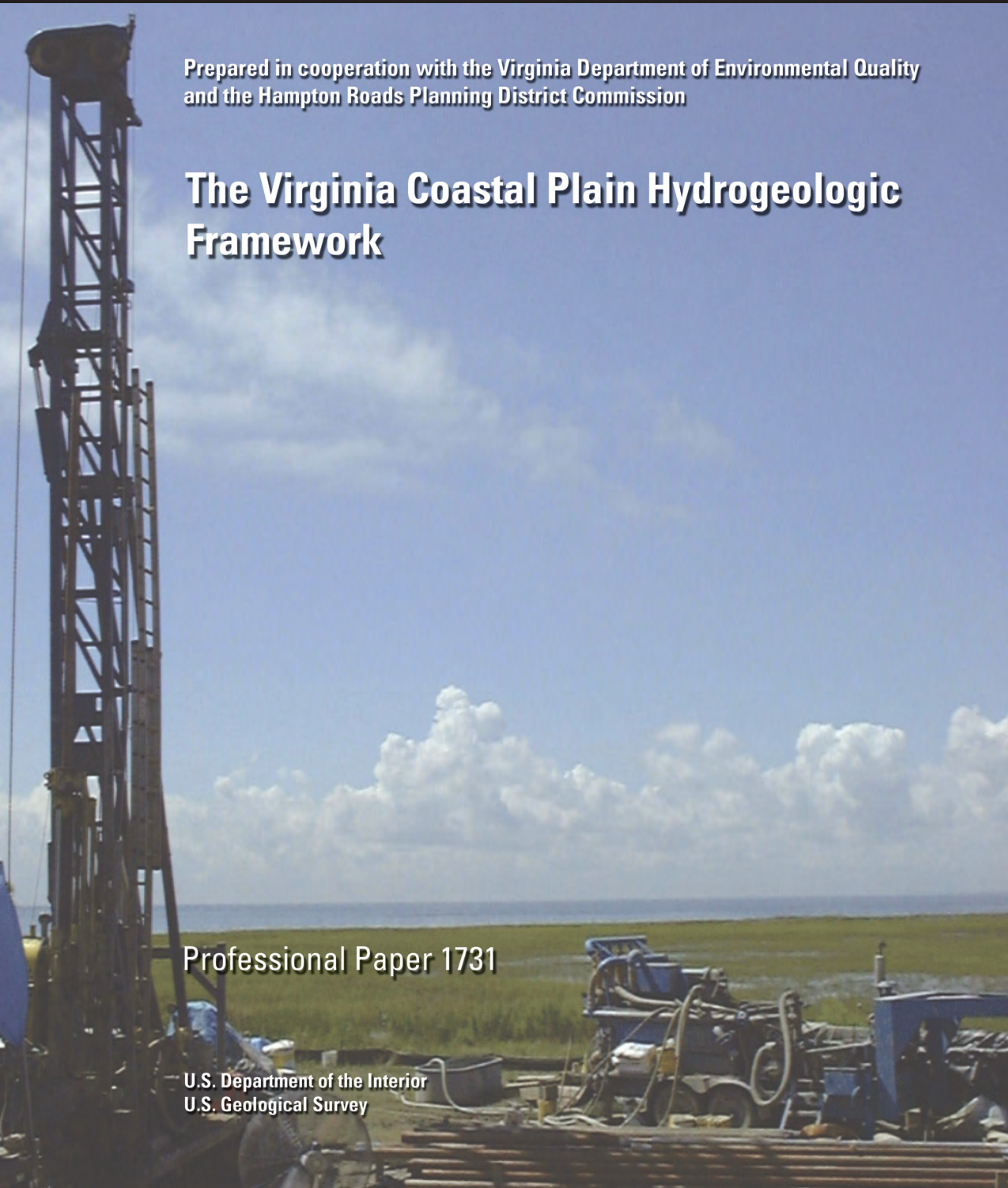

Prepared in cooperation with the Virginia Department of Environmental Quality and the Hampton Roads Planning District Commission

The Virginia Coastal Plain Hydrogeologic Framework

Professional Paper 1731

U.S. Department of the Interior
U.S. Geological Survey

Cover. Sediment-core drilling site near Bayside, Mathews County, Virginia (borehole local number 60G 5-7). View is southward overlooking tidal wetland to Chesapeake Bay on the horizon. During summer 2001, continuous core was obtained of sediments filling the 35-million-year-old Chesapeake Bay impact crater, overlying post-impact sediment, and underlying crystalline bedrock at an altitude of –2,322 feet. The continuous wire-line hydraulic rotary coring rig shown was operated by staff of the U.S. Geological Survey (USGS) Water Discipline Drilling Project in cooperation with the USGS Eastern Earth Surface Processes Team, the Virginia Department of Environmental Quality, and the Hampton Roads Planning District Commission.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information (latitude and longitude) is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above or below the vertical datum.

All photographs are by the authors except where indicated otherwise.

Acronyms:

ASTM	American Society of Testing Materials
DEM	Digital elevation model
DEQ	Department of Environmental Quality
GIS	Geographic information system
GPS	Global positioning system
HRPDC	Hampton Roads Planning District Commission
RASA	Regional Aquifer-System Analysis
USGS	U.S. Geological Survey

The Virginia Coastal Plain Hydrogeologic Framework

By E. Randolph McFarland[1] and T. Scott Bruce[2]

Abstract

A refined descriptive hydrogeologic framework of the Coastal Plain of eastern Virginia provides a new perspective on the regional ground-water system by incorporating recent understanding gained by discovery of the Chesapeake Bay impact crater and determination of other geological relations. The seaward-thickening wedge of extensive, eastward-dipping strata of largely unconsolidated sediments is classified into a series of 19 hydrogeologic units, based on interpretations of geophysical logs and allied descriptions and analyses from a regional network of 403 boreholes.

Potomac aquifer sediments of Early Cretaceous age form the primary ground-water supply resource. The Potomac aquifer is designated as a single aquifer because the fine-grained interbeds, which are spatially highly variable and inherently discontinuous, are not sufficiently dense across a continuous expanse to act as regional barriers to ground-water flow. Part of the Potomac aquifer in the outer part of the Chesapeake Bay impact crater consists of megablock beds, which are relatively undeformed internally but are bounded by widely separated faults. The Potomac aquifer is entirely truncated across the inner part of the crater. The Potomac confining zone approximates a transition from the Potomac aquifer to overlying hydrogeologic units.

New or revised designations of sediments of Late Cretaceous age that are present only south of the James River include the upper Cenomanian confining unit, the Virginia Beach aquifer and confining zone, and the Peedee aquifer and confining zone. The Virginia Beach aquifer is a locally important ground-water supply resource.

Sediments of late Paleocene to early Eocene age that compose the Aquia aquifer and overlying Nanjemoy-Marlboro confining unit are truncated along the margin of the Chesapeake Bay impact crater. Sediments of late Eocene age compose three newly designated confining units within the crater, which are from bottom to top, the impact-generated Exmore clast and Exmore matrix confining units, and the Chickahominy confining unit.

Piney Point aquifer sediments of early Eocene to middle Miocene age overlie most of the Chesapeake Bay impact crater and beyond, but are a locally significant ground-water supply resource only outside of the crater across the middle reaches of the Northern Neck, Middle, and York-James Peninsulas. Sediments of middle Miocene to late Miocene age that compose the Calvert confining unit and overlying Saint Marys confining unit effectively separate the underlying Piney Point aquifer and deeper aquifers from overlying shallow aquifers. Saint Marys aquifer sediments of late Miocene age separate the Calvert and Saint Marys confining units across two limited areas only.

Sediments of the Yorktown-Eastover aquifer of late Miocene to late Pliocene age form the second most heavily used ground-water supply resource. The Yorktown confining zone approximates a transition to the overlying late Pliocene to Holocene sediments of the surficial aquifer, which extends across the entire land surface in the Virginia Coastal Plain and is a moderately used supply. The Yorktown-Eastover aquifer and the eastern part of the surficial aquifer are closely associated across complex and extensive hydraulic connections and jointly compose a shallow, generally semiconfined ground-water system that is hydraulically separated from the deeper system.

Vertical faults extend from the basement upward through most of the hydrogeologic units but may be more widespread and ubiquitous than recognized herein, because areas of sparse boreholes do not provide adequate spatial control. Hydraulic conductivity probably is decreased locally by disruption of depositional intergranular structure by fault movement in the generally incompetent sediments. Localized fluid flow in open fractures may be unique in the Chickahominy confining unit. Some hydrogeologic units are partly to wholly truncated where displacements are large relative to unit thickness, resulting in lateral flow barriers or flow conduits.

The tops of the Saint Marys confining unit, Yorktown-Eastover aquifer, and Yorktown confining zone are widely sculpted by erosion that reflects both the present-day topography and buried paleochannels. Fault displacements across the top surfaces of these hydrogeologic units probably have been beveled by erosion. Additionally, erosion has modified the margins of many hydrogeologic units by truncation along the valleys of major rivers and their tributaries, beneath which underlying hydrogeologic units are incised. As a result, the surficial aquifer is in contact with a “patchwork” of underlying hydrogeologic units that create a complex array of hydraulic connections between the confined and unconfined ground-water systems.

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Introduction

The eastern part of Virginia lies within the Atlantic Coastal Plain Physiographic Province, hereafter referred to as the Coastal Plain (fig. 1). Ground water in the Virginia Coastal Plain is a heavily used resource. During the late 1800s, the rate of ground-water withdrawal is estimated to have been close to zero, but the withdrawal rate has increased nearly continuously during the 20th century (Harsh and Laczniak, 1990). During 1992, major ground-water users regulated by the Virginia Department of Environmental Quality (DEQ) reported withdrawal rates totaling approximately 94 million gallons per day (Mgal/d) from Coastal Plain aquifers (Hammond and Focazio, 1995); additional unregulated withdrawals at that time were unknown. During 2002 at the height of a Statewide 4-year drought, a regulated rate of 106 Mgal/d was reported (J. Pope, U.S. Geological Survey, written commun., 2003). Additionally, the unregulated withdrawal rate was estimated to be 29 Mgal/d, for a total of 135 Mgal/d in 2002. During 2003 and following the break of the drought, the regulated withdrawal rate remained large at 94 Mgal/d, and the total withdrawal rate, including unregulated withdrawals, was estimated to be 123 Mgal/d.

As a result of long-term withdrawals, ground-water levels in the Coastal Plain aquifers have declined by as much as 200 feet (ft) near large withdrawal centers. In addition, flow gradients have been altered from a previously seaward direction to a landward direction (Harsh and Laczniak, 1990), creating the potential for saltwater intrusion. Increasing withdrawals are projected, which could result in further water-level declines and potential intrusion, thereby limiting continued use of the ground-water resource.

To manage the ground-water resource, the DEQ regulates ground-water withdrawals in the most heavily used parts of the Virginia Coastal Plain, designated as Ground Water Management Areas, which include southeastern Virginia and the Virginia Eastern Shore. Withdrawals greater than 300,000 gallons per month in these areas must be approved under the DEQ Groundwater Withdrawal Permit Program, which requires ground-water users to submit withdrawal-related information that is needed to evaluate the potential effects of the withdrawals on the ground-water system.

In addition, the DEQ relies on a sound scientific understanding of Virginia Coastal Plain geology and hydrology to provide a valid context within which to make ground-water management decisions. Accordingly, the DEQ has maintained a cooperative program for hydrogeologic investigations with the U.S. Geological Survey (USGS), which has been advancing the knowledge of the geology and hydrology of the Virginia Coastal Plain since the beginning of the 20th century. Using an incremental approach, new findings have formed the basis for refinement of previous concepts and identifying needs for further investigation. Thus, major ground-breaking works have been sequentially augmented by followup investigations.

The most current and widely recognized description of the hydrogeology of the Virginia Coastal Plain resulted from the USGS Regional Aquifer-System Analysis (RASA) and allied investigations completed during the 1980s. A description of the aquifer system, termed a hydrogeologic framework, was developed by Meng and Harsh (1988) from which a digital computer model of the ground-water-flow system was constructed (Harsh and Laczniak, 1990). Although originally developed for scientific analysis of the aquifer system, the framework and model have since been partly updated and adopted by the DEQ as a resource-management tool for evaluating the potential effects of existing and proposed withdrawals (McFarland, 1998).

Several developments have occurred to further the advancement of understanding of the Virginia Coastal Plain hydrogeology. Geological relations have emerged recently but have not been incorporated into a regional hydrogeologic perspective. Most significant among these is the discovery of the world's sixth largest meteor-impact crater beneath the lower Chesapeake Bay, which poses profound implications for accurate understanding of the ground-water system (Powars and Bruce, 1999; Powars, 2000). In addition, increases in the locations and rates of ground-water withdrawals have imposed further stresses on the flow system. Resource-management efforts cannot adequately address these developments without a contemporary analysis of hydrologic conditions.

A comprehensive effort was begun in 2000 by the USGS, in cooperation with the DEQ and the Hampton Roads Planning District Commission (HRPDC), to develop a new, regional perspective of the hydrogeology of the Virginia Coastal Plain that reflects current ground-water conditions and incorporates the most up-to-date knowledge of the geology and hydrology of the area. This effort has entailed the synthesis of a large amount of information gained since 1985, and the tailoring of results toward meeting the needs for future ground-water resource management. Accordingly, during 2000–2004, hydrogeologic data were broadly collected and analyzed to formulate a refined description of the aquifer system that provides an enhanced level of detail and is based on newly emerged geologic relations. In turn, these findings are being applied to support the development of a revised digital computer model of the ground-water-flow system that is consistent with present-day hydrologic conditions and can project future conditions (Heywood, 2003).

Purpose and Scope

A description of the aquifer system of the Virginia Coastal Plain is documented herein as a hydrogeologic framework. The hydrogeologic framework serves as an information resource for ground-water investigation and development by providing a geologic understanding of the Virginia Coastal Plain in a hydrologic context.

Two distinct levels of information are presented. The first part of the report develops a conceptual perspective

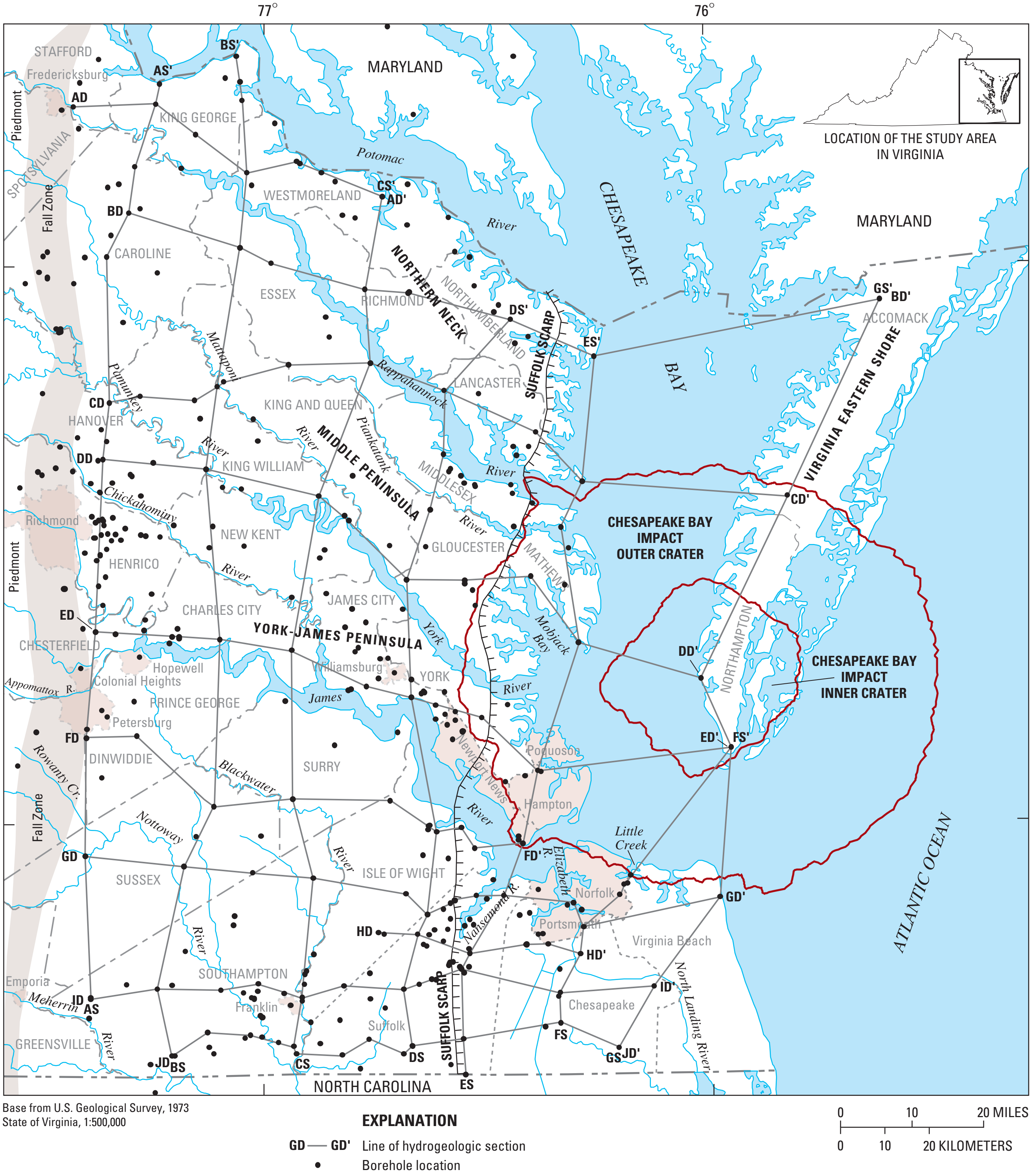


Figure 1. Locations of boreholes and hydrogeologic sections in the Virginia Coastal Plain. (Further details are shown on plate 1. Location of the Chesapeake Bay impact crater is from Powers and Bruce, 1999.)

of elements that form the scientific rationale behind the hydrogeologic framework. The context of the current study is established by summarizing the most significant previous investigations. Fundamental geologic relations are then conveyed by an account of the stratigraphic and structural evolution of the Virginia Coastal Plain. A description of the interpretations in the current study follows to provide an understanding of the analytical approach and its limitations.

The second part of the report presents detailed descriptions of each of the 19 regional hydrogeologic units that compose the Virginia Coastal Plain aquifer system. These descriptions provide specific information about each hydrogeologic unit to support ground-water resource development and management activities, and collectively provide a uniform, consistent, and stratigraphically based frame of reference. For each hydrogeologic unit, relations to geologic formation lithologies, ages, and depositional environments are discussed, along with the rationale for the unit's hydrologic designation. Comparisons are made with designations from previous studies in Virginia and adjacent States. The structural configuration of each hydrogeologic unit is presented in the form of tabulated altitudes, hydrogeologic sections, and structural contour maps based on interpretations of borehole geologic information and geophysical data. The extent, orientation, depth, and thickness of each hydrogeologic unit are described along with spatial relations to adjacent units, land surface, and structural features such as faults and paleochannels. Identification of each hydrogeologic unit penetrated during borehole drilling is discussed, including diagnostic aspects of lithologic composition, texture, and color, and drilling responses and geophysical log signatures. Lastly, each hydrogeologic unit is discussed in terms of its general function in the aquifer system, the extent and degree of its use as a water supply, its physical and hydraulic properties, recent withdrawal rates, historic and potential future trends, and general considerations for development. Each hydrogeologic-unit description is cast to serve as a stand-alone reference that can be readily accessed on an individual basis, although the discussions also include relations with other hydrogeologic units that are needed to support a system-wide perspective.

Description of Study Area

The Virginia Coastal Plain occupies an area of approximately 13,000 square miles (mi^2) between approximately latitude 36°30' and 39°00' N. and longitude 75°15' and 77º30' W. (fig. 1). The climate is temperate and humid, with annual precipitation of approximately 40 inches (in.; National Weather Service, 1996), and the region is generally heavily vegetated. Major urban centers along the western margin of the area include Fredericksburg and Richmond. A large metropolitan area, collectively referred to as Hampton Roads, occupies the southeast and consists of 16 localities including the counties of Gloucester, Isle of Wight, James City, Southampton, Surry, and York, and the cities of Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Williamsburg, Chesapeake, Suffolk, and Virginia Beach. The latter three cities are large and comparable to the counties in land area, and these cities encompass rural as well as urban land uses. The rest of the Virginia Coastal Plain is mostly rural and fairly evenly divided between cropland and forest. Small towns are widely scattered, many of which serve as county seats. Residential development is increasing by conversion of farmland in proximity to urban centers and along major waterfronts.

The Virginia Coastal Plain is characterized by rolling terrain and deeply incised stream valleys in the northwestern part, and gently rolling-to-level terrain, broad stream valleys, and extensive wetlands in the eastern and southern parts. Topography is dominated by valleys of the major rivers, including the Potomac, Rappahannock, Piankatank, Mattaponi, Pamunkey, York, Chickahominy, James, Appomattox, Blackwater, Nottoway, Meherrin, Nansemond, Elizabeth, and North Landing (fig. 1). Lowlands consisting of terraces, flood plains, and wetlands occupy valley floors and are flanked by broad uplands along basin boundaries. The uplands and lowlands are bounded by relict erosional scarps associated with the rivers (Johnson and Ramsey, 1987); these scarps are obscured in places by the present-day tributary drainage pattern. Land-surface altitude ranges from higher than 200 ft across some western uplands to 0 ft along the Atlantic coast.

The major rivers receive flow from dense and extensive networks of tributaries that extend across their entire drainage basins. These rivers collectively drain to the east and southeast into Chesapeake Bay, a large estuary formed by submersion of the Susquehanna River Valley as a result of rising sea level. Major rivers draining from the west also become estuarine upon entering the Coastal Plain. Chesapeake Bay separates most of the Virginia Coastal Plain to the west from the Virginia Eastern Shore to the east, which makes up the southernmost part of the Delmarva Peninsula. The Potomac River between Washington, D.C., and Fredericksburg diverges from the generally eastward drainage and thereby hydraulically isolates the northernmost part of the Virginia Coastal Plain, which is excluded from this investigation.

Geologic Setting

The Coastal Plain is underlain by a seaward-thickening wedge of regionally extensive, eastward-dipping strata of unconsolidated to partly consolidated sediments of Cretaceous, Tertiary, and Quaternary age that unconformably overlie a basement of consolidated bedrock (figs. 2 and 3). The sediment wedge extends from Cape Cod, MA, southward to the Gulf of Mexico and offshore to the Continental Shelf. The thickness of the sediment wedge in Virginia ranges from 0 ft at its western margin to more than 6,000 ft along the Atlantic coast (Onuschak, 1972). The sediments were deposited by seaward progradation of fluvial plains and deltas along the North American continental margin, followed by a series of transgressions and regressions by the Atlantic

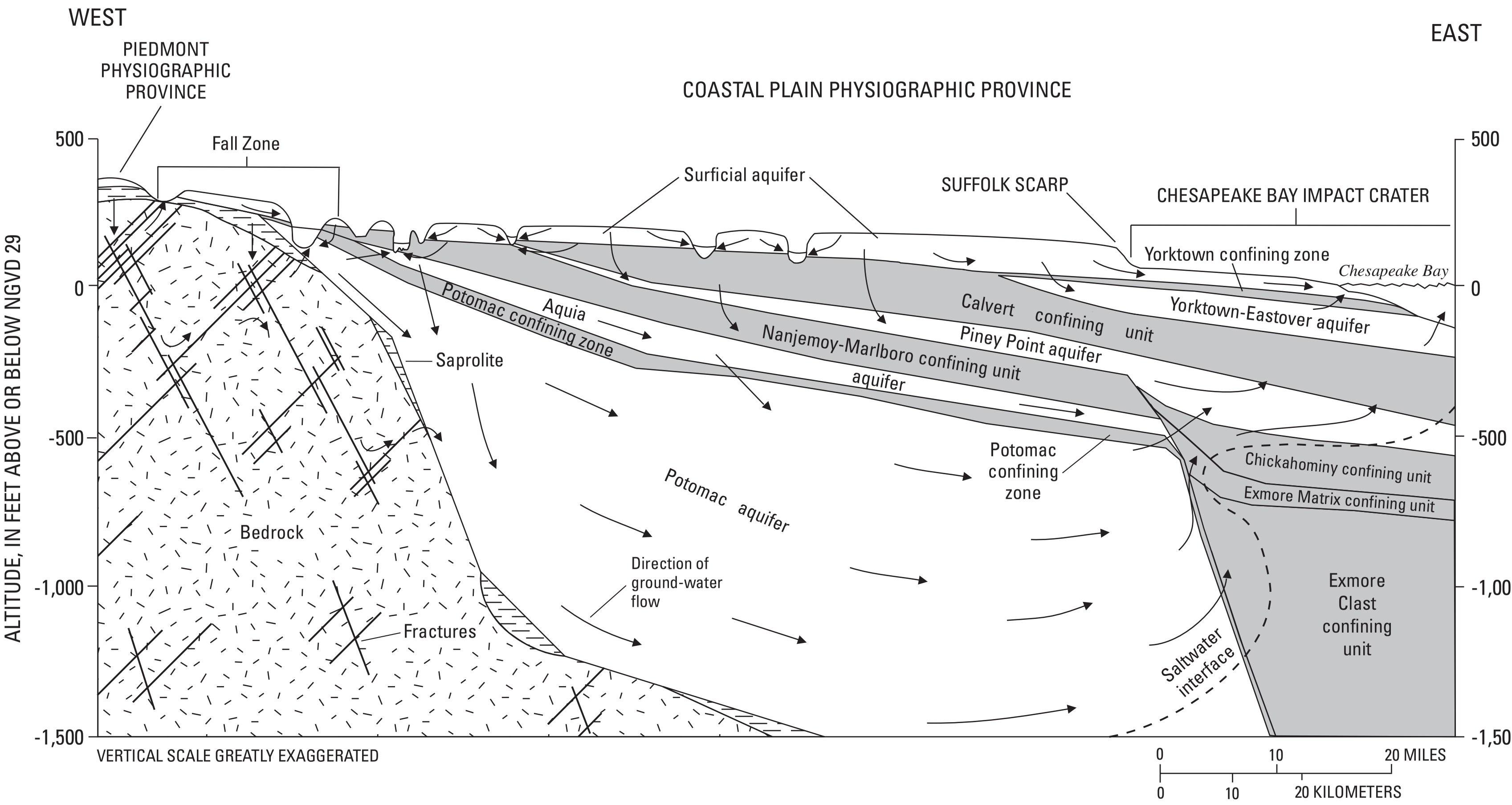
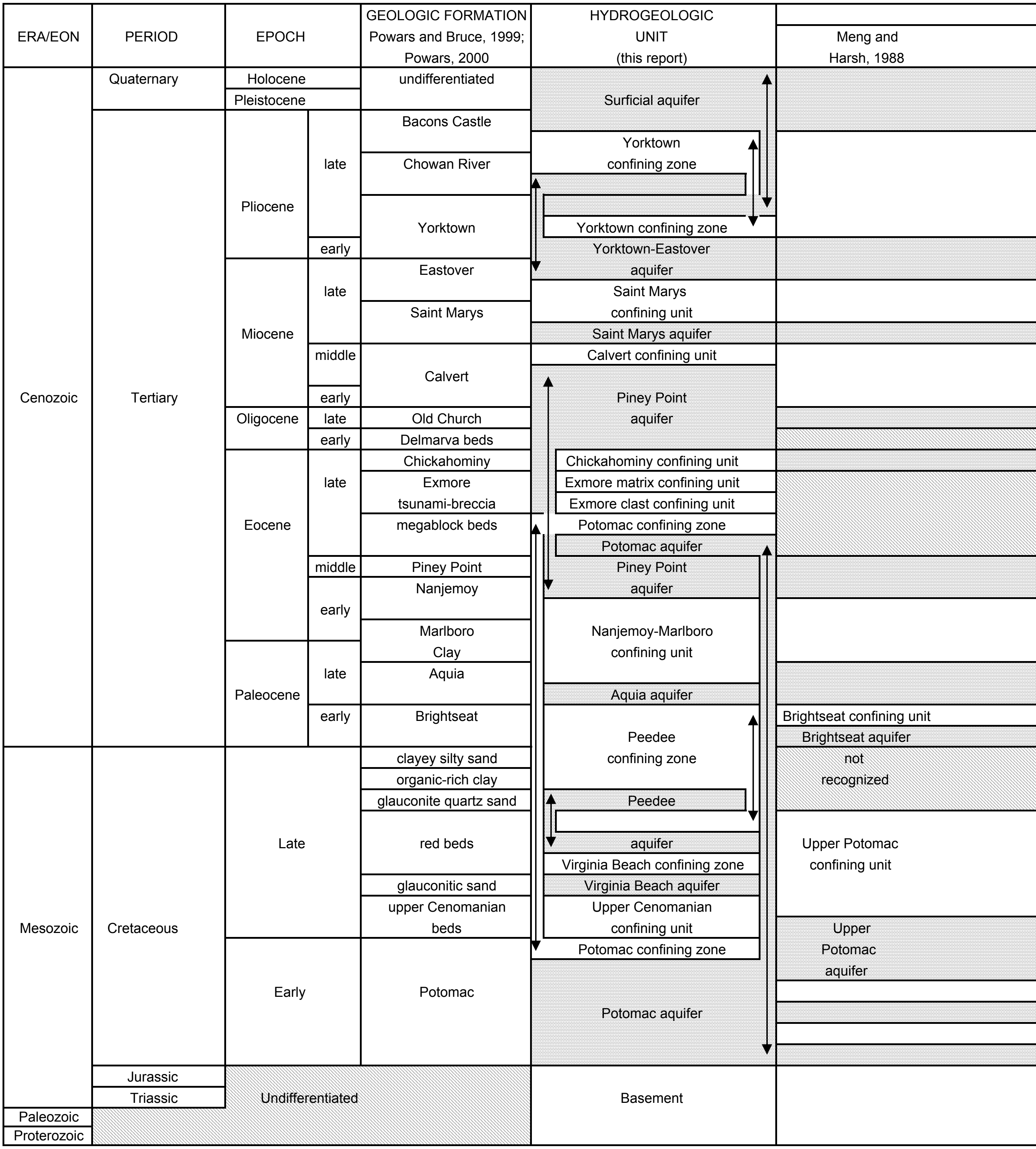


Figure 2. Generalized hydrogeologic section and directions of ground-water flow in the Virginia Coastal Plain (altitude relative to National Geodetic Vertical Datum of 1929).



ERA/EON	PERIOD	EPOCH		GEOLOGIC FORMATION Powars and Bruce, 1999; Powars, 2000	HYDROGEOLOGIC UNIT (this report)	Meng and Harsh, 1988
Cenozoic	Quaternary	Holocene		undifferentiated	Surficial aquifer	
		Pleistocene				
	Tertiary	Pliocene	late	Bacons Castle		
				Chowan River	Yorktown confining zone	
				Yorktown	Yorktown confining zone	
			early		Yorktown-Eastover aquifer	
		Miocene	late	Eastover		
				Saint Marys	Saint Marys confining unit	
					Saint Marys aquifer	
			middle	Calvert	Calvert confining unit	
			early		Piney Point aquifer	
		Oligocene	late	Old Church		
			early	Delmarva beds		
		Eocene	late	Chickahominy	Chickahominy confining unit	
				Exmore tsunami-breccia	Exmore matrix confining unit Exmore clast confining unit	
				megablock beds	Potomac confining zone Potomac aquifer	
			middle	Piney Point	Piney Point aquifer	
			early	Nanjemoy	Nanjemoy-Marlboro confining unit	
				Marlboro Clay		
		Paleocene	late	Aquia	Aquia aquifer	
			early	Brightseat	Peedee confining zone	Brightseat confining unit Brightseat aquifer
Mesozoic	Cretaceous	Late		clayey silty sand		not recognized
				organic-rich clay		
				glauconite quartz sand	Peedee aquifer	
				red beds		Upper Potomac confining unit
				glauconitic sand	Virginia Beach confining zone Virginia Beach aquifer	
				upper Cenomanian beds	Upper Cenomanian confining unit	Upper Potomac aquifer
		Early		Potomac	Potomac confining zone Potomac aquifer	
	Jurassic	Undifferentiated			Basement	
	Triassic					
Paleozoic						
Proterozoic						

Figure 3. Stratigraphic correlations of hydrogeologic units of the Virginia Coastal Plain. (Vertical arrows indicate major hydrologic not depicted.)

PREVIOUS INVESTIGATIONS IN VIRGINIA		MARYLAND	NORTH CAROLINA
Harsh and Laczniak, 1990	Hamilton and Larson, 1988; Laczniak and Meng, 1988	Vroblesky and Fleck, 1991	Winner and Coble, 1996
Columbia aquifer		Surficial aquifer	Surficial aquifer
Not recognized			Yorktown confining unit
Yorktown confining unit		Upper Chesapeake confining unit	
Yorktown-Eastover aquifer		Upper Chesapeake aquifer	Yorktown aquifer
Saint Marys confining unit		Saint Marys confining unit	Pungo River confining unit
Saint Marys-Choptank aquifer		Lower Chesapeake aquifer	Pungo River aquifer
Calvert confining unit		Lower Chesapeake confining unit	Castle Hayne confining unit
Not recognized		Not recognized	
Chickahominy-Piney Point aquifer			
Not recognized			
		Piney Point aquifer	Castle Hayne aquifer
Nanjemoy-Marlboro confining unit		Nanjemoy-Marlboro confining unit	Beaufort confining unit
Aquia aquifer		Aquia-Rancocas aquifer	Beaufort aquifer
Brightseat-Upper Potomac confining unit	Upper Potomac confining unit	Upper Brightseat confining unit	Not recognized
		Brightseat aquifer	
Confining unit 5	Peedee confining unit	Lower Brightseat confining unit	Peedee confining unit
Aquifer 5	Peedee aquifer	Severn aquifer	Peedee aquifer
		Severn confining unit	
		Matawan aquifer	
Confining unit 4	Virginia Beach confining unit	Matawan confining unit	Black Creek confining unit
Aquifer 4	Virginia Beach aquifer	Magothy aquifer	Black Creek aquifer
		Potapsco confining unit	Upper Cape Fear confining unit
Brightseat-Upper Potomac aquifer	Upper Potomac aquifer	Potapsco aquifer	Upper Cape Fear aquifer
Middle Potomac confining unit			Lower Cape Fear confining unit
Middle Potomac aquifer			Lower Cape Fear aquifer
Lower Potomac confining unit		Potomac confining unit	Lower Cretaceous confining unit
Lower Potomac aquifer		Patuxent aquifer	Lower Cretaceous aquifer
Basement			

associations that cross stratigraphic boundaries. Minor overlaps of hydrogeologic units among adjacent geologic formations are

Ocean in response to changes in sea level. A thick sequence of nonmarine strata primarily of Cretaceous age is overlain by a much thinner sequence of marine strata of Tertiary age, which is in turn overlain by a veneer of nearly flat-lying terrace and flood-plain deposits primarily of Quaternary age (Meng and Harsh, 1988).

Coastal Plain sediments in Virginia were further affected during the Tertiary Period by the impact of an asteroid or comet near the mouth of Chesapeake Bay (Powars and Bruce, 1999). The Chesapeake Bay impact crater is greater than 50 mi in diameter and extends across a large part of the southeastern Virginia Coastal Plain (fig. 1). The crater was formed within the preexisting sediments and contains a unique assemblage of impact-related material. Subsequent sediment deposition has buried the crater approximately 1,000 ft below the present-day land surface.

The area to the west of the Coastal Plain is the Piedmont Physiographic Province (Piedmont, figs. 1 and 2), which is characterized by rolling terrain. Residual soils range from nearly 0 to 100 ft thick and are underlain by igneous and metamorphic bedrock of late Proterozoic and early Paleozoic age, along with fault-bounded structural basins containing sedimentary and igneous bedrock of Triassic and Jurassic age. Shallow alluvial deposits of Quaternary age are localized in stream valleys. The transitional part of the Coastal Plain toward the Piedmont is designated as the Fall Zone. Numerous falls and rapids are present along streams across the Fall Zone because the gradients increase as the streams flow generally eastward from resistant bedrock onto more easily eroded sediments. From the Fall Zone, the Piedmont bedrock dips beneath the sediment wedge to constitute the basement that underlies the Coastal Plain. The configuration of the Fall Zone is intricate because streams have eroded through Coastal Plain sediments to expose Piedmont bedrock in their valley floors; interstream divides are capped by uneroded sediments overlying the bedrock (Mixon, Berquist, and others, 1989). Hence, the Fall Zone constitutes a belt several miles wide.

Ground-Water Conditions

The Coastal Plain sedimentary strata form a hydrogeologic framework of aquifers and confining units (Meng and Harsh, 1988). Permeable formations from which substantial amounts of water can be withdrawn are designated as aquifers, and less permeable formations that restrict ground-water flow are considered to be confining units. Because of their great thicknesses and large areal extents, Coastal Plain aquifers provide a widely used ground-water supply (Heath, 1984).

None of the aquifers or confining units extend across the entire Virginia Coastal Plain. A complex history of sediment deposition has produced numerous lateral variations in lithology. Consequently, the positions of aquifer and confining-unit margins are divergent, and their areal distribution has a complex overlapping “patchwork” configuration. In particular, some aquifers and confining units pinch out westward toward the Fall Zone where the vertical sequence of aquifers and confining units varies widely compared to other parts of the Coastal Plain. In addition, major discontinuities among aquifers and confining units are present along the margin of the Chesapeake Bay impact crater.

Hydrogeologic conditions in the Coastal Plain are distinct from the Piedmont. In the Coastal Plain, ground water is present in pores between the sediment grains. By contrast, ground water in the Piedmont is present mostly in fractures in the bedrock and in pores in weathered residuum on the bedrock.

Ground water in the Coastal Plain is recharged principally by precipitation infiltration and percolation to the water table. Most of the unconfined ground water flows relatively short distances and discharges to nearby streams but a small amount flows downward to recharge the deeper confined aquifers (fig. 2), primarily along the Fall Zone and beneath surface-drainage divides between major river valleys (Harsh and Laczniak, 1990). Because aquifers in the Fall Zone are shallow and subcrop along major rivers, flow interactions with the rivers result from direct hydraulic connections to the land surface (McFarland, 1999). The basement generally is conceptualized as an underlying impermeable boundary. Flow interaction may occur between bedrock fractures and the overlying sediments, but this has not been clearly identified.

Because of stratification of the Coastal Plain sediments, horizontal hydraulic conductivity generally is greater than vertical hydraulic conductivity. Hence, flow through the confined aquifers primarily is lateral in the down-dip direction to the east (fig. 2) and toward large withdrawal centers and major discharge areas near large rivers and the Atlantic coast. Dense saline water at the interface between freshwater and saltwater causes the confined ground water to discharge by upward flow across intervening confining units. In addition, stagnant saltwater within the Chesapeake Bay impact crater has been theorized to cause a lateral divergence of flow to either side of the crater (McFarland and Bruce, 2005).

Methods of Investigation

Direct examination of the sediment wedge underlying the Virginia Coastal Plain is inherently limited because most of the sediments are positioned hundreds to thousands of feet below land surface and do not crop out. Surface exposures are very sparse because of lush vegetation and low topographic relief and generally are restricted to the cut banks of the largest rivers and a few relatively shallow quarries. Accordingly, various forms of drilling were used to examine the sediments. Because most of the sediments are unconsolidated, hydraulic rotary techniques that can maintain open boreholes in these materials to depths of several hundred feet or more were used most frequently, although augering also was undertaken to shallower depths. Thus, examination of the sediments generally was not based on direct observation across broad areas but rather at discrete borehole locations. Consequently, further description of the aquifer system at the regional scale generally was inferred from correlations made between boreholes across relatively large areas that were not directly examined.

Borehole Geophysical-Log Network

For this study, description of the Virginia Coastal Plain aquifer system is based on interpretations of data obtained from a network of 403 boreholes located across the area (fig. 1; pl. 1; Attachment 1). Geophysical logs and other borehole data were selected from records on file at the USGS Virginia Water Science Center in Richmond, VA. These records were compiled by the USGS in cooperation with the DEQ and HRPDC, the Virginia Division of Mineral Resources, local and State health departments, water-well drilling contractors and hydrogeologic consulting firms, and other agencies and organizations. Although some of these data were collected and the records compiled specifically for and during the period of this study (2000–2004), the majority were collected and compiled previously either as part of earlier studies or for ongoing data-collection programs. Hence, the data span a period of several decades during which many individuals, both inside and outside the USGS, have contributed to the current body of information (see “Acknowledgments”). A small minority of the most recent geophysical logs was generated in electronic form using modern digital equipment. The majority of logs, however, was generated by using analog equipment and exists solely as paper strip charts, many of which have been handled extensively and exhibit substantial degrees of wear. Many of these logs were used in earlier studies of the Virginia Coastal Plain (see “Previous Investigations”) and, in some cases, have undergone alternative interpretations, depending on the nature of supportive information and conceptual views held at the time.

One or more types of geophysical logs represent each borehole and compose the primary information baseline for all of the boreholes. Methods of borehole geophysical log interpretation are presented generally by Keys (1990), and application specifically to the Virginia Coastal Plain is described in Meng and Harsh (1988) and largely followed herein. Interpretations for this study were based primarily on combined logs of spontaneous potential, single-point resistance, and(or) long- and short-normal resistivity, commonly referred to as electric logs (fig. 4). Relative variations among spontaneous potential and electrical resistance or resistivity measured in the boreholes were examined to identify intervals of contrasting sediment texture and inferred permeability. Intervals having increased values of specific conductance and resistance or resistivity indicate the presence of coarse-grained sediments and(or) shell material and were inferred to reflect relatively large permeabilities that represent aquifers. Conversely, intervals having decreased values indicate

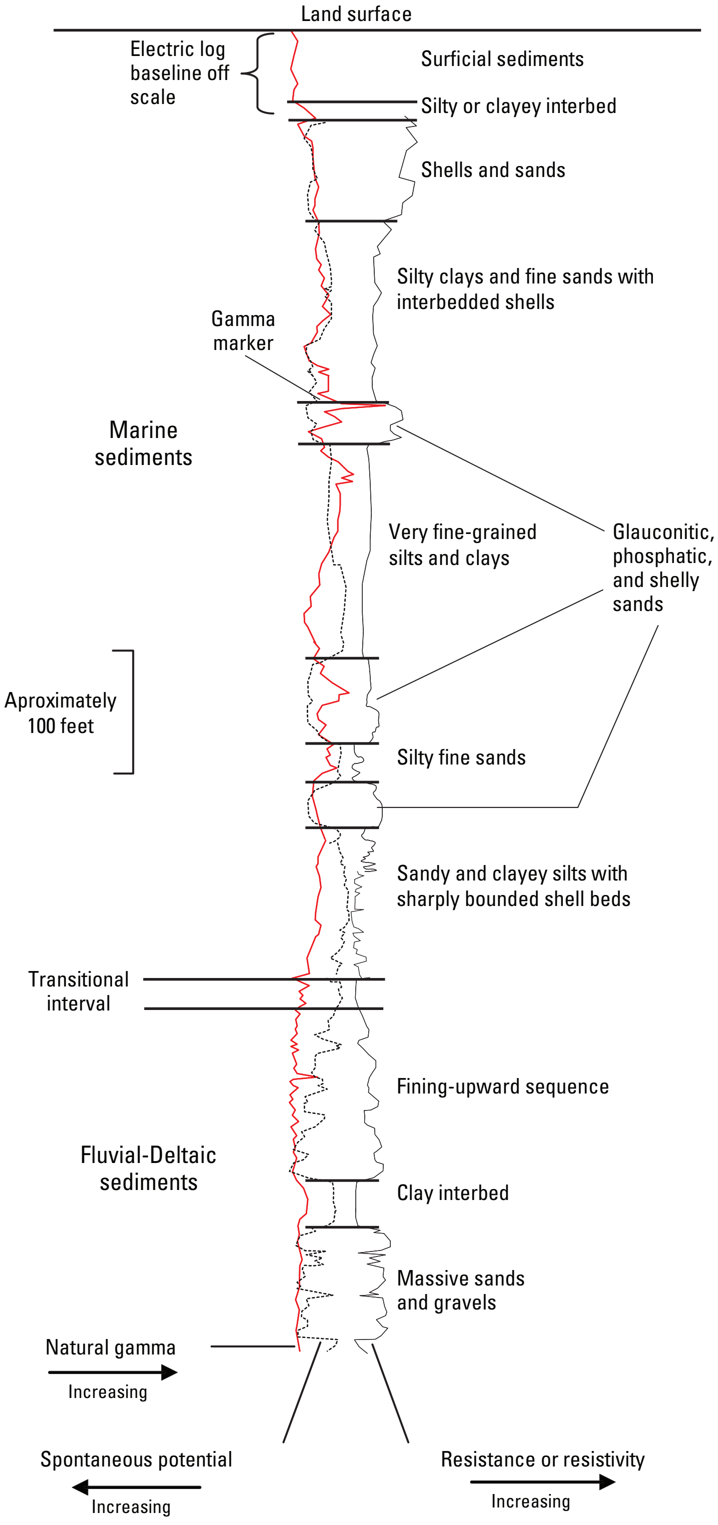


Figure 4. Generalized composite electric and gamma borehole geophysical logs.

the presence of primarily fine-grained sediments, and were inferred to reflect relatively small permeabilities that represent confining units.

Intervals identified on electric logs were tabulated as hydrogeologic-unit top-surface altitudes (Attachment 1). All top-surface altitudes are referenced to NGVD 29, as calculated from surface depths below the altitudes of land surface at the borehole locations. Most borehole-location altitudes were estimated from topographic maps to within plus or minus (+/–) 5 ft. In addition, borehole measured depths for geophysical logs and associated data can commonly vary by several feet, depending on whether the measurement was taken from true land surface, the top of a surface casing, or some other datum usually not recorded. Hence, hydrogeologic-unit top-surface altitudes generally are accurate to within +/–10 ft.

In addition to electric logs, some boreholes were used to generate natural gamma logs, which were used as a form of supportive information in interpreting the electric logs (fig. 4). Gamma logs indicate the intensity of naturally occurring radiation as a function of sediment mineralogy. Certain minerals common to Coastal Plain sediments, such as potassium-containing clays, produce relatively intense radiation. In particular, compounds of phosphate, such as apatite, contain trace quantities of uranium and thorium that produce radiation. By contrast, most sands and gravels are dominated by quartz, which has low-radiation intensity. Thus, relative variations in radiation intensity exhibited on gamma logs reflect fine-grained clays and course-grained sands and gravels, and commonly parallel electric logs of the same borehole. An important exception can result, however, when phosphate is present. Sands of marine origin commonly contain appreciable amounts of glauconite and quartz but also lesser amounts of phosphate, which can produce elevated radiation intensities. Accordingly, electric logs were used in tandem with available gamma logs to distinguish marine sands from purer quartz sands that are typically of terrestrial origin. In addition, certain intervals contain purer phosphatic sands that, despite being relatively coarse grained, exhibit among the highest radiation intensities observed. Such intervals were treated as key stratigraphic control markers to further support electric log interpretation.

Borehole-Data Quality

Geophysical logs are indirect examinations of the materials penetrated by boreholes. Particular variations in specific conductance and resistance and(or) resistivity on electric logs, however, can be distinguished as log signatures that are diagnostic of the presence of certain aquifers or confining units, depending on the nature of additional supportive information. Conversely, variations can be obscured by indistinct contacts created by burrowing or re-working between contrasting sediments, or as a result of differences in measurement technique and(or) borehole conditions, such as changes in diameter or wall mud-cake thickness, which in most cases are unknown. Further complications arise in some coastal areas where saltwater alters measurement response. Similarly, the shallowest several tens of feet of most electric logs generally are obscured because the baseline of measurement response is shifted beyond the scale of the log. Thus, some logs or parts of logs have a higher degree of uncertainty, and their interpretation is more dependent on supportive information.

A comprehensive effort was undertaken during this study to make full use of the large amount of information available as described above. Although detailed geologic information is available for some locations, the data from many of the boreholes originated from activities beyond the scope of this study, such as water-supply construction operations. Hence, the information inevitably is not of equal quality for every borehole. For the purposes of discussion, a three-tiered ranking is described herein to distinguish different levels of borehole-data quality.

Only a geophysical log and(or) little or no additional information is available for 346 boreholes, which represent 86 percent of the borehole network and constitute the first tier of data quality. Some of these boreholes have generalized descriptions of sediment lithology, such as drillers' logs, which have only very limited interpretive value. In addition, a relatively small number of boreholes for which geophysical logs are not available was included to determine the altitude of bedrock basement. Most of these boreholes are located within or close to the Fall Zone and serve solely to extrapolate the basement surface westward from the study area. A few boreholes in the Coastal Plain are of sufficient depth to penetrate to basement, and geophysical logs were produced from most of these. In addition, for most first tier boreholes, location information was taken directly from compiled records and was not field verified. The considerable uncertainty inherent in interpretations based solely on geophysical logs was addressed in this study to the extent possible by tandem use of nearby boreholes for which higher levels of supportive information is available.

An enhanced level of supportive information is available for 27 boreholes from which, in addition to geophysical logs, relatively detailed information on sediment lithology and other geological aspects has been collected. These 27 boreholes, which represent 7 percent of the borehole network and constitute the second tier of data quality, consist primarily of water-supply and observation wells drilled during the study period. Drill cuttings were collected for these wells and are described directly by the authors of this report. The cuttings were collected under controlled conditions whereby hydraulic drilling techniques were adapted to improve the degree to which cuttings represent the actual sediment lithology. Whenever possible, a drag bit was used to help produce sediment chips that can be identified more readily in hand specimens instead of the more typical roller bit, which usually results in nearly liquefied cuttings. In addition, drill-rod advancement and drilling-fluid circulation and weight were regulated to stabilize the rate-of-cuttings return between drill runs and to minimize and account for the degree of mixing of freshly drilled material with unflushed material remaining in the borehole from earlier runs. Locations of the boreholes were determined with a global positioning system (GPS). Information available from nearby boreholes also was used to provide a perspective on the placement of the borehole being drilled within the regional setting. Thus, the cuttings were used to compile a lithologic log for each borehole that is not only relatively detailed and accurate but also incorporates a conceptual understanding of geologic aspects among the sediments that were penetrated, such as relative ages and formation relations. Because lithologic logs based on cuttings descriptions are an indirect means of examining the sediments, however, varying degrees of uncertainty still exist in the interpretation of the geophysical logs.

The highest level of supportive information is available for 31 boreholes, which represent 8 percent of the borehole network and constitute the third tier of data quality. In addition to geophysical logs, sediment cores were retrieved from these boreholes and provide the most direct and detailed information on sediment lithology and other geological aspects. Relatively shallow auger techniques were used at 12 of these boreholes by McFarland (1997, 1999) and at one other borehole by Bybell and Gibson (1994). The remaining cores were collected by the DEQ and USGS Eastern Earth Surface Processes Team using continuous wire-line techniques. Of these, 11 were documented in Powars and Bruce (1999) and Powars (2000), and three others were documented by Reinhardt and others (1980), Mixon, Powars, and others (1989), and Powars and others (2001). One additional core located at Jamestown and documented in Powars and Bruce (1999) was used to support interpretation of geophysical logs from nearby boreholes but is not included as part of the borehole network because the geophysical log of the cored borehole was not obtained. All of the cores were collected either specifically as part of a study of the geology of the Chesapeake Bay impact crater or for earlier studies of the geology or hydrology of the Virginia Coastal Plain, which largely led to the discovery of the crater. Locations of most of the cored boreholes were determined with a GPS.

Core consists of a vertically oriented, cylindrical mass of sediment retrieved from the subsurface through the borehole that generally is structurally intact and precisely referenced to depth below land surface. Thus, core provides direct hand specimens of the vertical sequence of sediments at the borehole location and largely eliminates the uncertainties inherent in less direct means of sediment examination, such as cuttings descriptions or drillers' logs. The cores collected in the Virginia Coastal Plain have been very closely examined, and highly detailed lithologic logs have been compiled as a result. In addition, the cores have undergone mineralogical and paleontological analyses to establish sediment ages and formational relations (Reinhardt and others, 1980; Mixon, Powars, and others, 1989; Bybell and Gibson, 1994; Powars and Bruce, 1999; Powars, 2000; Powars and others, 2001). For this study, the cores were used in tandem with corresponding geophysical logs to distinguish diagnostic log signatures of various hydrogeologic units, which provide the strongest possible baseline of information for description of the aquifer system. Formational relations are based on the sources cited above, and geologic-age designations generally follow Berggren and others (1995).

Also as part of this study, sediment core collected within the area of the Chesapeake Bay impact crater was further analyzed hydrologically and texturally (table 1). Permeameter samples were collected from sections of core selected as representative of predominant hydrogeologic-unit lithologies. For each sample, a structurally intact, approximately 1-ft section was isolated upon retrieval from the borehole within a closely fitting steel tube and subsequently sealed with melted wax to preserve sediment structure during transport from the drill site. The vertical hydraulic conductivity of each sample was determined by using the flexible-wall, falling-head permeability, American Society of Testing Materials (ASTM) method D5084 (American Society of Testing Materials, 1990). Vertical hydraulic conductivity values generally are considered representative only within an order of magnitude because of (1) the small size of the sample relative to the scale of sediment variations within the aquifer system, and (2) the possibility of disruption of sediment structure during sample collection and(or) analysis. In addition, the high end of the possible range of values is likely underrepresented because the most coarse-grained sediments are wholly noncohesive and could not be viably collected and analyzed.

In addition to vertical hydraulic conductivity, sediment grain-size distributions of the sediment core samples were characterized by the sieve and hydrometer analysis ASTM method D422 (American Society of Testing Materials, 1990), which is summarized as a gross measure herein by the mass percentage of sediment grains having diameters less than 0.074 millimeter (passing through a number 200 sieve; table 1). A large value indicates a generally fine-grained texture. Porosities of the samples also were calculated from measurements of specific gravity, moisture content, and dry density. For comparison with the permeameter samples, hydraulic conductivities of each of the hydrogeologic units reported in previous studies were compiled (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Harsh and Laczniak, 1990), and include values derived by calibration of ground-water models, specific-capacity and slug tests of wells, and laboratory analyses of cores (table 2).

Table 1. Vertical hydraulic conductivity, texture, and porosity values for permeameter samples from sediment cores, Virginia Coastal Plain.

[Borehole numbers refer to locations on plate 1; NGVD 29, National Geodetic Vertical Datum of 1929; NASA, National Aeronautics and Space Administration]

Borehole number – site name	Geologic formation	Sample altitude (feet, referenced to NGVD 29)	Vertical hydraulic conductivity (feet per day)	Mass smaller than 0.074-millimeter diameter (percent)	Porosity (percent)
Surficial aquifer					
59E 32 – Watkins	Shirley	–55	0.45	8.1	35
Yorktown-Eastover aquifer					
59E 31 – NASA Langley	Yorktown	–50	0.0022	45.6	45
Do.	Eastover	–76	.00062	84.1	53
59E 32 – Watkins	......do.	–135	.0022	30.1	43
Saint Marys confining unit					
60G 5-7 – Bayside	Eastover	–207	0.0023	57.7	32
59E 31 – NASA Langley	Saint Marys	–247	.00023	94.2	47
59E 32 – Watkins	......do.	–279	.000034	99.7	54
60G 5-7 – Bayside	......do.	–267	.0026	99.3	51
Calvert confining unit					
59E 32 – Watkins	Calvert	–343	0.000057	99.3	60
60G 5-7 – Bayside	......do.	–386	.060	99.0	57
Piney Point aquifer					
59E 31 – NASA Langley	Old Church	–469	0.010	22.5	41
59E 32 – Watkins	......do.	–430	.00042	27.8	42
60G 5-7 – Bayside	......do.	–588	.017	19.7	33
Chickahominy confining unit					
59E 31 – NASA Langley	Chickahominy	–635	0.011	98.8	49
59E 32 – Watkins	......do.	–537	.000031	98.7	50
60G 5-7 – Bayside	......do.	–797	.00057	95.2	49
Exmore matrix confining unit					
59E 31 – NASA Langley	Exmore (matrix)	–788	0.00037	31.0	35
59E 32 – Watkins	......do.	–615	.00018	29.4	33
60G 5-7 – Bayside	......do.	–931	.00085	25.0	34
Do.	......do.	–1,068	.0034	29.4	37
Exmore clast confining unit					
60G 5-7 – Bayside	Exmore (matrix)	–1,467	0.00060	30.8	32
59E 31 – NASA Langley	Exmore (sand clast)	–997	.00065	65.1	35
60G 5-7 – Bayside	......do.	–1,138	.054	26.7	35
59E 31 – NASA Langley	Exmore (clay clast)	–926	.0028	90.3	37
60G 5-7 – Bayside	......do.	–1,606	.000060	95.1	34
Potomac aquifer					
59E 31 – NASA Langley	Potomac (sand)	–1,859	0.012	11.7	37
Do.	......do.	–2,032	2.8	36.3	28
59E 32 – Watkins	......do.	–675	1.4	20.4	35
Do.	......do.	–955	.31	15.9	30
60G 5-7 – Bayside	......do.	–2,126	.00059	23.7	24
59E 31 – NASA Langley	Potomac (clay)	–1,905	.00034	97.0	37
59E 32 – Watkins	......do.	–635	.000025	89.6	43
60G 5-7 – Bayside	......do.	–1,965	.0021	99.1	37

Table 2. Summary of published values of horizontal hydraulic conductivity in aquifers and vertical hydraulic conductivity in confining units in the Virginia Coastal Plain.

[All values shown are in feet per day; —, no value published]

Hydrogeologic unit (fig. 2)	Literature citation					
	Harsh and Laczniak (1990)	Laczniak and Meng (1988)	Hamilton and Larson (1988)	Richardson (1994)	McFarland (1997)	McFarland (1999)
Surficial aquifer	18.1[a]	6.4 – 170[b]	18.1[a] 6.4 – 170[b]	—	0.0084 – 76[c] 12 – 120[a]	50 – 100[a]
Yorktown confining zone	0.000864[a] 0.0039 – 0.00059[d]	0.000864[d]	0.000864[a]	0.000013 – .000016[d]	—	—
Yorktown-Eastover aquifer	14.7[a]	0.7 – 353[b]	14.7[a] 0.7 – 353[b]	1.6 – 60[b]	—	—
Saint Marys confining unit	0.000415[a] 0.00002 – 0.0000028[d]	0.000415[d]	0.000415[a]	—	—	—
Saint Marys aquifer	14.7[a]	—	—	—	—	—
Calvert confining unit	0.000112[a] 0.0000092[d]	0.0000449 – 0.000588[d]	0.0000389[a]	—	—	—
Piney Point aquifer	25.1[a]	1.5 – 442[b]	12.1[a] 1.5 – 701[b]	—	—	—
Nanjemoy-Marlboro confining unit	0.0000536[a] 0.0000022 – 0.00002[d]	0.0000126 – 0.0000363[d]	0.0000648[a]	—	—	0.000035[a]
Aquia aquifer	26.9[a]	1.8 – 219[b]	15.1[a] 1.8 – 301[b]	—	—	50[a]
Peedee confining zone	0.0000778[a]	—	0.0000691[a]	—	—	—
Peedee aquifer	23.3[a]	—	23.3[a]	—	—	—
Virginia Beach confining zone	0.0000346[a]	0.0000518[d]	0.0000734[a]	—	—	—
Virginia Beach aquifer	25.9[a]	—	43.2[a]	—	—	—
Potomac confining zone	0.0000441[a]	0.0000363[d]	0.0000605[a]	—	—	0.0001 – 0.0003[a]
Potomac aquifer	32.8 – 51.8[a] 0.000023 – 0.0000019 (clay)[d]	0.7 – 344[b] 0.00002 – 0.000081 (clay)[d]	41.5 – 64.8[a] 0.7 – 347[b]	—	0.22 – 6.1[c] 10[a]	50[a]

[a] Value was determined by ground-water model calibration.
[b] Value was determined by well specific-capacity test.
[c] Value was determined by well slug test.
[d] Value was determined by core laboratory analysis.

Hydrogeologic Framework

The hydrogeologic framework is an important information resource for ground-water investigation and development in the Virginia Coastal Plain. Following establishment of a sound conceptual perspective, detailed descriptions of the aquifer system can be applied in support of ground-water resource development and management.

Conceptual Development

A complete understanding of the Virginia Coastal Plain hydrogeologic framework necessitates a perspective that encompasses elements that form its scientific rationale. The current study is founded on several decades of geologic and hydrologic investigation. Moreover, an approximately 140-million-year history of stratigraphic and structural evolution of the Virginia Coastal Plain has resulted in geologic relations that underpin the controls on ground-water flow. Analyses of hydrogeologic information and the limitations of these analyses are integral to this study and must be understood to enable valid applications of the hydrogeologic framework.

Previous Investigations

Several publications document the most important contributions to the evolving knowledge of the hydrogeology of the Virginia Coastal Plain. Among the earliest are Clark and Miller (1912), which presents a regional geologic framework, and Sanford (1913), which presents an assessment of underground water resources; both of these were ground breaking but preliminary in scope. Subsequent and more in-depth works are cited throughout this report to reference information supporting particular discussions. Numerous studies of a topic-specific or geographically limited scope also have been conducted but have not been referenced herein. The discussion in this report is not meant to be wholly inclusive but to highlight some of the efforts that have had regional significance.

Pioneering Investigations by D.J. Cederstrom

Among the investigators cited herein, perhaps the single most prolific contributor was D.J. Cederstrom of the USGS. During three decades spanning the middle part of the 20th century, Cederstrom compiled a series of reports that remain collectively the most comprehensive documentation of ground-water conditions in the Virginia Coastal Plain. Cederstrom's work greatly expanded the results of earlier studies to provide a far more in-depth analysis than had been given previously. Many studies during the latter part of the 20th century have drawn heavily on Cederstrom's work, which continues to be cited as the fundamental information baseline from which to pursue further efforts. Hence, although the results of earlier studies are significant in their own right, Cederstrom's studies are considered herein as having the earliest, most lasting relevance to contemporary understanding of Virginia Coastal Plain hydrogeology.

Cederstrom (1939) described ground-water conditions in Sussex, Southampton, and Isle of Wight Counties. Release of this information was followed soon with a summary of conditions south of the James River (Cederstrom, 1941), which was a preliminary release of information contained in a comprehensive report published a few years later (Cederstrom, 1945a). A separate publication contains tabulations of geologic well logs collected throughout these efforts (Cederstrom, 1945b). In the interim, however, an in-depth assessment was made of high chloride concentrations in ground water in the central and southeastern Virginia Coastal Plain (Cederstrom, 1943). High chloride concentrations in ground water and other hydrogeochemical relations were described further in two reports (Cederstrom, 1946a, b). A decade later, results of a comprehensive study encompassing the York-James Peninsula were published (Cederstrom, 1957), as were the results of a similar investigation of the Middle Peninsula (Cederstrom, 1968). The following year, a manuscript of equal scope and similar organization was compiled for the Northern Neck by Sinnott (1969), who worked closely with Cederstrom to complete some of his latest work.

Cederstrom's reporting is unique in that his hydrogeologic interpretations are represented mostly by sectional illustrations and a few structural maps. The structural development of the Virginia Coastal Plain is described beginning with the deposition of sediments of Cretaceous age. Specific aquifers or confining units were not designated. Instead, Cederstrom focused his reporting on descriptions of geologic formations or groups. The distribution, chemical quality, utilization, and other aspects of specific water-bearing zones were identified in parts of some formations or groups, whereas other formations or groups were described more broadly as either water bearing or not. Particular note often was made of lithologic variations that largely determine the water-bearing potential within a formation or group. In addition, numerous anecdotal examples were given of geologic and ground-water conditions based on many lithologic logs and some chemical analyses. The manuscripts were extensively supplemented with descriptions of well-construction and water-supply development practices and background information on the physiography, economy, history, and demographics of the study areas.

Geologic Refinement

Studies during the 1970s and 1980s that followed the final contribution of Cederstrom (1968) included four investigations focusing primarily on geologic aspects that encompass most or all of the Virginia Coastal Plain. In the first of these studies, Brown and others (1972) presented a regional analysis of the Atlantic Coastal Plain extending from Long Island, New York, south through North Carolina. A detailed stratigraphic correlation was made of the entire sedimentary section across the region and has been cited frequently by many investigators since. Less widely recognized, however, is an elaborate tectonic model that also was presented to portray the structural evolution of the continental margin and its consequent control on the depositional history of Coastal Plain sediments.

One of the more recent sources most often cited in discussions of the geology of the Virginia Coastal Plain is Teifke (1973), who discussed the stratigraphy, structure, and depositional history of the entire Virginia Coastal Plain except for the far northern panhandle and the Eastern Shore. Although no description was given of ground-water conditions, the broad scope of the discussion represented a significant development in the basic geologic understanding that was necessary to adequately characterize the ground-water system.

Teifke's (1973) stratigraphic correlations were based on lithologies of well-cutting samples. Although the basic stratigraphic and structural configurations of the Virginia Coastal Plain were described similarly as those in other studies, only seven major stratigraphic units were recognized, which is fewer than the number recognized by both earlier and later investigators. Teifke (1973) acknowledged some of the earlier recognized formations but included them within his units. Most groupings of formations were not recognized. The geologic structure of the Virginia Coastal Plain was presented in several stratigraphic sections along with top-surface altitude and isopach (thickness) structural contour maps of most of the formations. The depositional history of the Virginia Coastal Plain was described with the aid of a series of maps that depict changes in the configuration of the basement surface. The basement-surface maps were constructed using the individual formation structural maps and were based on the assumption that the top surface of each formation was essentially level at the time of deposition.

During the 1980s, separate studies of sediments of Cretaceous and Tertiary age in the Virginia Coastal Plain were conducted. On the assertion that no comprehensive survey had been made of the Cretaceous depositional history of the entire Atlantic Coastal Plain, Owens and Gohn (1985) presented what they described as a preliminary and necessarily incomplete summary. The tectonic framework discussed was much more generalized than that presented by Brown and others (1972). Ward and Strickland (1985) summarized the depositional history of Tertiary sediments in the Atlantic Coastal Plain, augmenting that presented by Ward (1985). A detailed account was given of the depositional history of the Salisbury embayment, which is centered to the north but occupies most of the Virginia Coastal Plain.

Regional Aquifer-System Analysis

Following the period of primarily geological characterization of the Virginia Coastal Plain, the USGS undertook the first specifically hydrogeological analysis as part of the Regional Aquifer-System Analysis (RASA) program. Meng and Harsh (1988) defined a hydrogeologic framework of the Virginia Coastal Plain as a complex of nine aquifers and eight intervening confining units, based on interpretations of electric logs, lithologies, pollen, and water levels. The aquifers were designated by using hydrogeologic names based on the geologic formations present within the Salisbury embayment, which is more dominant in Virginia than the Albemarle embayment centered to the south. Although a substantial body of investigation has followed, the Meng and Harsh (1988) framework has remained to date (2006) the single, most definitive source of information on Virginia Coastal Plain hydrogeology.

The Meng and Harsh (1988) framework formed the basis for a numerical analysis of ground-water flow in the Virginia Coastal Plain using a digital computer model by Harsh and Laczniak (1990). The primary purpose of this RASA ground-water model was to provide an enhanced understanding of the ground-water-flow system. Because of the advanced analytical capabilities of the model, however, it was adopted by the DEQ as a tool in managing the ground-water resource by evaluating the potential effects of existing and proposed ground-water withdrawals (McFarland, 1998).

The Virginia Coastal Plain hydrogeologic framework and ground-water model were developed as part of the larger USGS RASA program in which the hydrogeologic framework was defined and the ground-water model was developed for each State in the northern Atlantic Coastal Plain extending from New York south through North Carolina. Vroblesky and Fleck (1991) defined the hydrogeologic framework of the Maryland Coastal Plain directly north of Virginia, as including 11 aquifers and 10 confining units, based on literature, detailed well data from Cambridge and Lexington Park, and reinterpretations of borehole data. This framework formed the basis for a ground-water model of the Maryland Coastal Plain by Fleck and Vroblesky (1996).

Similarly, Winner and Coble (1996) defined the hydrogeologic framework of the North Carolina Coastal Plain directly south of Virginia as including 10 aquifers and 9 confining units. Their interpretations of borehole logs were based on evaluating the continuity of groupings of similar beds and not on individual beds. Correlations incorporated the persistence of head relations; water levels were viewed to differ across confining units but to be similar within an aquifer, even if the aquifer contained clay interbeds. Similarly, chloride concentrations were used for correlation; differences across confining units were viewed to indicate the vertical extent of recharge from leakage and freshwater flushing. This framework formed the basis for a ground-water model of the North Carolina Coastal Plain by Giese and others (1997).

As the culmination of the USGS RASA program in the northern Atlantic Coastal Plain, the Virginia, Maryland, and North Carolina hydrogeologic frameworks and ground-water models were synthesized with those of the other States northward through New York. A hydrogeologic framework encompassing the entire northern Atlantic Coastal Plain was defined by Trapp (1992) and formed the basis for a corresponding ground-water model by Leahy and Martin (1993). Parallel RASA studies have been completed in the southern Coastal Plain and in 23 other regions across the United States.

Recent Hydrogeologic Advances

Since the culmination of the USGS RASA program, continued development of ground-water resources in the Virginia Coastal Plain has led to many hydrogeologic investigations. Most of these have been of a site-specific nature for individual water-supply systems and not widely published. Particular resource-management needs also have been addressed in several local- or county-scale studies conducted by the USGS, which are beyond the scope of this report. Other studies of a larger scale have been undertaken, however, that have contributed to a broader regional understanding. Among these are hydrogeologic characterizations of the York-James Peninsula by Laczniak and Meng (1988), southeastern Virginia by Hamilton and Larson (1988), the Virginia Eastern Shore by Richardson (1994), and the Fall Zone by McFarland (1997, 1999). All of these studies except for the Fall Zone focused primarily on development of area-wide ground-water-flow models and included predictive simulation analyses of water-management alternatives. The models were based largely on summary analyses of the hydrogeologic framework with limited revisions in some cases. Laczniak and Meng (1988) also provided a description of ground-water chemical quality in the York-James Peninsula. In the Fall Zone, McFarland (1997, 1999) placed relatively greater emphasis on refinement of the hydrogeologic framework by analyzing sediment cores at key locations and borehole geophysical logs from an enhanced network. A series of simple local-scale ground-water models also was developed, however, to provide an understanding of recharge-discharge relations. Although the works discussed here have made important contributions in their own right, they have not been synthesized comprehensively for the entire Virginia Coastal Plain. Lastly, shallow unconfined ground water in the Coastal Plain from New Jersey through North Carolina is discussed by Ator and others (2005).

Chesapeake Bay Impact Crater and the James River Structural Zone

Recently, the description of the Chesapeake Bay impact crater presented by Powars and Bruce (1999) has become a major milestone in the geologic understanding of the Virginia Coastal Plain. The crater was formed when a comet or asteroid collided with Earth near the mouth of the Chesapeake Bay approximately 35 million years (m.y.) ago during the late Eocene Epoch. The crater currently (2006) is the seventh largest such structure known on Earth and the largest in the United States, encompassing an area greater than 50 miles (mi) wide across the southern half of the Virginia Eastern Shore, westward to the lower reaches of the Middle and York-James Peninsulas, southward to Norfolk, and eastward onto the Continental Shelf (fig. 1; pl. 1).

The comet or asteroid, which is estimated to have been approximately 1 mi in diameter and traveling at very high velocity, penetrated the shallow, near-shore ocean and approximately 2,500 ft of underlying sediment of Cretaceous through middle Eocene age before terminating into the bedrock basement. Many millions of tons of water, sediment, and debris are theorized to have been cast tens of miles landward and into the atmosphere. A series of large-magnitude tsunamis probably engulfed most of the Piedmont and possibly overtopped the Blue Ridge Mountains. The resulting cavity was filled within hours to days by a violent backwash of sediment and bedrock fragments disrupted by the blast. Since then, continued adjustment of the Earth’s crust has affected the structural development of the area, while sediment deposition under otherwise normal conditions continued to bury the chaotic array of materials approximately 1,000 ft deep and hidden from view at land surface. Discovery of the crater resulted from drilling a series of high-quality sediment cores from which unique aspects of the crater fill were discerned, and from surface-geophysical surveying that identified key structural elements. The finding poses serious implications for earlier conceptualizations of the continuity of the aquifer system in the Virginia Coastal Plain.

Building upon investigations of the Chesapeake Bay impact crater, Powars (2000) described the “James River structural zone,” which separates areas of different depositional histories to the north of the James River from those to the south. Based on pollen zonation of sediment cores from an area to the south and west of the impact crater, a unique sequence of sediments of Late Cretaceous age was identified that is present in Virginia only south of the James River. Thus, sediment deposition and(or) preservation is theorized to have shifted southward from the Early to Late Cretaceous Period. Applying the same rationale on a broader scale, alternating shifts were discerned to have occurred northward during the Tertiary Period prior to the Chesapeake Bay impact followed by a return southward after the impact. The James River structural zone is theorized to have acted dynamically over time, by faulting and(or) pivoting along a northwest-to-southeast trending offset or hinge line, across which areas on either side have been alternately uplifted and downwarped. In addition, ongoing adjustment of the Earth’s crust in response to the impact is suggested as a cause for reactivation of the structural zone. Stratigraphic and structural relations are likely complex among the sediments of various ages that are thinned or truncated across the structural zone and have been only approximately described thus far. Similar to the impact crater, however, recognition of the structural zone calls into question earlier conceptualizations of a regionally uniform distribution of aquifers. Neither the Chesapeake Bay impact crater nor the James River structural zone has been synthesized comprehensively into a hydrogeologic analysis of the entire Virginia Coastal Plain.

Stratigraphic and Structural Evolution

Since its initial formation during the Triassic and Jurassic Periods approximately 240 to 140 m.y. ago, the eastern margin of the North American Continent has undergone deposition of a stratified sequence of sediments dating from the Cretaceous, Tertiary, and Quaternary Periods spanning 140 m.y. ago to the present day. Geologic events and the associated evolution of conditions at the Earth's surface during this period have led in direct consequence to the complex array of materials that now exerts primary control on ground-water flow beneath the Atlantic Coastal Plain. The sediments have been classified in geologic studies into a series of formations (fig. 3) based on their depositional histories and associated stratigraphic and structural relations. Although full discussion is beyond the scope of this report, a basic understanding of the geologic relations provides a fundamental perspective of the configurations, properties, and functions of the hydrogeologic units of the Virginia Coastal Plain.

Formation of the Virginia Coastal Plain

The current configurations of North America and the other major continents resulted from the breakup of a single global supercontinent and subsequent separation of its remnants during the Triassic and Jurassic Periods 240 to 140 m.y. ago. During this time, a north-south trending rift zone developed to divide the granitic continental crust into sections that now constitute North and South America to the west and Europe, Africa, and Asia to the east. The intervening area, broadened as basaltic oceanic crust, was extruded from the floor of the opening Atlantic basin along its spreading center at the mid-Atlantic ridge. Extrusion has continued to the present. Numerous incipient, failed spreading centers are preserved along the continental margins on both sides of the Atlantic basin as rift basins that are in-faulted onto the continental crust and contain sedimentary rocks of Triassic to Jurassic age and coeval volcanic and contact metamorphic rocks.

Sediment has been deposited along the eastern margin of the North American Continent since its separation from Europe and Africa. Continental crust presently exposed at the land surface along the east-central margin of North America constitutes bedrock of the Piedmont (see "Description of Study Area"). The seaward-thickening sediment wedge of the Coastal Plain extends from the Fall Zone eastward beneath Chesapeake Bay (fig. 2) and continues to the Atlantic coast and approximately 70 mi farther across the Continental Shelf beneath the Atlantic Ocean. Both the sediment wedge and underlying continental crust terminate at the continental slope, beyond which the Atlantic basin is floored by basaltic oceanic crust and a relatively thin overlying blanket of very fine-grained abyssal sediments.

The east-central margin of North America has been structurally dynamic over much of its history, during which sedimentation has been affected both by tectonic movement and global sea-level fluctuations (Ward and Strickland, 1985). Tectonic activity was greatest during the early opening of the Atlantic basin, whereby the seaward part of the margin, which became the Coastal Plain, subsided while the landward part, which became the Piedmont, was uplifted. Subsidence across the Coastal Plain resulted from sediment loading and a combination of extension and thinning during rifting (Owens and Gohn, 1985). The continental crust became a bedrock basement that formed the surface upon which Coastal Plain sediments were deposited. The basement beneath the Virginia Coastal Plain is composed primarily of igneous and metamorphic rocks as old as 2,500 m.y. (Paleozoic to Proterozoic ages; Powars and Bruce, 1999). For this study, rocks of Triassic to Jurassic age contained in five rift basins beneath the Virginia Coastal Plain (Horton and others, 1991) also are considered part of the basement (fig. 3).

The basement surface dips from the uplifted Piedmont eastward across the subsided Coastal Plain (fig. 5; plate 2). Broad regional inflections in the basement surface form the relatively deep and steeply dipping Salisbury embayment centered to the north in Maryland and the Albemarle embayment to the south in North Carolina, which are separated across a shallower east-west trending belt, termed the Norfolk arch, that extends across southeastern Virginia. The arch and embayment configuration resulted from differential subsidence of the basement (Meng and Harsh, 1988), possibly among an array of fault-bounded crustal segments lying along the continental margin (Brown and others, 1972). The fault boundaries may represent landward extensions of oceanic transform faults (Powars, 2000) or other preexisting structures formed along the Appalachian fold belt during Precambrian and Paleozoic time (Owens and Gohn, 1985). Local-scale basement-surface irregularities also are present, possibly from erosion or minor faulting, and coincide at some locations with saprolite preserved over the bedrock (Meng and Harsh, 1988).

The present-day regional configuration of the Coastal Plain basement surface likely was formed early in the evolution of the continental margin (Owens and Gohn, 1985) and possibly prior to sediment deposition (Teifke, 1973). Successively planar sediments filled in the Salisbury and Albemarle embayments to level the surface over time, and generally are thinnest across the Norfolk arch but thicken over its flanks (Teifke, 1973). Sediments of various ages are correlative between the embayments (Ward and Strickland, 1985), although sediments of some ages are not preserved across the Norfolk arch (Meng and Harsh, 1988). Deposition over buried rift basins of Triassic to Jurassic age possibly resulted in locally reversed (westward) directions of dip (Ward and Strickland, 1985). Large regional changes in locations of seaward subsidence and landward uplift also occurred periodically in response to tectonic movement during sediment deposition (Owens and Gohn, 1985) and largely controlled directions and rates of sedimentation (Brown and others, 1972). Sedimentation apparently has shifted three times across an east-west trending zone, termed the James River structural zone, that corresponds approximately with the present-day James River (Powars, 2000) (see "Previous Investigations" and "Chesapeake Bay Impact Crater and the James River Structural Zone").

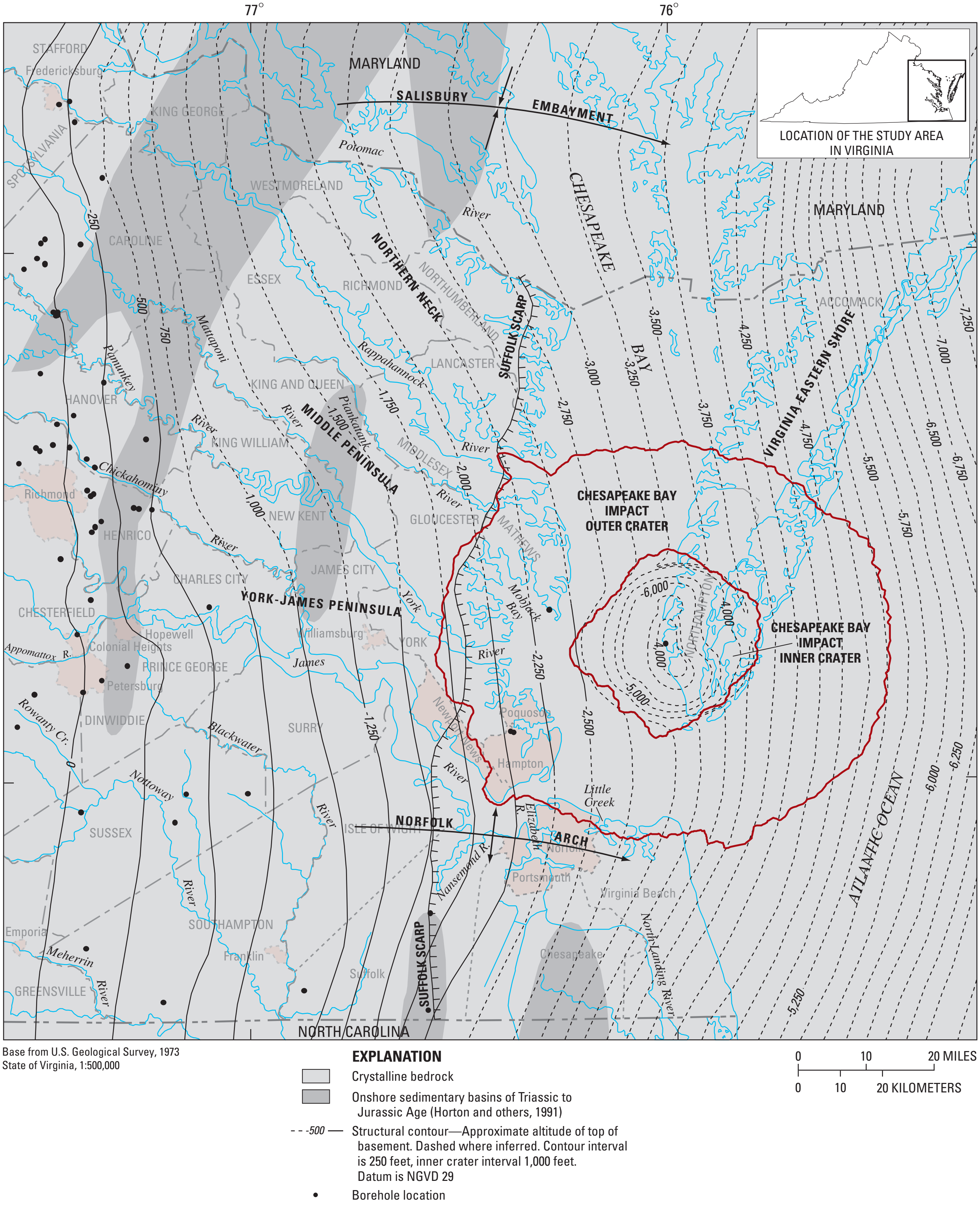


Figure 5. Approximate altitude and configuration of the top of basement in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred from Brown and others (1972), and within the inner crater from G.S. Gohn, U.S. Geological Survey, unpublished data, 2004. Further details are shown on plate 2.)

Cretaceous Period

The oldest sediments in the Virginia Coastal Plain belong to the Potomac Formation (Owens and Gohn, 1985) of Early Cretaceous age (99 to 140 m.y. ago) (fig. 3). The Potomac Formation consists of sediments deposited by a series of fluvial plains and deltas that prograded seaward over the basement during the Early Cretaceous Epoch while the Coastal Plain subsided and the Piedmont was uplifted (Meng and Harsh, 1988). The high structural gradient between the two areas resulted in rapid rates of erosion across the Piedmont source area. Consequently, thick sediment sequences as great as several hundred feet or more were effectively dumped over much of the Coastal Plain depocenter. The Salisbury embayment was 70 percent filled during the Early Cretaceous Period (Meng and Harsh, 1988).

The Potomac Formation is a record of the evolution of the margin of North America from a tectonically active terrane to one that is more stable. Braided streams that transported large volumes of sediment eroded from the rapidly uplifting Piedmont are preserved in the lower part of the section, which exhibits immature lithologies dominated by poorly sorted coarse-grained quartz and feldspar sands and gravels. As erosion of the Piedmont and deposition onto the Coastal Plain continued, the structural gradient between the two regions lessened. Meandering streams and subsequently deltas developed to maintain transport in equilibrium with the slowing sediment supply and are preserved in the upper part of the section. Relatively mature lithologies consist of repetitive sequences that fine upward from basal coarse-grained quartz sand and gravel to medium-grained sand to terminal fine-grained silt and clay.

Diverse depositional environments during the Early Cretaceous Epoch resulted in many local-scale variations in lithologic character and geometric configuration among Potomac Formation sediments. At the regional scale, however, the Potomac Formation consistently exhibits sharp contrasts in sediment texture across small distances as a result of the highly variable and frequently changing depositional environments. Coarse sands and gravels are preserved along relatively narrow, generally east-trending belts, lobes, or sheets that accumulated in fluvial and deltaic distributary channels, where high-flow velocities produced high-energy sediment-transport conditions. Sediments of more variable texture are preserved as bars and levees along channel margins, across which energy conditions fluctuated from changing flow velocities. Lastly, fine-grained silts and clays are preserved across larger areas of low energy between channels, such as flood plains, lakes, and interdistributary lagoons and marshes. At the local scale, flooding events frequently realigned the various environments as the differing sediments accumulated, producing over time a complex, overlapping, and variably incised configuration among discontinuous and contrasting lithologies (fig. 6)

With continued stabilization of the continental margin during the Late Cretaceous Period (65 to 99 m.y. ago), a period of transition to a marine shelf environment began in the Virginia Coastal Plain as inundation by the Atlantic Ocean occurred. Following the fluvial-deltaic sedimentation

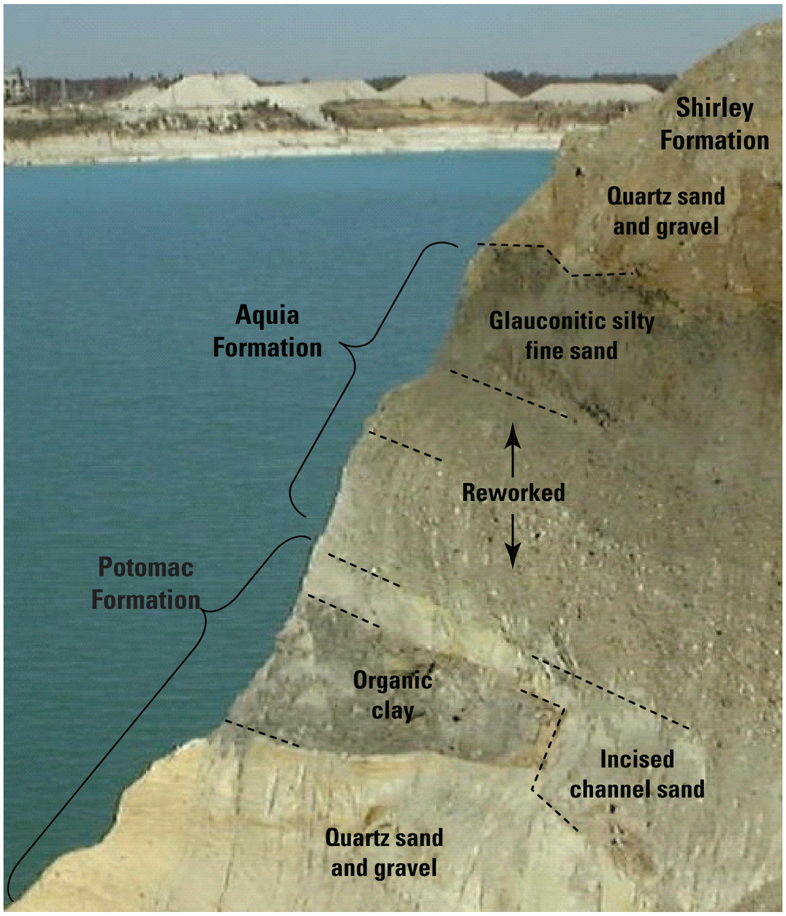


Figure 6. Rare exposure at the south pit of Puddleduck quarry, Petersburg, Virginia, of stratigraphic relations among sediments underlying the Virginia Coastal Plain. View is north with regional eastward dip to the right. Height of pit face is approximately 80 feet. The Potomac Formation of Early Cretaceous age is overlain by the Aquia Formation of late Paleocene age and Shirley Formation of middle Pleistocene age. Within the Potomac Formation, dark organic clay is interbedded with lighter sand and gravel and laterally truncated by incised channel sand. The lower part of the Aquia Formation includes two distinct intervals of reworked Potomac Formation sediments that are overlain by wholly marine glauconitic sand. The Shirley Formation underlies pre-excavation land surface that forms an approximately 40-foot altitude terrace adjacent to the Appomattox River. An unexcavated terrace forms the horizon beyond the floor of the inactive pit, which is below sea level and flooded. Outcrops in the Virginia Coastal Plain generally are sparse, and outcrops of this extent are very few. (Site access courtesy of Mr. Tom Brazell, Vulcan Materials Company.)

preserved in the Early Cretaceous Potomac Formation, the earliest marine sediments preserved are of Late Cretaceous age (Meng and Harsh, 1988). Recent classification of Late Cretaceous sediments in the Virginia Coastal Plain is based on pollen zonation and superposition (Powars, 2000).

Marine sediments generally are more mature than their terrestrial counterparts and commonly include distinctly marine lithologic components, such as glauconite and calcareous and phosphatic fossil material. Sediment-transport conditions also can be more uniform across broad areas of the open Continental Shelf, resulting in more uniformly distributed lithologies and regionally continuous bedding than in terrestrial environments. Consequently, monotonous lithologies can be exhibited by thick and regionally extensive volumes of marine sediment. Lithologic variation is produced gradationally with proximity to the coast and associated water depth, energy conditions, and marine ecology.

During the Late Cretaceous Epoch, the Virginia Coastal Plain fluctuated between marine shelf and fluvial-deltaic depositional environments. Hence, the Late Cretaceous Epoch includes both marine and terrestrial sediments (Powars, 2000). These include near-shore marine, glauconitic and sandy, clayey silts as much as 212 ft thick and termed the upper Cenomanian beds (fig. 3), which exhibit numerous thin and sharply bounded fossiliferous beds containing the distinctively light red mollusk Exogyra woolmani. By contrast, the overlying fluvial-deltaic Upper Cretaceous red beds consist of oxidized clays and interbedded pebbly coarse-grained sands approaching 100 ft in thickness. The upper Cenomanian beds are partly separated from the Upper Cretaceous red beds by very coarse-grained, glauconitic quartz sands. In addition, the uppermost part of the Late Cretaceous Epoch includes other near-shore sediments of very limited extent.

Although deposition during the Late Cretaceous Epoch possibly extended across the entire Virginia Coastal Plain, sediments of this age are now present only in the far southeast. Erosion elsewhere probably resulted in the present-day distribution (Owens and Gohn, 1985). Differential subsidence, possibly associated with faulting and(or) pivoting along the James River structural zone, also influenced preferential deposition to the southeast (Powars, 2000; see “Previous Investigations” and “Chesapeake Bay Impact Crater and the James River Structural Zone”).

Tertiary Period

Marine sedimentation dominated the Virginia Coastal Plain during the Tertiary Period approximately 1.8 to 65 m.y. ago. Global sea-level fluctuations became the prevailing mechanism of deposition as the continental margin further stabilized and tectonic movement lessened. With the Salisbury and Albemarle embayments already substantially filled, a series of relatively quiescent marine transgressions further subdued the preexisting topography of the basement (Teifke, 1973). Sediments of different ages within the Tertiary Period are distinguished on the basis of an array of paleobiological zonations.

The Tertiary Period includes a series of thin shallow-shelf open-marine deposits that resulted from small sediment loads and shallow subsidence (Ward and Strickland, 1985). Only a partial record of deposition is preserved, however. Each marine transgression during sea-level rise was followed by a regression as sea level fell. Hence, transgressive marine sediments likely were overlain initially by regressive near-shore sediments. Deltaic, marginal-marine, and barrier sequences originally deposited after each marine sequence, however, were subsequently beveled off during the next onlap cycle to leave only a sharp well-defined contact marked by coarser sediments, a lag deposit, or a burrowed surface (Ward and Strickland, 1985). Extensive burrowing, created by marine organisms during extended periods of non-deposition represented by major stratigraphic unconformities, is commonly observed across contacts between sequences.

Late Paleocene and Early to Middle Eocene Epochs

The lower part of the Tertiary Period includes primarily shallow-shelf sediments constituting four formations (fig. 3) deposited during the late Paleocene (55 to 61 m.y. ago) and early (49 to 55 m.y. ago) to middle (37 to 49 m.y. ago) Eocene Epochs (Ward and Strickland, 1985). Although the early Paleocene (61 to 65 m.y. ago) Brightseat Formation has been described in Maryland, a significant southward extension into Virginia appears doubtful. Sediments in the Virginia Coastal Plain of late Paleocene to middle Eocene age are thickest to the north and thin southward. Whereas deposition during the Late Cretaceous Period was focused southward, a northward preference was apparently exerted near the beginning of the Tertiary Period, possibly from an alteration in the direction of faulting and(or) pivoting along the James River structural zone with a resulting shift in subsidence (Powars, 2000).

Across most of the Virginia Coastal Plain, the base of the Tertiary Period includes as much as several tens of feet of glauconitic sands and silts of the Aquia Formation of late Paleocene age (fig. 3). Proportions are variable among sand, silt, and calcareous fossil shells, and among glauconite and quartz sand components. Shells can be concentrated, and at some locations form discrete calcite-cemented ledges of local extent. Elsewhere, the Aquia Formation silt and fine sand are more dominant (fig. 6). A basal interval of several or more feet can include reworked, fluvial-deltaic, coarse-grained sands and gravels of the underlying Potomac Formation.

The Aquia Formation is overlain by the distinctively very fine grained and restricted lagoonal, light-gray to grayish-pink Marlboro Clay of late Paleocene to early Eocene age (fig. 3). The Marlboro Clay is overlain by the Nanjemoy Formation representing the remainder of the early Eocene and consisting, in places, of more than 100 ft of largely shallow-shelf lithologies very similar to the fine-grained components of the Aquia Formation. Hence, the Nanjemoy and Aquia Formations commonly are distinguishable to the eye solely by the position of the intervening Marlboro Clay, although it is only several feet thick or less across much of its extent. In some areas, the upper part of the Nanjemoy Formation, termed the Woodstock Member, is distinctly composed of well-sorted fine-grained sands.

Overlying the Nanjemoy Formation is as much as several tens of feet of very fossiliferous and variably calcite-cemented, glauconitic quartz sands and moldic limestones of middle Eocene age belonging to the Piney Point Formation (fig. 3). Unlike the Aquia, Marlboro Clay, and Nanjemoy Formations, the Piney Point Formation does not extend across the entire Virginia Coastal Plain but is restricted primarily to north of the James River.

Late Eocene Epoch – Chesapeake Bay Impact Crater

During the late Eocene Epoch (37 to 34 m.y. ago), the configuration of the Virginia Coastal Plain was altered substantially approximately 35 m.y. ago across the area now occupied by the lower Chesapeake Bay by the formation of the Chesapeake Bay impact crater (see “Previous Investigations” and “Chesapeake Bay Impact Crater and the James River Structural Zone”). Although details of the impact event and associated processes remain a topic of active research, some aspects are well established (Powars and Bruce, 1999). The entire Virginia Coastal Plain was inundated at the time by a marine transgression. A comet or asteroid first penetrated the shallow-shelf water column before striking and disrupting sediments of Cretaceous through middle Eocene-age and the underlying bedrock basement. The basement was altered most intensely by forces focused on the approximately 20-mi diameter inner crater at the center of the structure, where substantial amounts of bedrock and overlying sediment and water were excavated wholly to create a depression of several thousand feet (plate 7; fig. 5) and consisting of a central peak surrounded by a deeper concentric depression or “moat.” Remnants of bedrock within the inner crater exhibit exotic impact-related lithologies and structures, including various forms of rock melted under the heat and pressure of impact. Materials within the inner crater possibly were altered further during the first several minutes following the blast by the collapse of a transient water column that initially was thrust into the atmosphere.

Excavation of basement bedrock generally did not occur across the approximately 50-mi diameter of the outer crater (Powars and Bruce, 1999), but complementary sets of radial and concentric fractures are theorized to have been propagated several miles deep. In addition, water and sediments were blasted or scoured off large expanses of the underlying basement across the outer crater during a period of seconds to minutes to create initially an empty cavity bounded by a steep, unstable, 1,000- to 4,000-ft scarp along the truncated margin of the sediments. Partially scoured sediment remnants were left at farther distances. During a period of minutes to hours thereafter, parts of the scarp collapsed as large volumes of sediment along the truncated margin, termed megablock beds (fig. 3), slumped or slid into the cavity to mantle the basement bedrock and the remnants of undisrupted sediments across much of the outer crater. Individual megablock beds consist of broken segments of Potomac Formation strata, from 700- to 2,500-ft thick and thousands of feet or more wide, which were translocated as much as several tens of miles but only slightly deformed internally.

Following the series of landward tsunamis produced by the initial blast, a violent backwash of water and excavated sediment rushed inward and across the megablock beds and inner crater, possibly while the megablock beds were still being emplaced but probably extending for days afterward. Much of the cavity was refilled by a chaotic mass of partly to wholly disaggregated sediments as much as several thousand feet thick and termed the Exmore tsunami-breccia (fig. 3). Pebble- to very large boulder-size clasts are preserved intact and surrounded by a matrix of disaggregated and very poorly sorted sands, silts, and clays. Clasts are commonly recognizable from their pre-impact formation lithologies but, in many instances, exhibit intense internal deformation, such as dense fracturing or highly contorted and convoluted bedding, which likely resulted following excavation and being washed, rolled, or hurled several miles or more into the cavity. The clasts are a roughly fining-upward sequence in which boulders of diameters as much as several tens of feet grade upward to cobble and pebble sizes.

The matrix of the Exmore tsunami-breccia consists of disaggregated and fluidized sediments that washed inward to fill volumes between clasts and has a disparate lithology that includes both marine and terrestrial components. Distinctly impact-related components also are present, such as quartz and feldspar sand grains that exhibit shock lamellae, and blast-deformed microfossils, such as fractured calcareous nannofossils and fused, bubbled, and curled dinoflagellate cysts (Horton and others, 2005). Additional components of probable impact origin include cataclasites and melt-derived spherulitic felsite. The lower part of the Exmore tsunami-breccia is clast supported, in that the boulders are in direct contact with each other, with matrix filling relatively narrow voids between clasts. Although the boulders have some lithologic variation, they generally are dominated in core obtained to date (2006) by clays of the Potomac Formation, which commonly are highly fractured. Potomac Formation clays possibly were preserved preferentially as boulders as a result of their denseness, while most of the other less structurally competent lithologies became more widely disaggregated. The upper part of the Exmore tsunami-breccia is matrix supported in that cobbles and pebbles are separated by and suspended in a matrix groundmass. In addition, the cobbles and pebbles are relatively diverse and include a substantial proportion of Tertiary formation lithologies. Hydrochemical data from pore water extracted from cores of the Exmore tsunami-breccia indicate that seawater entrained with emplacement of the breccia possibly still is present within the crater (McFarland and Bruce, 2005). Subsequent dissipation of residual heat from the impact is theorized to have resulted in chemical evolution of the trapped seawater into hydrothermal brine (Sanford, 2003).

Near-surface conditions returned to relative normality following the disruptive processes associated with the impact event. Although much of the cavity initially formed by the impact was filled by the Exmore tsunami-breccia and underlying megablock beds, restoration of the sea level left a submerged depression across the crater, where the depositional environment mimicked that of the abyssal ocean basin and contrasted with the surrounding shallow shelf. As a result, much of the remaining cavity was filled during the remainder of the late Eocene Epoch with more than 200 ft, in places, of gray-brown, microfossiliferous and pyritic silts and clays of the Chickahominy Formation (fig. 3).

Oligocene, Miocene, and Pliocene Epochs

Marine sedimentation returned to dominate the Virginia Coastal Plain during the remainder of the Tertiary Period. The periodic transgressions that resumed eventually to deposit sediments across the entire Virginia Coastal Plain were affected in the aftermath of the Chesapeake Bay impact (Powars and Bruce, 1999). Recognition of the crater has led to a revised understanding of structural and stratigraphic relations among sediments deposited after the impact. Deposition over the crater prograded to the south and southeast, eventually burying the crater approximately 1,000 ft below land surface. Sediments initially deposited across most of the area outside the crater generally dip eastward and thicken northward in the same fashion established before the impact. Across the crater, however, sediments are aligned concentrically inward. In addition, the sediments are relatively coarse grained along the crater margin as a result of shoaling conditions but are thicker and finer grained toward the crater center. The sediments also dip concentrically away from the crater and reverse from the regional eastward trend along a belt extending several miles outside the landward margin of the crater (Johnson and others, 1998). Reversed dips in this area are distinct from those farther west that are related to deposition over buried rift basins of Triassic to Jurassic age.

Structural anomalies exhibited by postimpact sediments were produced by synchronous deformation of the sediments as they were deposited (Johnson and others, 1998). Ongoing compaction of the Exmore tsunami-breccia is theorized to have produced movement throughout a complementary network of concentric and radial faults that translated upward into the overlying sediments. Complex lithofacies distributions and thicknesses in the shallowest sediments, observed in relatively abundant outcrops and shallow borehole data, resulted from episodic differential rotation of slump blocks along faults that bound the crater margin. Similar controls also are theorized to have affected earlier deposition of deeper sediments. Shoaling conditions focused along the crater margin throughout the period following the impact and produced parallel and concentric lenticular bioclastic sands.

The later part of the Tertiary Period in the Virginia Coastal Plain includes primarily shallow-shelf and marginal marine sediments constituting eight formations (fig. 3). Deposition during the Oligocene Epoch was closely associated with the Chesapeake Bay impact crater (Powars and Bruce, 1999). The recently recognized Delmarva beds are of early Oligocene age (34 to 29 m.y. ago) and contain generally glauconitic and phosphatic but variably textured and microfossiliferous sediments as much as several tens of feet thick. The Delmarva beds extend across but only marginally beyond the Chesapeake Bay impact crater and are overlain by as much as several tens of feet of glauconitic and fossiliferous silty-quartz sands of late Oligocene age (24 to 29 m.y. ago). These sands form the Old Church Formation, which also is present across the crater but extends farther westward nearly to the Fall Zone, although it remains restricted to north of the James River. Sediments of both the Delmarva beds and Old Church Formation are fine grained and well sorted over the crater but coarser and more poorly sorted beyond the crater margin.

Marine sedimentation broadened substantially beyond the Chesapeake Bay impact crater during the early and middle Miocene Epoch (Powars and Bruce, 1999), as primarily silty diatomaceous sands and clays of the Calvert Formation (fig. 3) were deposited in a series of restricted coastal embayments (Ward and Strickland, 1985). The lower part of the Calvert Formation, termed the Newport News Member, is of early Miocene age (16 to 24 m.y. ago) and only a few tens of feet or less thick. Olive-gray, very fossiliferous, glauconitic and phosphatic pebbly quartz sands form a belt along the western landward margin of the crater but become fine grained eastward into the crater and offshore and more variably textured northward across the Northern Neck (Powars and Bruce, 1999). The upper part of the Calvert Formation includes the Plum Point and Calvert Beach Members, which are of middle Miocene age (11 to 16 m.y. ago) and consist mostly of olive-gray, diatomaceous and foraminiferous fine sands and silts that extend across most of the Virginia Coastal Plain north of the James River and also along a belt across the southeast. Coarse-grained phosphatic sands several feet thick or more commonly are present as a basal lag deposit. Total thicknesses are as much as several tens of feet across most areas outside of the crater but are as much as several hundred feet across the crater and northward beneath the Virginia Eastern Shore.

Marine sedimentation broadened further during the late Miocene Epoch (5.2 to 11 m.y. ago) to encompass all except the far northwest of the Virginia Coastal Plain (Powars and Bruce, 1999). In addition, sediments of late Miocene age and younger in the Virginia Coastal Plain are thick to the south and thin northward. Although prior southward deposition during the Late Cretaceous Period shifted northward at the beginning of the Tertiary Period, a return southward began in the late Miocene Period. Ongoing crustal adjustment associated with the Chesapeake Bay impact crater possibly reactivated earlier directions of faulting and(or) pivoting along the James River structural zone, with a resulting shift in subsidence (Powars, 2000).

During the late Miocene Epoch, greenish-gray, micaceous, pyritic, and lignitic clays of the Saint Marys Formation (fig. 3) were deposited as much as several tens of feet thick across most of the area outside of the Chesapeake Bay impact crater but greater than 200 ft inside the crater (Powars and Bruce, 1999). Variably silty and clayey-quartz sands several or more feet thick commonly are present as a basal lag deposit. Additionally, fossiliferous sands greater than 100 ft thick predominate beneath most of the Virginia Eastern Shore and adjacent parts of Chesapeake Bay. Overlying the Saint Marys Formation and extending slightly beyond it are greenish-gray, variably glauconitic and micaceous, fine- to coarse-grained sands of the Eastover Formation. Thicknesses exceed 100 ft outside of the crater, but are greater than 200 ft across the crater. Coarse-grained fossiliferous sands a few feet thick commonly are present as a basal lag deposit. Most of the lower part of the Eastover Formation is clayey and grades upward to abundantly fossiliferous sands that include the distinctively pearly lustrous mollusk *Isognomon maxillata*.

Estuarine to marine sedimentation in the Virginia Coastal Plain during the Pliocene Epoch (1.8 to 5.2 m.y. ago) continued the southward shift begun during the late Miocene Period. Bluish-gray, variably textured, glauconitic, phosphatic, and commonly abundantly fossiliferous quartz sands and interbedded silts and clays belonging to the Yorktown Formation (fig. 3) were deposited across an alternately emerged and submerged open shelf, recording three distinct marine transgressions (Ward and Strickland, 1985). Shell content generally increases downward through thicknesses as much as several tens of feet outside of the Chesapeake Bay impact crater to greater than 100 ft across the crater, and sediment is fine grained concentrically inward (Powars and Bruce, 1999). Numerous outcrops in dissected eastern parts of the Virginia Coastal Plain along the lower reaches of major rivers and their tributaries exhibit the distributions and thicknesses of complex lithofacies, which are associated with synchronous deformation along the margin of the crater.

Other than the relatively narrow outcrop areas, the marine Yorktown Formation sediments are present primarily in the subsurface extending across most of the area south of the James River and northeastward along the lower and middle reaches of the Middle Peninsula and Northern Neck. By contrast, fluvial-deltaic sediments, possibly contemporary with the Yorktown Formation, mantle broad land-surface areas that straddle the Fall Zone and widen progressively northward across the upper reaches of the York-James and Middle Peninsulas and Northern Neck (Mixon, Berquist, and others, 1989), reflecting the now uplifted position of the sediments. The western uplands thereby exhibit the oldest surficial deposits in the Virginia Coastal Plain, which are the first terrestrial sediments to be preserved since those of the Late Cretaceous Period approximately 60 m.y. earlier.

During the late Pliocene Epoch (1.8 to 3.5 m.y. ago), marine sedimentation migrated farther to the southeast as terrestrial sedimentation continued to expand. Shallow-shelf, variably textured, bioclastic sands a few tens of feet thick or less and belonging to the Chowan River Formation (fig. 3) were deposited over the Yorktown Formation across a small area to the far southeast (Powars and Bruce, 1999). To the north and west during the late Pliocene Period, diverse fluvial-deltaic, estuarine, tidal-flat, and shallow-marine, variably colored, clayey silts and silty-fine sands belonging to the Bacons Castle Formation were deposited over the Yorktown Formation. The Bacons Castle Formation mantles the land surface across a 20- to 30-mi wide, southwest-to-northeast trending belt encompassing the southern Fall Zone and middle reaches of the York-James and Middle Peninsulas and Northern Neck (Mixon, Berquist, and others, 1989), where it constitutes the surficial deposits in areas of intermediate altitude.

Quaternary Period

Primarily terrestrial and near-shore sedimentation occurred in the Virginia Coastal Plain during the Quarternary Period (present to 1.8 m.y. ago) across broad areas of lower altitude in southeastern Virginia, the lower reaches of the York-James and Middle Peninsulas, Northern Neck, and areas to the east. In addition, upstream reaches of rivers and streams are mantled by sediments of Quaternary age beneath localized channels, flood plains, and terraces along valley floors. Other than the surficial deposits of Pliocene age in areas of high to intermediate altitude described above, the remainder of the surficial deposits in the area are of Quaternary age (fig. 3) and consist of a relatively thin veneer of variably colored and textured interbedded gravels, sands, silts, clays, and peat generally a few tens of feet thick or less.

Most of the sediments of Quaternary age in the Virginia Coastal Plain were deposited during the Pleistocene Epoch (10,000 years to 1.8 m.y. ago) during a closely spaced series of sea-level fluctuations resulting from large changes in continental glaciation. Coincident geomorphic processes formed the present-day topography and related shallow structural features in close association with sediment deposition. The Windsor, Charles City, Chuckatuck, Shirley, and Tabb Formations landward of Chesapeake Bay and their stratigraphic equivalents on the Virginia Eastern Shore (Mixon, Berquist, and others, 1989) include sediments that differ in age and occupy a step-like succession of terraces separated by intervening scarps that parallel the coast and major streams and dominate the topography of the Coastal Plain (Johnson and Ramsey, 1987).

Terraces decrease in altitude toward the coast and major streams, and decrease in age with lower altitude. Terrace sediments were deposited at successively lower altitudes as a result of a staged sequence of sea-level declines. The scarps initially were cut into the older formations as shorelines but since have been subjected to subaerial erosion and are now obscured in places. One of the most extensive of these, termed the Suffolk scarp (fig. 1; pl. 1), trends from central City of Suffolk northward across the lower York-James and Middle Peninsulas and Northern Neck, and represents a widespread topographic boundary between areas generally below 50-ft altitude to the east and higher altitudes to the west. The Suffolk scarp and some other landward scarps in proximity to Chesapeake Bay exhibit an arcuate alignment and coincide with the margin of the Chesapeake Bay impact crater. Continued sediment compaction and associated subsidence possibly created one or more embayments across the crater during the Pleistocene Epoch, with shorelines positioned along the crater margin (Powars and Bruce, 1999). Sediments of Holocene age (present to 10,000 years ago) have been superimposed on sediments of Pleistocene age along relatively narrow margins of present-day rivers and streams, as well as Chesapeake Bay and the Atlantic coast, as essentially modern alluvial, colluvial, estuarine, marsh, swamp, and dune deposits.

Periodic interglacial sea-level high stands and associated terrace deposition and scarp formation during the Pleistocene Epoch were separated by glacial sea-level low stands, during some of which sea level was lower than at present. Consequently, subaerial erosion occurred across emergent parts of Chesapeake Bay and the Continental Shelf east of the present-day Atlantic coast. Land areas that were emergent prior to and during the Pleistocene Epoch were drained by a network of streams and rivers that only partly coincides with the present network. Terrace bottom surfaces are not uniformly plane but rather exhibit sharp incisions along narrow belts that correspond to paleochannels produced by erosion. Some paleochannels underlie and parallel the courses of present-day rivers, whereas others are aligned beneath modern drainage divides. The paleochannels were cut into the top surfaces of Pliocene and older sediments, then backfilled and masked as terraces were emplaced. A deeper and older paleochannel network possibly underlies and predates the Yorktown Formation.

At the extreme of the last Pleistocene glacial maximum of 18,000 years ago, sea levels were as much as 390 ft lower than at present (Bradley, 1999), and the Atlantic shore was located several tens of miles east of its present position and nearly to the continental slope. The network of paleochannels was expanded from its current landward extent far to the east across areas now occupied by Chesapeake Bay, the Virginia Eastern Shore, and the Atlantic Ocean and subsequently was reinundated as a result of warming during the Holocene Epoch.

Three particularly large paleochannels as deep as 200 ft and extending across several tens of miles beneath Chesapeake Bay and the Virginia Eastern Shore were created by distinct alignments of the ancestral valley of the Susquehanna River (Mixon, 1985; D.L. Powars, U.S. Geological Survey, written commun., 2004). The Susquehanna River has undergone a staged southward migration associated with the formation of the Delmarva Peninsula. Large volumes of sediment that were deposited along the Atlantic coast to the north prograded southward incrementally during interglacial sea-level high stands to progressively build the peninsula. The direction of progradation toward the center of the Chesapeake Bay impact crater possibly was influenced by continued sediment compaction and resulting subsidence (Powars and Bruce, 1999). During intervening glacial sea-level low stands, the Susquehanna River resumed draining the reemerged land surface, but with its course realigned southward around the advancing peninsula.

Reinundation during the Holocene Epoch of the most recent alignment of the Susquehanna River Valley created the modern Chesapeake Bay, which now covers approximately one-fifth of the Virginia Coastal Plain and determines the present-day coastal configuration. The land surface that remains emergent is mantled by surficial sediments generally of Pliocene age in areas of high to intermediate altitude and Quaternary age at low altitude. Sediments of older Tertiary and Cretaceous age are covered almost entirely other than at sparse outcrops along the cut banks of major rivers and a few relatively shallow quarries.

Sea-level fluctuation during the Quaternary Period also largely has controlled the present-day distribution of fresh and saline ground water (McFarland and Bruce, 2005). Following emergence of the Continental Shelf from the most recent regional inundation during the Pliocene Epoch, seawater that had been emplaced throughout the sediments was flushed partly by areal recharge of fresh ground water. At the Pleistocene glacial maximum, freshwater flushing extended nearly to the edge of the Continental Shelf but was impeded across the Chesapeake Bay impact crater by the Exmore tsunami-breccia and overlying Chickahominy Formation. Although flushing occurred laterally along the outer rim of the crater, saltwater remained trapped within the crater. Sea level has since risen to its present (2006) position, seawater has reinundated the Continental Shelf and Chesapeake Bay, and the saltwater transition zone has migrated landward and merged with trapped saltwater in the crater. Seawater has begun to reenter the sediments but at a rate slower than sea-level rise, because the seawater advance has been relatively rapid compared to ground-water flow rates. Hence, the Atlantic Ocean and Chesapeake Bay have overlain a volume of freshwater that is stalled beneath saltier shallow ground water. As a result, an inverted and hydrodynamically unstable saltwater transition zone along the western margin of the crater separates fresh ground water to the west from saltwater to the east.

Interpretive Analysis

A complex array of sediments with diverse physical characteristics underlies the Virginia Coastal Plain. Spatial relations among contrasting sediments exert a primary control on the movement of ground water in a manner analogous to the control of topography on the movement of surface water. In addition, the internal configuration of the sediments is a function of the stratigraphic relations of the sequences produced by depositional history. Accordingly for this study, a descriptive hydrogeologic framework was developed to encompass stratigraphic aspects of the hydraulic connectivity through the sediments (fig. 3).

Hydrogeologic-Unit Classification

Sediments of the Virginia Coastal Plain are classified herein in a series of 19 hydrogeologic units (fig. 3). The classification provides a means of identifying distinct parts of the sediments and describing their functions within the ground-water-flow system. Each hydrogeologic unit was designated based on its specific position within the sediment volume and its unique function in the overall, regional-scale flow of ground water throughout the Virginia Coastal Plain.

Each hydrogeologic unit encompasses a volume of sediment designated alternately as an aquifer and a confining unit, or confining zone (fig. 7). For this study, aquifers are considered to be composed generally of relatively coarse-grained sediments with relatively large permeabilities that function as principal pathways for ground-water flow. In addition, the aquifers generally are regarded as significant sources for ground-water withdrawal. As designated herein, however, not all parts of every aquifer represent a significant water-supply resource. Variations in the thickness and(or) sediment composition of some aquifers render them impractical for water-supply development in some areas.

Although all aquifers in the Virginia Coastal Plain have some degree of variability in sediment texture and composition, they are broadly distinguished herein as being either homogeneous or heterogeneous (fig. 7). Homogeneous aquifers can have locally gradational changes in texture and(or) composition but generally function hydraulically as a continuous medium. Water flows throughout the greater volume of the aquifer essentially uninterrupted at both local and regional scales. By contrast, heterogeneous aquifers exhibit sharp contrasts in sediment texture across small distances in the form of discontinuous and locally variable fine-grained sediments that are interbedded with coarse-grained sediments. Some interbeds have thicknesses as great as several tens of feet and lateral extents of less than one mile. Across some larger areas, interbeds can be densely spaced and partly coalesced, whereas in other areas they can be sparse or absent. Water flows mostly through the coarse-grained sediments, moving around and between relatively stagnant fine-grained interbeds. Thus, heterogeneous aquifers generally are hydraulically continuous at the regional scale but discontinuous locally where flow is impeded by fine-grained interbeds.

Adjacent aquifers are separated vertically in most instances by an intervening confining unit (fig. 7). In the context discussed above, confining units are essentially homogeneous and dominated by hydraulically continuous fine-grained sediments that impede horizontal flow and allow only relatively slow ground-water movement mostly as vertical leakage. Most of the flow into and out of the aquifers takes place across the top and bottom surfaces as leakage from or to vertically adjacent confining units.

Some aspects of the configuration of sediments in the Virginia Coastal Plain warrant an interpretation that extends beyond classification solely as aquifers or confining units. In some instances, the separation between a heterogeneous aquifer and an adjacent aquifer or confining unit is designated as a confining zone (fig. 7). Across the top or bottom surface of the heterogeneous aquifer, either coarse-grained sediments or one or more fine-grained interbeds may be present at any given location. Where interbeds are present, vertical leakage into or out of the aquifer can be impeded locally. This interval is designated as a confining zone, defined locally as the fine-grained interbed or group of interbeds that approximates a transition from the heterogeneous aquifer to an adjacent aquifer or confining unit.

Designation of confining zones serves to account for the variable configurations and, in some cases, indistinguishable

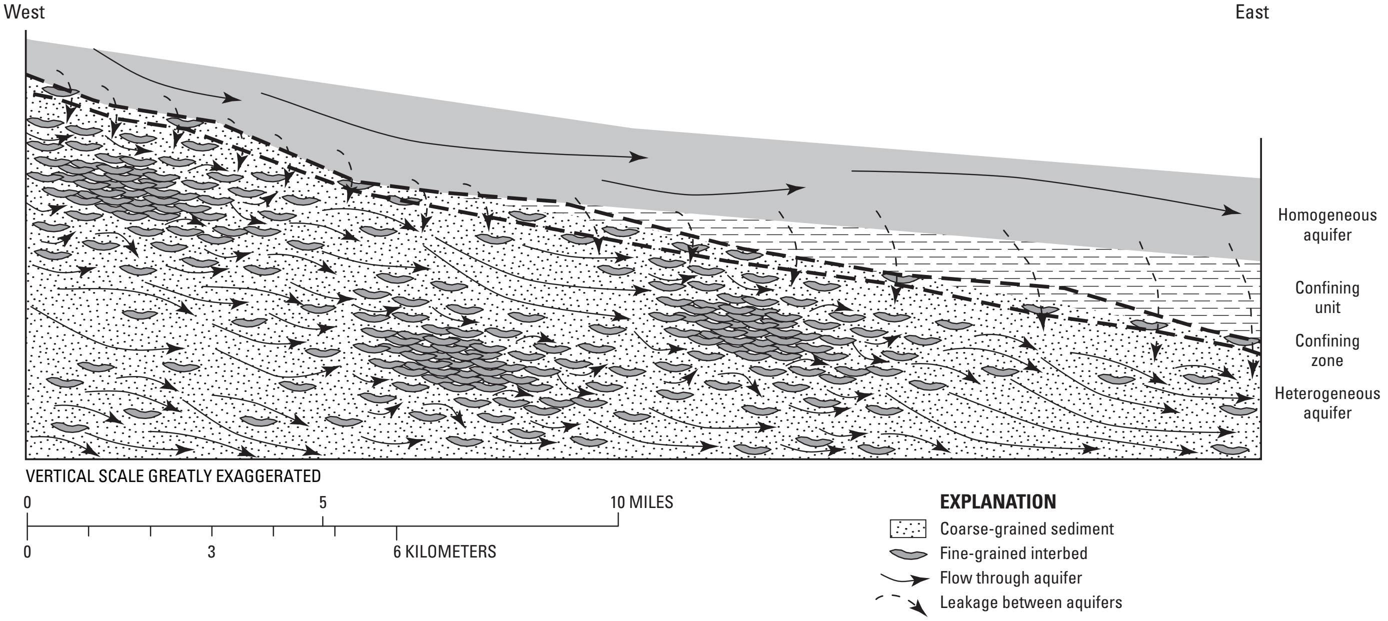


Figure 7. Simplified section showing conceptualized flow relations among homogeneous and heterogeneous aquifers, confining units, and confining zones in the Virginia Coastal Plain.

relations that can exist adjacent to heterogeneous aquifers. Confining zones bound major parts of heterogeneous aquifers that extend across distances as great as several tens of miles and that are separated from adjacent aquifers solely by interbeds because no confining unit is present (fig. 7, left side). Moreover, neither an interbed nor a confining unit may be present at many locations across the confining zones, thereby allowing direct contact of the coarse-grained sediments of the adjacent aquifers. Such contacts can be obscured from observation in drill cuttings and(or) borehole geophysical logs by sediment burrowing and reworking. Conversely, the presense in other areas of both an interbed and a confining unit cannot always be clearly distinguished (fig. 7, right side).

Classification of the sediments includes relations of the hydrogeologic units to geologic formations that are based on sediment-depositional history (fig. 3). In some instances, two or more geologic formations compose a single hydrogeologic unit. Conversely, in other instances a single geologic formation is divided into more than one hydrogeologic unit. In addition, the stratigraphic sequence is not complete at all locations because spatial trends of sediment deposition have diverged repeatedly over time (see “Stratigraphic and Structural Evolution”). As a result, hydrologic associations among distinct parts of the sediments cross stratigraphic boundaries (as indicated by the vertical arrows in fig. 3). Several of the hydrogeologic units consist of sediments that, although hydraulically continuous, include geologic formations from disparate positions in the stratigraphic sequence.

Regional Correlation

Classification of the 19 hydrogeologic units of the Virginia Coastal Plain was based on analyses undertaken at contrasting scales ranging from microscopic examination of the sediments in hand specimens, to determinations of the extents, depths, and thicknesses of the hydrogeologic units extending across several tens of miles. Because sediment examination was made at discrete borehole locations, description of the aquifer system at the regional scale was based on interpretation of borehole data in tandem with correlations between boreholes across comparatively large areas that were not directly examined. Certain challenges and limitations are inherent in accurate interpretation of data at the borehole scale and in regional correlation. Because future investigators of the Virginia Coastal Plain hydrogeology likely will encounter similar circumstances, a clear understanding of borehole-data interpretation and correlation is important in maintaining a valid perspective of the results presented herein and in applying them appropriately to further studies.

A network of 17 hydrogeologic sections illustrates the correlations of hydrogeologic units across the Virginia Coastal Plain (fig. 1; pls. 1, 3–7). Manually digitized traces of electric logs (and gamma logs where available) positioned along each section approximately are spaced proportionately to the scaled distances between borehole locations. The different quality of data among boreholes also is indicated at each location. In addition, all of the sections have a common vertical scale to facilitate visual comparisons among them.

The hydrogeologic sections are aligned to intersect the largest number of boreholes possible from which the highest quality of data were obtained and are oriented to closely follow the regional structural trend. Two sets of sections are designated herein to facilitate spatial referencing. One set of sections follows the regional dip of aquifers and confining units, generally from west to east (secs. AD–AD', BD–BD', CD–CD', DD–DD', ED–ED', FD–FD', GD–GD', HD–HD', ID–ID', and JD–JD', fig. 1; pls. 1, 3–5). Those sections are spaced sequentially along latitude; section AD-AD' is farthest north, and section JD-JD' is farthest south. The common letter “D” in each section designation refers to the section orientation along the regional dip. Conversely, the second set of sections follows the regional strike, generally from south to north (secs. AS–AS', BS–BS', CS–CS', DS–DS', ES–ES', FS–FS', and GS–GS', fig. 1; pls. 1, 6–7), which is indicated by the common letter “S”. These sections are spaced sequentially along longitude; section AS-AS' is farthest west, and section GS-GS' is farthest east.

Hydrogeologic units that extend continuously across borehole locations are indicated in the sections as solid shaded areas for aquifers and hatched lines corresponding to the top surfaces of confining units or confining zones. Bedrock basement is shown only where it is penetrated at relatively shallow depths by boreholes in the Fall Zone. Because of space limitations and the number of sections being presented, the sections are not fully extended vertically to reach bedrock basement across their entire lengths. The surficial aquifer at most boreholes was interpreted based largely on lithologic descriptions, because the baselines of electric-log measurement responses were off the scales for many of the logs. The approximate configuration of the surficial aquifer between borehole locations was inferred from topographic relations described by McFarland (1999). Faults, paleochannels, and other structural features associated with the Chesapeake Bay impact crater were transcribed onto the sections as inferred from structural contour maps described below. Most margins of hydrogeologic units between borehole locations are depicted as pinchouts, although a few are bounded by faults.

The aquifer system is represented further by two alternate sets of 18 structural contour maps that depict the configurations of the top surfaces of 18 of the hydrogeologic units as correlated between boreholes. One set of page-size figures (figs. 8, 10–11, 13–14, 16–18, 20, 22, 24–25, 27, 29, 31–32, 34, 36) provides generalized maps of the hydrogeologic-unit top surfaces that readily supplement written descriptions of each of the hydrogeologic units presented later in this report. The second set of over-size maps (pls. 8–25) provides additional information, including altitude values at each borehole and more detailed base-map information. These maps can be applied to purposes beyond this report, such as well-drilling operations and other field activities.

The structural contour maps feature lines of equal hydrogeologic-unit top-surface altitude that were drawn manually to interpolate altitudes across areas between boreholes and, in some instances, extrapolate altitudes beyond the area spanned by boreholes. Contour lines were aligned parallel to the strike of the hydrogeologic units, and the gradient between contour lines parallels the dip. A contour interval of 50 ft was used on most of the maps. The bedrock basement has a steeper dip that was represented with a contour interval of 250 ft. Conversely, less steep dips of the four shallowest hydrogeologic units were represented with an interval of 25 ft. Local-scale variations in directions of strike and dip were inferred within the Chesapeake Bay impact crater for some of the relatively deep hydrogeologic units and along present-day major river valleys and possible buried paleochannels for some shallower units. The top surface of the surficial aquifer is equivalent to land surface and was not mapped for this study.

Margins of the hydrogeologic units were inferred on the structural contour maps from their positions along the hydrogeologic sections. The configurations of the margins were refined further by using a geographic information system (GIS) in conjunction with a land-surface digital elevation model (DEM). Truncation across the margins along river valleys was projected from the DEM and hydrogeologic-unit top and bottom altitudes. Similarly, areas were projected along valleys and across low altitudes adjacent to and beneath Chesapeake Bay, where the hydrogeologic units possibly have been incised partially by the surficial aquifer and channel- and bay-fill deposits.

In addition, faults are depicted on many of the structural contour maps. Faults located to the far northwest in Caroline and King George Counties were inferred partly by interpolation between borehole geophysical logs but also with recognition of the Port Royal and Skinkers Neck fault systems documented by Mixon and others (2000). Elsewhere, the presence and alignment of faults was inferred primarily by log interpolation. Regional trends of strike and dip exhibit apparent local-scale offsets in some areas that were interpreted as resulting from vertical movement of generally several tens of feet or less along high-angle faults located across the southernmost part of the Virginia Coastal Plain, along the western margin of the Chesapeake Bay impact crater, and in eastern parts of Henrico and Hanover Counties. Attribution of the offsets to faults was made conservatively and only where an interruption of the regional strike and dip is abrupt. In some instances, the direction of offset across a fault differs among vertically adjacent hydrogeologic units, inferring that the relative movement along the fault has alternated over time between upward and downward as sediments composing the hydrogeologic units were deposited.

Construction of hydrogeologic sections and structural contour maps were used as a form of analysis with which to test alternate interpretations of, and associated correlations between, borehole geophysical logs. Log interpretation and correlation thereby constituted complementary aspects of a single iterative process. Only at the small number of boreholes where advanced analyses of core have been performed, could key geologic aspects among the sediments, such as relative ages and formational relations, be determined on a relatively independent basis. At most boreholes, log interpretation was more subjective and relied on information beyond that associated directly with the logs. Accordingly, the placement of each borehole within the regional setting was recognized to provide a context within which alternative interpretations could be reasonably constrained. Virtually no logs were interpreted in an isolated fashion, but rather geologic relations established from boreholes with the highest data quality were extrapolated to boreholes with less data quality. Interpretation of logs was undertaken concomitantly with correlation between logs to construct both the hydrogeologic sections and structural contour maps.

Information not directly associated with the borehole network was applied to support log interpretation and correlation as described above and to infer additional features shown on the hydrogeologic sections and structural contour maps that are not discernible solely from the logs. Geologic and hydrogeologic maps and sections (based in some cases on surface geophysical data), outcrop descriptions, and supporting discussions documented by earlier studies (and in some cases from unpublished sources) were drawn on to constrain alternative log interpretations and associated stratigraphic and structural relations. These sources contributed many geologic relations that underpin the log interpretations but that also were applied beyond their direct relation to the logs. More broadly, the geologic relations provided a regional context within which to infer structural features that were not apparent from logs or associated borehole information.

Detailed outcrop descriptions were used primarily from Ward and Blackwelder (1980) and Ward and Strickland (1985). Maps, sections, and associated discussions of stratigraphic relations and structural features were used as follows:

- Across the Fall Zone, from Daniels and Onuschak (1974), Dischinger (1987), Bell (1996), Harlow and Bell (1996), McFarland (1997, 1999), Mixon and others (2000), and R.E. Weems, U.S. Geological Survey, unpublished data, 2004;

- Across the York-James Peninsula and adjacent areas, from Bick and Coch (1969), Coch (1971), Johnson (1972, 1976), Brockman and Richardson (1992), and Brockman and others (1997);

- Across the Virginia Eastern Shore, from Mixon (1985) as modified by D.S. Powars, U.S. Geological Survey, unpublished data, 2004;

- Across the Chesapeake Bay impact crater and adjacent areas, from Powars and Bruce (1999), Powars (2000), Catchings and others (2001), and G.S. Gohn, U.S. Geological Survey, unpublished data, 2004; and

- Across the entire Virginia Coastal Plain, from Mixon, Berquist, and others (1989).

Limitations

Hydrogeologic sections and structural contour maps represent different levels of analysis of the aquifer system. The hydrogeologic sections represent individual interpretations of and correlations among most of the highest quality borehole geophysical logs used in this study. The sections thereby serve primarily to illustrate hydrogeologic-unit top-surface altitudes determined at borehole locations (Attachment 1), and secondarily to depict stratigraphic relations among the hydrogeologic units. For completeness, other structural elements that did not result directly from correlation between the logs along each section were transcribed onto the sections as inferred from the structural contour maps. Additionally, some hydrogeologic-unit margins possibly exist as gradational lithologic facies changes rather than relatively abrupt pinch outs as depicted, but this cannot be discerned from the logs. A vertical exaggeration of 130 is necessary on the sections to show vertical relations, but this exaggeration also causes hydrogeologic units to appear many times thicker than they are in relation to their horizontal extents. Hence, the sections provide schematic rather than wholly realistic depictions, and should be viewed in a diagrammatic sense rather than as precise portrayals of the subsurface.

In comparison to the hydrogeologic sections, the structural contour maps represent a broader interpretation of the diverse sources of information applied to describe the aquifer system. Subjective judgment was required in manually generating contours and margins to depict plausibly the hydrogeologic-unit top-surface configurations and extents, which are consistent with the top-surface altitudes determined at borehole locations but not wholly constrained by them. Specifically, contours were aligned across some areas between boreholes to reflect the local-scale variations in directions of strike and dip likely exhibited by structural features associated with the Chesapeake Bay impact crater, present-day major river valleys and buried paleochannels, and faults, with some leeway exercised in considering the accuracy of borehole altitude values. Further subjectivity was used in applying published and unpublished maps, sections, outcrop descriptions, and other information not directly associated with the borehole network to infer hydrogeologic-unit margins, geologic relations, and structural features not apparent from logs or associated borehole information (see “Regional Correlation”). Assumptions based on these sources were applied in extrapolating contours across some areas beyond the extent of the borehole network. Assumptions also were made in applying generalized topographic relations during the GIS operations to refine hydrogeologic-unit margins and estimate areas of near-surface incision.

Thus, various aspects of uncertainty are associated with the aquifer-system analysis. Hydrogeologic-unit top-surface altitudes determined from borehole geophysical logs generally are accurate only to within +/–10 ft, and the quality of data from which hydrogeologic units were identified on the logs differs among the boreholes (see “Methods of Investigation”). In addition, the spatial distribution of boreholes is not uniform across the entire Virginia Coastal Plain (fig. 1; pl. 1), and borehole geophysical logs were correlated over varying distances ranging from a few hundred feet or less to several miles or more. Because of the reliance on data from water-supply construction projects and other activities beyond the scope of this study, borehole locations are concentrated primarily in southeastern Virginia, the York-James Peninsula, and eastern Henrico and Hanover Counties, to a lesser extent, where development of the ground-water resource is greatest. The intervening areas are more rural, and data were obtained from more widely spaced wells serving small towns or recently built residential developments. Hence, the description of the aquifer system is comparatively uncertain across a broad north-south trending belt of low-borehole density extending across large parts of most western Coastal Plain counties, Virginia Beach, and the Virginia Eastern Shore. Many wells exist in the latter two areas but are shallow because of the presence of saltwater at depth. Because data could not be obtained from these wells on most of the aquifer system, they were omitted from this study. Lastly, boreholes are wholly lacking across submerged areas beneath Chesapeake Bay and the Atlantic Ocean where hydrogeologic-unit top-surface altitudes were approximated by extrapolation. The aquifer system is likely especially complex within the Chesapeake Bay impact crater and will require more detailed study of the crater to delineate with greater certainty.

Faults particularly illustrate the uncertainty arising from the nonuniform distribution of boreholes. Recognition of faults in some areas was a function of relatively high borehole density that provides adequate spatial control from which generally small and closely spaced structural offsets could be discerned. Conversely, faults were not recognized in areas where boreholes are comparatively sparse; thus, faults potentially could be more widespread and ubiquitous throughout the Virginia Coastal Plain than is indicated herein. Particularly complex fault configurations likely are associated with the Chesapeake Bay impact crater but remain a topic of active research and are not yet fully characterized at the regional scale as of this writing (2006).

Additional uncertainty is associated with confining zones (see “Hydrogeologic-Unit Classification”). Whereas aquifers and confining units are based on distinct geologic aspects and hydrologic characteristics, confining zones are inherently indistinct. The confining zones were correlated between fine-grained interbeds across relatively large distances, as great as several miles or more, between borehole locations. Because the interbeds are discontinuous, some correlated segments almost certainly also encompass coarse-grained sediments of adjacent aquifers (fig. 6) and possibly include burrowed or reworked intervals. Conversely, interbeds in other areas can be indistinguishable from the fine-grained sediments of an adjacent confining unit. Confining zones cannot represent distinct contact surfaces but rather serve to approximate parts of the aquifer system that are so locally variable that extrapolation to the regional scale cannot be made without an inherent loss of certainty.

As is likely true for many areas, description of the aquifer system of the Virginia Coastal Plain is an inherently exploratory undertaking. Frequently during this study, information gained from a newly drilled borehole provided new insights on the regional perspective, thereby prompting revision of earlier interpretations. Likewise, information generated by future drilling could result in further refinement. Additionally, studies of broader scope hopefully will continue to contribute improved understanding. In particular, many complex geologic relations associated with the Chesapeake Bay impact crater are only beginning to emerge, and sustained effort will be required to fully explore this area. Hence, results documented herein should not be viewed as a final product but rather as interim baseline information that can be applied toward gaining yet greater understanding of the Virginia Coastal Plain aquifer system.

Hydrogeologic Units

The Virginia Coastal Plain hydrogeologic framework is documented herein as a collective description of 19 hydrogeologic units (fig. 3). The description of each hydrogeologic unit is organized into four parts that include the following:

1. Relations to geologic formation lithologies, ages, and depositional environments; the rationale for the hydrologic-unit designation; and comparisons with designations given in previous studies in Virginia and adjacent States;

2. Structural configuration of each hydrogeologic unit presented in the form of tabulated altitudes, hydrogeologic sections, and structural contour maps and described in terms of extent, orientation, depth, thickness, spatial relations to adjacent units and land surface, and structural features, such as faults and paleochannels;

3. Diagnostic aspects of lithologic composition, texture, and color; drilling responses, and geophysical log signatures as recognized during borehole drilling operations;

4. General function within the aquifer system, extent and degree of use as a water supply, physical and hydraulic properties, recent rates of withdrawal (table 3), historic and potential future trends, and general considerations for development.

The descriptions serve as a reference resource from which various aspects of each hydrogeologic unit can be readily accessed. A sound conceptual perspective (see “Conceptual Development”) is also needed, however, for valid application of the descriptions in support of ground-water-resource development and management activities.

Potomac Aquifer

The Potomac aquifer is the largest, deepest, and most heavily used source of ground water in the Virginia Coastal Plain (fig. 2; table 3). The Potomac aquifer extends across the entire Virginia Coastal Plain except for the inner part of the Chesapeake Bay impact crater (fig. 8; pl. 8), is as thick as several thousand feet at depths of equal magnitude, and occupies the lowermost stratigraphic position within the area (fig. 3). The Potomac aquifer supplies major industries, many

Table 3. Summary of ground-water withdrawals in the Virginia Coastal Plain during 2002 and 2003.

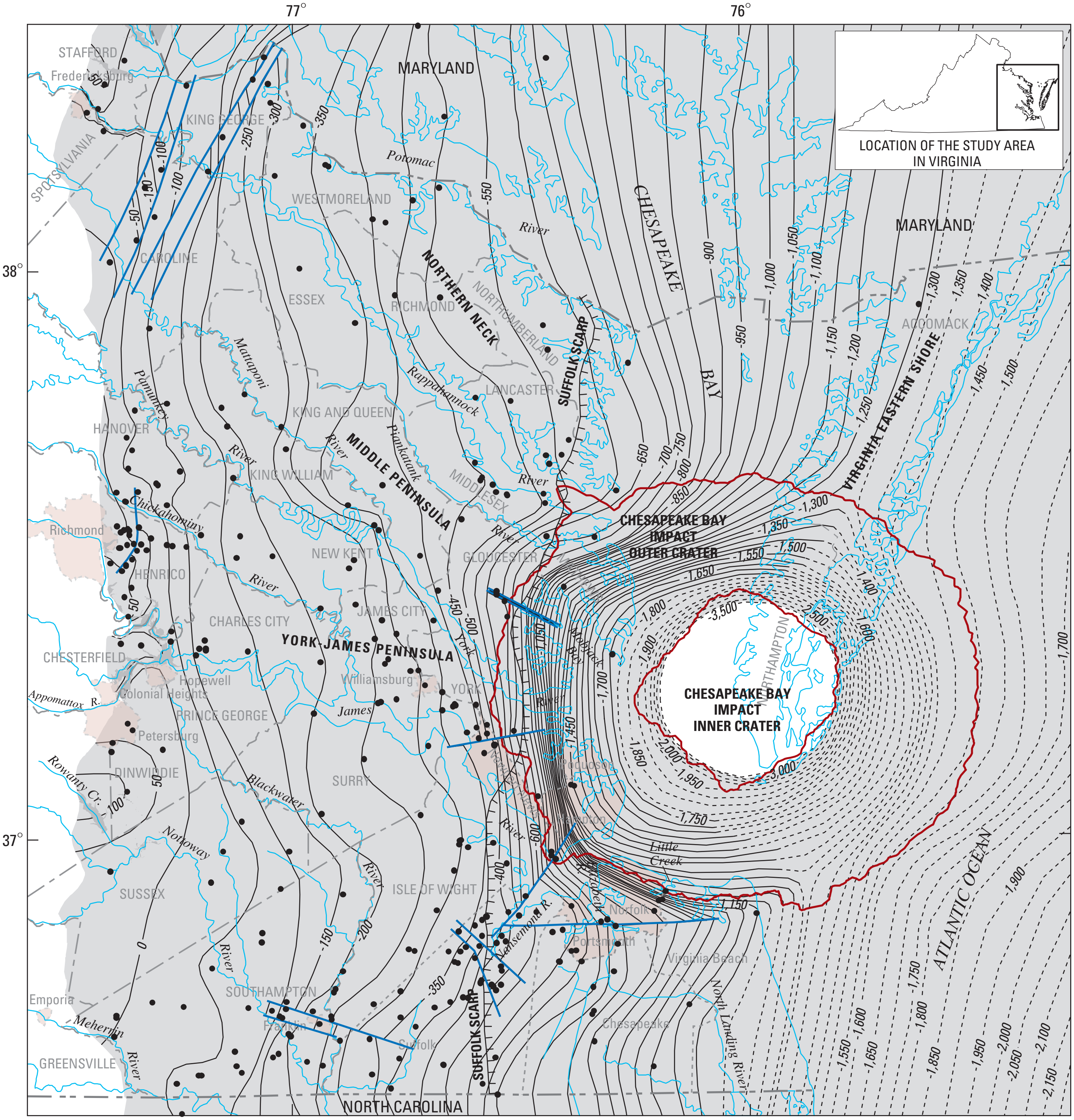
[Mgal/d, million gallons per day; <, less than]

Aquifer	Domestic[a] (Mgal/d)	2002			2003		
		Regulated[b] (Mgal/d)	Total[c]		Regulated[b] (Mgal/d)	Total[c]	
			Mgal/d	Percent		Mgal/d	Percent
Surficial	5.2	0.56	5.8	4	0.56	5.8	5
Yorktown-Eastover	11	5.9	17	13	5.4	16	13
Saint Marys	.05	.0	.05	<1	.0	.05	<1
Piney Point	1.9	4.9	6.8	5	4.6	6.5	5
Aquia	2.8	.59	3.4	3	.48	3.3	3
Peedee	.0	.0	.0	0	.0	.0	0
Virginia Beach	.09	.08	.17	<1	.08	.17	<1
Potomac	7.9	94	102	76	83	91	74
Totals	29	106	135	100	94	123	100

[a] Values were estimated from 2000 census data (Pope and others, 2002).

[b] Values were provided by the Virginia Department of Environmental Quality, Groundwater Withdrawal Permit Program, Richmond, VA.

[c] Total values were compiled for ground-water model development (Heywood, 2003).



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

▭ Extent of Potomac aquifer

▨ Incised area of aquifer

- - -500 — Structural contour—Approximate altitude of top of Potomac aquifer. Dashed where inferred. Contour interval is 50 feet. Datum is NGVD 29

— Fault

● Borehole location

0 10 20 MILES

0 10 20 KILOMETERS

Figure 8. Approximate altitude and configuration of the top of the Potomac aquifer in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of radial symmetry about the impact crater and eastward dip offshore. Further details are shown on plate 8.)

towns and cities, and low-density residential developments in rural areas. Increased development of the Potomac aquifer in conjunction with desalinization is expected during the coming decade and beyond as a means of addressing growing water demands in the metropolitan area to the southeast.

Geologic Relations

The Potomac aquifer consists primarily of fluvial-deltaic coarse-grained quartz and feldspar sands and gravels and interbedded clays (fig. 9) of the Potomac Formation. Both undisrupted Potomac Formation sediments of Early Cretaceous age outside of the Chesapeake Bay impact crater and megablock beds of the Potomac Formation that formed within the crater during the late Eocene Epoch compose the Potomac aquifer (fig. 3). Both megablock beds and underlying undisrupted parts of the Potomac Formation possibly extend across part of the crater (Powars and Bruce, 1999). The presence of megablock beds was inferred primarily from seismic surveys; however, they are not everywhere distinct from undisrupted parts of the Potomac Formation, and their configuration and extent are uncertain. In addition, some localized areas across the top of the southernmost part of the Potomac aquifer possibly include a basal part of the upper Cenomanian beds of Late Cretaceous age, which consists of variable but generally coarse-grained, deltaic sediments that directly overlie the Potomac Formation. Most of the upper Cenomanian beds are composed of near-shore marine, fine-grained sediments that are not considered part of the Potomac aquifer but are designated as the upper Cenomanian confining unit (see “Upper Cenomanian Confining Unit”). Lastly, small amounts of saprolite that developed over basement bedrock possibly are included locally along the base of the Potomac aquifer.

The Potomac aquifer is a heterogeneous aquifer (see “Hydrogeologic-Unit Classification”). Potomac Formation sediments deposited by braided streams, meandering streams, and deltas exhibit sharp contrasts in texture across small distances as a result of the highly variable and frequently changing depositional environments (see “Cretaceous Period”). Thus, the Potomac aquifer is hydraulically continuous on a regional scale, but locally exhibits discontinuities where flow is impeded by fine-grained interbeds. Likewise, megablock beds of the Potomac Formation within the Chesapeake Bay impact crater are essentially undeformed internally and likely function hydraulically similarly to undisrupted Potomac Formation sediments. Although Potomac Formation sediments have been juxtaposed across faults between megablock beds, the resulting contrasts in hydraulic conductivity are not intrinsically different from those throughout the Potomac aquifer. Inclusion of the megablock beds as part of the Potomac aquifer is made tentatively, however, with the recognition that much of the volume of the megablock beds is not directly observed in detail. A large potential exists for the configuration and other aspects of the megablock beds to differ substantially from those that have been theorized to date (2006). For example, the direction of anisotropy of individual megablock beds that are highly rotated could differ considerably from that of undisturbed Potomac Formation sediments. The Chesapeake Bay impact crater remains a topic of active research. Future hydrogeologic reclassification of the megablock beds could be warranted given a more accurate description of their configuration and an improved understanding of depositional processes within the Chesapeake Bay impact crater.

Designation of Potomac Formation sediments as composing a single Potomac aquifer or equivalent was made in

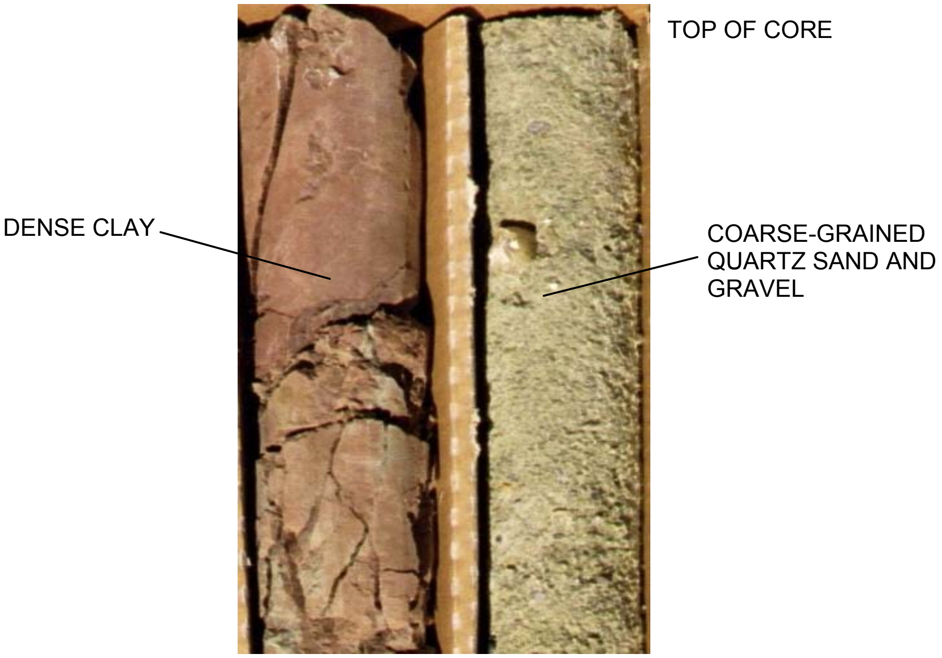


Figure 9. Fluvial-deltaic sediments of Early Cretaceous age from the Potomac Formation in the National Aeronautic and Space Administration (NASA) Langley core, borehole local number 59E 31, in Hampton, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and intervals are between approximately 1,593 and 1,595 feet below land surface. Section to right consists of coarse-grained quartz sand and gravel that constitutes the Potomac aquifer. Section to left consists of dense clay that is widely interbedded within the Potomac aquifer. Blocky structure of clay reflects paleosol development, and red color results from oxidized iron. Secondarily reduced clays, colored green and other variations, also are common at other locations. Less widespread organic clays are black and commonly have a pronounced mica content that imparts a greasy consistency.

previous studies of part or all of the Virginia Coastal Plain by the USGS (Cederstrom, 1957, 1968; Sinnott, 1969; Brown and Cosner, 1974; Cosner, 1975, 1976; Hopkins and others, 1981; Larson, 1981), by the DEQ (Commonwealth of Virginia, 1973, 1974; Newton and Siudyla, 1979; Siudyla and others, 1977, 1981), and by the Virginia Division of Mineral Resources (Cederstrom, 1939, 1945a). Subsequent studies in Virginia by the USGS during the 1980s subdivided the Potomac aquifer into upper, middle, and lower aquifers separated by intervening confining units (fig. 3). Among these, Meng and Harsh (1988) included all recognized sediments of Late Cretaceous age as parts of the upper Potomac aquifer and confining unit. By contrast, Laczniak and Meng (1988), Hamilton and Larson (1988), and Harsh and Laczniak (1990) designated most sediments of Late Cretaceous age as composing four distinct hydrogeologic units but also included sediments of the early Paleocene age Brightseat Formation as parts of the upper Potomac aquifer and confining unit. Similar designations were made in studies during approximately the same period in adjacent States. Vroblesky and Fleck (1991) in Maryland divided most of the sediments equivalent to the Potomac Formation into the Patuxent aquifer and overlying Potapsco aquifer, which are separated by the Potomac confining unit composed in part of the Arundel Clay. Most sediments of Late Cretaceous age were designated as seven distinct hydrogeologic units. Winner and Coble (1996) in North Carolina designated sediments of Early and Late Cretaceous age in a manner essentially parallel to the designations of Laczniak and Meng (1988), Hamilton and Larson (1988), and Harsh and Laczniak (1990), with the exception of not recognizing the Brightseat Formation.

The presence of confining units in Potomac Formation sediments in Virginia was based on stratigraphic correlations among borehole intervals that have fine-grained characteristics (see “Borehole Geophysical-Log Network”). Although the results of the aforementioned studies indicate that the confining units do not represent a single fine-grained interbed, the results of these studies indicate that interbeds within the designated intervals are of sufficient density across a continuous expanse to function hydraulically as regional barriers to flow among discrete and vertically separated volumes of Potomac Formation sediments.

The Potomac aquifer was subdivided in USGS studies during the 1980s as a means of vertical discretization of the aquifer to support development of a series of ground-water flow models (see “Previous Investigations”). The quasi-three-dimensional modeling techniques required the designation of separate aquifers to enable the representation as separate model layers needed to simulate vertical flow. Current modeling techniques have no such dependency, and an aquifer can readily be represented by multiple model layers that enable simulation of vertical flow within the single aquifer.

Examination of stratigraphic relations among fine-grained borehole intervals in Potomac Formation sediments during this investigation indicates that the confining units as previously described probably are not present. Correlated intervals extend across volumes of Potomac Formation sediments in which fine-grained interbeds are either thin and isolated or absent. Concentrations of fine-grained interbeds appear to be primarily of local extent, as indicated in some areas extending across as much as several miles where boreholes exhibit fine-grained intervals of similar thickness and altitude. Continuity across even local distances remains uncertain, however, considering the inherent discontinuity of the sediments resulting from their fluvial-deltaic origin (see “Cretaceous Period”). Additionally, potentiometric surfaces mapped for the three separate Potomac aquifers (Hammond and others, 1994a, b, c) are broadly similar and do not indicate widespread vertical hydraulic gradients that would result from regionally continuous confining units.

Structural Configuration

The Potomac aquifer is underlain across its entire extent by basement bedrock (fig. 5; pl. 2), consisting of mostly igneous and metamorphic rock but also consolidated sedimentary rock in five basins of Triassic to Jurassic age. The base of the Potomac aquifer across the basement surface has an altitude of approximately 100 ft along the Fall Zone, and dips along the Norfolk arch to approximately –3,000 ft near Norfolk but more steeply to the north and south into the Salisbury and Albemarle embayments, respectively. Although local-scale variations in the base of the Potomac aquifer of as much as several tens of feet are apparent in a few areas having sufficient borehole density, such detail generally is not discernible across a large expanse of the basement surface, which is inferred from Brown and others (1972).

The maximum altitude of the top of the Potomac aquifer is near its western margin along the Fall Zone (fig. 8; pl. 8). Borehole geophysical logs from north to south indicate altitudes of 58 ft in eastern Stafford County, increasing to 90 ft in eastern Henrico County and 95 ft in eastern Dinwiddie County. The highest altitudes are associated with a fault in eastern Henrico County (fig.1; pl. 8; pl. 6, sec. AS–AS'), and with the western part of the Norfolk arch in eastern Dinwiddie County. From there, the Potomac aquifer declines southward to nearly 0 ft in western Southampton County. The Potomac aquifer is extrapolated updip a few miles or less westward of these locations before pinching out against the basement at altitudes of approximately 100 ft or less.

The Potomac aquifer is overlain across almost all of its extent by the Potomac confining zone (fig. 10; pl. 9). Locally incised areas are projected as very narrow belts crossing the Fall Zone along the Potomac, Rappahannock, James, Appomattox, and Nottoway Rivers, and by Rowanty Creek in eastern Dinwiddie County. The Potomac aquifer crops out across the steepest slopes in these incised areas, but is mostly covered by several feet or more of flood plain, terrace, and channel-fill sediments that compose the surficial aquifer. Additional outcrops are present along smaller streams crossing the Fall Zone but are very small and isolated. More extensive outcrops are present westward of the Potomac River between Washington, D.C. and Fredericksburg, but these are beyond the area of this study. Direct contact between the Potomac aquifer and surficial aquifer across the incised areas possibly creates direct hydraulic connections between the confined and unconfined ground-water systems.

The Potomac aquifer thickens as it dips generally eastward to an altitude of approximately –500 ft along the western margin of the Chesapeake Bay impact crater (fig. 8; pl. 8; pl. 3, sec. CD–CD'; pl. 4, all secs.). Here the altitude of the base of the Potomac aquifer at basement ranges approximately from –1,700 to –2,500 ft (fig. 5; pl. 2), resulting in a thickness range of approximately 1,200 to 2,000 ft. The top of the Potomac aquifer dips concentrically and more steeply along the crater margin to approximately –1,400 ft, then less steeply across the outer crater to an extrapolated altitude of –4,000 ft at the inner crater. The Potomac aquifer decreases in thickness across the outer crater to approximately 1,000 ft before being truncated at the inner crater by the Exmore clast confining unit.

The top of the Potomac aquifer outside of the Chesapeake Bay impact crater continues to dip eastward to an altitude of approximately –1,400 ft along the Atlantic coast and extends offshore (fig. 8; pl. 8). The altitude of the base of the Potomac aquifer at basement along the coast is projected to range from approximately –3,000 to –7,000 ft (fig. 5; pl. 2), resulting in a thickness range of approximately 1,600 to 5,600 ft. The Potomac aquifer along the coast is thinnest across the eastward limb of the Norfolk arch just south of the crater. It deepens and thickens to the south of the Norfolk arch into the Albemarle embayment beyond the study area, and to the north of the crater into the Salisbury embayment. Where no borehole data are available across the Atlantic Ocean and much of Chesapeake Bay and the Virginia Eastern Shore, an approximate configuration of the Potomac aquifer is extrapolated assuming continued eastward dip and radial symmetry about the crater. Additionally, and based on previous studies, the Potomac aquifer is extrapolated southward into North Carolina (Winner and Coble, 1996) and northward into Maryland (Vroblesky and Fleck, 1991).

Some borehole geophysical logs indicate that the top of the Potomac aquifer has closely spaced displacements generally several tens of feet that are attributed to faults (fig. 8; pls. 3–8). Displacement of sediments generally occurs along the faults that extend vertically downward through the Potomac aquifer at least to basement. Because the faults probably were created by tectonic movement of the basement, they likely continue downward into the basement. Borehole data are not adequate, however, to determine whether the basement surface exhibits displacements along the faults. Because the faults likely propagated upward synchronously with sediment deposition, the largest displacements have occurred in the Potomac aquifer, which consists of the oldest sediments. Younger, overlying hydrogeologic units generally have smaller displacements.

Because the sediments are unconsolidated and generally incompetent, the faults probably have propagated as localized zones of disrupted sediment along which movement has occurred rather than as a series of discrete fractures in competent rock. Hence, flow is likely not enhanced along open fractures nor impeded by fractures lined with fault gouge. Partial or complete destruction of depositional intergranular structure by movement across faulted intervals, however, possibly has resulted in poorly sorted texture and(or) compaction and, consequently, to some decrease in hydraulic conductivity, which could locally impede flow. Similar conditions could exist locally at potentially many other locations where faults are not recognized because of sparse borehole data, particularly within the part of the Potomac aquifer composed of megablock beds where faults likely are most widespread but of uncertain configuration and extent.

In addition to possible intergranular effects, most of the observed faults create local-scale irregularities in the altitude of the Potomac aquifer and, in close association, laterally abut relatively small volumes across the top of the aquifer against overlying hydrogeologic units. Because of the inherent discontinuity of Potomac Formation sediments, the hydrologic effect of the contrasts in texture resulting from internal sediment juxtaposition across most of the faults is not intrinsically different from that produced by contrasting textures throughout the Potomac aquifer. An important exception, however, is a pair of closely spaced parallel faults along the northwest margin of the Chesapeake Bay impact crater, across which displacements exceed 500 ft (fig. 8; pl. 4, sec. DD–DD'; pl. 8). These faults possibly represent a deep graben created in association with the crater (see “Late Eocene Epoch – Chesapeake Bay Impact Crater”). Much of the original thickness of the Potomac aquifer across this feature has been filled by the Exmore clast confining unit. Hence, the feature may create a significant localized barrier to lateral ground-water flow (see “Exmore Clast Confining Unit”). The presence of the feature is inferred from displacements observed in several nearby borehole geophysical logs. Similar structures possibly exist at other locations along the margin of the crater but are not recognized because of scarce borehole data and inadequate spatial control (see “Limitations”).

Recognition

Coarse-grained intervals within the Potomac aquifer are the most effective water-production zones in the Virginia Coastal Plain. Penetration of the top of the Potomac aquifer by boreholes generally is noted by medium- to very coarse-grained quartz and feldspar sands and gravels (fig. 9) as much as several tens of feet thick that create a pronounced gritty sound and feel in drilling response and result in wholly disaggregated drill cuttings. The sands and gravels are devoid of fossil shells; however, shell material that originates from overlying marine sediments of shallower hydrogeologic units commonly remains unflushed from the borehole while drilling in the Potomac aquifer and, consequently, persists in cuttings. In borehole electric logs (see “Borehole Geophysical-Log Network”), massively bedded sands and gravels have a blocky signature, whereas fining-upward sequences have a roughly pyramidal signature (fig. 4). Gamma logs have a low response in the absence of minerals that produce radioactivity. Electric-log signatures can be dampened across megablock beds relative to undisrupted Potomac Formation sediments (Powars and Bruce, 1999), but the effect is subtle or not apparent in some instances. Sandy saprolite at the base of the Potomac aquifer and overlying basement is not distinguishable from Potomac aquifer sands in some instances.

Fine-grained interbeds within the Potomac aquifer commonly include some of the most dense clays in the Virginia Coastal Plain (fig. 9). Drilling response is smooth and quiet, but the rate of advancement can be slowed substantially. Use of a drag bit results in cuttings as intact and recognizable chips generally less wide than one inch that have distinct but commonly quite variable colors. Well-developed paleosols are widely preserved, consisting of oxidized clays typically colored light reddish brown (Munsell soil color classification 5YR 6/4), light yellowish brown (2.5Y 6/4), and similar colors. In core and outcrop, the paleosol clays have soil-related features, such as roots and a blocky, pervasively fractured weathered structure. Some paleosols have undergone secondary reduction, altering their color to grayish green (5G 5/2) among numerous other variations. Less widespread than the paleosols are highly organic, micaceous clays that were deposited in swamps and similar anoxic environments. These organic, micaceous clays have remained reduced and exhibit a dark gray (N3) color and greasy texture. Preserved in places with the organic clays are carbonized wood fragments, ranging in size from twigs to whole trees, and pollen that provides the sole means of paleontological dating of the Potomac Formation sediments that are otherwise entirely barren. Use of a roller bit largely liquefies fine-grained interbeds into the drilling fluid, but these can be discerned in some instances by a change in fluid color. Fine-grained interbeds typically have a flat signature in borehole electric logs and a moderately elevated response in gamma logs (fig. 4). Clayey saprolite at the base of the Potomac aquifer and overlying basement is not distinguishable from Potomac aquifer clays in some instances.

Hydrologic Aspects

Because of its great thickness, extent, and very coarse-grained texture, the Potomac aquifer is the most dominant hydrogeologic unit of the Virginia Coastal Plain. Most of the ground water flows through and is stored in the Potomac aquifer, which makes it the primary ground-water supply resource. Major water-supply wells completed in the central and southeastern parts of the Potomac aquifer commonly have yielded 100 to 500 gallons per minute (gal/min), with some yields in James City County as large as 3,000 gal/min.

Vertical hydraulic conductivity values of permeameter samples of sands from the Potomac aquifer range over four orders of magnitude from 0.00059 to 2.8 feet per day (ft/d; table 1). Sand porosity varies over a relatively small range from 24 to 37 percent. Small vertical hydraulic conductivity values were obtained from samples having relatively poor sediment sorting, and the sample having the lowest value also was the least porous. In poorly sorted and immature Potomac Formation sands deposited by braided streams, ground water flows through variably sized pores that are partly blocked by small grains that create bridges and “dead-ends” between large grains. In better sorted and more mature sands deposited by meandering streams, ground water flows through more uniformly sized and continuously connected pores that efficiently conduct water. In previously published results, horizontal hydraulic conductivity values varied similarly over three orders of magnitude from 0.22 ft/d from a slug test to 347 ft/d from a specific-capacity test (McFarland, 1997, and Hamilton and Larson, 1988, respectively; table 2). In addition, the vertical hydraulic conductivity values of permeameter samples are lower than the published horizontal hydraulic conductivity values partly because of anisotropy but also because samples of wholly noncohesive sands could not be viably collected. The highest hydraulic conductivity values resulted from specific-capacity tests or calibration of ground-water models and probably are the most representative of the effective hydraulic conductivity of the Potomac aquifer at the regional scale.

In addition to the high-yielding sands, the Potomac aquifer also contains clay interbeds that do not effectively contribute to ground-water production. Vertical hydraulic conductivity values of permeameter samples of clays from the Potomac aquifer range from 0.000025 to 0.0021 ft/d (table 1). Porosity values are nearly uniform, between 37 and 43 percent. The range in vertical hydraulic conductivity values over two orders of magnitude possibly results from variations in the degree of fracturing of the clays. Published vertical hydraulic conductivity values generally are smaller, ranging over only one order of magnitude from 0.0000019 to 0.000081 ft/d (Harsh and Laczniak, 1990, and Laczniak and Meng, 1988, respectively; table 2). The permeameter samples collected during this study were all from within the Chesapeake Bay impact crater, where clays in the Potomac aquifer possibly have undergone more fracturing than elsewhere.

During 2002, the Potomac aquifer produced an estimated 76 percent of the ground water used in the Virginia Coastal Plain, a rate of 102 Mgal/d (table 3). Of this usage, a rate of 94 Mgal/d was reported to DEQ by regulated industrial, municipal, and commercial users, and an additional 7.9 Mgal/d was estimated for unregulated domestic users. Similar levels of production took place during the several preceding years (Jason Pope, U.S. Geological Survey, oral commun., 2005). During 2003, however, increased precipitation facilitated a greater reliance by regulated users on surface-water supplies, resulting in a reduced rate in regulated withdrawal to 83 Mgal/d and, consequently, a total withdrawal of 91 Mgal/d from the Potomac aquifer. Withdrawal from most other aquifers also decreased during 2003, so the relative contribution of the Potomac aquifer remained essentially unchanged.

Industrial withdrawals from the Potomac aquifer at the two largest pumping centers in the Virginia Coastal Plain have been maintained at relatively stable rates for several decades, resulting in two regional cones of depression that have water-level declines as great as 200 ft and dominate the head distribution across the entire Potomac aquifer (Hammond and others, 1994a, b, c). Most other regulated withdrawals from the Potomac aquifer are located in metropolitan areas along the middle and lower reaches of the York-James Peninsula and south of the James River. Many of the regulated withdrawals are for municipally operated public-water supplies and historically have been episodic, varying in duration from several months to several years to supplement surface-water supplies during periods of prolonged drought and alternately interrupted by extended periods of no withdrawal (Focazio and Speiran, 1993). Public-supply withdrawal generally has increased along the western margin of the Chesapeake Bay impact crater but is limited by the presence of brackish ground water associated with the crater (see “Quaternary Period”). Desalinization is being developed to address growing water demands and is expected to be relied on increasingly during the coming decade in response to population growth, with municipal withdrawals projected to reach magnitudes that rival the two historically largest industrial withdrawals. In addition to elevated salinity near the crater, concentrations of iron in water from the Potomac aquifer can be problematic at widely scattered locations. Concentrations of fluoride also are high in parts of Southampton and Isle of Wight Counties and around the City of Suffolk (fig. 8; pl. 8).

Unregulated withdrawals from the Potomac aquifer generally are widely dispersed across rural areas. A random sample of domestic-well records from county health departments indicates that the Potomac aquifer is tapped for unregulated withdrawals by more than one-half of the wells constructed since approximately 1985 in King George, Southampton, and Isle of Wight Counties and the city of Suffolk (Jason Pope, U.S. Geological Survey, written commun., 2005), possibly because of its relative proximity to land surface and a lack of shallower alternative aquifers. Unregulated withdrawal from the Potomac aquifer also is widespread across most of the remainder of the Virginia Coastal Plain, except in brackish areas in proximity to the Chesapeake Bay and Atlantic Ocean.

Potomac Confining Zone

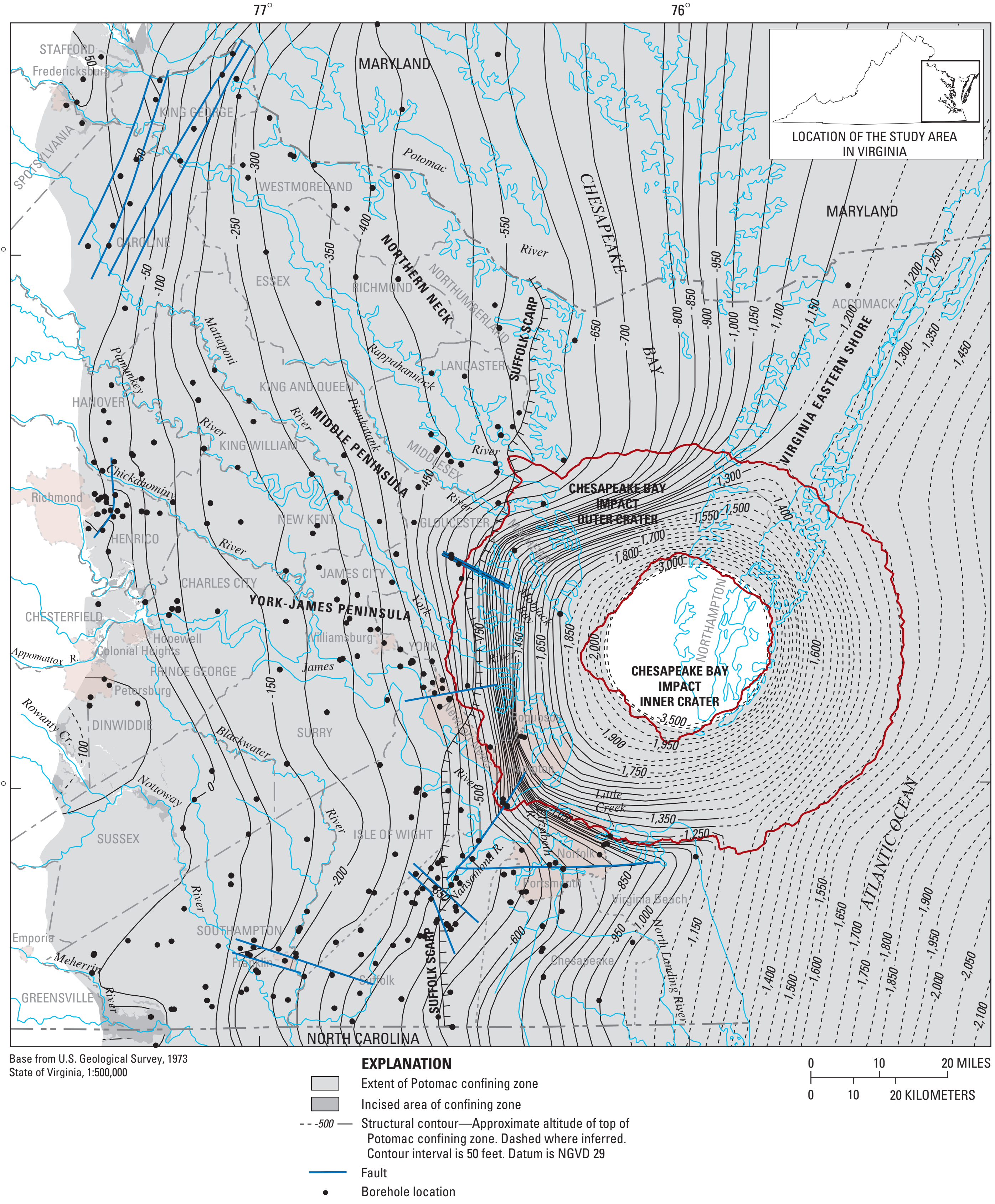
The Potomac confining zone is widespread, generally deep, and a local impediment to ground-water flow in the Virginia Coastal Plain. The Potomac confining zone extends across the entire Virginia Coastal Plain except for the inner part of the Chesapeake Bay impact crater (fig. 10; pl. 9). Thickness ranges up to several tens of feet at depths as great as a few thousand feet. The Potomac confining zone is stratigraphically above the Potomac aquifer and approximates a transition to overlying hydrogeologic units.

Geologic Relations

The Potomac confining zone generally is defined locally as the uppermost clay that is interbedded with coarse-grained quartz and feldspar sands and gravels of the fluvial-deltaic Potomac Formation. The Potomac confining zone includes undisrupted Potomac Formation sediments of Early Cretaceous age outside of the Chesapeake Bay impact crater and megablock beds of the Potomac Formation formed within the crater during the late Eocene Epoch (fig. 3). The remainder of the Potomac Formation beneath the Potomac confining zone is designated as the Potomac aquifer (see “Potomac Aquifer”). In addition, some localized areas across the southernmost part of the Potomac confining zone possibly include fine-grained interbeds within the basal part of the upper Cenomanian beds of Late Cretaceous age, which consist of deltaic sediments that directly overlie the Potomac Formation. Most of the upper Cenomanian beds consist of near-shore marine sediments and are not considered part of the Potomac confining zone, but are designated as the upper Cenomanian confining unit (see “Upper Cenomanian Confining Unit”).

Designation of the Potomac confining zone accounts for variable configurations and, in some cases, indistinguishable relations that can exist above the Potomac aquifer. The Potomac aquifer is a heterogeneous aquifer (see “Hydrogeologic-Unit Classification”). Potomac Formation sediments deposited by braided streams, meandering streams, and deltas exhibit sharp contrasts in texture across small distances as a result of the highly variable and frequently changing depositional environments (see “Cretaceous Period”). Fine-grained interbeds composing the Potomac confining zone are positioned across the top of the Potomac Formation and locally impede vertical leakage between the Potomac aquifer and the overlying hydrogeologic units. The interbeds are discontinuous, however, and were correlated across relatively large distances as great as several miles or more between borehole locations. As a result, the Potomac confining zone as mapped probably includes coarse-grained sediments of the Potomac Formation and(or) the overlying Aquia Formation, which are in direct contact where no interbeds are located (fig. 7, left side). As a further complication at some locations, reworked Potomac Formation sediments have mixed with marine sediments of the Aquia Formation (fig. 6). Elsewhere, differences between Potomac Formation interbeds and fine-grained sediments of overlying confining units can be obscured (fig. 7, right side), including those of the upper Cenomanian, Nanjemoy-Marlboro, or Chickahominy confining units. Thus, the Potomac confining zone does not represent a distinct contact surface but rather approximates a transition from the Potomac aquifer to various overlying hydrogeologic units.

A single Potomac aquifer or equivalent was designated in some previous studies, but a distinct body of sediment to act as an overlying hydrologic barrier or boundary was not specified (Cederstrom, 1939, 1945a, 1957, 1968; Sinnott, 1969; Commonwealth of Virginia, 1973, 1974; Brown and Cosner, 1974; Cosner, 1975, 1976; Newton and Siudyla, 1979;



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

- ▨ Extent of Potomac confining zone
- ▨ Incised area of confining zone
- - - -500 — Structural contour—Approximate altitude of top of Potomac confining zone. Dashed where inferred. Contour interval is 50 feet. Datum is NGVD 29
- — Fault
- • Borehole location

Figure 10. Approximate altitude and configuration of the top of the Potomac confining zone in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of radial symmetry about the impact crater and eastward dip offshore. Further details are shown on plate 9.)

Hopkins and others, 1981; Larson, 1981; Siudyla and others, 1981). An "aquitard confining layer" was first described for sediments cited as the Mattaponi Formation of Paleocene age (Siudyla and others, 1977). In subsequent studies, the designated intervening and overlying confining units of the subdivided Potomac aquifer (fig. 3) included various sediments of Late Cretaceous and early Paleocene age as the upper Potomac confining unit (Hamilton and Larson, 1988; Meng and Harsh, 1988; and Harsh and Laczniak, 1990) or the Brightseat-upper Potomac confining unit (Laczniak and Meng, 1988). Similar designations were made during approximately the same period in studies in adjacent States—the Potapsco confining unit in Maryland (Vroblesky and Fleck, 1991) and the upper Cape Fear confining unit in North Carolina (Winner and Coble, 1996).

Although it was acknowledged in these earlier studies that the upper Potomac confining unit and its counterparts that subdivide the Potomac aquifer do not each represent a single fine-grained interbed, it also was expressed or implied that interbeds in the designated intervals are of sufficient density across a continuous expanse to act hydraulically as regional barriers to flow. By contrast, the Potomac aquifer is not subdivided herein based on stratigraphic relations determined during the current study (see "Potomac Aquifer"). Fine-grained intervals observed in boreholes within Potomac Formation sediments appear to be primarily of local extent and do not represent confining units either within or overlying the Potomac aquifer.

Structural Configuration

The Potomac confining zone is underlain across its entire extent by the Potomac aquifer (fig. 8; pl. 8). The maximum altitude of the Potomac confining zone is near the western margin along the Fall Zone (fig. 10; pl. 9). Borehole geophysical logs from north to south indicate altitudes of 66 ft in eastern Stafford County, increasing to 99 ft in eastern Henrico County, and 88 ft in southern Petersburg. The highest altitudes are associated with a fault in eastern Henrico County (fig. 8; pl. 6, sec. AS–AS') and with the western part of the Norfolk arch in eastern Dinwiddie County. From there, the Potomac confining zone declines southward to nearly 0 ft in western Southampton County. The Potomac confining zone is extrapolated updip a few miles or less westward of these locations before pinching out against the basement at altitudes of approximately 100 ft or less. Differentiation along the Fall Zone of the Potomac confining zone from the overlying Nanjemoy-Marlboro, Calvert, and(or) Saint Marys confining units and from the Yorktown confining zone can be obscured because all of these hydrogeologic units are relatively thin and have indistinct borehole geophysical log signatures. Truncation of the Potomac confining zone is projected across the western margin along the valleys of the Potomac, James, and Appomattox Rivers and some of their tributaries, and along Rowanty Creek in eastern Dinwiddie County. In addition, an internal opening or "window" is projected along the valley of the Nottoway River, which creates an incised area across the Potomac aquifer (fig. 8; pl. 8).

The Potomac confining zone is overlain across most of its extent by the Aquia aquifer (fig. 18; pl. 15). To the south it is overlain by the upper Cenomanian confining unit, extending across most of the cities of Virginia Beach, Chesapeake, and Suffolk and southern Isle of Wight County and southeastern Southampton County (fig. 11; pl. 10). Beyond the eastern margin of the Aquia aquifer, the Potomac confining zone is overlain by the Chickahominy confining unit across the Chesapeake Bay impact crater and northward along the Virginia Eastern Shore (fig. 25; pl. 19), and by the Nanjemoy-Marlboro confining unit beneath upper Chesapeake Bay, the northern part of the Delmarva Peninsula, and offshore (fig. 20; pl. 16).

Locally incised areas are projected across the Potomac confining zone generally as narrow belts along the Potomac, Rappahannock, James, Appomattox, Nottoway, and Meherrin Rivers and some of their tributaries, and along Rowanty Creek in eastern Dinwiddie County (fig. 10; pl. 9). The Potomac confining zone crops out across the steepest slopes in the incised areas, but is mostly covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer. Additional outcrops are present along smaller streams crossing the Fall Zone but are very small and isolated. More extensive outcrops are present west of the Potomac River between Washington, D.C., and Fredericksburg, but these are beyond the area of this study. Thinning of the Potomac confining zone where it is overlain by the surficial aquifer across the incised areas possibly enhances hydraulic connections between the confined and unconfined ground-water systems. Confined and unconfined connections are further enhanced across the "window" along the valley of the Nottoway River, where the Potomac confining zone has been truncated by erosion and the Potomac aquifer and surficial aquifer are in direct contact.

The Potomac confining zone varies in thickness from only a few feet across a single fine-grained interbed to as much as several tens of feet where multiple interbeds probably are present. The Potomac confining zone dips generally eastward to an altitude of approximately –500 ft at the western margin of the Chesapeake Bay impact crater (fig. 10; pls. 9, 3 (sec. CD–CD'), 4 (all secs.)). The top of the Potomac confining zone dips concentrically and more steeply along the crater margin to approximately –1,400 ft, then less steeply across the outer crater to an extrapolated altitude of –3,500 ft at the inner crater. The Potomac confining zone is truncated at the inner crater by the Exmore clast confining unit.

The top of the Potomac confining zone outside of the Chesapeake Bay impact crater continues to dip eastward to an altitude of approximately –1,300 along the Atlantic coast and extends offshore (fig. 10; pl. 9). Where no borehole data are available across the Atlantic Ocean and much of Chesapeake Bay and the Virginia Eastern Shore, an approximate configuration of the Potomac confining zone is extrapolated assuming continued eastward dip along with radial symmetry about the crater. Additionally and based on previous studies, the Potomac confining zone is extrapolated southward into North Carolina (Winner and Coble, 1996) and northward into Maryland (Vroblesky and Fleck, 1991).

The top of the Potomac confining zone on some borehole geophysical logs exhibits closely spaced displacements generally of several tens of feet which have been attributed to faults (fig. 10; pls. 3–7, 9). The faults intersect the Potomac confining zone by extending upward from the Potomac aquifer (see "Potomac Aquifer"). Although discrete fractures that are either open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of their depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. In addition, the faults create local-scale irregularities in the altitude of the Potomac confining zone, and laterally abut generally small volumes across the top and base of the confining zone against overlying hydrogeologic units. Because of the inherent discontinuity of Potomac Formation sediments, contrasts in texture resulting from internal sediment juxtaposition across most of the faults are not intrinsically different from those throughout the Potomac confining zone. One notable exception is a pair of closely spaced parallel faults inferred along the northwestern margin of the Chesapeake Bay impact crater, across which displacements exceed 500 ft (fig. 10; pls. 4 (sec. DD–DD'), 9) and possibly represent a deep graben associated with the crater (see "Late Eocene Epoch – Chesapeake Bay Impact Crater"). Much of the original thickness of the Potomac aquifer across this feature has been filled by the Exmore clast confining unit (see "Exmore Clast Confining Unit"). Faults possibly exist in other locations but are not recognized because of sparce borehole data and inadequate spatial control (see "Limitations").

Recognition

Borehole penetration of the top of the Potomac confining zone generally is noted with the first fine-grained interbed or group of interbeds across the top of the Potomac Formation, which lithologically contrasts markedly with the overlying sediments of the Aquia aquifer or the upper Cenomanian, Nanjemoy-Marlboro, or Chickahominy confining units. Fine-grained interbeds that locally define the Potomac confining zone essentially are of identical lithology as deeper interbeds throughout the greater part of the Potomac Formation, which constitutes the Potomac aquifer (fig. 9; see "Potomac Aquifer"). Dense clays are variably colored and include light reddish brown (5YR 6/4), light yellowish brown (2.5Y 6/4), and grayish green (5G 5/2) clays among numerous other variations; in addition, more rare organic and micaceous clays are dark gray (N3) and exhibit a greasy texture. Drilling response typically is smooth and quiet, but the rate of advancement can be slow. Similarly fine-grained interbeds at the top of the basal deltaic part of the upper Cenomanian Beds potentially can be included in some localized areas across the southernmost part of the Potomac confining zone.

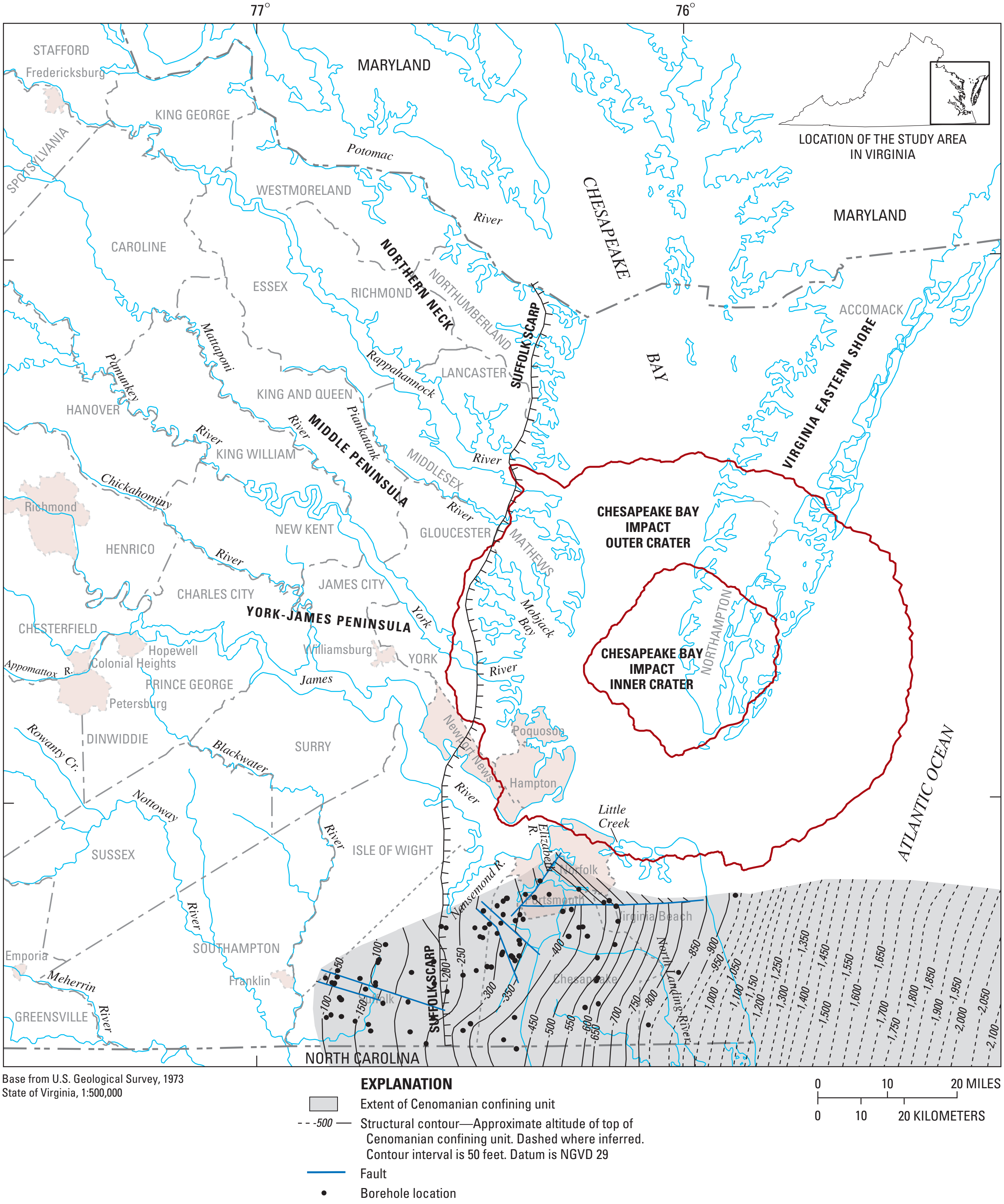
Medium- to very coarse-grained quartz and feldspar sands and gravels of the Potomac Formation that underlie the uppermost fine-grained interbed(s) mark the top of the Potomac aquifer (see "Potomac Aquifer"). Sediments of the Aquia aquifer or of the upper Cenomanian, Nanjemoy-Marlboro, or Chickahominy confining units likely directly overlie the Potomac aquifer at many locations where no intervening interbeds are present. In addition, reworked Potomac Formation sediments can be mixed with marine sediments of the Aquia Formation across some intervals (fig. 6). Such configurations can be discerned clearly in core or in rare outcrops but generally are more obscure if based solely on drill cuttings and(or) borehole geophysical logs. As a result, the Potomac confining zone is, in most instances, designated on geophysical logs as an interval that is transitional from the intervals recognizable as adjacent hydrogeologic units (fig. 4). The Potomac confining zone generally exhibits a flat signature on electric logs and a moderately elevated response on gamma logs. Differentiation across the interval of fine-grained interbeds of the Potomac Formation from some sediments of adjacent hydrogeologic units can be obscured by the commonly indistinct log signatures, especially where the different units are relatively thin.

Hydrologic Aspects

Although the Potomac confining zone is regionally extensive, it impedes ground-water flow primarily at a local scale. Potomac Formation clays generally exhibit small vertical hydraulic conductivities (see "Potomac Aquifer"), including permeameter-sample values as small as 0.000025 ft/d (table 1) and published values ranging from 0.0000019 to 0.000081 ft/d (Harsh and Laczniak, 1990, and Laczniak and Meng, 1988, respectively; table 2). Hence, leakage locally into or out of the Potomac aquifer can be impeded substantially where interbeds are present. The discontinuity of the interbeds, however, results in the Potomac confining zone producing greater leakage at the regional scale but focused at locations where interbeds do not exist. The Potomac confining zone does not represent a lithologically uniform mass of sediment through which leakage is enhanced as a result of overall relatively large vertical hydraulic conductivity, and description as a leaky confining unit is not conceptually accurate.

Upper Cenomanian Confining Unit

The upper Cenomanian confining unit has a limited regional extent, is generally deep, and locally impedes ground-water flow in the Virginia Coastal Plain. The upper Cenomanian confining unit extends across most of the cities of Virginia Beach, Chesapeake, and Suffolk and along southern Isle of Wight County and southeastern Southampton County (fig. 11; pl. 10). Thickness ranges up to approximately 200 ft at depths as much as several hundred feet. The upper Cenomanian confining unit is stratigraphically above the Potomac confining zone.



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

Figure 11. Approximate altitude and configuration of the top of the upper Cenomanian confining unit in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 10.)

Geologic Relations

The upper Cenomanian confining unit consists of primarily near-shore marine, glauconitic, micaceous, lignitic, fossiliferous and variably calcified sandy and clayey silts (fig. 12) recently recognized as the upper Cenomanian beds of Late Cretaceous age (Powars, 2000; fig. 3). The predominantly fine-grained sediments are interbedded with numerous thin and sharply bounded deposits of shells and biofragmental sands (shell hashes) that, in places, are cemented with calcite. In some areas, a lowermost basal part of the upper Cenomanian beds consists of variable and generally coarse-grained deltaic sediments that are not considered part of the upper Cenomanian confining unit but are, instead, included as part of the Potomac aquifer and(or) Potomac confining zone.

Relatively uniform sediment-transport conditions deposited the marine sediments of the upper Cenomanian beds along the near-shore shelf. Hence, the predominantly silty sediments that compose the upper Cenomanian confining unit vary gradationally and function hydraulically as a continuous medium that impedes horizontal flow but allows relatively slow ground-water movement, mostly as vertical leakage.

Designation herein of a distinct upper Cenomanian confining unit is new. Alternative interpretations have been made in previous studies of the Virginia Coastal Plain to sediments of Late Cretaceous age of which the upper Cenomanian beds are a part. In some studies, sediments of Early and Late Cretaceous age (Commonwealth of Virginia, 1974) or alternatively of Late Cretaceous through Eocene age (Siudyla and others, 1981) were designated as a single aquifer. In more recent USGS studies, sediments of Late Cretaceous age were designated primarily as constituting the Upper Potomac confining unit (Meng and Harsh, 1988) and subsequently were divided to include the Brightseat-Upper Potomac confining unit (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Harsh and Laczniak, 1990; fig. 3). Equivalent sediments were similarly designated in studies in adjacent States during approximately the same period—the Potapsco confining unit in Maryland (Vroblesky and Fleck, 1991) and the Upper Cape Fear confining unit in North Carolina (Winner and Coble, 1996). The upper Cenomanian beds were recognized following these studies (Powars, 2000).

Figure 12. Near-shore marine sediments of Late Cretaceous age from the upper Cenomanian beds in the Dismal Swamp core, borehole local number 58A 76, in the city of Suffolk, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and interval is between approximately 585 and 586 feet below land surface. Glauconitic sandy and clayey silts constitute the upper Cenomanian confining unit. Pronounced mica content imparts a greasy consistency. Interbeds of fossil shells and biofragmental sands are intersected across top and middle parts of interval. Interbeds are calcite cemented at some other locations. Shells include the distinctively light red (7.5R 6/6) mollusk *Exogyra woolmani*.

Structural Configuration

The upper Cenomanian confining unit is entirely below land surface, does not crop out, and is underlain across its entire extent by the Potomac confining zone (fig. 10; pl. 9). It is overlain by the Virginia Beach aquifer across most of Virginia Beach westward through central and southern city of Chesapeake, southern city of Suffolk, and the southeastern corner of Southampton County (fig. 13; pl. 11). The Virginia Beach aquifer pinches out to the north, beyond which the remaining part of the upper Cenomanian confining unit is overlain by the Aquia aquifer from southern Norfolk westward and broadening through southern Isle of Wight County and a small part of eastern Southampton County.

The upper Cenomanian confining unit is at its maximum altitude near its western terminus in southeastern Southampton County where borehole geophysical logs indicate altitude up to –47 ft (fig. 11; pl. 10). The upper Cenomanian confining unit is extrapolated westward to pinch out against the Potomac confining zone (pl. 5, secs ID–ID', JD–JD'). Differentiation of the upper Cenomanian confining unit from the Potomac confining zone can be obscured where both hydrogeologic units are relatively thin and have indistinct borehole geophysical log signatures. Sediments of the upper Cenomanian beds, possibly extending a short distance farther west, are included with the Potomac confining zone.

The upper Cenomanian confining unit dips generally eastward across its entire extent (fig. 11; pl. 10) and is thickest (194 ft) at altitudes from –848 ft to –1,042 ft in the Fentress core on the far eastern side of the city of Chesapeake (pls. 5, 7, secs. ID–ID', GS-GS', respectively; Attachment 1, borehole 61B 11). The upper Cenomanian confining unit is extrapolated northward to pinch out against the Potomac confining zone along the western part of its northern margin across eastern Southampton County and southern Isle of Wight County, at altitudes ranging from approximately –50 ft to –400 ft (pl. 6, secs. CS–CS', DS–DS'). The altitude of the top of the upper Cenomanian confining unit near the southwestern margin of the Chesapeake Bay impact crater is approximately –600 ft (fig. 11; pl. 10). The upper Cenomanian confining unit is extrapolated northward along the eastern part of its northern margin to be truncated at progressively lower altitudes by the Exmore clast confining unit and the Exmore matrix confining unit (pl. 7, all secs.). The upper Cenomanian confining unit also is extrapolated eastward offshore and southward into North Carolina based on a previous study (Winner and Coble, 1996).

The top of the upper Cenomanian confining unit on some borehole geophysical logs exhibits closely spaced displacements generally of a few tens of feet or less which have been attributed to faults (fig. 11; pls. 5–7, 10). The faults intersect the upper Cenomanian confining unit by extension upward from the Potomac aquifer (see “Potomac Aquifer”) and through the intervening Potomac confining zone, which generally exhibit larger displacements. Although discrete fractures that are either open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of their depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. In addition, the faults create local-scale irregularities in the altitude of the upper Cenomanian confining unit and laterally abut generally small volumes across the top and base of the confining unit against adjacent hydrogeologic units. An exceptional case exists beneath the Nansemond River, where the upper Cenomanian confining unit is substantially thin across a fault (pl. 5, sec. GD–GD'). Faults possibly are at other locations but are not recognized because of sparse borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the upper Cenomanian confining unit in boreholes is generally noted by glauconitic, lignitic, fossiliferous, and commonly very micaceous sandy and clayey silts (fig. 12) that are in contrast to the more coarse-grained and well-sorted sands of the overlying Virginia Beach aquifer where it is present. Beyond the Virginia Beach aquifer where the upper Cenomanian confining unit is overlain by the Aquia aquifer, penetration of the top of the upper Cenomanian confining unit is less discernible because the lithologies of the two hydrogeologic units can be similar in color and texture. Cuttings of upper Cenomanian beds sediments returned by drag bits during this study were dark greenish gray (10Y 4/1). Differentiation of the upper Cenomanian confining unit is commonly dependent on recognition of pronounced mica content that imparts a greasy feel to cuttings. In addition, shell beds contain the distinctively light red (7.5R 6/6) mollusk *Exogyra woolmani*. Drilling response typically is mostly smooth and the rate of advancement is moderate, but shell beds can produce some grittiness or chatter over intervals where shell material has been cemented by calcite.

On borehole electric logs (see “Borehole Geophysical-Log Network”) the upper Cenomanian confining unit exhibits a generally flat signature typical of fine-grained marine sediments, but is uniquely interspersed with many narrow spikes from thin and sharply bounded shell beds (fig. 4). Gamma logs generally have a moderately elevated response with occasional high gamma spikes from phosphate-bearing sediments, in contrast to the generally lower response of the overlying Virginia Beach aquifer where it is present.

Hydrologic Aspects

The upper Cenomanian confining unit is a regionally limited hydrogeologic unit that locally impedes horizontal ground-water flow. Vertical leakage through the upper Cenomanian confining unit occurs between the overlying Virginia Beach and Aquia aquifers and the underlying Potomac aquifer (through the intervening Potomac confining zone). Although the upper Cenomanian confining unit is of limited extent, it is appreciably thick and thereby provides an effective local hydraulic separation between the adjacent aquifers. Where the upper Cenomanian confining unit thins near its western margin and the western part of its northern margin, leakage between the aquifers probably is more pronounced.

Permeameter samples collected during this study were all from within the Chesapeake Bay impact crater where the upper Cenomanian confining unit is not present. Because the upper Cenomanian confining unit is newly designated herein, published values of vertical hydraulic conductivity do not exist for it. Previous studies probably included the upper Cenomanian beds with other sediments of Late Cretaceous age and clays of the Potomac Formation of Early Cretaceous age as part of the Upper Potomac confining unit or equivalent hydrogeologic units (fig. 3). No means exist by which to differentiate which published values of vertical hydraulic conductivity correspond to the currently individually recognized sediments constituting the Upper Potomac confining unit. Accordingly, published values of vertical hydraulic conductivity for the Upper Potomac confining unit are presented and discussed herein for the Potomac confining zone (see “Potomac Confining Zone”).

Virginia Beach Aquifer

The Virginia Beach aquifer is of limited regional extent, moderately deep, and a locally significant source of ground water in the Virginia Coastal Plain. The Virginia Beach aquifer extends across most of Virginia Beach and westward across the cities of Chesapeake and Suffolk into the southeastern corner of Southampton County (fig. 13; pl. 11). The thickness of the Virginia Beach aquifer ranges up to approximately 70 ft at depths as great as several hundred feet. The Virginia Beach aquifer is stratigraphically above the upper Cenomanian confining unit across most of its extent (fig. 3) except in the far western extent where it is above the Potomac confining zone. The Virginia Beach aquifer provides public water supplies to some small towns and light commercial and industrial operations, and private supplies for low-density residential development in some rural areas.

Geologic Relations

The Virginia Beach aquifer consists of marine, coarse-grained and well-sorted glauconitic quartz sands recently designated as the glauconitic sand unit of Late Cretaceous age (Powars, 2000; fig. 3). The Virginia Beach aquifer is considered to be a homogeneous aquifer (see “Hydrogeologic-Unit Classification”). The marine sands of the glauconitic sand unit were deposited under relatively uniform sediment-transport conditions across the Continental Shelf and function hydraulically as a continuous medium through which water flows essentially uninterrupted at both local and regional scales.

In previous studies of the Virginia Coastal Plain, alternative interpretations were applied to sediments of Late Cretaceous age. In some studies, sediments of Early and Late Cretaceous age were designated as a single aquifer (Commonwealth of Virginia, 1974) as were sediments of Late Cretaceous through Eocene age (Siudyla and others, 1981). In more recent studies, sediments of Late Cretaceous age were designated as primarily constituting the Upper Potomac confining unit (Meng and Harsh, 1988) and were subsequently divided to include “Aquifer 4,” which consists of sediments of the Black Creek Formation (Harsh and Laczniak, 1990; fig. 3). Similar designations were made to equivalent sediments in studies in adjacent States during approximately the same period—the Magothy aquifer in Maryland (Vroblesky and Fleck, 1991) and the Black Creek aquifer in North Carolina (Winner and Coble, 1996). Designation of a distinct Virginia Beach aquifer was made in a subsequent study of the area south of the James River (Hamilton and Larson, 1988). Some sediments of Late Cretaceous age were included as part of the Virginia Beach aquifer but are now recognized as being distinct from the glauconitic sand unit (Powars, 2000) and are designated herein as composing several other hydrogeologic units.

Structural Configuration

The Virginia Beach aquifer is underlain nearly entirely by the upper Cenomanian confining unit (fig. 11; pl. 10) except for the far western end, which is underlain by the Potomac confining zone (fig. 10; pl. 9). The Virginia Beach aquifer is overlain almost completely by the Virginia Beach confining zone (fig. 14; pl. 12) and essentially is below land surface. A very small incised area is projected at the western margin along the Meherrin River near and slightly into North Carolina, where the Virginia Beach aquifer possibly crops out but is more likely covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer.

The Virginia Beach aquifer is at its maximum altitude near the western terminus in southeastern Southampton County (fig. 13; pl. 11), where borehole geophysical logs indicate altitudes ranging from –8 to –32 ft. The Virginia Beach aquifer is extrapolated westward of these locations to pinch out against the Potomac confining zone (pl. 5, sec. JD–JD'). The Virginia Beach aquifer dips generally eastward across its entire extent and is as thick as approximately 70 ft across altitudes from approximately –100 ft to as much as –900 ft (pl. 5, all secs.; pl. 6, secs. CS–CS', DS–DS'; pl. 7, all secs.).

The Virginia Beach aquifer pinches out northward against the upper Cenomanian confining unit (pl. 6, sec. DS–DS'; pl. 7, all secs.). The Virginia Beach aquifer also is truncated along part of the northern margin in Southampton County and the city of Suffolk by faults that are upwardly traceable through underlying hydrogeologic units (fig. 13; pl. 11) and abut the Virginia Beach aquifer against the upper Cenomanian confining unit (pl. 6; sec. CS–CS'). The Virginia Beach aquifer is extrapolated eastward offshore and southward into North Carolina based on a previous study (Winner and Coble, 1996).

Recognition

Penetration of the top of the Virginia Beach aquifer in boreholes generally is noted by coarse-grained and well-sorted glauconitic quartz sands of the glauconitic sand unit that contrast with the predominately clayey red beds that make up the overlying Virginia Beach confining unit (fig. 3). Drilling response typically can have grittiness across intervals of several feet or more, and the rate of advancement is moderate to rapid. The glauconitic sand unit is notably noncohesive and was discerned primarily by wholly disaggregated sands returned in drill cuttings, because no recovery was achieved from cored intervals. On borehole electric logs (see “Borehole Geophysical-Log Network”), the Virginia Beach aquifer in some places has a lobate signature typical of medium- to coarse-grained marine sediments (fig. 4) and elsewhere a blocky signature where the sands are more massive. Gamma logs generally exhibit a low response.

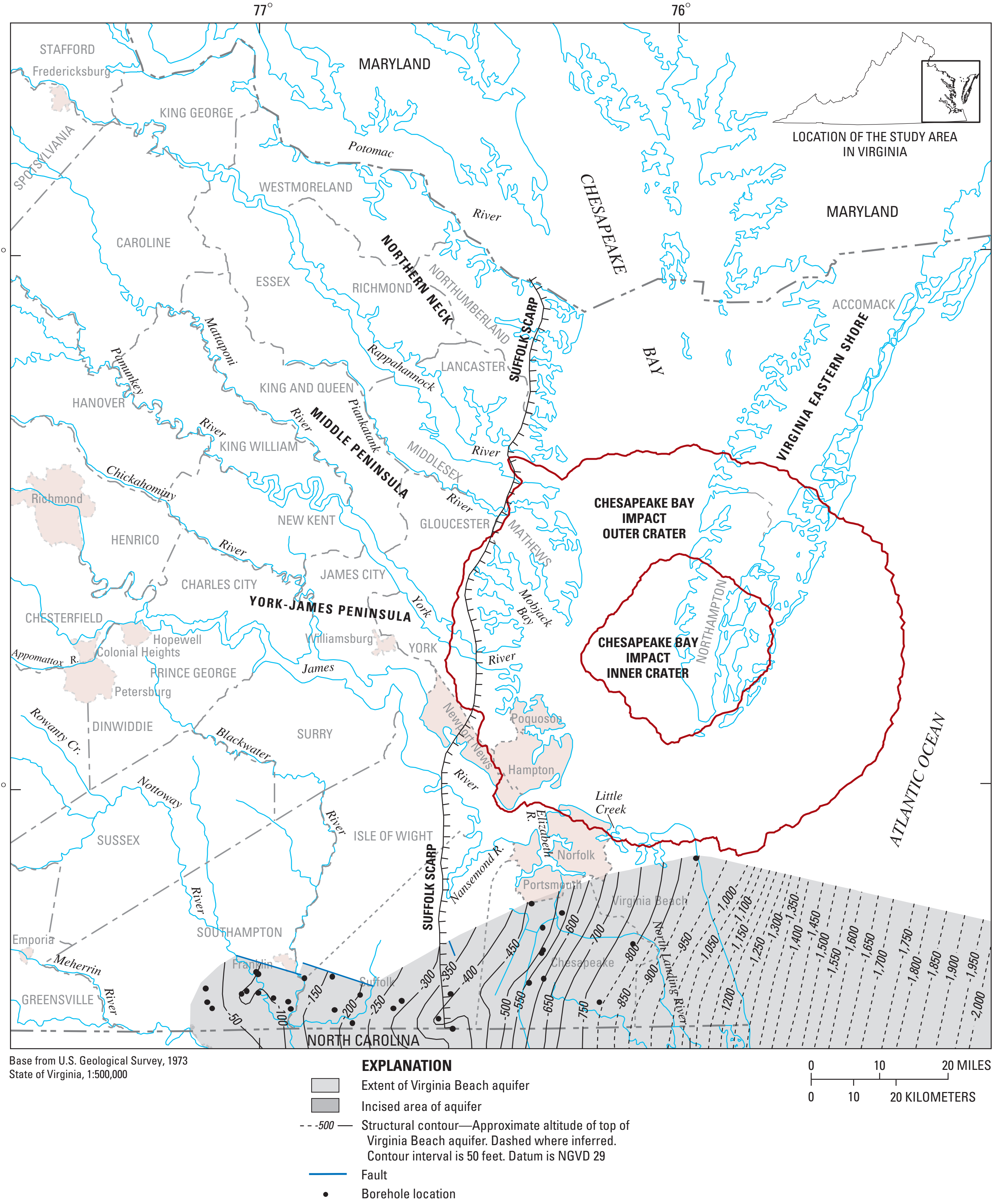


Figure 13. Approximate altitude and configuration of the top of the Virginia Beach aquifer in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 11.)

Hydrologic Aspects

The Virginia Beach aquifer is a regionally limited hydrogeologic unit but functions locally as a pathway for ground-water flow. Part of the Virginia Beach aquifer is also an important ground-water supply resource. Water wells can commonly yield 10 to 50 gal/min. Completion of wells in the Virginia Beach aquifer, where it is present, is favored over the deeper Potomac aquifer because of the resulting higher static water levels.

Less than 1 percent of the ground water used in the Virginia Coastal Plain is estimated to have been produced at a rate of 0.17 Mgal/d by the Virginia Beach aquifer during 2002 and 2003 (table 3). Withdrawal from the Virginia Beach aquifer at a rate of 0.08 Mgal/d was reported to the DEQ by regulated industrial, municipal, and commercial users. Additional unregulated domestic withdrawal was estimated at a rate of 0.09 Mgal/d. Most of the unregulated withdrawals from the Virginia Beach aquifer are possibly in the city of Suffolk. A random sample of domestic well records from county health departments indicates that the Virginia Beach aquifer supplies unregulated withdrawals from approximately 5 percent of the wells constructed during the past two decades in Suffolk (Jason Pope, U.S. Geological Survey, written commun., 2005), and probably little use is made of the Virginia Beach aquifer elsewhere. Most domestic wells in Southampton County are completed in the Potomac aquifer, which shallows to the west. Given the increasing depth of the Virginia Beach aquifer eastward across the cities of Chesapeake and Virginia Beach, it likely contains brackish water (see “Quaternary Period”).

No permeameter samples of the Virginia Beach aquifer were collected during this study. Only two values of 25.9 ft/d (Harsh and Laczniak, 1990) and 43.2 ft/d (Hamilton and Larson, 1988) have been published for the horizontal hydraulic conductivity of the Virginia Beach aquifer, which were derived from ground-water model calibration (table 2).

Virginia Beach Confining Zone

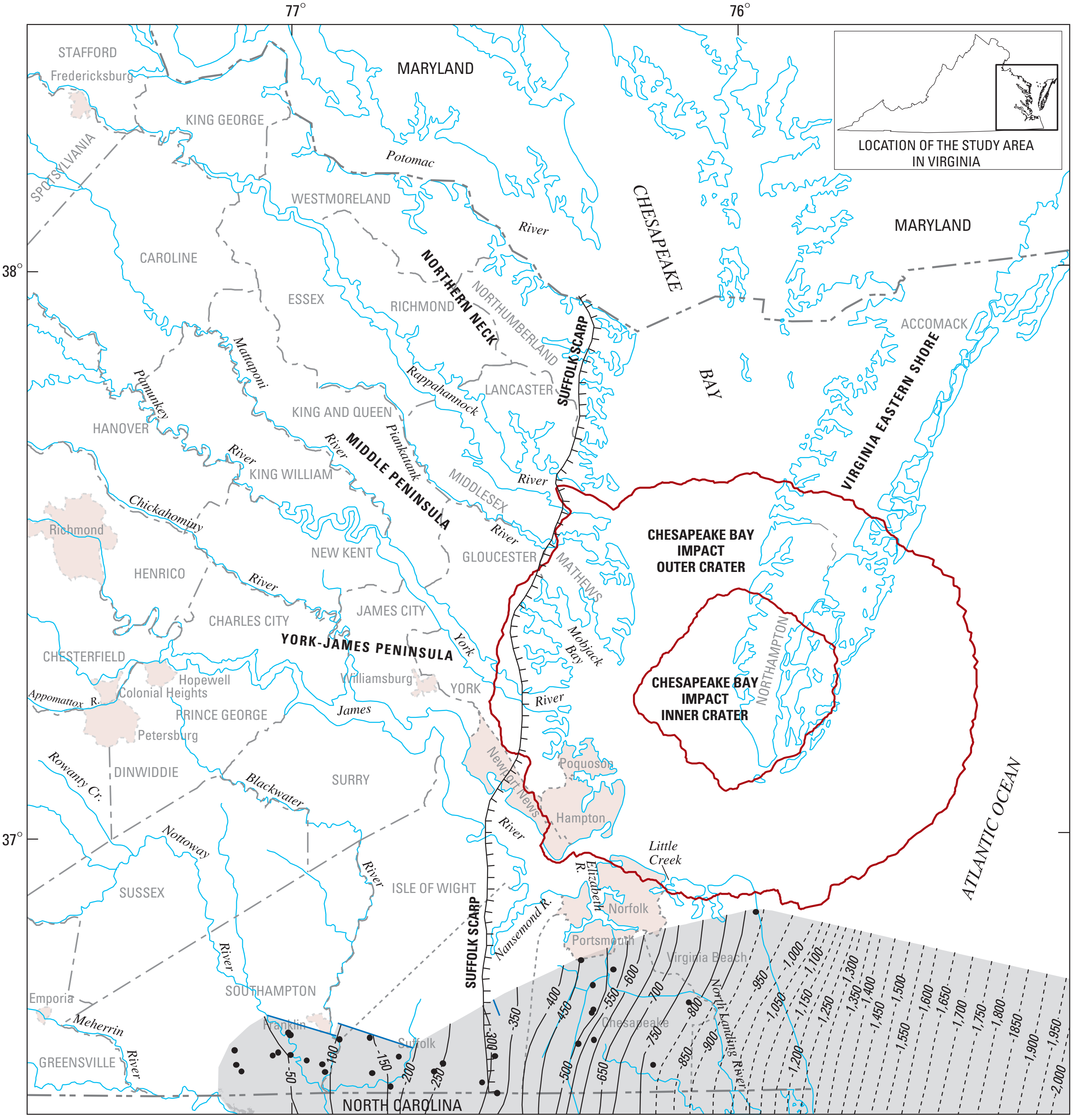
The Virginia Beach confining zone is of limited extent, is moderately deep, and locally impedes ground-water flow in the Virginia Coastal Plain. The Virginia Beach confining zone extends across most of the city of Virginia Beach and westward across the cities of Chesapeake and Suffolk into the southeastern corner of Southampton County (fig. 14; pl. 12). Thickness are as much as several tens of feet at depths of several hundred feet. The Virginia Beach confining zone is stratigraphically above the Virginia Beach aquifer (fig. 3) and approximates a transition to the overlying Peedee and Aquia aquifers.

Geologic Relations

The Virginia Beach confining zone consists of part of the fluvial-deltaic fine-grained clays, silty clays, and silty-fine sands (fig. 15) recently recognized as the red beds of Late Cretaceous age (fig. 3; Powars, 2000). Overlying, variably textured, quartz sands and gravels in the far southeastern part of the red beds constitute part of the Peedee aquifer (see “Peedee Aquifer”). Fine-grained red beds overlying the Peedee aquifer compose part of the Peedee confining zone (see “Peedee Confining Zone”). Conversely, fine-grained red beds that extend westward beyond the Peedee aquifer are included as part of the Virginia Beach confining zone.

Designation of the Virginia Beach confining zone accounts for variable configurations and, in some cases, indistinguishable relations that can exist between the Virginia Beach aquifer and the overlying Peedee and Aquia aquifers. The Peedee aquifer is a heterogeneous aquifer (see “Hydrogeologic-Unit Classification”). Sediments deposited by braided streams, meandering streams, and deltas have sharp contrasts in texture across small distances as a result of the highly variable and frequently changing depositional environments (see “Cretaceous Period”). Dominantly coarse-grained red beds composing the Peedee aquifer are positioned above relatively fine-grained red beds that compose the Virginia Beach confining zone and locally impede vertical leakage between the Peedee aquifer and the underlying Virginia Beach aquifer. Both fine- and coarse-grained intervals are discontinuous, however, and were correlated across relatively large distances as great as several miles or more between borehole locations. As a result, the Virginia Beach confining zone as mapped probably encompasses some coarse-grained sediments of the red beds, which possibly are in direct contact with the underlying Virginia Beach aquifer at some locations where fine-grained red beds are not present. Additionally beyond the Peedee aquifer to the north and west, the Virginia Beach confining zone thins, the presence of red beds becomes irregular, and the Virginia Beach aquifer can be in direct contact with the overlying Aquia aquifer at some locations. Thus, the Virginia Beach confining zone does not represent a distinct contact surface but rather approximates a transition from the Virginia Beach aquifer to the overlying Peedee and Aquia aquifers.

In previous studies of the Virginia Coastal Plain, alternative interpretations were applied to sediments of Late Cretaceous age. In some studies, sediments of Early and Late Cretaceous age were designated as a single aquifer (Commonwealth of Virginia, 1974) as were sediments of Late Cretaceous through Eocene age (Siudyla and others, 1981). In more recent studies, sediments of Late Cretaceous age were designated as primarily constituting the Upper Potomac confining unit (Meng and Harsh, 1988) and subsequently were divided to include “confining unit 4” (Harsh and Laczniak, 1990; fig. 3). Similar designations were made to equivalent sediments in studies in adjacent States during approximately the same period—the Black Creek confining unit in North Carolina (Winner and Coble, 1996) and the Matawan confining unit in Maryland (Vroblesky and Fleck, 1991). Designation of a distinct Virginia Beach confining unit was



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

░	Extent of Virginia Beach confining zone
▒	Incised area of confining zone
- - -500 —	Structural contour—Approximate altitude of top of Virginia Beach confining zone. Dashed where inferred. Contour interval is 50 feet. Datum is NGVD 29
—	Fault
•	Borehole location

Figure 14. Approximate altitude and configuration of the top of the Virginia Beach confining zone in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 12.)

Figure 15. Fluvial-deltaic sediments of Late Cretaceous age from the red beds in the Fentress core, borehole local number 61B 11, in the city of Chesapeake, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and interval is between approximately 762 and 763 feet below land surface. Interbedded clay, silty clay, and silty fine-grained sand constitute the Virginia Beach confining zone and part of the Peedee confining zone. Variably oxidized clays exhibit a range of typically mottled colors.

made subsequently in a study of the area south of the James River (Hamilton and Larson, 1988). Some sediments of Late Cretaceous and(or) Paleocene age were previously included as part of the Virginia Beach confining unit but now are recognized as being distinct from the red beds (Powars, 2000) and are designated herein as composing parts of the Peedee aquifer and confining unit.

Structural Configuration

The Virginia Beach confining zone is entirely underlain by the Virginia Beach aquifer (fig. 13; pl. 11). The eastern part of the Virginia Beach confining zone is overlain by the Peedee aquifer (fig. 16; pl. 13), and the remaining western part is overlain almost entirely by the Aquia aquifer (fig. 18; pl. 15); thus, the Virginia Beach confining zone is nearly entirely below land surface. Very small truncated and incised areas are projected at the western margin along the Meherrin River near and slightly into North Carolina, where the Virginia Beach confining zone possibly crops out but is more likely covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer.

The Virginia Beach confining zone is at its maximum altitude near the western terminus in southeastern Southampton County (fig. 14; pl. 12), where borehole geophysical logs indicate altitudes ranging from –4 to –26 ft. The Virginia Beach confining zone is extrapolated westward of these locations to pinch out against the Potomac confining zone (pl. 5, sec. JD–JD'). The Virginia Beach confining zone dips generally eastward across its entire extent and is as thick as approximately 80 ft across altitudes from approximately –50 ft to as much as –900 ft (pl. 5, all secs.; pl. 6, secs. CS–CS', DS–DS'; pl. 7, all secs.).

The Virginia Beach confining zone pinches out northward against the upper Cenomanian confining unit (pl. 6, sec. DS–DS'; pl. 7, all secs.). The Virginia Beach confining zone also is truncated along part of the northern margin in Southampton County and the city of Suffolk by faults that are upwardly traceable through underlying hydrogeologic units (fig. 14; pl. 12) and abut the Virginia Beach confining zone against the upper Cenomanian confining unit (pl. 6, sec. CS–CS'). The Virginia Beach confining zone is extrapolated eastward offshore and southward into North Carolina based on a previous study (Winner and Coble, 1996).

Recognition

Penetration of the top of the Virginia Beach confining zone in boreholes generally is noted by fine-grained red beds (fig. 15) that contrast markedly with the overlying glauconitic sands of the Aquia aquifer. Where overlain by the Peedee aquifer, the Virginia Beach confining zone is differentiated primarily by an increase in fine-grained sediments in the red beds and a decrease in coarse sands and gravels. Fine-grained red beds generally are described as "… gray and green and bright red, mottled purple, yellow, orange, and brown sequences of interbedded oxidized clay, silty clay, silty fine sand.… Some beds contain scattered mica, carbonaceous material, wood chunks, mudcracks, and rootlets." (Powars, 2000, p. 31) Fine-grained red beds observed during this study had relatively subdued colors including dark gray (5YR 4/1) and grayish green (5G 4/2). Drilling response typically is smooth with moderate grittiness in places, and the rate of advancement generally is slow to moderate.

On borehole electric logs (see "Borehole Geophysical-Log Network"), the Virginia Beach confining zone is designated as a transitional interval between the overlying Aquia and Peedee aquifers and the underlying Virginia Beach aquifer. The Virginia Beach confining zone generally has a relatively subdued signature compared to the Peedee aquifer but with some spikiness still apparent and likely resulting from variations in texture. Gamma logs exhibit a variable but generally moderately elevated response. Toward the northern and western margins of the Virginia Beach confining zone where the presence of red beds is irregular, differentiation from some sediments of adjacent hydrogeologic units can be obscured by indistinct log signatures, especially where the different units are relatively thin.

Hydrologic Aspects

The Virginia Beach confining zone is a localized hydrogeologic unit that impedes ground-water flow across the southern part of the Virginia Coastal Plain. No permeameter samples of the Virginia Beach confining zone were collected during this study. Published values of vertical hydraulic conductivity include one from a single laboratory analysis of sediment core (0.0000518 ft/d, Laczniak and Meng, 1988) and two values derived from ground-water model calibration (0.0000346 ft/d, Harsh and Laczniak, 1990, and 0.0000734 ft/d, Hamilton and Larson, 1988; table 2).

Locally, leakage through the Virginia Beach confining zone can be impeded substantially where fine-grained red beds are present. The discontinuity and variable composition of the Virginia Beach confining zone, however, results in greater leakage across its extent in locations where clays are less dominant. The Virginia Beach confining zone does not represent a lithologically uniform mass of sediment through which leakage is enhanced by a relatively large vertical hydraulic conductivity, and description as a leaky confining unit is not conceptually accurate.

Peedee Aquifer

The Peedee aquifer is localized, deep, and unused as a source of ground water in the Virginia Coastal Plain. The extent of the Peedee aquifer is limited to the southern parts of the cities of Chesapeake and Virginia Beach (fig. 16; pl. 13). Thicknesses range up to several tens of feet at depths of several hundred feet. The Peedee aquifer is stratigraphically above the Virginia Beach confining zone (fig. 3), and is tentatively designated as a locally important pathway for ground-water flow.

Geologic Relations

The Peedee aquifer consists of primarily fluvial-deltaic and variably textured quartz sands and gravels in the far southeastern part of the recently recognized red beds of Late Cretaceous age (fig. 3; Powars, 2000). Also included in the eastward upper part of the Peedee aquifer is part of the recently recognized lower glauconitic quartz sand of Late Cretaceous age that overlies the red beds (Powars, 2000). The red beds, which are composed mostly of fine-grained sediments, primarily constitute the Virginia Beach confining zone and underlie or extend beyond the Peedee aquifer (see "Virginia Beach Confining Zone"). Fine-grained red beds overlying part of the Peedee aquifer also compose part of the Peedee confining zone (see "Peedee Confining Zone").

The Peedee aquifer is a heterogeneous aquifer (see "Hydrogeologic-Unit Classification"), in which discontinuous and locally variable fine-grained sediments are interbedded with coarse-grained sediments. The red beds exhibit sharp contrasts in sediment composition and texture across small distances as a result of fluctuation among fluvial and deltaic depositional environments. Thus, the Peedee aquifer likely has discontinuities where flow is impeded by fine-grained interbeds.

In previous studies of the Virginia Coastal Plain, alternative interpretations were applied to sediments of Late Cretaceous age. In some studies, sediments of Early and Late Cretaceous age were designated as a single aquifer (Commonwealth of Virginia, 1974) as were sediments of Late Cretaceous through Eocene age (Siudyla and others, 1981). In more recent studies, sediments of Late Cretaceous age were designated as primarily composing the Upper Potomac confining unit (Meng and Harsh, 1988) and subsequently were divided to include "Aquifer 5," which consists of sediments of the Peedee Formation (Harsh and Laczniak, 1990; fig. 3). Similar designations were made to equivalent sediments in studies in adjacent States during approximately the same period—the Peedee aquifer in North Carolina (Winner and Coble, 1996) and the Severn and Matawan aquifers in Maryland (Vroblesky and Fleck, 1991). Initially, these aquifers were not considered to be present in Virginia. The Peedee aquifer in North Carolina was delineated to extend no farther northward than Albemarle Sound, whereas the Severn and Matawan aquifers spanned separate areas distantly located to the north. Subsequently, the extent of the Peedee aquifer was broadened northward nearly to the Virginia-North Carolina State line in a study of the area south of the James River (Hamilton and Larson, 1988).

Some sediments of Late Cretaceous age in southeastern Virginia that previously were included as part of the Virginia Beach aquifer are now recognized distinctly as the glauconitic sand unit and overlying red beds (Powars, 2000). The glauconitic sand unit is considered herein as composing the Virginia Beach aquifer (see "Virginia Beach Aquifer"). Because of their overlying stratigraphic relation, coarse-grained intervals identified within the red beds in Virginia are considered to be part of a northward extension of the Peedee aquifer.

The Peedee aquifer in Virginia is newly recognized herein, and is tentatively designated primarily on the basis of stratigraphic analyses of sediment cores obtained from two boreholes (Powars, 2000). Based on borehole geophysical logs augmented with lithologic descriptions, a relatively

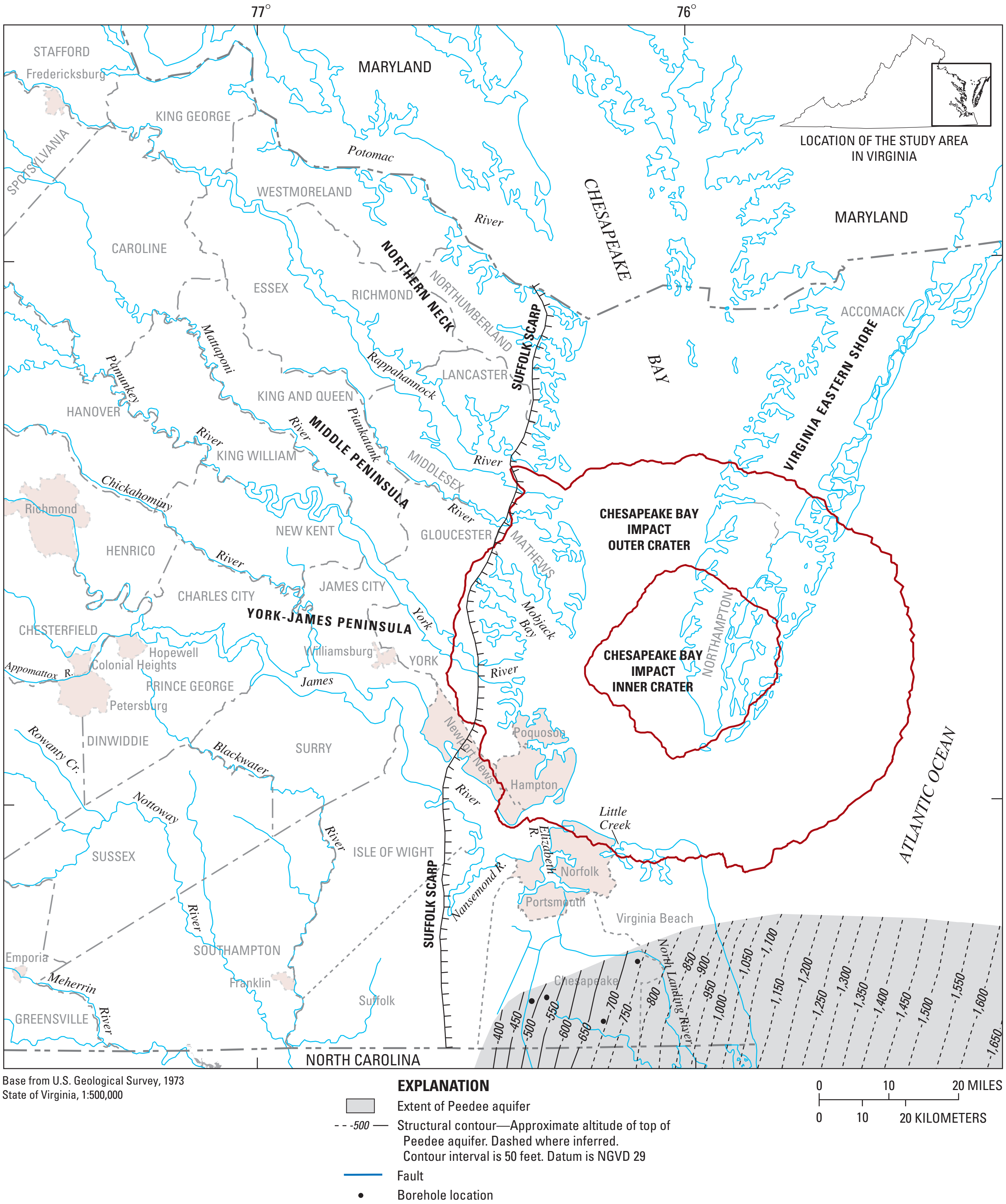


Figure 16. Approximate altitude and configuration of the top of the Peedee aquifer in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 13.)

coarse-grained interval is indicated in a section of the red beds recognized in the Fentress core from the far eastern part of the city of Chesapeake (Attachment 1, borehole 61B 11; pl. 5, sec. ID–ID'; pl. 7, sec. GS–GS'). A similar interval is indicated in the Northwest River core from the southeastern part of the city of Chesapeake (borehole 61A 12; pl. 5, sec. JD–JD'; pl. 7, sec. GS–GS'), which also partly extends upward into the overlying glauconitic quartz sand. From the two core locations, the Peedee aquifer is correlated westward to similar intervals in only two additional and closely spaced boreholes in the south-central part of the city of Chesapeake (boreholes 60B 1 and 60B 3; pl. 5, sec. JD–JD'), primarily on the basis of geophysical logs and partly supplemented with drillers' logs.

Structural Configuration

The Peedee aquifer is entirely below land surface and does not crop out. It is underlain by the Virginia Beach confining zone across its entire extent (fig. 14; pl. 12). Because of the variability of the Virginia Beach confining zone (see "Virginia Beach Confining Zone"), the Peedee aquifer possibly directly overlies the Virginia Beach aquifer in some locations and is entirely overlain by the Peedee confining zone (see "Peedee Confining Zone").

The maximum altitude of the Peedee aquifer is along its western margin in the southern area of the city of Chesapeake (fig. 16; pl. 13), where boreholes 60B 1 and 60B 3 indicate altitudes of –479 and –531 ft, respectively (Attachment 1). The Peedee aquifer is extrapolated westward of these locations to pinch out against the Virginia Beach confining zone (pl. 5, secs. ID–ID', JD–JD'). The Peedee aquifer dips eastward across its entire extent and is as thick as 87 ft in the Northwest River core (borehole 61A 12) across altitudes from approximately –400 ft to below –700 ft. The Peedee aquifer pinches out northward against the Virginia Beach confining zone (pl. 7, secs. FS–FS', GS–GS') and is extrapolated eastward offshore and southward into North Carolina based on a previous study (Winner and Coble, 1996).

Recognition

Because the Peedee aquifer, as recognized herein, is identified at only four locations, observational aspects are limited. Penetration of the top of the Peedee aquifer generally occurs as quartz sands and gravels that contrast from the overlying predominantly clayey red beds. Additionally in some areas to the east, glauconitic quartz sands can be present that contrast with overlying fine-grained and clayey or silty sands. On borehole electric logs (see "Borehole Geophysical-Log Network"), the Peedee aquifer generally exhibits a blocky signature that indicates massive sands and gravels (fig. 4), although a fining upward signature may be exhibited. Gamma logs generally exhibit a low response.

Hydrologic Aspects

The Peedee aquifer is a localized hydrogeologic unit that possibly functions as a pathway for ground-water flow across the far southeastern part of the Virginia Coastal Plain. The Peedee aquifer is not known to be used as a ground-water supply resource in Virginia. No permeameter samples of the Peedee aquifer were collected during this study, and only a single horizontal hydraulic conductivity value of 23.3 ft/d is published, which was derived from ground-water model calibration (Harsh and Laczniak, 1990; table 2). Given the depth and eastward location of the Peedee aquifer in Virginia, it likely contains brackish water (see "Quaternary Period").

Extension of the Peedee aquifer into Virginia is important as a possible refinement of the previously designated northern margin of the Peedee aquifer in North Carolina, where the Peedee aquifer is widespread and represents a major ground-water resource (Winner and Coble, 1996). Information from additional deep boreholes in far southeastern Virginia is needed to verify the geologic relations and structural configuration of the Peedee aquifer that are tentatively presented herein.

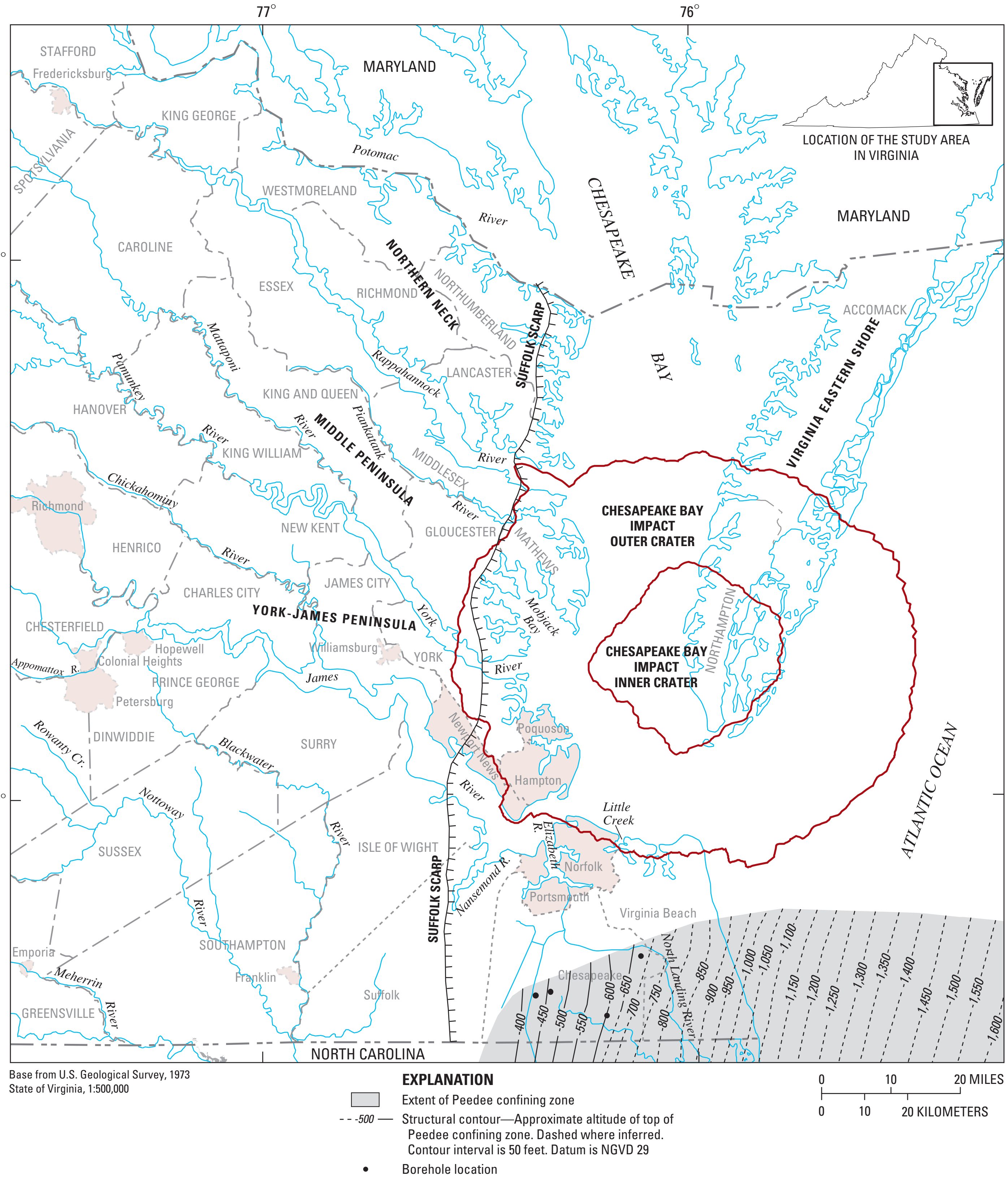
Peedee Confining Zone

The Peedee confining zone is deep, has a limited extent, and locally impedes ground-water flow in the Virginia Coastal Plain. The Peedee confining zone extends across the southern parts of the cities of Chesapeake and Virginia Beach (fig. 17; pl. 14) and is as thick as several tens of feet at depths of several hundred feet. The Peedee confining zone is stratigraphically above the Peedee aquifer (fig. 3), and approximates a transition to the overlying Aquia aquifer.

Geologic Relations

The Peedee confining zone consists partly of fluvial-deltaic, fine-grained clays, silty clays, and silty-fine sands in the far southeastern part of the red beds of Late Cretaceous age, and partly of overlying deltaic fine-grained sands and clays of Late Cretaceous and(or) Paleocene age (fig. 3), both of which have been identified recently (Powars, 2000). Underlying, variably textured, quartz sands and gravels of the red beds and part of the lower glauconitic quartz sand constitute the Peedee aquifer (see "Peedee Aquifer"). Fine-grained red beds that underlie or extend westward beyond the Peedee aquifer constitute the Virginia Beach confining zone (see "Virginia Beach Confining Zone").

Designation of the Peedee confining zone accounts for variable configurations and, in some cases, indistinguishable relations that can exist overlying the Peedee aquifer. The Peedee aquifer is a heterogeneous aquifer (see "Hydrogeologic-Unit Classification"). Sediments deposited by braided or



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

Figure 17. Approximate altitude and configuration of the top of the Peedee confining zone in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 14.)

meandering streams and deltas have sharp contrasts in texture across small distances as a result of the highly variable and frequently changing environments (see “Cretaceous Period”). The dominant fine-grained red beds that compose the Peedee confining zone are positioned above relatively coarse-grained red beds that compose the Peedee aquifer and locally impede vertical leakage between the Peedee aquifer and the overlying Aquia aquifer. Both fine- and coarse-grained intervals are discontinuous, however, and are correlated across relatively large distances as great as several miles or more between borehole locations. As a result, the Peedee confining zone, as mapped, probably encompasses some coarse-grained sediments of the red beds. As a further complication, overlying deltaic fine-grained sands and clays that also compose the Peedee confining zone are not present at all locations, and differences can be obscure between these overlying sands and clays, underlying fine-grained red beds, and overlying sediments of the Aquia aquifer. Thus, the Peedee confining zone does not represent a distinct contact surface but rather approximates a transition from the Peedee aquifer to the Aquia aquifer.

In previous studies of the Virginia Coastal Plain, alternative interpretations were applied to sediments of Late Cretaceous age. In some studies, sediments of Early and Late Cretaceous age were designated as a single aquifer (Commonwealth of Virginia, 1974) as were sediments of Late Cretaceous through Eocene age (Siudyla and others, 1981). In more recent studies, sediments of Late Cretaceous age were designated as primarily composing the Upper Potomac confining unit (Meng and Harsh, 1988) and subsequently were divided to include “confining unit 5” (Harsh and Laczniak, 1990; fig. 3). Similar designations were made to equivalent sediments in studies in adjacent States during approximately the same period—the Peedee confining unit in North Carolina (Winner and Coble, 1996) and the Severn and lower Brightseat confining units in Maryland (Vroblesky and Fleck, 1991). Initially, these confining units were not considered to be present in Virginia. The Peedee confining unit in North Carolina was delineated to extend no farther northward than Albemarle Sound, whereas the Severn and lower Brightseat confining units spanned separate areas distantly located to the north. Subsequently, the extent of the Peedee confining unit was broadened northward nearly to the Virginia-North Carolina State line in a study of the area south of the James River (Hamilton and Larson, 1988).

Some sediments of Late Cretaceous and(or) Paleocene age in southeastern Virginia that previously were included as part of the Virginia Beach aquifer and confining unit are now recognized distinctly as the red beds and overlying deltaic sands and clays (Powars, 2000). Coarse-grained intervals within the red beds and overlying coarse-grained deltaic sands are considered herein as composing the Peedee aquifer (see “Peedee Aquifer”). Because of their overlying stratigraphic relation, fine-grained intervals identified within the red beds in Virginia and overlying fine-grained deltaic sands and clays are considered to be a northward extension of the Peedee confining zone.

The Peedee confining zone in Virginia is newly recognized herein and is tentatively designated primarily on the basis of stratigraphic analyses of sediment cores obtained from two boreholes (Powars, 2000). Based on borehole geophysical logs augmented with lithologic descriptions, a relatively fine-grained interval is indicated in a section of the red beds recognized in the Fentress core from the far eastern part of the city of Chesapeake (Attachment 1, borehole 61B 11; pl. 5, sec. ID–ID'; pl. 7, sec. GS–GS'). An interval of fine-grained deltaic sands and clays is indicated in the Northwest River core from the southeastern part of the city of Chesapeake (borehole 61A 12; pl. 5, sec. JD–JD'; pl. 7, sec. GS–GS'). From the two core locations, the Peedee confining zone is correlated westward to similar intervals in only two additional and closely spaced boreholes in the south-central part of the city of Chesapeake (boreholes 60B 1 and 60B 3; pl. 5, sec. JD–JD'), primarily on the basis of geophysical logs partly supplemented with drillers’ logs.

Structural Configuration

The Peedee confining zone is entirely below land surface and does not crop out. It is entirely underlain by the Peedee aquifer (fig. 16; pl. 13). The Peedee confining zone is overlain by the Aquia aquifer across its entire landward extent (fig. 18; pl. 15). Offshore and beyond the Aquia aquifer, the Peedee confining zone is extrapolated to be overlain by the Nanjemoy-Marlboro confining unit (fig. 20; pl. 16).

The maximum altitude of the Peedee confining zone is along its western margin in the southern part of the city of Chesapeake (fig. 17; pl. 14), where boreholes 60B 1 and 60B 3 indicate altitudes of –437 and –452 ft, respectively (Attachment 1). The Peedee confining zone is extrapolated westward of these locations to pinch out against the Virginia Beach confining zone (pl. 5, secs. ID–ID', JD–JD'). The Peedee confining zone dips eastward across its entire extent and is as thick as 93 ft in the Northwest River core (borehole 61A 12) across altitudes from approximately –400 ft to nearly –700 ft. The Peedee confining zone pinches out northward against the Virginia Beach confining zone (pl. 7, secs. FS–FS', GS–GS') and is extrapolated eastward offshore and southward into North Carolina based on a previous study (Winner and Coble, 1996).

Recognition

Because the Peedee confining zone, as recognized herein, is identified at only four locations, observational aspects are limited. Penetration of the top of the Peedee confining zone generally occurs as fine-grained red beds that contrast markedly from the overlying glauconitic sands of the Aquia aquifer.

Fine-grained red beds generally are described as "… gray and green and bright red, mottled purple, yellow, orange, and brown sequences of interbedded oxidized clay, silty clay, silty fine sand…. Some beds contain scattered mica, carbonaceous material, wood chunks, mudcracks, and rootlets" (Powars, 2000, p. 31). Fine-grained red beds observed during this study had relatively subdued colors including dark gray (5YR 4/1) and grayish green (5G 4/2).

In some areas toward the east, the Peedee confining zone potentially is composed partly or entirely of fine-grained deltaic sands and clays that overlie the red beds and have been described to include organic rich clays and clayey-silty sands (Powars, 2000). Unlike the fine-grained red beds, differentiation of the fine-grained deltaic sediments from those of the overlying Aquia aquifer can potentially be obscured, based mostly on drill cuttings.

On borehole electric logs (see "Borehole Geophysical-Log Network"), the Peedee confining zone is designated as an interval that is transitional from those recognizable as the overlying Aquia aquifer and underlying Peedee aquifer. The Peedee confining zone generally has a relatively subdued signature compared to the Peedee aquifer but with some spikiness still apparent, likely resulting from variations in texture. Gamma logs exhibit a variable but generally moderately elevated response.

Hydrologic Aspects

The Peedee confining zone is a localized hydrogeologic unit that impedes ground-water flow across the far southeastern part of the Virginia Coastal Plain. No permeameter samples of the Peedee confining zone were collected during this study, and only two vertical hydraulic conductivity values derived from ground-water model calibration are published (0.0000778 ft/d, Harsh and Laczniak, 1990, and 0.0000691 ft/d, Hamilton and Larson, 1988; table 2).

Locally, leakage through the Peedee confining zone can be impeded substantially where fine-grained red beds and(or) overlying deltaic sediments are present. The discontinuity and variable composition of the Peedee confining zone, however, results in greater leakage across its extent in locations where clays are less dominant. The Peedee confining zone does not represent a lithologically uniform mass of sediment through which leakage is enhanced by a relatively large vertical hydraulic conductivity, and description as a leaky confining unit is not conceptually accurate.

Aquia Aquifer

The Aquia aquifer is widespread, generally deep, but relatively sparsely used as a ground-water resource in the Virginia Coastal Plain. The Aquia aquifer extends across all of the Virginia Coastal Plain except for the Chesapeake Bay impact crater, the Virginia Eastern Shore, and the southern half of the Fall Zone (fig. 18; pl. 15). The Aquia aquifer is several tens of feet or more thick at depths as much as several hundred feet. Second to the Potomac aquifer, the Aquia aquifer is stratigraphically the next lowest aquifer across most of its extent except where the intervening Virginia Beach and Peedee aquifers are present to the far south (fig. 3). The Aquia aquifer provides public water supplies to some small towns and private supplies for low-density residential development in some rural areas, mostly to the north.

Geologic Relations

The Aquia aquifer consists of marine, medium- to coarse-grained, glauconitic and fossiliferous quartz sands (fig. 19) of the Aquia Formation of late Paleocene age (fig. 3). A basal interval of several feet or more consists of reworked fluvial-deltaic coarse-grained sands and gravels of the underlying Potomac Formation, which are mixed at some locations with marine sediments (fig. 6). Other parts of the Aquia Formation consist solely of fine-grained sands and silts and are not considered part of the Aquia aquifer but instead are included as part of the Nanjemoy-Marlboro confining unit (see "Nanjemoy-Marlboro Confining Unit").

The Aquia aquifer is a homogeneous aquifer (see "Hydrogeologic-Unit Classification"). Aquia Formation sediments were deposited under relatively uniform sediment-transport conditions across the Continental Shelf. Sands, silts, and calcareous fossil shells vary gradationally but function hydraulically as a continuous medium through which water flows essentially uninterrupted at both local and regional scales.

Designation of Aquia Formation sediments as composing a distinct Aquia aquifer was made in previous studies of part or all of the Virginia Coastal Plain (Cederstrom, 1957; Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designations were made to equivalent sediments in studies in adjacent States during approximately the same period—the Aquia-Rancocas aquifer in Maryland (Vroblesky and Fleck, 1991) and the Beaufort aquifer in North Carolina (Winner and Coble, 1996). In various other mostly earlier studies, sediments belonging to the Pamunkey and(or) Chesapeake Groups or their equivalents, of which the Aquia Formation is only one of several parts, were designated as a single aquifer.

The designation of the Aquia aquifer in Virginia in previous studies appears to have included some sediments that are now recognized as distinct from the Aquia Formation. Because of similar structural positions and other features, parts of the Exmore tsunami-breccia possibly were included along the margin of the Chesapeake Bay impact crater (Powars and Bruce, 1999) as were various sediments of Early and Late Cretaceous age on the York-James Peninsula and south of the James River (Powars, 2000). These sediments are designated herein as composing several other hydrogeologic units and are not included as parts of the Aquia aquifer.

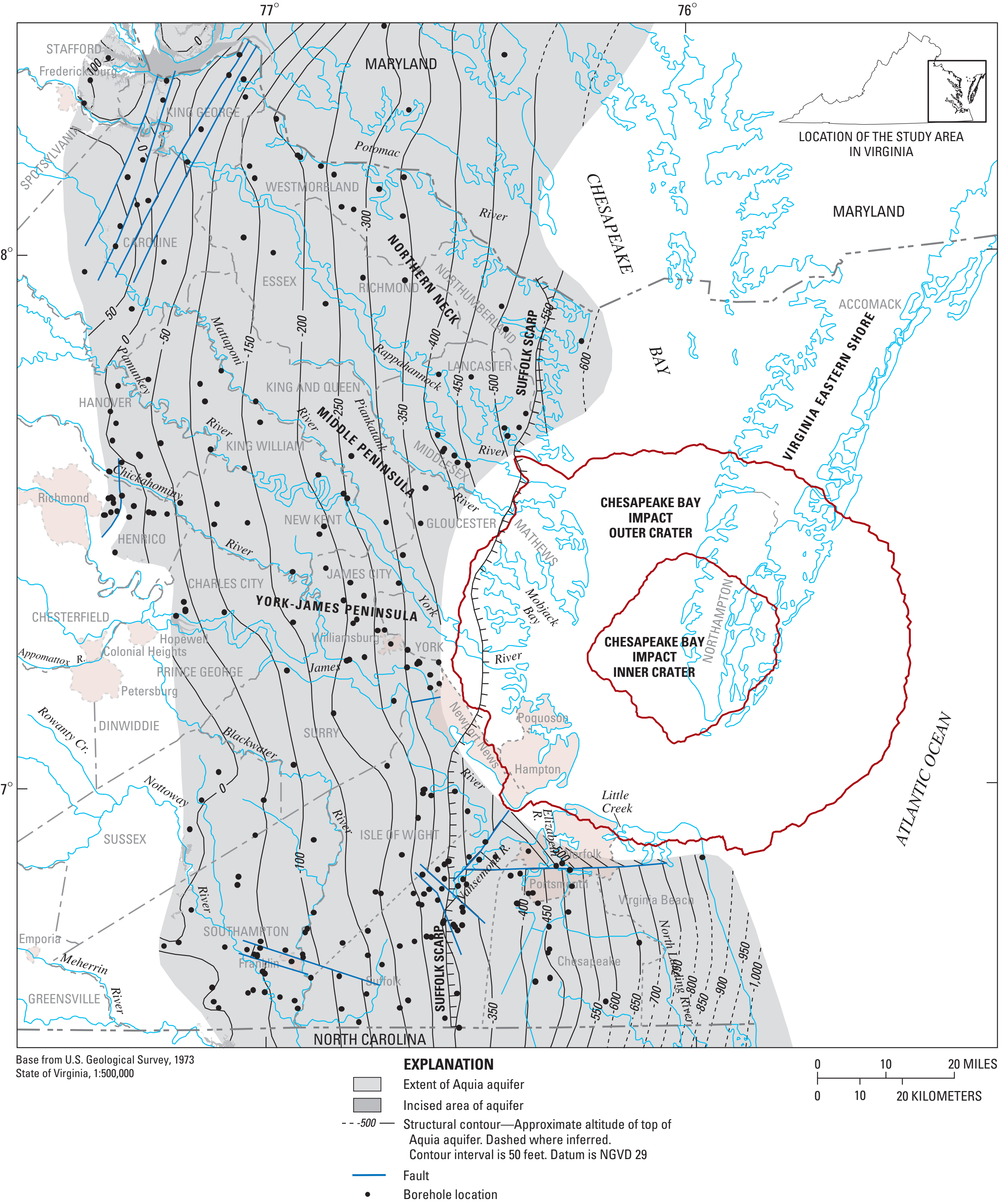


Figure 18. Approximate altitude and configuration of the top of the Aquia aquifer in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Further details are shown on plate 15.)

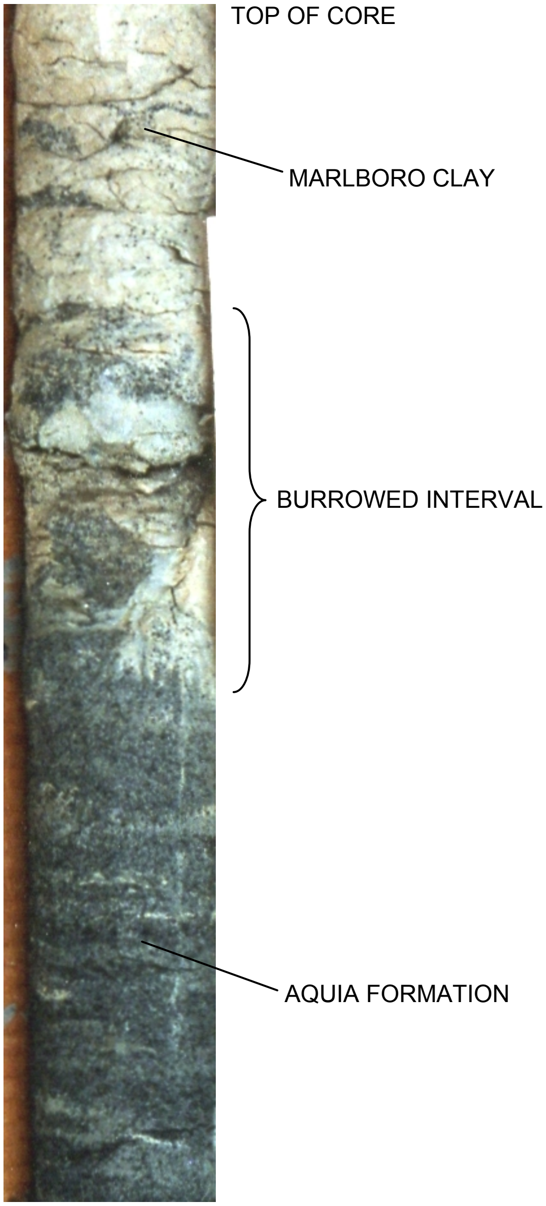


Figure 19. Marine sediments from the Aquia Formation of late Paleocene age overlain by the Marlboro Clay of late Paleocene to early Eocene age in the Jamestown core at Jamestown, Virginia. Core diameter is approximately 2 inches, and interval is from between approximately 218 and 219 feet below land surface. Medium- to coarse-grained glauconitic sand constitutes the Aquia aquifer across the lower half of the interval. Interbedded fossil shells are common at other locations and, in places, are calcite-cemented. Additionally, at some other locations, a basal interval includes reworked Potomac Formation sands and gravels (fig. 6). Kaolinitic and micaceous Marlboro Clay across the upper half of the interval constitutes part of the Nanjemoy-Marlboro confining unit. Color varies between reddish gray (shown here) and greenish gray at other locations (fig. 21). Consistency is markedly plastic. Marlboro Clay is burrowed into Aquia Formation across the middle part of the interval.

Structural Configuration

The Aquia aquifer is underlain by the Potomac confining zone (fig. 10; pl. 9) across most of the Virginia Coastal Plain except to the southeast. Across the southern halves of Virginia Beach and the city of Chesapeake, the Aquia aquifer is underlain by the Peedee confining zone (fig. 17; pl. 14). Farther to the north and west, both the Peedee confining zone and underlying Peedee aquifer pinch out (pl. 5, secs. ID-ID', JD–JD'; pl. 7, secs. FS–FS', GS–GS'), beyond which the Aquia aquifer is underlain by the Virginia Beach confining zone across most of the northern halves of Virginia Beach and the city of Chesapeake, the southern third of the city of Suffolk, and the southeastern corner of Southampton County (fig. 14; pl. 12). The Virginia Beach confining zone and Virginia Beach aquifer pinch out and are truncated by faults westward and northward (pls. 5, 7, all secs.; pl. 6, secs. CS–CS', DS–DS'), beyond which the Aquia aquifer is underlain by the upper Cenomanian confining unit along the southern margin of the Chesapeake Bay impact crater and westward across the northern two-thirds of the city of Suffolk, the southern corner of Isle of Wight County, and a small part of eastern Southampton County (fig. 11; pl. 10). The upper Cenomanian confining unit pinches out farther northwest (pl. 5, all secs.; pl. 6, secs. CS–CS', DS–DS'), beyond which the remaining greater part of the Aquia aquifer is underlain by the Potomac confining zone. The Aquia aquifer and underlying upper Cenomanian confining unit are both truncated to the north along the southern margin of the Chesapeake Bay impact crater by the Chickahominy, Exmore matrix, and Exmore clast confining units (pl. 7, all secs.).

The maximum altitude of the Aquia aquifer is near the western margin across the northern half of the Fall Zone (fig. 18; pl. 15). Borehole geophysical logs from north to south indicate an altitude of 117 ft in eastern Stafford County, declining to –15 ft in eastern Hanover County, and then increasing to 47 ft in eastern Henrico County. The Aquia aquifer is extrapolated updip a few miles or less west of these locations before pinching out against the Potomac confining zone at altitudes of approximately 120 ft or less. Truncation of the Aquia aquifer along the valleys of the Potomac and Rappahannock Rivers and their tributaries is projected across the northernmost part of the western margin in eastern Stafford and Spotsylvania Counties. Across the southern Fall Zone, the Aquia aquifer pinches out generally near 0 ft along the western margin (fig. 18; pl. 15; pl. 4, secs. ED–ED', FD–FD'; pl. 5, all secs.).

The Aquia aquifer is overlain across almost its entire extent by the Nanjemoy-Marlboro confining unit (fig. 20; pl. 16). Locally incised areas are projected across the Fall Zone along the Potomac, Rappahannock, James, and Nottoway Rivers and some of their tributaries (fig. 18; pl. 15), where the Aquia aquifer crops out across the steepest slopes but is mostly covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer.

Additional outcrops possibly exist along smaller streams crossing the Fall Zone but are likely very small and isolated. Direct contact between the Aquia aquifer and surficial aquifer across the incised areas possibly creates significant hydraulic connections between the confined and unconfined ground-water systems, particularly along the main stem of the Potomac River where a relatively broad area is incised almost by the entire river channel.

The Aquia aquifer dips generally eastward across its entire extent (fig. 18; pl. 15). Its greatest thickness of nearly 150 ft is across the upper reaches of the Northern Neck at altitudes from approximately –300 ft to –450 ft (pl. 3, secs. AD–AD', BD–BD'). The Aquia aquifer also thickens across the uppermost part of the Middle Peninsula to more than 100 ft at altitudes from approximately –200 ft to –300 ft, (pl. 3, sec. CD–CD'). Both to the south and east of these areas, the thickness of the Aquia aquifer generally is approximately 50 ft or less. Across the lower Northern Neck and eastward, it thins and is extrapolated to pinch out at an altitude of approximately –600 ft beneath the upper Chesapeake Bay (pl. 3, sec. BD–BD'). Across the upper York-James Peninsula and south of the James River, the Aquia aquifer becomes thin and shallow by as much as 250 ft across the western part of the Norfolk arch (pls. 5 and 6, all secs.). The altitude of the Aquia aquifer near the margin of the Chesapeake Bay impact crater ranges from approximately –300 to –900 ft (fig. 18; pl. 15). The Aquia aquifer is extrapolated eastward to be truncated either by the Exmore clast confining unit (pl. 3, sec. CD–CD'; pl. 7, sec. ES–ES'), the Exmore matrix confining unit (pl. 4, all secs.), or the Chickahominy confining unit (pl. 7, secs. FS–FS', GS–GS'). South of the crater, the Aquia aquifer is extrapolated eastward to pinch out several miles offshore of Virginia Beach at an altitude of approximately –1,000 ft. Additionally, and based on previous studies, the Aquia aquifer is extrapolated southward into North Carolina (Winner and Coble, 1996) and northward into Maryland (Vroblesky and Fleck, 1991).

On some borehole geophysical logs, the top of the Aquia aquifer has closely spaced displacements generally of a few tens of feet or less that have been attributed to faults (fig. 18; pls. 3, 5–7, 15). The faults intersect the Aquia aquifer by extension upward from the Potomac aquifer (see “Potomac Aquifer”) and through intervening hydrogeologic units, which generally exhibit larger displacements. Although discrete fractures that are either open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of the depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. In addition, the faults create local-scale irregularities in the altitude of the Aquia aquifer and laterally abut varying volumes of the aquifer against adjacent hydrogeologic units. Where displacements are small relative to the thickness of the Aquia aquifer, relatively small volumes across the top and base of the aquifer are affected (pl. 3, sec. AD–AD'; pl. 6, sec. BS–BS'). Where displacements are large relative to the thickness of the aquifer, however, the aquifer can be truncated partly to wholly by adjacent hydrogeologic units across the fault. A lateral-flow barrier is created where the Aquia aquifer is truncated by the upper Cenomanian confining unit (pl. 5, sec. GD–GD' beneath the Nansemond River). Conversely, a lateral-flow conduit is created where the Aquia aquifer is truncated by the Potomac aquifer (pl. 6, sec. AS–AS' near the James River). Some faults have combinations of both barriers and conduits (pl. 6, sec. AS–AS' near the Rappahannock River). Faults possibly exist at other locations but are not recognized because of sparse borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the Aquia aquifer in boreholes is noted generally by fine- to medium-grained glauconitic sands with variable amounts of shell (fig. 19), silt, and clay that are below the uniquely textured and colored Marlboro Clay (see “Nanjemoy-Marlboro Confining Unit”). Drilling response typically is relatively smooth, and the rate of advancement is moderate. Cuttings returned by drag bit were observed during this study to have colors varying among dark greenish gray (5G 4/1 and 5GY 3/1), greenish black (5GY 2/1), and light olive (10Y 5/4). Where present, calcite-cemented fossil-shell ledges create a pronounced chatter in drilling response but generally are no more than a few feet thick individually. Disaggregated shells and granules and pebbles consisting of calcite-cemented quartz and glauconite-sand grains and shells can be returned in cuttings. Additionally, across a basal interval of several or more feet, the Aquia aquifer can include reworked fluvial-deltaic, coarse-grained sands and gravels of the underlying Potomac Formation, which create a pronounced gritty sound and feel in drilling response and are returned in drill cuttings in a wholly disaggregated state. Generally, coarse textures were observed in the Aquia aquifer as it thickens and deepens northward into Maryland, and much of the quartz is iron stained with more of a yellow component in the colors including very dark and dark grayish brown (2.5Y 3/2 and 2.5Y 4/2), olive gray (5Y 4/2), olive (5Y 4/3 and 5Y 5/4), dark greenish gray (10Y 4/1), and grayish olive (10Y 4/2).

Aquia Formation sediments in Virginia are, in many places, very similar to those of the overlying Nanjemoy Formation, making distinction dependent upon identification of the intervening Marlboro Clay (see “Nanjemoy-Marlboro Confining Unit”). Additionally, Aquia Formation sediments to the southeast can be similar to those of the underlying upper Cenomanian beds, and distinction depends upon the latter sediments being generally fine grained and micaceous and containing the distinctly light-red colored, diagnostic fossil mollusk *Exogyra woolmani* (see “Upper Cenomanian Confining Unit”). Although having a distinct appearance in core, the Exmore tsunami-breccia within the Chesapeake Bay impact crater can appear similar in cuttings to Aquia Formation sediments if drilling operations and cuttings collection have not been adequately controlled to account for the unique assemblage of components that constitute the breccia (see "Exmore Matrix Confining Unit"). Because of a similar structural position, borehole intervals penetrating the Exmore tsunami-breccia were widely misinterpreted prior to discovery of the crater as penetrating Aquia Formation sediments.

On borehole electric logs (see "Borehole Geophysical-Log Network"), the Aquia aquifer generally exhibits a lobate signature typical of medium- to coarse-grained marine sediments, with some variations resulting from differences in shell, silt, and(or) clay content (fig. 4). Isolated sharp peaks correspond to calcite-cemented shell ledges. Gamma logs exhibit a moderately elevated response that commonly contrasts against the generally low response of the underlying Potomac Formation sediments. Where a basal interval of reworked Potomac Formation sands and gravels is present, both electric and gamma logs can have a hybridized response to the mixture of marine and fluvial-deltaic sediments, and the base of the Aquia aquifer can be obscured.

Hydrologic Aspects

The Aquia aquifer is an extensive hydrogeologic unit that functions as a pathway for ground-water flow across most of the Virginia Coastal Plain. Because of its lithologic composition and in some areas relative thinness, the Aquia aquifer is only a relatively minor ground-water supply resource. Observation wells in the southern part of the aquifer and completed entirely within glauconitic sands yield only 5 to 10 gal/min. At its most northern extent in Virginia across the Northern Neck, the Aquia aquifer potentially can provide nominally greater yields to water-supply wells because of greater proportions of quartz sand and shell. In addition, water-supply wells completed in basal parts of the Aquia aquifer containing coarse-grained sands and gravels of the Potomac Formation potentially can yield as much as 50 gal/min.

All permeameter samples collected during this study were from within the Chesapeake Bay impact crater where the Aquia aquifer is not present. Published values of horizontal hydraulic conductivity of the Aquia aquifer derived from well specific-capacity tests or ground-water model calibration range across two orders of magnitude from 1.8 to 301 ft/d (Hamilton and Larson, 1988; table 2). The range of specific-capacity test values encompasses those derived by model calibration. Higher values possibly indicate a preponderance of shelly material, and lower values indicate the greater presence of silty and fine-grained sands.

During 2002, the Aquia aquifer produced an estimated 3 percent of the ground water used in the Virginia Coastal Plain, at a rate of 3.4 Mgal/d (table 3). A rate of only 0.59 Mgal/d was reported to the DEQ by regulated industrial, municipal, and commercial users. An estimated 2.8 Mgal/d was withdrawn from the Aquia aquifer by unregulated domestic users. Regulated withdrawal declined slightly during 2003 to a rate of 0.48 Mgal/d; consequently, total withdrawal declined to 3.3 Mgal/d from the Aquia aquifer. The relative contribution of the Aquia aquifer to the total withdrawal in the Virginia Coastal Plain, however, remained essentially unchanged.

Across much of the Virginia Coastal Plain, the Aquia aquifer consists of an approximately 50-ft or less thick interval of fine- to medium-grained glauconitic sands. The Aquia aquifer generally is not considered an effective large-capacity water-production zone and is usually cased off. Where production is attempted across such intervals, mechanical weathering of glauconite grains by pumping-induced turbulence in proximity to well screens often results in poor water quality and eventual screen clogging. In addition, the most southeastern part of the Aquia aquifer probably contains brackish water (see "Quaternary Period"). The Aquia aquifer supplies greater levels of production where it thickens and deepens northward into Maryland and represents a major regional water supply (Chapelle and Drummond, 1983).

Unregulated withdrawals from the Aquia aquifer generally are dispersed widely across rural areas. A random sample of domestic well records from county health departments indicates that the Aquia aquifer supplies unregulated withdrawals from roughly a quarter of the wells constructed during the past two decades across the middle reaches of the Northern Neck and Middle Peninsula (Jason Pope, U.S. Geological Survey, written commun., 2005), possibly because of its relative thickness there. Only limited, unregulated withdrawals are made in thinner parts of the Aquia aquifer, including the northern Fall Zone, lower Northern Neck, and south of the James River.

Nanjemoy-Marlboro Confining Unit

The Nanjemoy-Marlboro confining unit is widespread, generally deep, and regionally impedes ground-water flow in the Virginia Coastal Plain. The Nanjemoy-Marlboro confining unit extends across all of the Virginia Coastal Plain and eastward offshore except for the Chesapeake Bay impact crater, northeastward along the Virginia Eastern Shore, and along the southernmost part of the Fall Zone (fig. 20; pl. 16). Thickness is as much as several tens of feet or more at depths as much as several hundred feet. The Nanjemoy-Marlboro confining unit is stratigraphically above the Aquia aquifer.

Geologic Relations

The Nanjemoy-Marlboro confining unit consists primarily of marine, silty and clayey, fine-grained glauconitic quartz sands (fig. 21) of the Nanjemoy Formation of early Eocene age (fig. 3). In addition, the lowermost interval of as much as several feet consists of the kaolinitic and micaceous Marlboro Clay of late Paleocene to early Eocene age. In places at further depth, the Nanjemoy-Marlboro confining unit also can include fine-grained sands and silts of the Aquia Formation of late Paleocene age that are not considered part of the Aquia

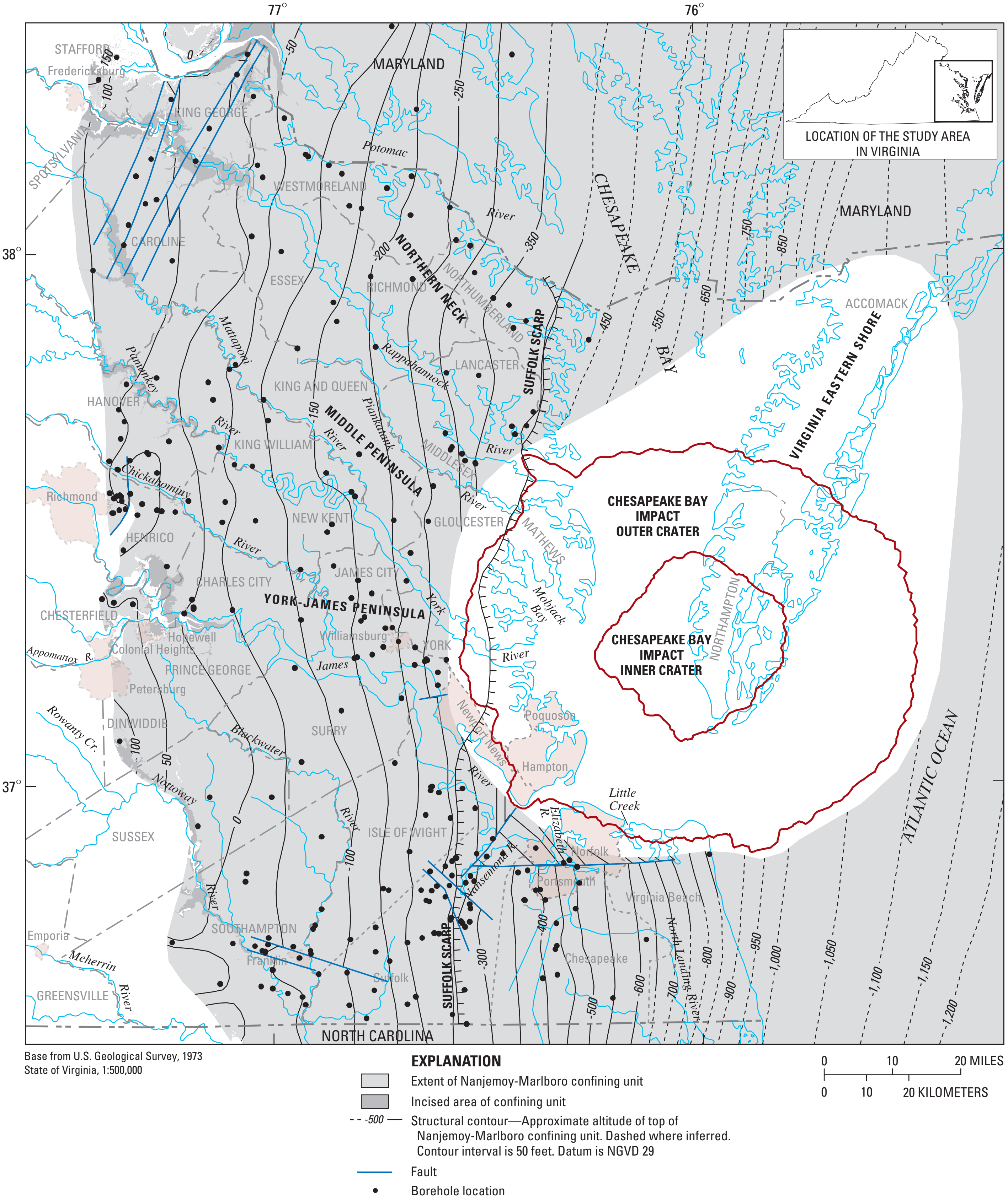


Figure 20. Approximate altitude and configuration of the top of the Nanjemoy-Marlboro confining unit in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Eastward extent of the confining unit is inferred on the basis of radial symmetry about the impact crater. Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 16.)

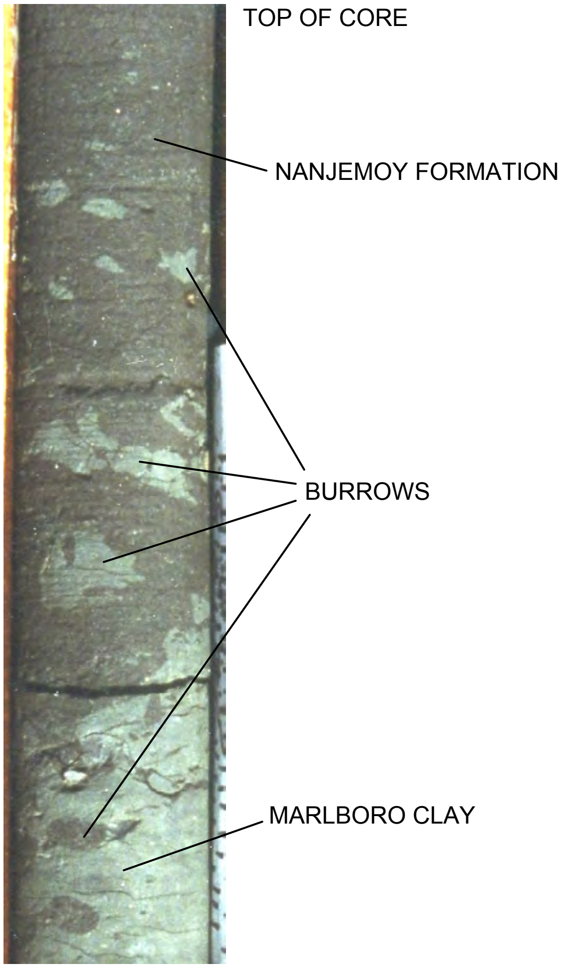


Figure 21. Marine sediments from the Marlboro Clay of late Paleocene to early Eocene age overlain by the Nanjemoy Formation of early Eocene age in the Jamestown core at Jamestown, Virginia. Core diameter is approximately 2 inches, and interval is between approximately 203 and 204 feet below land surface. Kaolinitic and micaceous Marlboro Clay across the lower third of the interval constitutes part of the Nanjemoy-Marlboro confining unit. Color varies between greenish gray (shown here) and reddish gray at other locations (fig. 19). Consistency is markedly plastic. Glauconitic, silty, and clayey fine-grained sand of the Nanjemoy Formation across the upper third of the interval constitutes the major part of the Nanjemoy-Marlboro confining unit. Nanjemoy Formation is burrowed into Marlboro Clay across the lower two-thirds of the interval.

aquifer (see “Aquia aquifer”). Conversely, the upper part of the Nanjemoy Formation in some areas consists of distinct, well-sorted, fine-grained sands of the Woodstock Member that are not considered part of the Nanjemoy-Marlboro confining unit but instead are part of the Piney Point aquifer (see ”Piney Point Aquifer”).

Relatively uniform sediment-transport conditions deposited sediments of the Nanjemoy and Aquia Formations across the Continental Shelf and of the Marlboro Clay in restricted lagoons. Hence, the predominantly silty and clayey fine-grained sands composing the Nanjemoy-Marlboro confining unit vary gradationally and function hydraulically as a continuous medium that impedes horizontal flow but allows relatively slow, vertical ground-water movement as vertical leakage.

Designation of the Nanjemoy Formation and Marlboro Clay as composing a distinct Nanjemoy-Marlboro confining unit was made in previous studies of part or all of the Virginia Coastal Plain (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designation was made to equivalent sediments in studies in adjacent States during approximately the same period—the Nanjemoy-Marlboro confining unit in Maryland (Vroblesky and Fleck, 1991) and the Beaufort confining unit in North Carolina (Winner and Coble, 1996). In various other, mostly earlier studies, sediments belonging to the Pamunkey and(or) Chesapeake Groups or their equivalents, of which the Nanjemoy Formation and Marlboro Clay are only two of several parts, were designated as an aquifer. Because of similar structural positions and other features, the designation of the Nanjemoy-Marlboro confining unit in Virginia in previous studies appears to have included some sediments across the Chesapeake Bay impact crater that are now recognized as the Chickahominy Formation. The Chickahominy Formation is designated herein as composing a distinct confining unit and is not included as part of the Nanjemoy-Marlboro confining unit.

Structural Configuration

The Nanjemoy-Marlboro confining unit is underlain across almost all of its extent by the Aquia aquifer (fig. 18; pl. 15). The Nanjemoy-Marlboro confining unit is underlain by the Potomac confining zone eastward beyond where the Aquia aquifer pinches out beneath the upper Chesapeake Bay (pl. 3, sec. BD-BD') and offshore of Virginia Beach, and westward in western Prince George County and far eastern Chesterfield County beyond where the Aquia aquifer pinches out in the subsurface along the southern part of the Fall Zone (pl. 4, sec. ED-ED'). Differentiation of the Nanjemoy-Marlboro confining unit from the Potomac confining zone can be obscured in the latter area, because both hydrogeologic units are relatively thin and have indistinct borehole geophysical-log signatures.

The maximum altitude of the Nanjemoy-Marlboro confining unit is near its western margin across the northern two-thirds of the Fall Zone (fig. 20; pl. 16). Borehole geophysical logs from north to south indicate altitudes of 152 ft in eastern Stafford County, declining to 28 ft in eastern Hanover and Henrico Counties, and then increasing to 130 ft in western Prince George County. The Nanjemoy-Marlboro confining unit is extrapolated updip a few miles or less westward across the northern Fall Zone before pinching out against the Potomac confining zone at altitudes of approximately 160 ft or less. Some sediments of the Nanjemoy and(or) Aquia Formations and(or) the Marlboro Clay possibly extending a short distance farther west are included with the Potomac confining zone. Across the southern Fall Zone, the Nanjemoy-Marlboro confining unit pinches out generally near 0 ft along its western margin (fig. 20; pl. 16; pl. 4, sec. FD-FD'; pl. 5, all secs.). Truncation of the Nanjemoy-Marlboro confining unit is projected along the valleys of the Potomac, Rappahannock, James, and Nottoway Rivers and some of their tributaries across the entire western margin.

The Nanjemoy-Marlboro confining unit is overlain across most of its extent by the Piney Point aquifer (fig. 27; pl. 20). The Nanjemoy-Marlboro confining unit extends beyond both the eastern and western margins of the Piney Point aquifer, where it is overlain primarily by the Calvert confining unit (fig. 29; pl. 21). The Calvert confining unit is not present to the southwest, where the Nanjemoy-Marlboro confining unit is overlain by the Saint Marys confining unit (fig. 32; pl. 23) across the western two-thirds of Isle of Wight County, all of Surry County except for Hog Island, and eastern parts of Prince George, Sussex, and Southampton Counties. Across most of its extent in western Prince George County, the Nanjemoy-Marlboro confining unit is overlain by the Yorktown-Eastover aquifer (fig. 34; pl. 24). Small areas of the Nanjemoy-Marlboro confining unit are extrapolated to be overlain by the surficial aquifer near the Fall Zone in Stafford, Caroline, and Prince George Counties. Similarly, locally incised areas are projected across the Fall Zone along the Potomac, Rappahannock, Mattaponi, Pamunkey, James, and Nottoway Rivers and some of their tributaries (fig. 20; pl. 16), where the Nanjemoy-Marlboro confining unit crops out across the steepest slopes but is mostly covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer. Additional outcrops possibly exist in small, isolated areas along smaller streams crossing the Fall Zone. Thinning of the Nanjemoy-Marlboro confining unit where it is overlain by the surficial aquifer across the incised areas possibly enhances hydraulic connections between the confined and unconfined ground-water systems, particularly along the main stem of the Potomac River where a relatively broad area is incised by almost the entire river channel.

The Nanjemoy-Marlboro confining unit dips generally eastward across its entire extent (fig. 20; pl. 16). Its greatest thickness of nearly 150 ft is at altitudes from approximately –150 ft to –300 ft and below across much of the Northern Neck (pl. 3, all secs.) and the middle part of the Middle Peninsula (pl. 4, sec. DD–DD'). Southward across the upper York-James Peninsula and south of the James River, the Nanjemoy-Marlboro confining unit thins to approximately 50 ft or less and shallows by as much as 100 ft across the western part of the Norfolk arch (pl. 6, secs. BS–BS', CS–CS', DS–DS'). The altitude of the Nanjemoy-Marlboro confining unit near the westernmost margin of the Chesapeake Bay impact crater is approximately –250 ft (fig. 20; pl. 16). It is extrapolated eastward to be truncated at progressively lower altitudes by various combinations of the Exmore clast confining unit, the Exmore matrix confining unit, and(or) the Chickahominy confining unit (pl. 3, sec. CD–CD'; pls. 4, 7, all secs.). Northward extension of the Chickahominy confining unit from the area of the crater is based on identification of the Chickahominy Formation in the Jenkins Bridge core (Powars and Bruce, 1999; Attachment 1, borehole local number 66M 23). Sediments constituting the Nanjemoy-Marlboro confining unit were not observed in this core, and the Nanjemoy-Marlboro confining unit is interpreted to be absent from the northern area of the Chickahominy confining unit. Eastward extrapolation of the Nanjemoy-Marlboro confining unit beyond the crater offshore is based on the assumption that other hydrogeologic units within the crater are symmetrically distributed. Additionally, based on previous studies, the Nanjemoy-Marlboro confining unit is extrapolated northward into Maryland (Vroblesky and Fleck, 1991) and southward into North Carolina as the Beaufort confining unit (Winner and Coble, 1996).

The top of the Nanjemoy-Marlboro confining unit on some borehole geophysical logs has closely spaced displacements generally of a few tens of feet or less, that are attributed to faults (fig. 20; pls. 3, 5–7, 16). The faults intersect the Nanjemoy-Marlboro confining unit by extension upward from the Potomac aquifer (see “Potomac Aquifer”) and through intervening hydrogeologic units, which generally have larger displacements. Although discrete fractures that are either open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of their depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. In addition, the faults create local-scale irregularities in the altitude of the Nanjemoy-Marlboro confining unit, and laterally abut relatively small volumes across the top and base of the confining unit against adjacent hydrogeologic units. Exceptions are beneath the Nansemond River, where the Nanjemoy-Marlboro confining unit is significantly thinned across a fault (pl. 5, sec. GD–GD'), and near the James River, where the confining unit is truncated by the Potomac aquifer across a fault (pl. 6, sec. AS–AS'). Faults possibly exist at other locations but are not recognized because of scarce borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the Nanjemoy-Marlboro confining unit in boreholes is noted generally by silty and(or) clayey fine-grained glauconitic sands (fig. 21) that contrast with coarse-grained overlying sediments, primarily of the Piney Point aquifer but also of the Yorktown-Eastover or surficial aquifers in some areas. Drilling response typically is smooth, and the rate of advancement is moderate. Cuttings of Nanjemoy Formation sediments returned by drag bit during this study have colors varying among greenish black (10G 2.5/1), very dark gray (5Y 3/1), dark olive gray (5Y 3/2), greenish gray (10Y 5/1), and dark greenish gray (5GY 3/1 and 10GY 4/1). Fine-grained sediments of the Aquia Formation included as part of the Nanjemoy-Marlboro confining unit have a similar composition. By contrast, the Marlboro Clay is distinctly dense and plastic and can slow significantly the rate of advancement if adequately thick. Colors of the Marlboro Clay observed during this study include dark greenish gray (10Y 4/1) but more typically reddish gray (5YR 5/2), reddish brown (5YR 4/4), and grayish brown (10YR 5/2). Although the Marlboro Clay is only a few feet or less thick in many places, recognition of its distinct texture and color can be critical in distinguishing Nanjemoy Formation sediments from those of the underlying Aquia Formation (see "Aquia Aquifer").

Recognition of the Nanjemoy-Marlboro confining unit can be obscured where it is overlain by either the Calvert or Saint Marys confining units, and relatively subtle differences in color, texture, and(or) lithologic components must be relied on. Although having a distinct appearance in core, the Chickahominy confining unit associated with the Chesapeake Bay impact crater occupies a similar structural position as the Nanjemoy-Marlboro confining unit outside of the crater and exhibits a generally similar drilling response. Prior to discovery of the crater, borehole intervals penetrating the Chickahominy confining unit were widely misinterpreted as penetrating the Nanjemoy-Marlboro confining unit.

On borehole electric logs (see "Borehole Geophysical-Log Network") the Nanjemoy-Marlboro confining unit generally exhibits a relatively flat signature typical of fine-grained marine sediments, with some variation resulting from differences in silt and(or) clay content (fig. 4). Gamma logs generally exhibit an elevated response that can contrast against the more moderate responses of the underlying Aquia aquifer and parts of the overlying Piney Point aquifer. The Marlboro Clay can be distinguished in places by a distinct gamma peak. In areas where the Nanjemoy-Marlboro confining unit is in direct contact with overlying confining units and(or) the underlying Potomac confining zone (see "Structural Configuration"), both electric and gamma logs can have indistinct responses to the similarly fine-grained sediments, and the base and top surfaces of the Nanjemoy-Marlboro confining unit can be obscure.

Hydrologic Aspects

The Nanjemoy-Marlboro confining unit is an extensive hydrogeologic unit that regionally impedes horizontal ground-water flow. Across most of its extent, vertical leakage through the Nanjemoy-Marlboro confining unit occurs between the overlying Piney Point aquifer and the underlying Aquia aquifer. The Nanjemoy-Marlboro confining unit is thickest north of the James River where it provides the most effective hydraulic separation between the Piney Point and Aquia aquifers, but thins progressively southward where leakage between the two aquifers probably is more pronounced.

All permeameter samples collected during this study were from within the Chesapeake Bay impact crater where the Nanjemoy-Marlboro confining unit is not present. Published values of vertical hydraulic conductivity of the Nanjemoy-Marlboro confining unit include some generated by laboratory analyses of sediment core, which range across an order of magnitude from 0.0000022 to 0.0000363 ft/d (Harsh and Laczniak, 1990, and Laczniak and Meng, 1988, respectively; table 2). Other published values derived from ground-water model calibration are near the upper end of this range and within an order of magnitude, from 0.000035 to 0.0000648 ft/d (McFarland, 1999, and Hamilton and Larson, 1988, respectively; table 2). The higher vertical hydraulic conductivity values derived from model calibration possibly are more representative of the vertical hydraulic conductivity of the Nanjemoy-Marlboro confining unit at the regional scale.

Exmore Clast Confining Unit

The Exmore clast confining unit is of limited regional extent, is very deep and thick, and locally impedes ground-water flow in the Virginia Coastal Plain. The Exmore clast confining unit extends across essentially all of the Chesapeake Bay impact crater including all of Mathews and Northampton Counties and most of the city of Hampton; lower parts of Middlesex, Gloucester, and York Counties; the southern tip of the city of Newport News; the northern shorelines of the cities of Norfolk and Virginia Beach; and the lower Chesapeake Bay (fig. 22; pl. 17). The Exmore clast confining unit is as thick as approximately 4,650 ft at depths as great as 6,000 ft. The Exmore clast confining unit is stratigraphically above the Potomac confining zone across most of its extent and above basement across the inner crater.

Geologic Relations

The Exmore clast confining unit consists primarily of boulder-size clasts of older formations with subordinate amounts of a matrix groundmass (fig. 23), that together comprise the lower part of the Exmore tsunami-breccia of late Eocene age (Powars and Bruce, 1999; Powars, 2000; fig. 3). The clasts potentially include any of the lithologies of the basement and sediments of Cretaceous, Paleocene, and early to middle Eocene age but generally are dominated by clays of the Potomac Formation of Cretaceous age in core obtained to date (2006). Sands of the Potomac Formation also are present, but lithologies of Tertiary age generally are rare. Clasts can be several tens of feet or more in diameter and are widely in direct contact. Conversely, the matrix fills relatively thin zones as minor voids between clasts with very poorly sorted sands, silts, and clays that include disparate marine and terrestrial components. Because the Exmore tsunami-breccia composes a roughly fining-upward sequence, its upper part consists of smaller pebble- to cobble-size clasts that are suspended in a continuous matrix and is designated separately as the Exmore matrix confining unit. Additionally, in some areas,

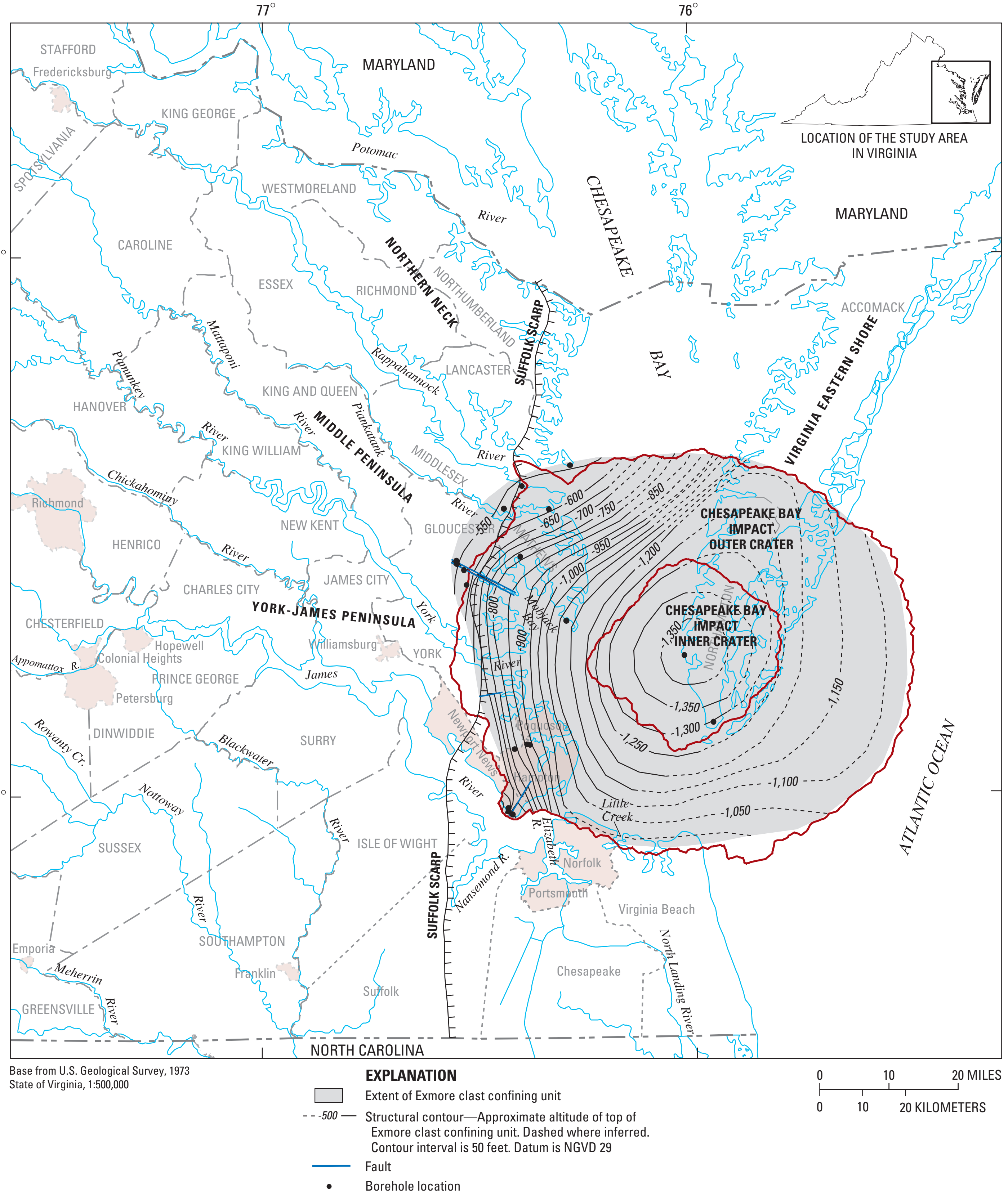


Figure 22. Approximate altitude and configuration of the top of the Exmore Clast confining unit in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of radial symmetry about the impact crater. Further details are shown on plate 17.)

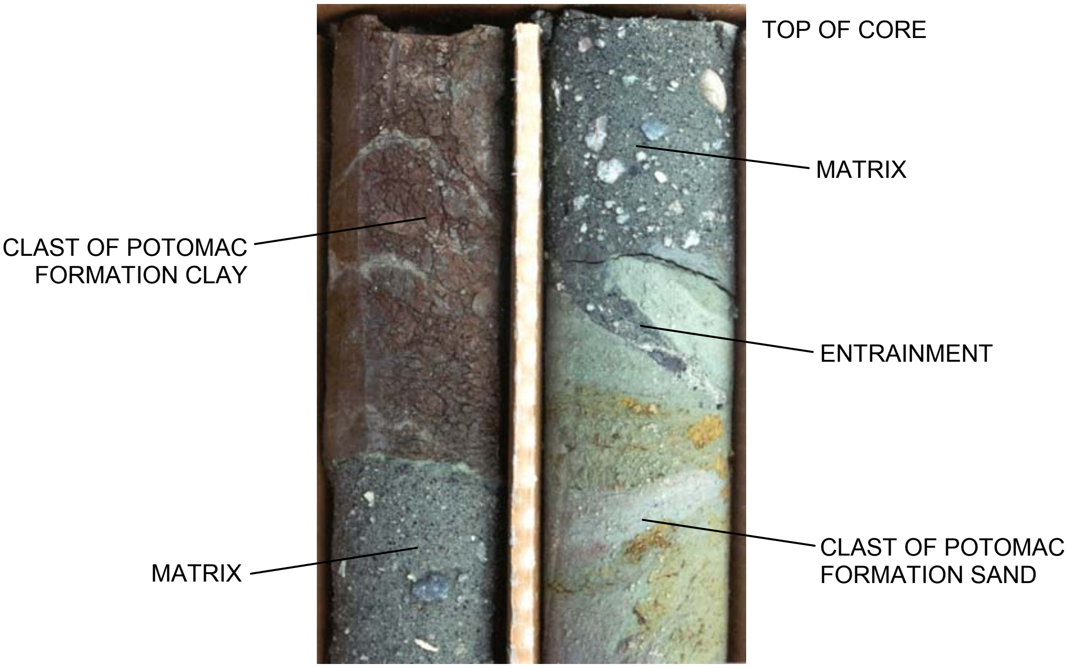


Figure 23. Impact-generated sediments of late Eocene age from the Exmore tsunami-breccia in the North core, borehole local number 59H 4, in Mathews County, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and intervals are between approximately 816 and 824 feet below land surface. The upper part of the left section intersects part of a clast consisting of intensely fractured clay of the Potomac Formation. The lower part of the right section intersects part of another clast consisting of highly contorted sand of the Potomac Formation. Parts of sections adjacent to clasts have matrix consisting of very poorly sorted sand, silt, and clay containing disparate marine and terrestrial lithologic components. Matrix emplacement contemporaneous with clast deformation is evidenced by entrainment of matrix in the contorted clast in the right section. The lower part of the Exmore tsunami-breccia is dominated by boulder-size and larger clasts that are in direct contact and constitutes the Exmore clast confining unit. The upper part of the Exmore tsunami-breccia contains cobble-size and smaller clasts suspended in matrix, and constitutes the Exmore matrix confining unit. *(Photograph by C. Wylie Poag, U.S. Geological Survey)*

the uppermost 2 to 20 ft of the Exmore tsunami-breccia can include fine-grained sediments that are texturally similar to the Chickahominy Formation that are included as the lowermost part of the Chickahominy confining unit.

Extremely violent sediment-transport conditions deposited the sediments of the Exmore tsunami-breccia during an inward rushing backwash of water and debris across the Chesapeake Bay impact crater (see “Late Eocene Epoch–Chesapeake Bay Impact Crater”). The Exmore clast confining unit is tentatively designated herein on the basis that clasts of Potomac Formation clays were preserved preferentially in the lower part of the Exmore tsunami-breccia as a result of their relative denseness compared with other less-structurally competent lithologies that were more widely disaggregated. Ground-water flow in the Exmore clast confining unit likely is through clasts that are in direct contact, which exert primary control on flow rather than the matrix that fills relatively minor voids. Although some clasts of Potomac Formation sands also are present and the clasts, in general, are variably deformed, the Exmore clast confining unit at the regional scale functions hydraulically as a continuous medium that impedes horizontal flow but allows relatively slow vertical ground-water movement as leakage. Vertical leakage possibly is enhanced, relative to other confining units, by sand clasts and by a commonly high degree of fracturing in clay clasts (fig. 23).

Designation of the Exmore clast confining unit is newly made herein (fig. 3). Because of similar structural positions and other features, sediments of the lower part of the Exmore tsunami-breccia appear to have been included as part of the Potomac aquifer series across the Chesapeake Bay impact crater in previous studies (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990). The Potomac aquifer, as designated herein, is composed of sediments of the undisturbed part of the Potomac Formation of Early Cretaceous age outside of and leading into the Chesapeake Bay impact crater, along with overlying megablock beds of the Potomac Formation within the crater, and is distinct from the Exmore clast confining unit. In addition and because of its association with the crater, the Exmore clast confining unit does not have equivalents in adjacent States.

Designation of the Exmore clast confining unit is made tentatively with the recognition that much of the volume of the Exmore tsunami-breccia remains not directly observed in detail. A large potential exists for the lithologic composition of parts of the Exmore clast confining unit to differ significantly from the lithologic composition that has been observed to date (2006) in only five cores (Attachment 1). The Chesapeake Bay impact crater remains a topic of active research. Future hydrogeologic reclassification of the Exmore tsunami-breccia could be warranted given a more widely based description of its composition and an improved understanding of depositional processes within the Chesapeake Bay impact crater.

Structural Configuration

The Exmore clast confining unit is entirely below land surface and does not crop out. It is underlain across most of its extent within the Chesapeake Bay impact crater by the Potomac confining zone (fig. 10; pl. 9). The Potomac confining zone is truncated along with the Potomac aquifer at the inner crater, within which the Exmore matrix confining unit is underlain by basement bedrock. Along the crater margin, structural relations are not wholly known regionally but are probably complex and variable. Here, the Exmore clast confining unit possibly overlies small parts of the Nanjemoy-Marlboro confining unit and(or) Aquia aquifer along their eastern margins, although this configuration is not interpreted at any borehole location as part of this study. The Exmore clast confining unit is overlain entirely by the Exmore matrix confining unit (fig. 24; pl. 18).

The maximum altitude of the Exmore clast confining unit is along the northwestern margin where borehole geophysical logs indicate altitude as high as –533 ft at the southwestern tip of Lancaster County (fig. 22; pl. 17). The Exmore clast confining unit is extrapolated to the north, west, and south from its margin to pinch out against the Nanjemoy-Marlboro confining unit, the Aquia aquifer, and(or) the Potomac confining zone (pl. 3, sec. CD–CD'; pls. 4 and 7, all secs.).

The Exmore clast confining unit dips generally concentrically into the Chesapeake Bay impact crater (fig. 22; pl. 17) and is thickest within the inner crater at approximately 4,650 ft across altitudes between approximately –1,350 and –6,000 ft. Thickness and altitude exhibit some variation across the crater. The greatest thickness is interpolated along the concentric depression or “moat” in the underlying basement. Toward the center of the crater, the Exmore clast confining unit thins to 1,692 ft and shallows slightly across altitudes from –1,308 ft to –3,000 ft at the central uplift (Attachment 1, borehole local number 62G 24). Based on these relations, the Exmore clast confining unit is interpolated within the crater to have a somewhat elongated but generally saucer-shaped configuration (pl. 7, sec. GS–GS') with a thickened central section. The Exmore clast confining unit is extrapolated to pinch out offshore on the assumption that it generally is concentrically distributed.

The top of the Exmore clast confining unit on borehole geophysical logs in two areas along the western margin exhibits closely spaced displacements generally of several tens of feet which have been attributed to faults (fig. 22; pl. 4, all secs.; pl. 7, sec. ES–ES'; pl. 17). The faults intersect the Exmore clast confining unit by extension upward from the Potomac aquifer (see “Potomac Aquifer”) and through the intervening Potomac confining zone. Although discrete fractures that are open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of the depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. Because the clasts making up the Exmore clast confining unit have undergone varying degrees of deformation, however, intergranular structure probably is widely altered throughout the confining unit.

In addition to possible intergranular effects, the faults create local-scale irregularities in the altitude of the Exmore clast confining unit and laterally abut relatively large volumes across the top and base of the confining unit against adjacent hydrogeologic units. In one area, a fault extends from beneath the Nansemond River to the northeast across the James River and intersects the southwestern margin of the Exmore clast confining unit, which is thin relative to displacement along the fault and is partly truncated (pl. 7, sec. ES–ES') to entirely truncated (pl. 4, sec. FD–FD'). In the second area, a pair of closely spaced parallel faults possibly representing a deep graben is inferred along the northwest margin of the Chesapeake Bay impact crater (pl. 4, sec. DD–DD'). Here, the thickness of the Exmore clast confining unit ranges from 52 ft to 79 ft outside of the graben (Attachment 1, borehole local numbers 58H 4, 58H 5, and 58H 9) but is 503 ft inside the graben (58H 11). The large thickness of the Exmore clast confining unit within the graben indicates that the graben formed as the Exmore tsunami-breccia was being deposited soon after the impact. In addition, the top of the Exmore clast confining unit within the graben is downwardly displaced by approximately 100 ft, which along with similar relations observed in overlying hydrogeologic units indicates continued movement along the bounding faults following the impact. The vertical wall of Exmore clast confining unit sediments within the graben possibly creates a substantial localized barrier to lateral ground-water flow through adjacent sediments composing the Potomac aquifer. Faults possibly exist at other locations, but are not recognized because of sparse borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the Exmore clast confining unit in boreholes generally is noted by successive intervals as great as several tens of feet through clasts of Potomac Formation clays and sands (fig. 23; see “Potomac Aquifer”), with only thin and occasional intervals of matrix in between (see “Exmore matrix confining unit”). Potomac Formation clays are dense and produce a smooth and quiet drilling response with a slow rate of advancement. In cuttings, Potomac Formation clays exhibit variable colors, including light reddish brown (5YR 6/4), light yellowish brown (2.5Y 6/4), and similar colors where oxidized, but grayish green (5G 5/2) and other variations where secondarily reduced. The sands consist of medium- to very coarse-grained quartz and feldspar sands and gravels that typically create a pronounced gritty sound and feel in drilling response and are returned in drill cuttings in a wholly disaggregated state. The matrix consists of very poorly sorted sands, silts, and clays that exhibit a disparate lithology. Normally terrestrial components, such as angular and very coarse quartz and feldspar sands, typically are mixed wholly and incorporated with marine components, such as glauconite and phosphate. Fossil shell fragments and minor components, such as mica, lignite, and pyrite, generally are common. Although the matrix is outwardly coarse grained in appearance, it includes a significant fraction of fine-grained sands, silts, and clays.

Different parts of the Exmore tsunami-breccia compose the Exmore clast confining unit and Exmore matrix confining unit, and differentiation between them is based primarily on the relative abundance between matrix and clasts. The upper part of the Exmore tsunami-breccia is designated as the Exmore matrix confining unit and generally contains intervals of matrix interspersed with relatively short intervals through lithologically diverse clasts as large as cobble size. At greater depth in the Exmore tsunami-breccia, the Exmore clast confining unit contains large boulder-sized clasts primarily of variably deformed Potomac Formation clays and sands that widely are in direct contact. The thin and sparse intervals of matrix between clasts commonly are obscured in drill cuttings. The underlying Potomac confining zone and Potomac aquifer are distinguished from the Exmore clast confining unit by a complete absence of matrix, and by Potomac Formation clays and sands that essentially are undeformed and present not as clasts but in bedded configuration.

During this study, recognition of the Exmore clast confining unit was based on sediment core. The gradationally downward coarsening of the Exmore tsunami-breccia results in a transition from the Exmore matrix confining unit to the Exmore clast confining unit, and a specific contact between the two hydrogeologic units is determined best by using core. Similarly, the contact between the Exmore clast confining unit and the underlying Potomac confining zone is determined best by using core to distinguish deformed clasts of Potomac Formation sediments from undeformed bedded Potomac Formation sediments and to identify the lowermost interval of matrix. Core was obtained from 5 of the 18 boreholes interpreted during this study to penetrate the Exmore clast confining unit (Attachment 1). Cuttings were collected at another 4 boreholes in the Exmore clast confining unit. The remaining 9 boreholes generated only geophysical logs and, in some cases, drillers' logs and were used to interpolate the position of the Exmore clast confining unit from the other boreholes.

On borehole electric logs (see "Borehole Geophysical-Log Network"), the Exmore clast confining unit exhibits a highly variable signature that ranges from relatively flat across clay clasts to blocky and(or) spiky across sand clasts and intervals of matrix (pl. 3, sec. CD–CD'; pls. 4, 7, all secs.). Gamma logs have moderately elevated responses from clays, low responses from sands, and variable responses from matrix resulting from differences in amounts of clay, glauconite, and(or) phosphate.

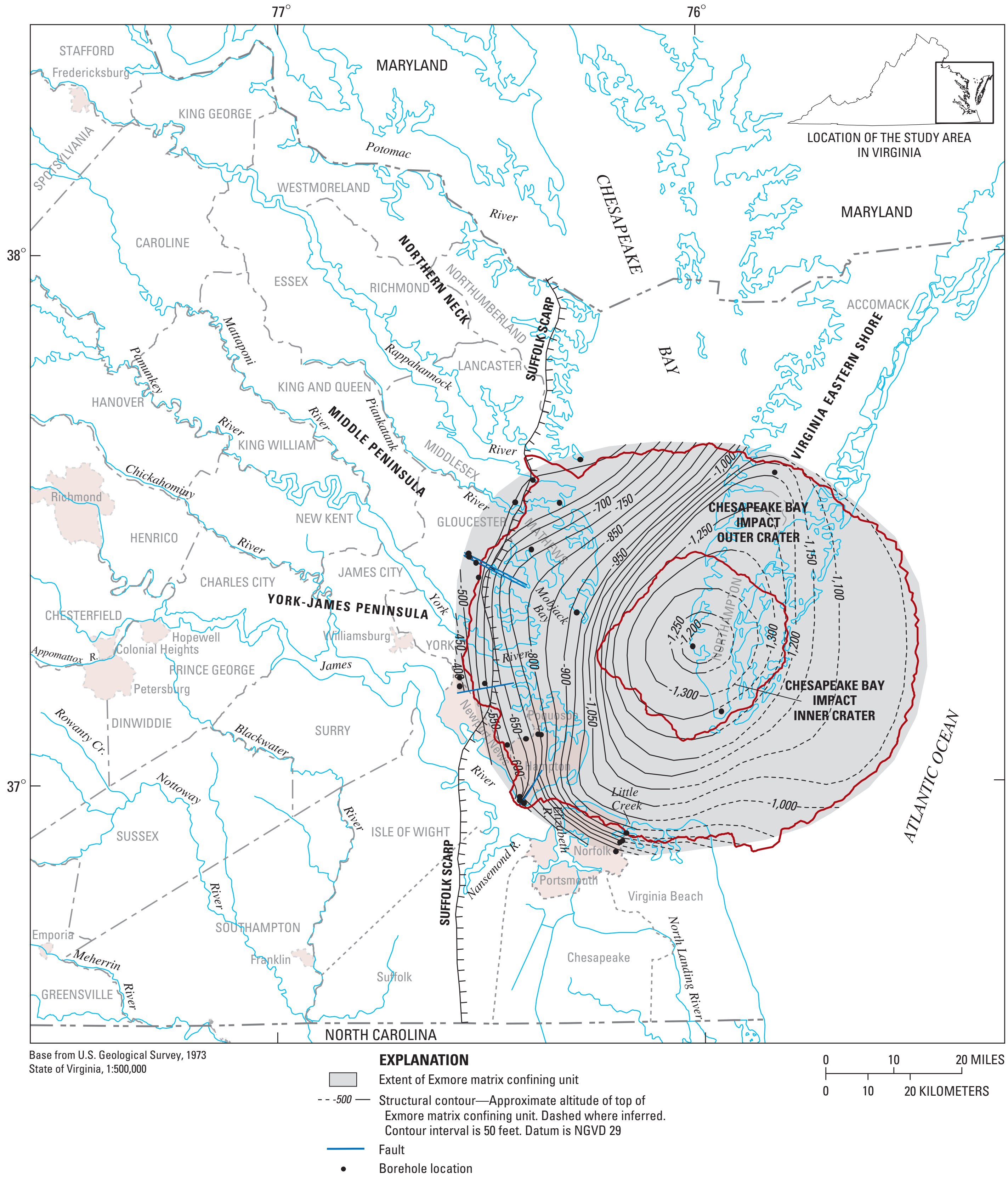
Hydrologic Aspects

The Exmore clast confining unit is a regionally limited hydrogeologic unit that locally impedes horizontal ground-water flow. Vertical leakage through the Exmore clast confining unit occurs between the overlying Piney Point aquifer and underlying Potomac aquifer (through the overlying Chickahominy and Exmore matrix confining units and underlying Potomac confining zone). Although it is limited in extent to the Chesapeake Bay impact crater, the Exmore clast confining unit is very thick. It thereby likely provides a very effective hydraulic separation, in combination with the adjacent confining units and zones, between the Piney Point and Potomac aquifers across most of the crater. Leakage between the aquifers probably is more pronounced where the Exmore clast confining unit thins near its western margin.

The vertical hydraulic conductivity values of five permeameter samples from the Exmore clast confining unit vary by three orders of magnitude between 0.000060 and 0.054 ft/d (table 1). The single matrix sample has a vertical hydraulic conductivity value similar to the matrix samples from the Exmore matrix confining unit, and its texture and porosity also are similar. The vertical hydraulic conductivity values of two samples of sand clasts range over two orders of magnitude, and these samples also have substantially different textures; the lower vertical hydraulic conductivity is associated with the fine-grained sample. Both the vertical hydraulic conductivities and textures are near or beyond the low end of the vertical hydraulic conductivities and texture ranges exhibited by samples of bedded sands of the Potomac aquifer, although the porosities are near the high end. The vertical hydraulic conductivity values of two samples of clay clasts range over two orders of magnitude, possibly as a result of the degree of fracturing of the clasts, although the textures and porosities are similar. All properties of the samples of clay clasts are similar to the properties of samples of bedded clays in the Potomac aquifer. Because the Exmore clast confining unit is newly designated herein, published values of vertical hydraulic conductivity do not exist. Previous studies probably included the lower part of the Exmore tsunami-breccia which now is recognized as part of the Potomac aquifer. No means exist, however, to differentiate which, if any, published values of vertical hydraulic conductivity correspond to sediments of the lower part of the Exmore tsunami-breccia.

Exmore Matrix Confining Unit

The Exmore matrix confining unit is of limited regional extent, is generally deep, and locally impedes ground-water flow in the Virginia Coastal Plain. The Exmore matrix confining unit extends across essentially all of the area of the Chesapeake Bay impact crater including all of Mathews and Northampton Counties; the city of Hampton; lower parts of Middlesex, Gloucester, and York Counties and the city of Newport News; northern parts of the cities of Norfolk and Virginia Beach; and the lower Chesapeake Bay (fig. 24; pl. 18). The Exmore matrix confining unit is as thick as approximately 200 ft at depths exceeding 1,000 ft. The Exmore matrix confining unit is stratigraphically above the Exmore clast confining unit.



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

Figure 24. Approximate altitude and configuration of the top of the Exmore Matrix confining unit in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of radial symmetry about the impact crater. Further details are shown on plate 18.)

Geologic Relations

The Exmore matrix confining unit consists of pebble- to cobble-sized clasts of older formations separated by and suspended in a matrix groundmass (fig. 23) that together compose the upper part of the Exmore tsunami-breccia of late Eocene age (Powars and Bruce, 1999; Powars, 2000; fig. 3). The clasts include diverse lithologies of the basement and sediments of Cretaceous, Paleocene, and early to middle Eocene age, whereas the matrix consists of very poorly sorted sands, silts, and clays that include disparate marine and terrestrial components. In some areas, the uppermost 2 to 20 ft of the Exmore tsunami-breccia can include fine-grained sediments that are texturally similar to the Chickahominy Formation and are not considered part of the Exmore matrix confining unit but instead are included as the lowermost part of the Chickahominy confining unit. Conversely, the lower part of the Exmore tsunami-breccia composes the Exmore clast confining unit and consists of boulder-sized clasts and subordinate amounts of matrix that fill relatively thin zones of minor voids between clasts.

Extremely violent sediment-transport conditions deposited the sediments of the Exmore tsunami-breccia during an inward rushing backwash of water and debris across the Chesapeake Bay impact crater (see “Late Eocene Epoch – Chesapeake Bay Impact Crater”). Although clasts are lithologically diverse and variably deformed, the matrix consists of disaggregated, fluidized, and generally well-mixed sediments of relatively uniform texture and composition that fill spaces between clasts. Within the upper part of the Exmore tsunami-breccia that constitutes the Exmore matrix confining unit, the matrix forms a continuous mass that surrounds and isolates relatively small individual clasts. Because clasts are separated by matrix, which likely exerts primary control on flow, ground water generally cannot flow appreciable distances solely through clasts. The Exmore matrix confining unit thereby functions hydraulically as a continuous medium that impedes horizontal flow but allows relatively slow ground-water movement, mostly as vertical leakage.

Designation of the Exmore matrix confining unit is newly made herein (fig. 3). Because of similar structural positions and other features, sediments of the upper part of the Exmore tsunami-breccia were included as part of the Aquia aquifer across the Chesapeake Bay impact crater in previous studies (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990). The Aquia aquifer as designated herein is composed of sediments of the Aquia Formation of late Paleocene age and is distinct from the Exmore matrix confining unit. In addition and because of its association with the crater, the Exmore matrix confining unit does not have equivalents in adjacent States.

Structural Configuration

The Exmore matrix confining unit is entirely below land surface and does not crop out. It is underlain across most of its extent within the Chesapeake Bay impact crater by the Exmore clast confining unit (fig. 22; pl. 17). Regional structural relations along the crater margin are not wholly known but are probably complex and variable. The Exmore matrix confining unit extends slightly beyond the Exmore clast confining unit along its western margin across lower parts of Lancaster and York Counties and the city of Newport News, and along its southern margin across northern areas of the cities of Norfolk and Virginia Beach. The Exmore matrix confining unit is interpreted to directly overlie the Potomac confining zone at 12 borehole locations (Attachment 1; pl. 4, sec. ED–ED'; pl. 7, sec. FS–FS'), where the intervening hydrogeologic units normally present outside of the crater have been truncated by the blast. Elsewhere, the Exmore matrix confining unit possibly overlies small parts of the Nanjemoy-Marlboro confining unit and(or) Aquia aquifer along the eastern margins, although this configuration is not interpreted at any borehole locations as part of this study. The Exmore matrix confining unit is entirely overlain by the Chickahominy confining unit (fig. 25; pl. 19).

The maximum altitude of the Exmore matrix confining unit is along the western margin, where borehole geophysical logs indicate an altitude as high as –374 ft at the northern tip of Newport News (fig. 24; pl. 18). The Exmore matrix confining unit is extrapolated to pinch out to the north, west, and south against the Nanjemoy-Marlboro confining unit and(or) the Aquia aquifer (pl. 3, sec. CD–CD'; pls. 4, 7, all secs.).

The Exmore matrix confining unit generally dips concentrically into the Chesapeake Bay impact crater (fig. 24; pl. 18) and thickens to as much as approximately 200 ft across altitudes as low as approximately –1,150 to –1,350 ft (pl. 3, sec. CD–CD', pls. 4, 7, all secs.). Thickness and altitude are variable across the crater. Near the northern margin at Exmore, the Exmore matrix confining unit is greater than 187 ft thick from an altitude of –1,179 ft to below the bottom of the core hole at –1,366 ft (Attachment 1, borehole local number 64J 14). Farther into the crater, however, near the southern part of the inner crater, the Exmore matrix confining unit is only 12 ft thick across altitudes from –1,279 ft to –1,291 ft (Attachment 1, borehole local number 63F 50). Toward the center of the crater, the Exmore matrix confining unit thickens again to 156 ft and also shallows across altitudes from –1,152 ft to –1,308 ft at the central uplift (borehole local number 62G 24). Based on these relations, the Exmore matrix confining unit is interpolated within the crater to have a somewhat elongated but generally saucer-shaped configuration (pl. 7, sec. GS–GS') and is extrapolated to pinch out offshore on the assumption that it generally is concentrically distributed.

On some borehole geophysical logs, the top of the Exmore matrix confining unit along its western margin exhibits closely spaced displacements generally of a few tens of feet or less that are attributed to faults (fig. 24; pl. 4, all secs.; pl. 7, sec. ES–ES'; pl. 18). The faults intersect the Exmore matrix confining unit by extension upward from the Potomac aquifer (see “Potomac Aquifer”) and through intervening hydrogeologic units, which generally exhibit larger displacements. Although discrete fractures that are either open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of their depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. In addition, the faults create local-scale irregularities in the altitude of the Exmore matrix confining unit and laterally abut generally small volumes across the top and base of the confining unit against adjacent hydrogeologic units. An exception is along one fault extending from beneath the Nansemond River to the northeast across the James River, where the Exmore matrix confining unit is thin relative to displacement along the fault and is entirely truncated (pl. 4, sec. FD–FD'; pl. 7, sec. ES–ES'). In addition, a pair of closely spaced parallel faults possibly representing a deep graben is inferred along the northwest margin of the Chesapeake Bay impact crater (pl. 4, sec. DD–DD'), where a segment of the Exmore matrix confining unit is downwardly displaced by approximately 100 ft and isolated within the graben. Faults possibly exist at other locations but are not recognized because of sparse borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the Exmore matrix confining unit in boreholes is generally noted by very poorly sorted sands, silts, and clays composing the matrix of the Exmore tsunami-breccia (fig. 23), which contrast markedly with the very fine-grained silts and clays of the overlying Chickahominy confining unit. The matrix has a disparate lithology that includes terrestrial components, such as angular and very coarse quartz and feldspar sands, that typically are mixed wholly and incorporated with marine components, such as glauconite and phosphate, although a non-marine form of the matrix rarely has been observed. Fossil shell fragments and minor components, such as mica, lignite, and pyrite, generally are common. Although the matrix is outwardly coarse grained in appearance, it includes a substantial fraction of fine-grained sands, silts, and clays.

Suspended within the matrix of the Exmore matrix confining unit are pebble- to cobble-sized clasts that have diverse lithologies of the basement and typically many of the older formation sediments. Drilling response typically is highly variable and is gritty through the matrix and sand-dominated clasts and smooth through clay-dominated clasts. In addition, considerable chatter through shelly and calcite-cemented clasts from the Piney Point Formation is particularly indicative of the Exmore matrix confining unit. The rate of advancement generally is equally variable.

On borehole electric logs (see “Borehole Geophysical-Log Network”), the Exmore matrix confining unit exhibits a highly variable signature that ranges from blocky and(or) spiky across intervals of matrix and coarse-grained clasts to nearly flat across fine-grained clasts. Gamma logs exhibit equally varied responses resulting from differences in amounts of clay, glauconite, and(or) phosphate.

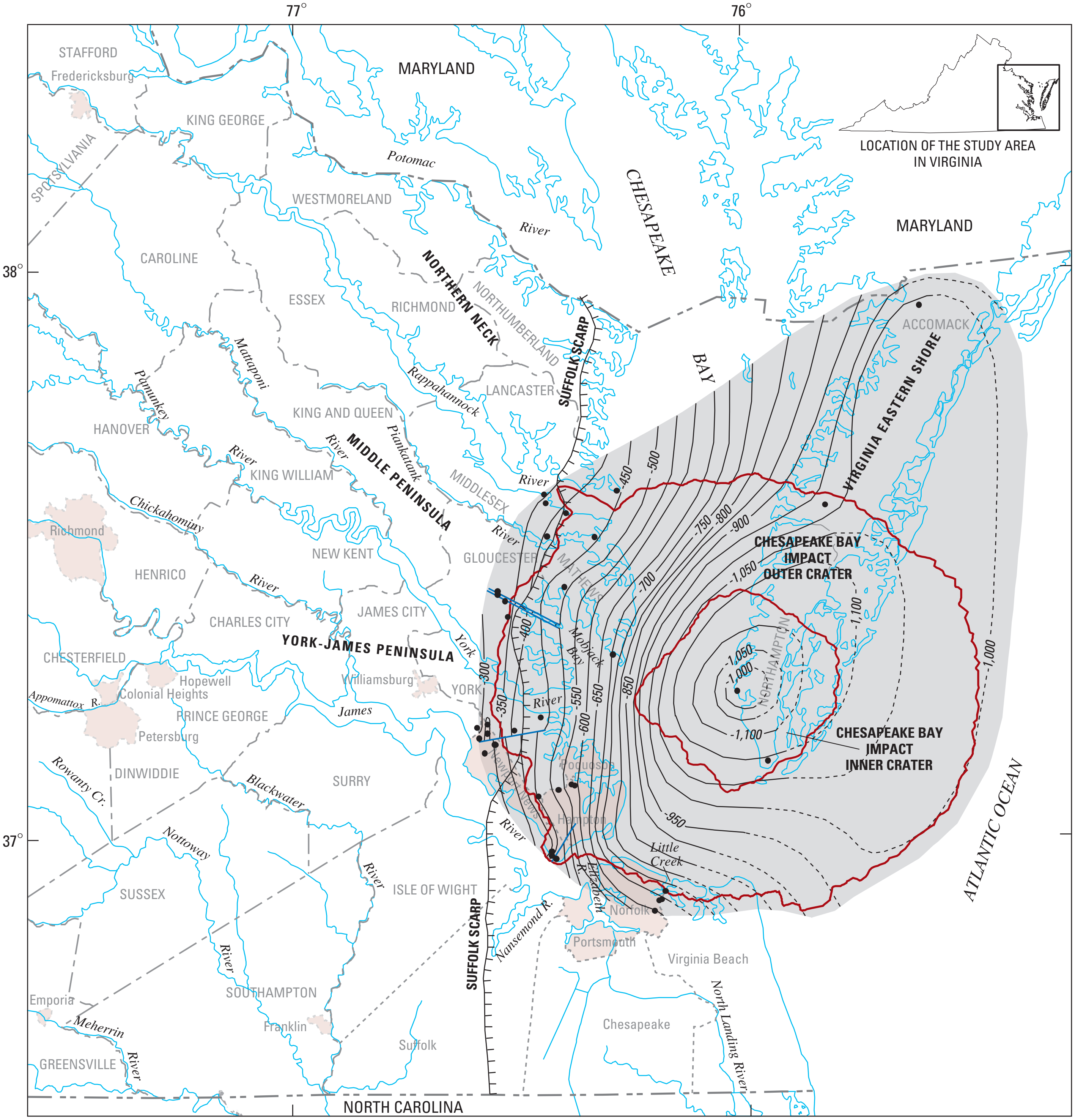
Hydrologic Aspects

The Exmore matrix confining unit is a regionally limited hydrogeologic unit that locally impedes horizontal ground-water flow. Vertical leakage through the Exmore matrix confining unit occurs between the overlying Piney Point aquifer and underlying Potomac aquifer (through the overlying Chickahominy confining unit and underlying Exmore clast confining unit and Potomac confining zone). Although the Exmore matrix confining unit is limited in extent to the Chesapeake Bay impact crater, it is appreciably thick and very poorly sorted. It thereby likely provides a very effective hydraulic separation, in combination with the adjacent confining units and zone, between the Piney Point and Potomac aquifers across most of the crater. Leakage between the aquifers is probably more pronounced where the Exmore matrix confining unit thins near its western margin.

Vertical hydraulic conductivities of four permeameter samples of the Exmore matrix confining unit vary by an order of magnitude between 0.00018 and 0.0034 ft/d (table 1) and are among the lowest from samples having similar textures. Because the matrix is poorly sorted, ground-water flow through variably sized pores is partly blocked by small grains that create “bridges” and “dead-ends” between large grains. Porosity ranges narrowly between 33 and 37 percent (table 1). Because the Exmore matrix confining unit is newly designated herein, published values of vertical hydraulic conductivity do not exist. In previous studies, the upper part of the Exmore tsunami-breccia was probably included as part of the Aquia aquifer. No means exist, however, to differentiate which, if any, published values of vertical hydraulic conductivity correspond to sediments of the upper part of the Exmore tsunami-breccia.

Chickahominy Confining Unit

The Chickahominy confining unit has a limited regional extent, is generally deep, and locally impedes ground-water flow in the Virginia Coastal Plain. The Chickahominy confining unit extends across essentially all of the area of the Chesapeake Bay impact crater, including all of Mathews and Northampton Counties; the city of Hampton; lower parts of Middlesex, Gloucester, and York Counties; most of the city of Newport News; northern parts of the cities of Norfolk and Virginia Beach; and the lower Chesapeake Bay (fig. 25; pl. 19). The Chickahominy confining unit extends farther to the northeast beyond the crater across most of Accomack County. Thickness ranges up to approximately 200 ft at depths exceeding 1,000 ft. The Chickahominy confining unit is stratigraphically above the Exmore matrix confining unit.



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

▨	Extent of Chickahominy confining unit
- - -500 —	Structural contour—Approximate altitude of top of Chickahominy confining unit. Dashed where inferred. Contour interval is 50 feet. Datum is NGVD 29
—	Fault
•	Borehole location

0 10 20 MILES
0 10 20 KILOMETERS

Figure 25. Approximate altitude and configuration of the top of the Chickahominy confining unit in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of radial symmetry about the impact crater. Further details are shown on plate 19.)

Geologic Relations

The Chickahominy confining unit consists primarily of abyssal marine, dense and very fine-grained, microfossiliferous and pyritic silts and clays (fig. 26) recently recognized as the Chickahominy Formation of late Eocene age (Powars and Bruce, 1999; Powars, 2000; fig. 4). Additionally, in some areas, the lowermost part of the Chickahominy confining unit can include fine-grained sediments of the upper 2 to 20 ft of the Exmore tsunami-breccia that are texturally similar to the Chickahominy Formation. Most of the Exmore tsunami-breccia is distinctly more coarse grained and is not considered part of the Chickahominy confining unit, but is designated either as the Exmore matrix confining unit or the Exmore clast confining unit.

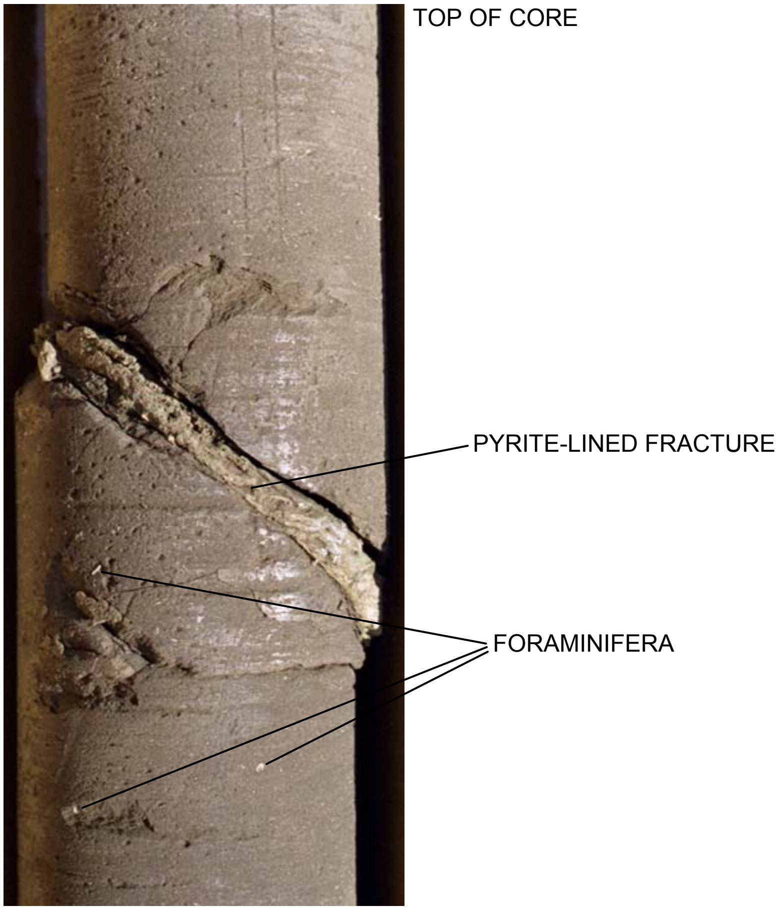


Figure 26. Abyssal marine sediments of late Eocene age from the Chickahominy Formation in the NASA Langley core, borehole local number 59E 31, in Hampton, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and interval is between approximately 754 and 755 feet below land surface. Dense silt and clay constitutes the Chickahominy confining unit. Abundant foraminifera are indicated by small white specks. The section intersects a slickensided fracture probably associated with faulting and lined with pyrite deposited by migrating fluid. Pyrite at other locations generally is present as isolated nodules of less than 1 inch diameter.

Very uniform sediment-transport conditions deposited the marine sediments of the Chickahominy Formation in an abyssal basin left in the surrounding continental shelf following the Chesapeake Bay impact. As a result, the dominant fine-grained sediments that compose the Chickahominy confining unit vary only slightly in texture and composition, and function hydraulically as a continuous medium that impedes horizontal flow but allows relatively slow groundwater movement, mostly as vertical leakage.

Designation of the Chickahominy confining unit is newly made herein. In previous studies of the Virginia Coastal Plain, the Chickahominy-Piney Point aquifer was designated based on sediments lithologically very similar to those of the Piney Point Formation that were thought to be of late Eocene age and were recognized as the Chickahominy Formation (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990). Following discovery of the Chesapeake Bay impact crater, sediments of late Eocene age in the Virginia Coastal Plain were reclassified to recognize the Chickahominy Formation as a distinctly fine-grained lithology associated with the crater (Powars and Bruce, 1999; Powars, 2000; fig. 3). Hence, inclusion as part of the Piney Point aquifer is superseded. In addition and because of its association with the crater, sediments of the Chickahominy Formation as it is currently recognized do not have equivalents in adjacent States.

Because of similar structural positions and other features, the Nanjemoy-Marlboro confining unit distinguished in previous studies appears to have included some sediments across the Chesapeake Bay impact crater that are now recognized as the Chickahominy Formation. The Nanjemoy-Marlboro confining unit as designated herein is composed of sediments other than the Chickahominy Formation and is distinct from the Chickahominy confining unit.

Structural Configuration

The Chickahominy confining unit is entirely below land surface and does not crop out. It is underlain across most of its extent within the Chesapeake Bay impact crater by the Exmore matrix confining unit (fig. 24; pl. 18). Structural relations along the crater margin are not wholly known regionally but are probably complex and variable. The Chickahominy confining unit extends slightly beyond the Exmore matrix confining unit along small segments of the western margin in lower Lancaster and Middlesex Counties and the city of Newport News. At some borehole locations, the Chickahominy confining unit is known with relative certainty to directly overlie the Potomac confining zone, where the intervening hydrogeologic units that normally would be present outside of the crater were truncated by the blast. Elsewhere, the Chickahominy confining unit probably overlies small parts of the Nanjemoy-Marlboro confining unit and(or) Aquia aquifer along the eastern margins, although this configuration has not been observed clearly in sediment core or cuttings collected as part of this study. Only in one case presented herein is the Chickahominy confining unit interpreted to be underlain by the Aquia aquifer, and the presence of the Nanjemoy-Marlboro confining unit is undetermined. This interpretation is based on a geophysical log supplemented with a driller's log (Attachment 1, borehole local number 58F127),

To the northeast and beyond the Chesapeake Bay impact crater, the Chickahominy confining unit is underlain by the Potomac confining zone across most of Accomack County and adjacent parts of Chesapeake Bay and the Atlantic Ocean (fig. 10; pl. 9), where neither the Nanjemoy-Marlboro confining unit nor Aquia aquifer are present. Northward extension of the Chickahominy confining unit from the area of the crater is based on identification of the Chickahominy Formation in the Jenkins Bridge core (Powars and Bruce, 1999; Attachment 1, borehole local number 66M 23). Sediments constituting the Nanjemoy-Marlboro confining unit were not observed in this core; therefore, the Nanjemoy-Marlboro confining unit is interpreted to be absent from the northern area of the Chickahominy confining unit (fig. 20; pl. 16).

The Chickahominy confining unit is overlain almost entirely by the Piney Point aquifer (fig. 27; pl. 20). The Piney Point aquifer pinches out offshore, beyond which the Chickahominy confining unit is overlain by the Calvert confining unit (fig. 29; pl. 21).

The maximum altitude of the Chickahominy confining unit is along the western margin, where borehole geophysical logs indicate an altitude as high as –273 ft at the eastern tip of James City County (fig. 25; pl. 19). The Chickahominy confining unit is extrapolated to pinch out to the north, west, and south against the Nanjemoy-Marlboro confining unit (pl. 3, secs. BD–BD', CD–CD'; pl. 4, all secs.; pl. 7, all secs.).

The Chickahominy confining unit generally dips concentrically into the Chesapeake Bay impact crater (fig. 25; pl. 19) and thickens to as much as approximately 200 ft across altitudes as low as approximately –1,100 to –1,300 ft (pl. 3, sec. CD–CD'; pls. 4, 7, all secs.). Near the inner crater at Kiptopeake, the Chickahominy confining unit is 202 ft thick across altitudes from –1,077 ft to –1,279 ft (Attachment 1, borehole local number 63F 50). Toward the center of the crater, the Chickahominy confining unit thins somewhat to 165 ft but more significantly shallows across altitudes from –987 ft to –1,152 ft at the central uplift (Attachment 1, borehole local number 62G 24). Based on this relation, the Chickahominy confining unit is interpolated to have a saucer-shaped configuration within the crater on the assumption that it is concentrically distributed (pl. 7, sec. GS–GS'). In addition, the northern part of the Chickahominy confining unit beneath Accomack County is extrapolated eastward to pinch out offshore based on the assumption that it is longitudinally symmetrical about the Virginia Eastern Shore.

On some borehole geophysical logs, the top of the Chickahominy confining unit along its western margin exhibits closely spaced displacements, generally of a few tens of feet or less, which are attributed to faults (fig. 25; pl. 4, all secs.; pl. 7, sec. ES–ES'; pl. 19). The faults intersect the Chickahominy confining unit by extension upward from the Potomac aquifer (see "Potomac Aquifer") and through intervening hydrogeologic units, which generally exhibit larger displacements. The faults create local-scale irregularities in the altitude of the Chickahominy confining unit and laterally abut relatively small volumes across the top and base of the confining unit against adjacent hydrogeologic units. In addition, disruption of the depositional intergranular structure of the sediment by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity.

Alternatively and unique to the Chickahominy confining unit, discrete open fractures possibly result in some local increase in hydraulic conductivity. Some cores of the Chickahominy Formation have slickensided fractures probably produced by brittle deformation associated with faulting. In addition, some fractures have pyrite mineralization (fig. 26) probably created by localized fluid migration. Brittle deformation in the form of fracturing could be relatively well developed in the Chickahominy Formation as a result of the denseness of the sediments compared to the structurally incompetent sediments of other hydrogeologic units. The fractures are not pervasive in core, however, but are relatively rare and isolated. Any ground-water flow through fractures probably is localized along zones in proximity to faults. The volumetric significance of fracture flow through the Chickahominy confining unit remains uncertain relative to intergranular vertical leakage on a regional scale. In addition, faults possibly exist at other locations but are not recognized because of scarce borehole data and inadequate spatial control (see "Limitations").

Recognition

Penetration of the top of the Chickahominy confining unit in boreholes is generally noted by very fine-grained silts and clays of the Chickahominy Formation (fig. 26) that contrast markedly with the generally coarse-grained and typically very glauconitic sands of the overlying Piney Point aquifer. Cuttings of Chickahominy Formation sediments returned by drag bit during this study were dark gray (2.5Y 4/1). Foraminifera and other microfossils can be seen commonly in cuttings by hand lens, and pyrite nodules typically of less than 1 inch in diameter can be seen intermittently. Some intervals can include small amounts of mica and lignite, as well as fine-grained sand that includes quartz and also glauconite and(or) phosphate. Drilling response is mostly smooth, and the rate of advancement can be slow.

On borehole electric logs (see "Borehole Geophysical-Log Network"), the Chickahominy confining unit typically exhibits a nearly flat signature in response to very fine-grained silts and clays (fig. 4). Gamma logs have a varied response that possibly results from differences in clay mineralogy and(or) amounts of glauconite and phosphate.

Hydrologic Aspects

The Chickahominy confining unit is a regionally limited hydrogeologic unit that locally impedes horizontal ground-water flow. Vertical leakage through the Chickahominy confining unit occurs between the overlying Piney Point aquifer and underlying Potomac aquifer (through the intervening Exmore matrix and Exmore clast confining units and Potomac confining zone). Although the Chickahominy confining unit is limited in extent to the Chesapeake Bay impact crater and northward across Accomack County, it is appreciably thick and very fine grained. The Chickahominy confining unit thereby likely provides a very effective hydraulic separation in combination with the underlying confining units and zone between the Piney Point and Potomac aquifers across most of the crater. Leakage between the aquifers probably is greater where the Chickahominy confining unit thins near the western margin, and possibly along zones in proximity to faults as a result of fracture flow.

Vertical hydraulic conductivities of three permeameter samples of the Chickahominy confining unit vary by three orders of magnitude between 0.000031 and 0.011 ft/d (table 1), possibly as a result of the degree of fracturing of the samples. The latter value is the second highest measured among the confining units, and possibly resulted from one or more fractures in the sample. Porosity varies little (49 and 50 percent, table 1) among the three samples, and textures are uniformly very fine grained. Because the Chickahominy confining unit is newly designated herein, published values of vertical hydraulic conductivity do not exist. In previous studies, the Chickahominy Formation as now recognized probably was included as part of the Nanjemoy-Marlboro confining unit. No means exist to differentiate which published values of vertical hydraulic conductivity correspond to Chickahominy Formation sediments, which are presented and discussed herein as part of the Nanjemoy-Marlboro confining unit (see “Nanjemoy-Marlboro Confining Unit”).

Piney Point Aquifer

The Piney Point aquifer is a widespread, generally deep, and moderately used source of ground water in the Virginia Coastal Plain. The Piney Point aquifer extends across most of the Virginia Coastal Plain except for the southern half of the Fall Zone (fig. 27; pl. 20), and is as thick as several tens of feet or more at depths as much as several hundred feet. The Piney Point aquifer is stratigraphically above the Nanjemoy-Marlboro confining unit across most of its extent except within the Chesapeake Bay impact crater, where it is above the Chickahominy confining unit (fig. 3). The Piney Point aquifer provides public water supplies for some small towns and private supplies for low-density residential development in some rural areas.

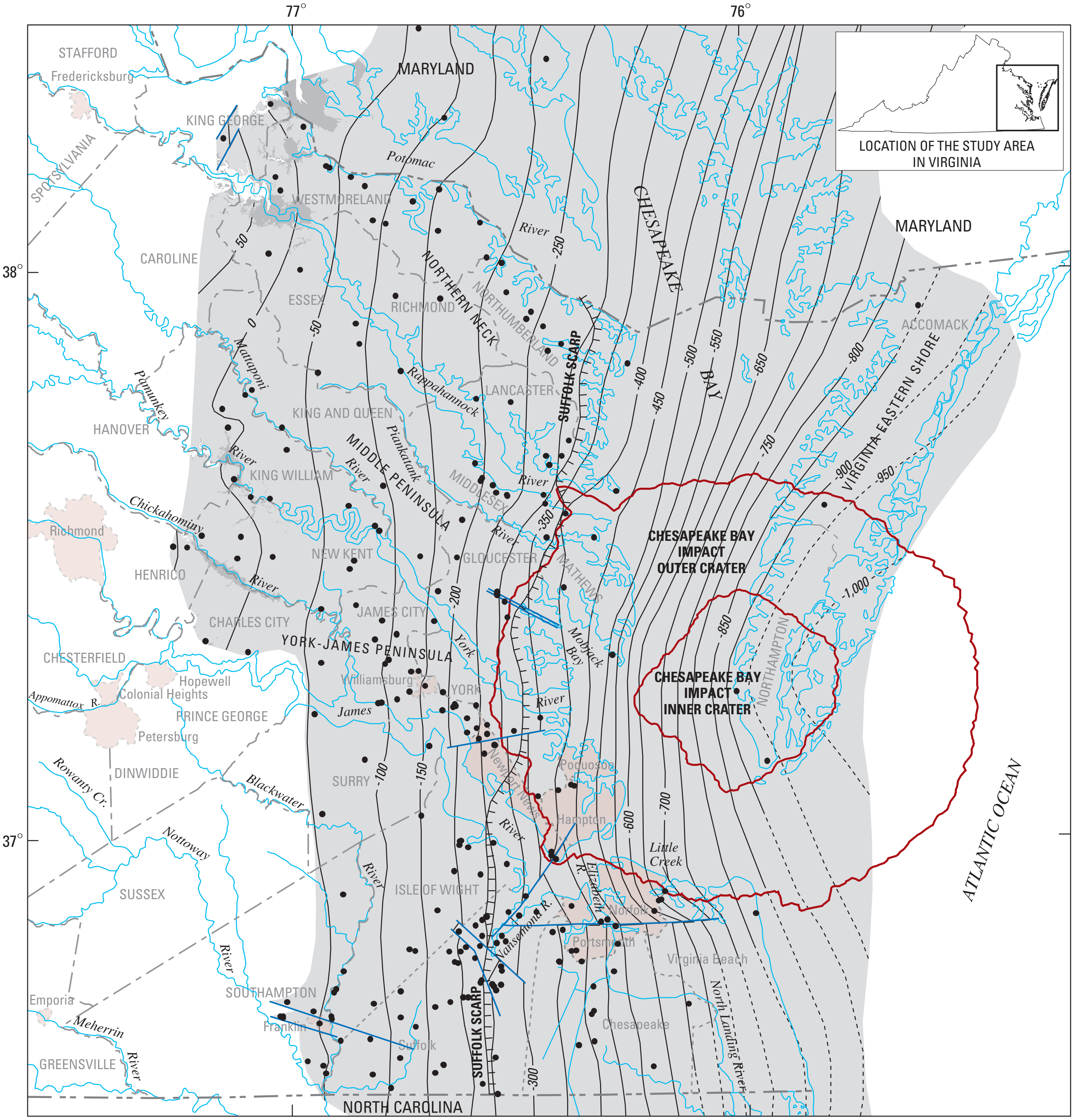
Geologic Relations

Hydraulically, the Piney Point aquifer is composed of a closely associated group of several geologic formations (fig. 3), consisting generally of marine, medium- to coarse-grained, glauconitic, phosphatic, variably calcified, and fossiliferous quartz sands. The base of the Piney Point aquifer in some places outside of the Chesapeake Bay impact crater includes well-sorted, fine-grained sands of the Woodstock Member that forms the upper part of the Nanjemoy Formation of early Eocene age. Most of the Piney Point aquifer extending across the area outside of the crater north of the James River is composed of variably calcite-cemented sands and moldic limestones (fig. 28) of the Piney Point Formation of middle Eocene age. Both the Nanjemoy Formation and the Piney Point Formation predate the crater, and their sediments are truncated along the crater margin. A second, upper part of the Piney Point aquifer consists of additional formations that postdate the crater and extend across it. Potentially included and present primarily along the margin of the crater and to the northwest are medium- to coarse-grained parts of the Delmarva beds of early Oligocene age, the Old Church Formation of late Oligocene age, and the Newport News Member of early Miocene age that forms the lower part of the Calvert Formation. In addition, much of the upper part of the Piney Point aquifer consists of a basal lag deposit of coarse-grained, very phosphatic sands within the Plum Point Member of middle Miocene age, which forms the middle part of the Calvert Formation. Other parts of the Calvert Formation consist primarily of fine-grained sands and silts and are not considered part of the Piney Point aquifer, but instead are designated as the Calvert confining unit (see “Calvert Confining Unit”).

The Piney Point aquifer is a homogeneous aquifer (see “Hydrogeologic-Unit Classification”). Each of the several geologic formations that compose the Piney Point aquifer represents a different period of time, but all of the sediments were deposited under relatively uniform sediment-transport conditions across the Continental Shelf and function hydraulically as a continuous medium through which water flows essentially uninterrupted at both local and regional scales.

In previous studies of part or all of the Virginia Coastal Plain, sediments of the Piney Point Formation and several closely associated formations were designated as composing the Chickahominy-Piney Point aquifer (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designation was made to equivalent sediments in studies in adjacent States during approximately the same period—the Piney Point aquifer in Maryland (Vroblesky and Fleck, 1991) and the Castle Hayne aquifer in North Carolina (Winner and Coble, 1996). In various other, mostly earlier studies, an aquifer was designated that consists of sediments of the Pamunkey and(or) Chesapeake Groups or their equivalents, of which the Piney Point Formation and associated formations are only parts.

Designation of the Chickahominy-Piney Point aquifer in Virginia in previous studies was based on sediments very



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

- ▭ Extent of Piney Point aquifer
- ▨ Incised area of aquifer
- - - -500 — Structural contour—Approximate altitude of top of Piney Point aquifer. Dashed where inferred. Contour interval is 50 feet. Datum is NGVD 29
- — Fault
- • Borehole location

Figure 27. Approximate altitude and configuration of the top of the Piney Point aquifer in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 20.)

Figure 28. Sediments composing different parts of the Piney Point aquifer. Core diameter is approximately 2 inches. Section on right consists of moldic limestone of the marine Piney Point Formation of middle Eocene age exhibited in the Haynesville core, borehole local number 57M 5, located in Richmond County, Virginia (borehole location shown on plate 1; photograph from Mixon, Powars, and others, 1989). Interval is from between approximately 307 and 308 feet below land surface. Lithology represents primary water-supply part of the Piney Point aquifer across the middle reaches of the Northern Neck and Middle and York-James Peninsulas. Lithology of section on left represents more regionally extensive but generally unused part of Piney Point aquifer. Glauconitic, phosphatic, and fossiliferous medium- to coarse-grained sand comprises the marine Newport News Member of the Calvert Formation of early Miocene age exhibited in the NASA Langley core, borehole local number 59E 31, located at the NASA Langley Research Center, Hampton, Virginia. The Delmarva Beds of early Oligocene age, the Old Church Formation of late Oligocene age, and the basal part of the Plum Point Member of the Calvert Formation of middle Miocene age are hydrologically closely associated and have similar lithologies, and comprise the remaining nonwater-supply part of the Piney Point aquifer.

similar lithologically to those of the Piney Point Formation that were thought to be of late Eocene age and were recognized at the time as the Chickahominy Formation. Following the discovery of the Chesapeake Bay impact crater, sediments of late Eocene age in the Virginia Coastal Plain were reclassified (Powars and Bruce, 1999; Powars, 2000). The Chickahominy Formation currently is recognized as a distinctly fine-grained clay associated with the crater (fig. 3) and designated herein as the Chickahominy confining unit (see “Chickahominy Confining Unit”). Hence, inclusion as part of the Piney Point aquifer is superseded.

Sediments included in previous studies as part of the Chickahominy-Piney Point aquifer generally south of the James River are now recognized as composing several geologic formations ranging in age from Late Cretaceous through late Miocene (Powars, 2000). These sediments are designated herein as composing several other hydrogeologic units and are not considered as part of the Piney Point aquifer. In addition, sediments designated in previous studies as part of the Chickahominy-Piney Point aquifer are designated herein as composing the southern extent of the Saint Marys aquifer (see “Saint Marys Aquifer”). Similar to the upper and lower parts of the Piney Point aquifer north of the James River, bimodal signatures on borehole geophysical logs south of the James River were interpreted in previous studies as the Chickahominy-Piney Point aquifer. Detailed descriptions of drill cuttings performed for this study (see “Borehole-Data Quality”) establish a revised stratigraphic relation whereby only the lower interval on logs south of the James River is attributable to the Piney Point aquifer. Designation of a distinct Saint Marys aquifer is based on recognition of the upper interval consisting of Saint Marys Formation sediments.

Structural Configuration

The Piney Point aquifer is underlain by the Nanjemoy-Marlboro confining unit (fig. 20; pl. 16) across most of the Virginia Coastal Plain. It is underlain by the Chickahominy confining unit in the Chesapeake Bay impact crater and northward across the Virginia Eastern Shore (fig. 25; pl. 19).

The maximum altitude of the Piney Point aquifer is near the western margin across the northern half of the Fall Zone (fig. 27; pl. 20). Borehole geophysical logs from north to south indicate 64 ft in central King George County, declining to 22 ft in western King William County, increasing to 57 ft in eastern Henrico County, and declining again to 19 ft in western

Charles City County. The Piney Point aquifer is extrapolated westward of these locations to pinch out against the Nanjemoy-Marlboro confining unit (pl. 3, secs. BD–BD', CD–CD'; pl. 4, secs. DD–DD', ED–ED'). A short segment of the western margin in central King George County is interpreted to be formed by truncation along a fault (pl. 3, sec. AD–AD') that is part of the Port Royal fault system (Mixon and others, 2000). Truncation of the Piney Point aquifer along the valleys of the Potomac, Rappahannock, Pamunkey, and James Rivers and their tributaries is projected across the northern part of the western margin. Across the southern Fall Zone, the Piney Point aquifer pinches out along its western margin at altitudes generally between –30 and –50 ft (pl. 4, sec. FD–FD'; pl. 5, secs. GD–GD', ID–ID', JD–JD').

The Piney Point aquifer is overlain across most of its extent by the Calvert confining unit (fig. 29; pl. 21). The Calvert confining unit is not present to the southwest, where the Piney Point aquifer is overlain by the Saint Marys confining unit across eastern Charles City County, most of the eastern two-thirds of Surry County, easternmost Sussex and Southampton Counties, the western half of Isle of Wight County, and westernmost city of Suffolk (fig. 32; pl. 23). Locally incised areas are projected across the Fall Zone along the Potomac, Rappahannock, Mattaponi, Pamunkey, and Chickahominy Rivers and some of their tributaries, where the Piney Point aquifer crops out across the steepest slopes but is mostly covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer (fig. 27; pl. 20). Additional outcrops possibly exist along smaller streams crossing the Fall Zone but likely are very small and isolated. Direct contact between the Piney Point aquifer and surficial aquifer across the incised areas possibly creates important hydraulic connections between the confined and unconfined ground-water systems, particularly along the main stem of the Potomac River where a relatively broad area is incised by almost the entire river channel.

The Piney Point aquifer dips generally eastward across its entire extent (fig. 27; pl. 20). The Piney Point aquifer is as thick as nearly 150 ft across the lower reaches of Northern Neck at altitudes from approximately –200 ft to –350 ft (pl. 3, sec. CD–CD') and continues beneath the upper Chesapeake Bay and northern part of the Virginia Eastern Shore to altitudes between approximately –850 to –1,000 ft (pl. 3, sec. BD–BD'). South of Northern Neck, the Piney Point aquifer thins considerably to less than 50 ft across most of its extent south of the James River and west of the Chesapeake Bay impact crater (pl. 6, secs. CS–CS', DS–DS'). The Piney Point aquifer also thins across parts of the margins of the crater but then thickens to approximately 150 ft or more as it dips concentrically into the crater to altitudes as low as approximately –900 to –1,100 ft (pl. 4, secs. DD–DD', ED–ED'; pl. 7, sec. ES–ES'). Near the inner crater at the Kiptopeke core hole, the Piney Point aquifer is 143 ft thick across altitudes from –934 ft to –1,077 ft (Attachment 1, borehole local number 63F 50). Toward the center of the crater, however, the Piney Point aquifer thins to 53 ft and shallows across altitudes from –935 ft to –987 ft at the central uplift (Attachment 1, borehole local number 62G 24). Based on this relation, the Piney Point aquifer in the crater is interpolated to have a saucer-shaped configuration on the assumption that it is distributed concentrically (pl. 7, sec. GS–GS'). The Piney Point aquifer is extrapolated eastward to pinch out offshore of the Virginia Eastern Shore and Virginia Beach at altitudes between approximately –900 to –1,000 ft. Additionally and based on previous studies, the Piney Point aquifer is extrapolated southward into North Carolina (Winner and Coble, 1996) and northward into Maryland (Vroblesky and Fleck, 1991).

The top of the Piney Point aquifer on some borehole geophysical logs has closely spaced displacements generally of a few tens of feet or less that are attributed to faults (fig. 27; pls. 3–7, 20). The faults intersect the Piney Point aquifer by extension upward from the Potomac aquifer (see “Potomac Aquifer”) and through intervening hydrogeologic units, which generally exhibit larger displacements. Although discrete fractures that are either open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of their depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. In addition, the faults create local-scale irregularities in the altitude of the Piney Point aquifer and laterally abut varying volumes of the aquifer against adjacent hydrogeologic units. Displacements generally are of similar magnitude relative to the thickness of the Piney Point aquifer, which in most cases results in a lateral-flow constriction where the aquifer is partly truncated by adjacent confining units. The Piney Point aquifer is entirely truncated along a short segment of the western margin (pl. 3, sec. AD–AD') by a fault that is part of the Port Royal fault system (Mixon and others, 2000). In another instance, a lateral-flow conduit possibly is where the Piney Point aquifer is partly truncated by the Saint Marys aquifer (pl. 6, sec. DS–DS'). Faults possibly are at other locations but are not recognized because of sparse borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the Piney Point aquifer in boreholes generally is noted by coarse-grained basal lag sands of the Plum Point Member of the Calvert Formation that composes the top several feet of the aquifer. Granule- to pebble-sized phosphatic components of distinct and recognizable bone fragments and sharks’ teeth are common in contrast with the more fine-grained sediments of the overlying Calvert or Saint Marys confining units. Where present, the Newport News Member of the Calvert Formation, the Old Church Formation, and the Delmarva beds that further compose the upper part of the Piney Point aquifer consist predominately of medium- to coarse-grained, glauconitic and commonly very phosphatic sands (fig. 28, left core section) with variable amounts of shell, silt, and clay. Drilling response typically is relatively smooth, and the rate of advancement is moderate to rapid. Cuttings of the upper part of the Piney Point aquifer returned by drag bit were observed for this study to exhibit colors varying among very dark grayish brown (2.5Y 3/2), grayish brown (2.5Y 5/2), dark olive gray (5Y 3/2), dark gray (5Y 3/2 and 4/1), olive gray (5Y 4/2), gray (5Y 5/1), dark greenish gray (10Y 3/1 and 4/1, and 5GY 4/1), greenish gray (10Y 5/1), and greenish black (5GY 2.5/1). At greater depth, calcite-cemented sands and moldic limestones (fig. 28, right core section) of the Piney Point Formation, which make up the dominant lower part of the Piney Point aquifer outside of the Chesapeake Bay impact crater north of the James River, typically produce a pronounced chatter in drilling response across intervals of several feet or more. Disaggregated shells and granules and pebbles consisting of calcite-cemented quartz and glauconite sand grains and shells can be returned in cuttings. With further depth, well-sorted, fine-grained sands of the Woodstock Member of the Nanjemoy Formation are present at scattered locations outside of the crater.

On borehole electric logs (see “Borehole Geophysical-Log Network”), unconsolidated sands in the Piney Point aquifer generally exhibit a lobate signature typical of medium- to coarse-grained marine sediments, with some variation resulting from differences in shell, silt, and(or) clay content (fig. 4). By contrast, calcite-cemented sands and(or) moldic limestones can exhibit a sharp peak or multiple peaks in succession. In areas where the Piney Point aquifer is appreciably thick, electric logs commonly exhibit two or rarely three, closely spaced but distinct intervals from which the geologic formations making up the aquifer can to varying degrees be discerned. Gamma logs have a moderately to highly elevated response, depending on the proportion of phosphatic material. Particularly across the top several feet of the aquifer, a pronounced very sharp gamma peak corresponds to the basal lag deposit of the Plum Point Member of the Calvert Formation, which contrasts markedly with the low response of the overlying quartzose Calvert confining unit (see “Calvert Confining Unit”). This gamma peak is a key stratigraphic control marker to support log interpretation and correlation.

Hydrologic Aspects

The Piney Point aquifer is an extensive hydrogeologic unit that functions as a pathway for ground-water flow across most of the Virginia Coastal Plain. The Piney Point aquifer also is a moderately used ground-water supply resource, which generally is limited geographically to the middle reaches of Northern Neck, Middle Peninsula, and York-James Peninsula where yields of 10 to 50 gal/min are common from water-supply wells. Locally, in James City County, some heavily used residential and municipal wells provide yields as great as 400 gal/min.

Permeameter samples of the Piney Point aquifer collected during this study were all from within the Chesapeake Bay impact crater where the Piney Point Formation and Woodstock Member of the Nanjemoy Formation are not present, and where the aquifer primarily consists of medium- to coarse-grained, glauconitic and phosphatic sands of the Old Church Formation of late Oligocene age (table 1). Vertical hydraulic conductivity values are virtually identical for two samples (0.010 and 0.017 ft/d) but lower by two orders of magnitude in a third sample (0.00042 ft/d). The latter sample is finer grained and more poorly sorted than the other two samples. Porosity varies from 33 to 42 percent (table 1). Published values of horizontal hydraulic conductivity of the Piney Point aquifer generated by well specific-capacity tests or derived from ground-water model calibration range across two orders of magnitude from 1.5 to 701 ft/d (Hamilton and Larson, 1988; table 2). The range of specific-capacity test values encompasses those derived by model calibration. Higher values possibly indicate a preponderance of coarse-grained sands and(or) moldic limestones, and lower values indicate more silty and medium-grained sands. In addition, the vertical hydraulic conductivity values of permeameter samples are less than the published horizontal hydraulic conductivity values, probably because of anisotropy. The highest hydraulic conductivity values resulted from some specific-capacity tests or were derived from calibration of ground-water models and probably are the most representative of the effective hydraulic conductivity of the Piney Point aquifer at the regional scale.

During 2002, the Piney Point aquifer produced an estimated 5 percent of the ground water used in the Virginia Coastal Plain at a rate of 6.8 Mgal/d (table 3). A rate of 4.9 Mgal/d was reported to the DEQ by regulated industrial, municipal, and commercial users; unregulated domestic use was estimated at a rate of 1.9 Mgal/d. Regulated withdrawal declined slightly during 2003 to a rate of 4.6 Mgal/d, and consequently, total withdrawal declined to 6.5 Mgal/d from the Piney Point aquifer, but the relative contribution of the Piney Point aquifer to the total withdrawal from the Virginia Coastal Plain remained essentially unchanged.

Water-supply wells generally are completed in the lower part of the Piney Point aquifer, which is composed of Piney Point Formation sediments that are present north of the James River, west of Chesapeake Bay, and outside of the Chesapeake Bay impact crater. The upper part of the Piney Point aquifer, which is dominated by the basal phosphatic sands of the Calvert Formation Plum Point Member, is not used because of low yields and a prevalence of hydrogen sulfide. Observation wells completed across this interval have yielded only 5 to 10 gal/min. South of the James River, the approximately 50-ft thick or less interval composes the entire Piney Point aquifer, which is not considered an effective water-production zone and is cased off. The Piney Point aquifer also is not used across the crater, northward along the Virginia Eastern Shore, and southward across the cities of Suffolk, Chesapeake, and Virginia Beach, where it consists, in varying proportions, of sediments of the Calvert Formation, Old Church Formation, and Delmarva beds that contain brackish water (see “Quaternary History”).

Unregulated withdrawals from the Piney Point aquifer generally are dispersed across rural areas. A random sample of domestic-well records from county health departments indicates that the Piney Point aquifer supplies unregulated withdrawals from roughly a quarter of the wells constructed since approximately 1985 across the middle reaches of Northern Neck, Middle Peninsula, and York-James Peninsula (Jason Pope, U.S. Geological Survey, written commun., 2005), probably for the reasons cited above. Essentially, no unregulated use is made of the Piney Point aquifer elsewhere.

Calvert Confining Unit

The Calvert confining unit is widespread and generally deep, and regionally impedes ground-water flow in the Virginia Coastal Plain. The Calvert confining unit extends across all of the Virginia Coastal Plain and eastward offshore, except for all or parts of several southwestern counties (fig. 29; pl. 21). Thickness of the Calvert confining unit ranges up to a few hundred feet, at depths as much as several hundred feet. The Calvert confining unit is stratigraphically above the Piney Point aquifer.

Geologic Relations

The Calvert confining unit consists of marine, silty and clayey, fossiliferous fine-grained quartz sands (fig. 30) of the Plum Point and Calvert Beach Members of the Calvert Formation of middle Miocene age (fig. 3). Shells generally are scattered, but foraminifera and diatoms are commonly abundant. The Calvert confining unit in core and outcrop widely exhibits jointing and a markedly crumbly structure that possibly results from numerous small-scale fractures. The joints and fractures do not appear to be associated with particular zones of deformation, such as faults, but rather more pervasively result from incompetence of the depositional intergranular structure of the sediment. The lowermost part of the Plum Point Member consists of a basal lag deposit of coarse-grained, very phosphatic sands, which is not considered part of the Calvert confining unit but is designated as part of the Piney Point aquifer (see "Piney Point Aquifer").

Relatively uniform sediment-transport conditions deposited the sediments of the Calvert Formation across the Continental Shelf. Hence, the silty and clayey fine-grained sands composing the Calvert confining unit vary gradationally and function hydraulically as a continuous medium that impedes horizontal flow but allows relatively slow ground-water movement, mostly as vertical leakage. Leakage possibly is enhanced, relative to other confining units, by pervasive joints and numerous small-scale fractures.

Designation of the Calvert Formation as composing a distinct Calvert confining unit was made in previous studies of part or all of the Virginia Coastal Plain (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designations were made for equivalent sediments in studies in adjacent States during approximately the same period—the Lower Chesapeake confining unit in Maryland (Vroblesky and Fleck, 1991) and the Castle Hayne confining unit in North Carolina (Winner and Coble, 1996). In various other, mostly earlier studies, sediments belonging to the Pamunkey and(or) Chesapeake Groups or their equivalents, of which the Calvert Formation is only a part, were designated as an aquifer.

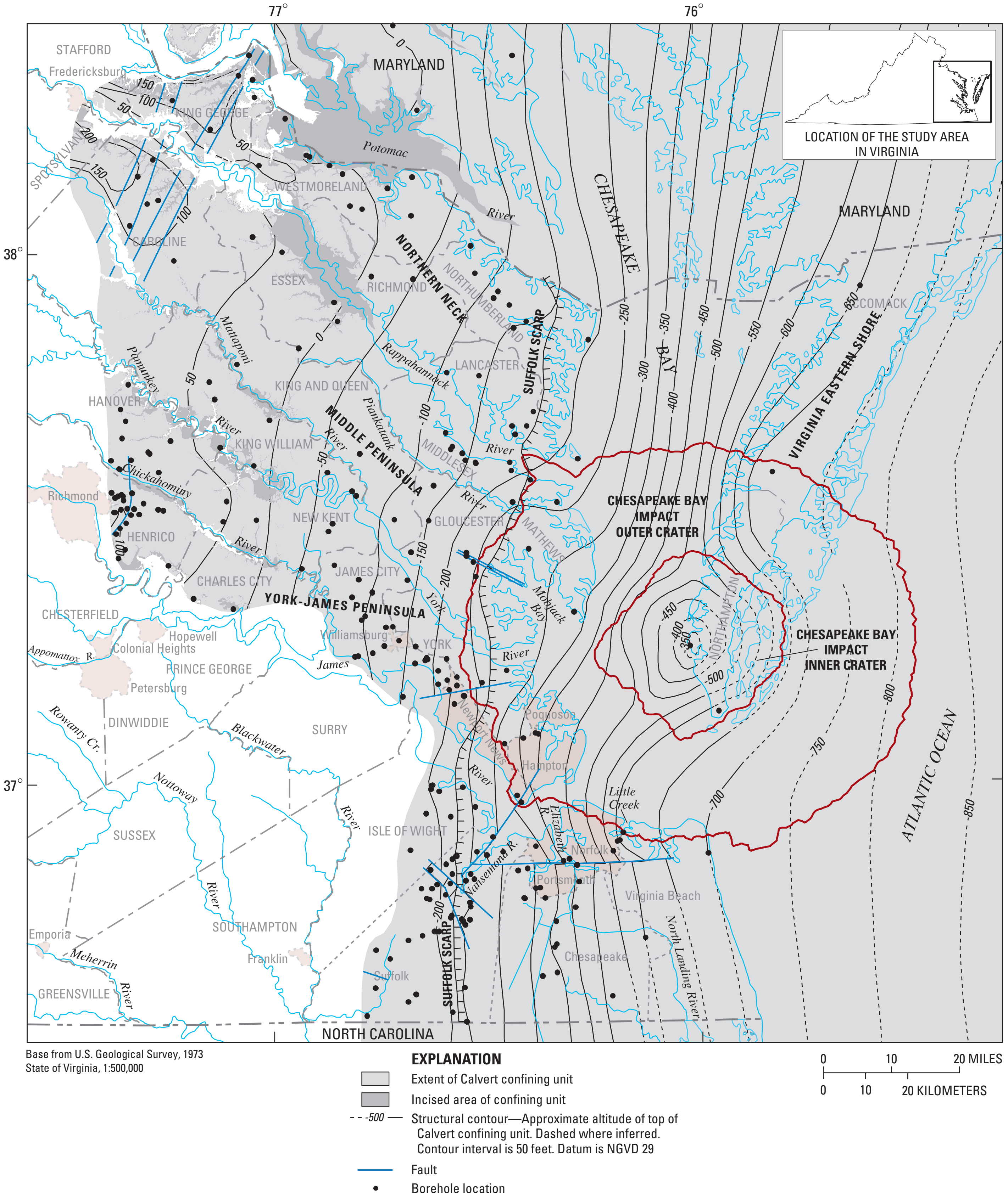
The Calvert confining unit south of the James River was delineated previously as having a relatively large thickness and westward extent (Hamilton and Larson, 1988; Meng and Harsh, 1988). Sediments were included that are recognized currently as composing the Saint Marys Formation (Powars, 2000) and designated herein as composing the Saint Marys confining unit.

Structural Configuration

The Calvert confining unit is underlain across most of its extent by the Piney Point aquifer (fig. 27; pl. 20) and by the Nanjemoy-Marlboro confining unit (fig. 20; pl. 16) beyond where the Piney Point aquifer pinches out eastward beneath the Delmarva Peninsula, offshore of Virginia Beach, and westward along the northern half of the Fall Zone (pl. 3, all secs.; pl. 4, sec. DD–DD'). Distinction between the Calvert confining unit and Nanjemoy-Marlboro confining unit can be obscured in the latter area, where both confining units thin progressively toward the Fall Zone and differences in the borehole geophysical log signatures become indiscernible. The Nanjemoy-Marlboro confining unit is not present offshore of the Virginia Eastern Shore and the mouth of Chesapeake Bay where the Chickahominy confining unit is extrapolated to underlie the Calvert confining unit (fig. 25; pl. 19).

The maximum altitude of the Calvert confining unit is near the western margin across the northern half of the Fall Zone (fig. 29; pl. 21). Borehole geophysical logs from north to south indicate altitudes of 148 ft in northern Caroline County, declining to 57 ft in eastern Hanover County, and then increasing to 110 ft in eastern Henrico County. The Calvert confining unit is extrapolated updip as much as a few miles westward across the northern Fall Zone before pinching out against the Potomac confining zone at altitudes of as much as 200 ft. Some Calvert Formation sediments, possibly extending a short distance farther west, are included in the Potomac confining zone. The Calvert confining unit does not extend southward from the upstream two-thirds of the James River. Hence, the southern part of the western margin lies to the east across central Isle of Wight County and western city of Suffolk. Here, the Calvert confining unit pinches out at altitudes ranging from approximately –100 to –200 ft (fig. 29; pl. 21; pl. 4, sec. FD–FD'; pl. 5, all secs.).

Because of its relative proximity to land surface, the Calvert confining unit is truncated extensively across the northern part of the western margin along major segments of the valleys of the Potomac, Rappahannock, and Pamunkey Rivers and some of their tributaries (fig. 29; pl. 21). In addition, internal openings or "windows" are projected along the valleys of the Mattaponi and Chickahominy Rivers, where erosion has progressed through the entire thickness of the Calvert confining



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

- ▢ Extent of Calvert confining unit
- ▨ Incised area of confining unit
- - - -500 —— Structural contour—Approximate altitude of top of Calvert confining unit. Dashed where inferred. Contour interval is 50 feet. Datum is NGVD 29
- —— Fault
- ● Borehole location

Figure 29. Approximate altitude and configuration of the top of the Calvert confining unit in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of radial symmetry about the impact crater and eastward dip offshore. Further details are shown on plate 21.)

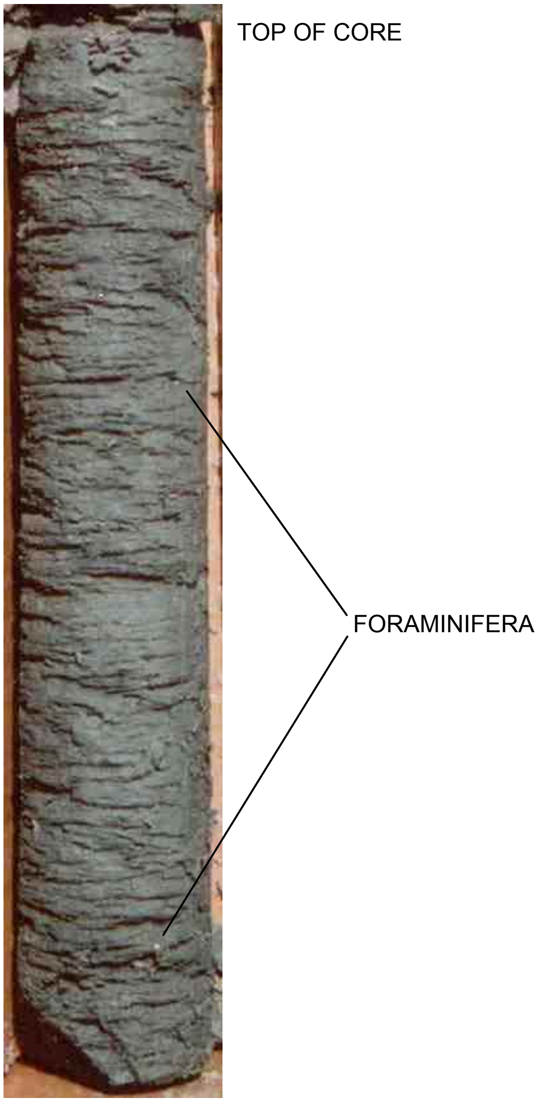


Figure 30. Marine sediments of middle Miocene age from the Calvert Formation in the Watkins Elementary School core, borehole local number 59E 32, in Newport News, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and interval is between approximately 363 and 364 feet below land surface. Fossiliferous, silty, and clayey fine-grained sand constitutes the Calvert confining unit. Foraminifera are indicated by small white specks. Crumbly structure results from numerous small-scale fractures.

unit and partly into underlying hydrogeologic units to produce incised areas across the Nanjemoy-Marlboro confining unit along the Mattaponi River (fig. 20; pl. 16) and the Piney Point aquifer along the Chickahominy River (fig. 27; pl. 20).

The Calvert confining unit is overlain across most of its extent by the Saint Marys confining unit (fig. 32; pl. 23). Where present, the intervening Saint Marys aquifer overlies the Calvert confining unit from the eastern half of the upper Chesapeake Bay across most of the Delmarva Peninsula and offshore, and along a second narrow belt to the south from eastern Isle of Wight County through central city of Suffolk (fig. 31; pl. 22). Beyond the extent of the Saint Marys confining unit to the northwest, the surficial aquifer overlies part of the Calvert confining unit and thereby represents the uppermost part of the confined ground-water system across uplands along the northernmost part of the Fall Zone through almost all of King George County and northern Westmoreland and Caroline Counties.

Extensively incised areas are projected along major segments of the Potomac and Rappahannock Rivers, with more localized areas along the Mattaponi, Pamunkey, Chickahominy, and James Rivers and some of their tributaries (fig. 29; pl. 21). The Calvert confining unit crops out along the steepest slopes but is mostly covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer. In addition and because of its relative proximity to land surface, the top of the Calvert confining unit has been sculpted widely by erosion across the uplands overlain by the surficial aquifer, as indicated by structural contours that reflect the present-day topography. Thinning of the Calvert confining unit where it is overlain by the surficial aquifer possibly enhances hydraulic connections between the confined and unconfined ground-water systems, particularly along the main stem of the Potomac River where a relatively broad area is incised by almost the entire river channel. Confined-unconfined hydraulic connections are further enhanced across the “windows” along the valleys of the Mattaponi and Chickahominy Rivers, where the entire thickness of the Calvert confining unit has been eroded.

The Calvert confining unit generally dips eastward across its entire extent (fig. 29; pl. 21). The Calvert confining unit ranges in thickness from approximately 100 to 200 ft across much of Northern Neck, Middle Peninsula, and eastward across upper Chesapeake Bay and the Virginia Eastern Shore, and deepens to altitudes from approximately –700 to –900 ft (pl. 3, all secs.). To the south, the Calvert confining unit thins to a few tens of feet or less across the lower York-James Peninsula and south of the James River (pl. 6, sec. DS–DS'). Conversely, the Calvert confining unit thickens considerably across the Chesapeake Bay impact crater. In the Exmore core, the Calvert confining unit is 199 ft thick across altitudes from –731 ft to –930 ft; and in the Kiptopeke core, the Calvert confining unit is 321 ft thick across altitudes from –613 ft to –934 ft (Attachment 1, borehole local numbers 64J 14 and 63F 50, respectively). Toward the center of the crater, the Calvert confining unit thickens to 609 ft and shallows across altitudes from –326 ft to –935 ft at the central uplift (borehole local number 62G 24). Based on this relation, the Calvert confining unit within the crater is interpolated to have a mounded configuration on the assumption that it is concentrically distributed (pl. 7, sec. GS–GS'). The Calvert confining unit is extrapolated eastward offshore. Additionally, and based on previous studies, the Calvert confining unit is extrapolated southward into North Carolina (Winner and Coble, 1996) and northward into Maryland (Vroblesky and Fleck, 1991).

The top of the Calvert confining unit on some borehole geophysical logs exhibits closely spaced displacements generally of a few tens of feet or less, which are attributed to faults (fig. 29; pl. 21). The faults intersect the Calvert confining unit by extension upward from the Potomac aquifer (see “Potomac Aquifer”) and through intervening hydrogeologic units, which generally exhibit larger displacements. Although discrete fractures that are either open or lined with fault gouge probably are not pervasive in the generally incompetent sediments, disruption of their depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and a decrease in hydraulic conductivity. In addition, the faults create local-scale irregularities in the altitude of the Calvert confining unit and laterally abut varying volumes across the top and base of the confining unit against adjacent hydrogeologic units. Where displacements are small relative to the thickness of the Calvert confining unit, relatively small volumes across the top and(or) base of the confining unit are affected (pl. 3, sec. AD–AD'; pl. 4, all secs.; pl. 6, sec. BS–BS'). Where the Calvert confining unit is thin, displacements are similar in magnitude, the confining unit is partly to wholly truncated, and in some instances, leakage between adjacent aquifers may increase (pl. 5, secs. GD–GD', ID–ID'; pl. 6, sec. DS–DS'; pl. 7, sec. ES–ES'). Faults possibly exist at other locations but are not recognized because of sparse borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the Calvert confining unit in boreholes generally is noted by silty and(or) clayey, fine-grained quartz sands (fig. 30) that contrast with overlying sediments, primarily of the Saint Marys confining unit but also of the Saint Marys or surficial aquifers. The latter two hydrogeologic units are distinctly more coarse grained than the Calvert confining unit. The colors of cuttings of the Calvert confining unit in most areas are a marked change from those of the overlying Saint Marys confining unit and, as returned by drag bit, were observed to include mostly dark olive gray (5Y 3/2) and olive gray (5Y 4/2 and 5/2) but also included dark gray (5Y 4/1), gray (5Y 5/1), dark grayish brown (2.5Y 4/2), grayish brown (2.5Y 5/2), and dark greenish gray (5GY 4/1). Drilling response typically is smooth, and the rate of advancement is moderate. Shells generally are scattered, but foraminifera and diatoms are commonly observed in cuttings with a hand lens.

On borehole electric logs (see “Borehole Geophysical-Log Network”), the Calvert confining unit generally exhibits a relatively flat signature typical of fine-grained, marine sediments with some moderate and generally isolated peaks resulting from interbedded shells (fig. 4). Gamma logs exhibit a low response where primarily fine-grained quartz is present but elsewhere exhibit a varied response from differences in clay content. The overlying Saint Marys confining unit generally exhibits a more uniformly elevated gamma response. The base of the Calvert confining unit is distinguished across most of its extent by the very sharp gamma peak across the uppermost part of the underlying Piney Point aquifer. The Calvert confining unit can be indistinct on both electric and gamma logs where it is in direct contact with adjacent, similarly fine-grained confining units.

Hydrologic Aspects

The Calvert confining unit is an extensive hydrogeologic unit that regionally impedes horizontal ground-water flow. Vertical leakage occurs between the Saint Marys aquifer, where present, and primarily the underlying Piney Point aquifer through the Calvert confining unit. Across much of its extent, the Calvert confining unit is directly overlain by the Saint Marys confining unit, through both of which vertical leakage occurs primarily between the overlying Yorktown-Eastover aquifer and underlying Piney Point aquifer. To the northwest, beyond the extent of the Yorktown-Eastover aquifer leakage through the Calvert and Saint Marys confining units occurs primarily between the overlying surficial aquifer and underlying Piney Point aquifer. North of the James River and across the Chesapeake Bay impact crater, the Calvert confining unit constitutes a substantial part of a combined thickness of as much as several hundred feet, which imposes an effective hydraulic separation between the relatively shallow surficial and Yorktown-Eastover aquifers and the much deeper Piney Point and other aquifers. The Calvert confining unit is distinct from the Saint Marys confining unit, however, by having a substantially different lithologic composition and sediment structure and associated hydraulic properties. South of the James River and the crater, the Calvert confining unit is thinner, and leakage is controlled primarily by the Saint Marys confining unit.

The vertical hydraulic conductivity values of two permeameter samples of the Calvert confining unit vary by three orders of magnitude between 0.000057 and 0.060 ft/d (table 1), possibly a result of the degree of fracturing of the samples (fig. 30). The latter value is the highest measured among the confining units and possibly resulted from numerous small-scale fractures that are widely exhibited by Calvert Formation sediments in core and outcrop. Porosity values for the two samples are very nearly identical at 60 and 57 percent (table 1). Published values of vertical hydraulic conductivity generated by laboratory analyses of sediment core vary over two orders of magnitude from 0.0000092 to 0.000588 ft/d (Harsh and Laczniak, 1990, and Laczniak and Meng, 1988, respectively; table 2), a lower range than the values obtained during this study. Other published values derived from ground-water model calibration are nearer the upper end of this range from 0.0000389 to 0.000112 ft/d (Hamilton and Larson, 1988, and Harsch and Laczniak, 1990, respectively; table 2). The higher vertical hydraulic conductivity values derived from model calibration possibly are more representative of the effective vertical hydraulic conductivity of the Calvert confining unit at the regional scale.

Saint Marys Aquifer

The Saint Marys aquifer has a limited regional extent, is moderately deep, and is sparsely used as a source of ground water in the Virginia Coastal Plain. The Saint Marys aquifer occupies two separate areas—one to the northeast encompassing much of the Virginia Eastern Shore and the other to the south mostly in the city of Suffolk (fig. 31; pl. 22). The northeastern part is approximately 150 ft to 200 ft thick and the southern part is only several tens of feet thick; both parts are at depths generally of a few hundred feet. The Saint Marys aquifer is stratigraphically above the Calvert confining unit (fig. 3). The Saint Marys aquifer possibly provides a small number of private water supplies in rural parts of the city of Suffolk.

Geologic Relations

The northeastern part of the Saint Marys aquifer consists of marine sands and shells that dominate part of the Saint Marys Formation of late Miocene age across the Virginia Eastern Shore and adjacent parts of Chesapeake Bay and the Atlantic Ocean (Powars and Bruce, 1999). Most of the remainder of the Saint Marys Formation is designated as part of the Saint Marys confining unit, where it is dominated by silts and clays but also widely includes a basal deposit of silty, glauconitic, phosphatic, and micaceous, fine- to medium-grained quartz sands and fossil shells that are only a few feet or less thick (see “Saint Marys Confining Unit”). The second part of the Saint Marys aquifer is a spatially limited part of the basal deposit that is coarse grained and thickens to several tens of feet along a narrow belt to the south.

The Saint Marys aquifer is a homogeneous aquifer (see “Hydrogeologic-Unit Classification”). The marine sands and shells of the Saint Marys Formation were deposited under relatively uniform sediment-transport conditions across the Continental Shelf and function hydraulically as a continuous medium through which water flows essentially uninterrupted, both locally and regionally.

In previous studies of the Virginia Coastal Plain, sediments of the Saint Marys Formation and the Choptank Formation were designated as composing the Saint Marys-Choptank aquifer (Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designation was made to equivalent sediments in studies in adjacent States during approximately the same period—the Lower Chesapeake aquifer in Maryland (Vroblesky and Fleck, 1991) and the Pungo River aquifer in North Carolina (Winner and Coble, 1996). In various earlier studies, an aquifer was designated as consisting of sediments belonging to the Pamunkey and(or) Chesapeake Groups, or their equivalents, of which the Saint Marys Formation is only a part.

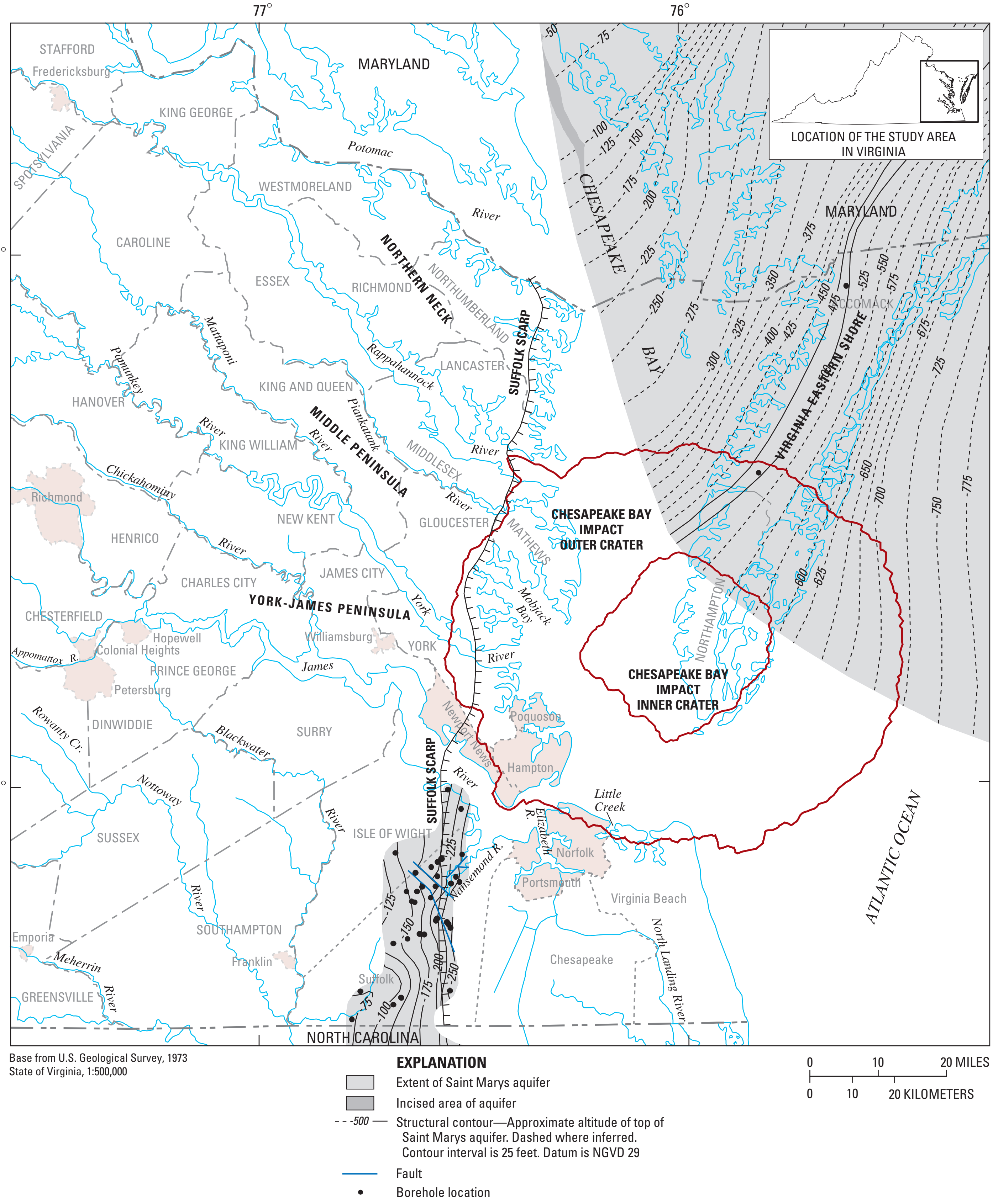
In previous studies, sediments of both the Saint Marys Formation of late Miocene age and the Choptank Formation of middle Miocene age composed the Saint Marys-Choptank aquifer. Subsequently, only the Saint Marys Formation was recognized as being present in Virginia (Powars and Bruce, 1999). The extent of the Saint Marys-Choptank aquifer in Virginia was previously delineated as extending across only the Virginia Eastern Shore and adjacent parts of Chesapeake Bay and the Atlantic Ocean. Existence of a separate second area to the south was not determined in these studies, nor in a subsequent study of the area south of the James River (Hamilton and Larson, 1988). The southern part of the Saint Marys aquifer is newly recognized herein.

In previous studies, the Chickahominy-Piney Point aquifer appears to have included the sediments composing the southern part of the Saint Marys aquifer. Generally north of the James River, the Piney Point aquifer designated herein widely exhibits distinct upper and lower parts that have different formational relations and are commonly discernible on borehole geophysical logs (see “Piney Point Aquifer”). Similar bimodal signatures observed on logs south of the James River were attributed in previous studies to the Chickahominy-Piney Point aquifer. Detailed descriptions of drill cuttings performed during this study (see “Borehole-Data Quality”) establish a revised stratigraphic relation whereby only the lower interval on logs south of the James River is attributable to the Piney Point aquifer. Designation of a distinct Saint Marys aquifer is based on recognition of the upper interval consisting of Saint Marys Formation sediments.

Structural Configuration

The Saint Marys aquifer is entirely below land surface and does not crop out. It is underlain across its entire extent by the Calvert confining unit (fig. 29; pl. 21) and is overlain across almost all of its extent by the Saint Marys confining unit (fig. 32; pl. 23). An incised area near the western margin of the northern part of the Saint Marys aquifer is projected along the axis of the upper Chesapeake Bay, where the entire thickness of the Saint Marys confining unit has eroded to produce an internal opening or “window” allowing the Saint Marys aquifer to be overlain by bay fill sediments.

The maximum altitude of the Saint Marys aquifer is along the western margin in western city of Suffolk and central Isle of Wight County (fig. 31; pl. 22). Borehole geophysical logs from south to north indicate –73 ft in far southern Suffolk, declining to –191 ft at the James River. The Saint Marys aquifer is extrapolated westward of these locations to pinch out against the Calvert confining unit (pl. 4, sec. FD–FD'; pl. 5, all secs.). The southern part of the Saint Marys aquifer generally dips eastward across its entire extent and is as thick as several tens of feet across altitudes from approximately –100 ft to –250 ft (pl. 4, sec. FD–FD'; pl. 5, all secs.; pl. 6, sec. DS–DS'; pl. 7, sec. ES–ES'). The Saint Marys aquifer is extrapolated southward into North Carolina based on a previous study (Winner and Coble, 1996).



EXPLANATION

▢	Extent of Saint Marys aquifer
▨	Incised area of aquifer
- - -500 —	Structural contour—Approximate altitude of top of Saint Marys aquifer. Dashed where inferred. Contour interval is 25 feet. Datum is NGVD 29
—	Fault
●	Borehole location

Figure 31. Approximate altitude and configuration of the top of the Saint Marys aquifer in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated northward beyond borehole locations are inferred from Vroblesky and Fleck (1991), and eastward on the basis of dip offshore. Further details are shown on plate 22.)

The northeastern part of the Saint Marys aquifer is represented by only two borehole geophysical logs on the Virginia Eastern Shore (fig. 31; pl. 22), where maximum altitudes are –490 ft and –496 ft. The northern part of the Saint Marys aquifer is thickest at 241 ft across altitudes from –490 ft to –731 ft in the Exmore core (Attachment 1, borehole local number 64J 14; pl. 7, sec. GS–GS'). From the two boreholes, the northern part of the Saint Marys aquifer is extrapolated eastward offshore and northward into Maryland based on a previous study (Vroblesky and Fleck, 1991).

The top of the southern part of the Saint Marys aquifer on some borehole geophysical logs exhibits closely spaced displacements that are attributed to faults which are upwardly traceable through the underlying hydrogeologic units (fig. 31; pl. 22; pl. 5, secs. GD–GD', ID–ID'; pl. 6, sec. DS–DS'; pl. 7, sec. ES–ES'). Although discrete fractures that are either open or lined with fault gouge are probably not pervasive in the generally incompetent sediments, disruption of their depositional intergranular structure by fault movement possibly has produced locally poor sorting, compaction, and some decrease in hydraulic conductivity. Continuing the underlying trend of upwardly decreasing fault displacement, the top of the Saint Marys aquifer exhibits displacements of, at most, only a few feet, and parts of some faults exhibit virtually no displacement. Hence, the faults produce only small, local-scale irregularities in the altitude of the Saint Marys aquifer, and further upward continuation of the faults through the Saint Marys confining unit is uncertain (see “Saint Marys Confining Unit”). Faults possibly exist at other locations, however, but are not recognized because of sparse borehole data and inadequate spatial control (see “Limitations”).

Recognition

Penetration of the top of the southern part of the Saint Marys aquifer in boreholes generally is noted by coarse-grained, glauconitic, phosphatic, and micaceous basal sands and shells of the Saint Marys Formation that contrast with silty and clayey sediments of the Saint Marys Formation that composes the overlying Saint Marys confining unit. Drilling response typically can exhibit grittiness and possibly some chatter across intervals of several feet or more, and the rate of advancement is moderate. The northern part of the Saint Marys aquifer is inferred herein from published geologic interpretations of historical borehole geophysical logs and associated geologic data (Powars and Bruce, 1999), and extrapolation based on a previous study (Vroblesky and Fleck, 1991).

On borehole electric logs (see “Borehole Geophysical-Log Network”) sands and shells of the Saint Marys aquifer generally exhibit a lobate signature typical of medium- to coarse-grained marine sediments, with some variations resulting from differences in silt and(or) clay content (fig. 4). Gamma logs exhibit a low to slightly elevated response, depending on the proportion of phosphatic material. Electric logs of the two boreholes in the northern part of the Saint Marys aquifer exhibit isolated peaks corresponding to distinct shelly interbeds (pl. 7, sec. GS–GS'). The southern part of the Saint Marys aquifer in combination with the Piney Point aquifer exhibits a bimodal signature on electric logs (pl. 4, sec. FD–FD'; pl. 5, all secs.; pl. 6, sec. DS–DS'; pl. 7, sec. ES–ES'), which resembles signatures attributable wholly to the Piney Point aquifer generally north of the James River. Where present, the Saint Marys aquifer is distinguished by the basal deposits of the Saint Marys Formation, which lithologically differ markedly from the basal deposits of the Plum Point Member of the Calvert Formation that corresponds to the interval north of the James River (see “Piney Point Aquifer”). Logs of boreholes located outside of the southern part of the Saint Marys aquifer exhibit a diminished signature that corresponds to the fine-grained and silty basal deposits of the Saint Marys Formation that are included as part of the Saint Marys confining unit.

Hydrologic Aspects

The Saint Marys aquifer is a regionally limited hydrogeologic unit that functions locally as a pathway for ground-water flow. The Saint Marys aquifer is a sparsely used ground-water supply resource that is limited geographically to the southern part, where the approximately 50-ft or less thick interval is considered a marginally effective water-production zone and commonly is cased off. Here, a single observation well yielded only 3.5 gal/min. Small-scale future development of the southern part of the Saint Marys aquifer possibly could address local limitations with use of the deeper Potomac aquifer, which is associated with high fluoride concentrations (see “Potomac Aquifer”). The northern part of the Saint Marys aquifer contains brackish water (see “Quaternary Period”) and is not used as a water-supply resource.

During 2002 and 2003, the Saint Marys aquifer produced an estimated less than 1 percent of the ground water used in the Virginia Coastal Plain at a rate of 0.05 Mgal/d (table 3). No withdrawal from the Saint Marys aquifer was reported to the DEQ by regulated industrial, municipal, and commercial users, and the entire withdrawal rate was estimated as unregulated domestic use. Unregulated withdrawals from the Saint Marys aquifer probably are entirely within the city of Suffolk. A random sample of domestic-well records from county health departments indicates that the Saint Marys aquifer supplies unregulated withdrawals from approximately 3 percent of the wells constructed since approximately 1985 in Suffolk (Jason Pope, U.S. Geological Survey, written commun., 2005), and no use is made of the Saint Marys aquifer elsewhere.

No permeameter samples from the Saint Marys aquifer were collected during this study. Only one value of 14.7 ft/d is published for the horizontal hydraulic conductivity of the northern part of the Saint Marys aquifer, which was derived from ground-water model calibration (Harsh and Laczniak, 1990; table 2).

Saint Marys Confining Unit

The Saint Marys confining unit is widespread and moderately deep, and regionally impedes ground-water flow in the Virginia Coastal Plain. The Saint Marys confining unit extends across all of the Virginia Coastal Plain and eastward offshore, except for the northern Fall Zone and the southern Fall Zone (fig. 32; pl. 23). The Saint Marys confining unit is as thick as a few hundred feet at depths as much as several hundred feet. The Saint Marys confining unit overlies the Saint Marys aquifer where the aquifer is present; otherwise, it primarily overlies the Calvert confining unit.

Geologic Relations

The lower part of the Saint Marys confining unit consists of marine, fossiliferous, silty clay (fig. 33) of the Saint Marys Formation, and the upper part consists of silty and clayey, glauconitic and phosphatic, fine-grained quartz sands of the Eastover Formation, both of late Miocene age (fig. 3). The Saint Marys Formation generally composes most of the thickness of the Saint Marys confining unit across most of its extent; the Eastover Formation generally composes a relatively subordinate upper interval. The Eastover Formation becomes more dominant toward the Fall Zone, however, where parts of the Saint Marys confining unit are composed mostly or entirely of the Eastover Formation (McFarland, 1997, 1999; Mixon and others, 2000). In addition, the Eastover Formation is dominant across the Virginia Eastern Shore where the Saint Marys Formation is composed mostly of the coarse-grained sediments that compose the Saint Marys aquifer (see “Saint Marys Aquifer”). Shells are present in parts of both formations composing the Saint Marys confining unit, generally along thin, isolated intervals in the Saint Marys Formation and thicker intervals in the Eastover Formation, but supported in both cases in a fine-grained matrix. In addition, the lowermost part of the Saint Marys Formation, which commonly consists of a basal deposit of silty, fine- to medium-grained sands and fossil shells, is only a few feet or less thick across most of its extent. The basal deposit is more coarse grained and thickens to several tens of feet or more along a narrow belt to the south, where it is not considered part of the Saint Marys confining unit but instead is included as part of the Saint Marys aquifer. Likewise, much of the upper part of the Eastover Formation consists primarily of fossil shells and is considered part of the Yorktown-Eastover aquifer (see “Yorktown-Eastover Aquifer”).

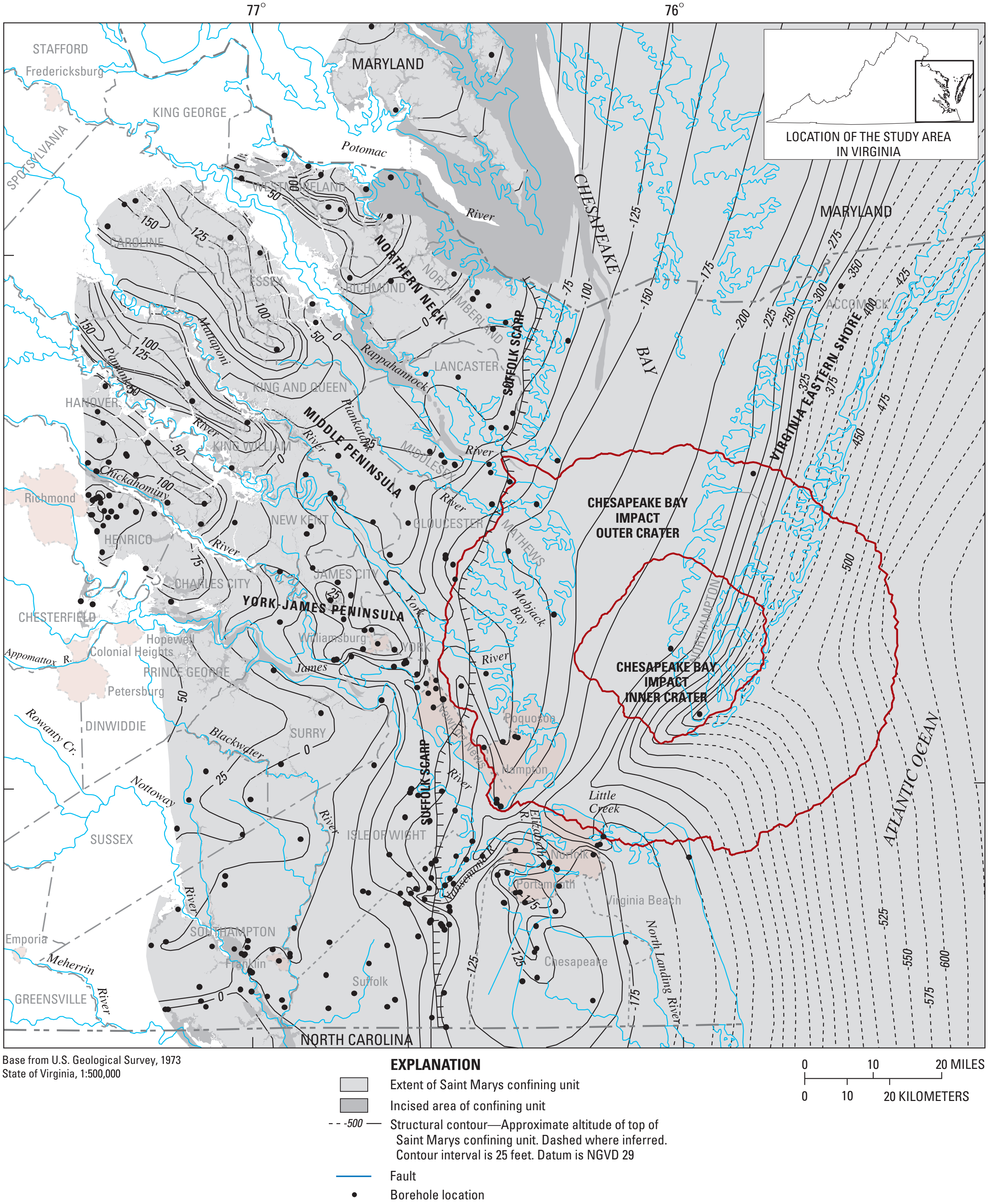
Relatively uniform sediment-transport conditions deposited the sediments of the Saint Marys and Eastover Formations across the Continental Shelf. Hence, the clays, silts, and fine sands composing the Saint Marys confining unit vary gradationally but function hydraulically as a continuous medium that impedes horizontal flow and allows relatively slow ground-water movement, mostly as vertical leakage.

Designation of the Saint Marys and Eastover Formations as composing a distinct Saint Marys confining unit was made in previous studies of part or all of the Virginia Coastal Plain (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designation was made to equivalent sediments in studies in adjacent States during approximately the same period—the Saint Marys confining unit in Maryland (Vroblesky and Fleck, 1991) and the Pungo River confining unit in North Carolina (Winner and Coble, 1996). In various earlier studies, an aquifer was designated consisting of sediments belonging to the Pamunkey and(or) Chesapeake Groups or their equivalents, of which the Saint Marys and Eastover Formations are only parts.

Structural Configuration

The Saint Marys confining unit is underlain across most of its extent by the Calvert confining unit (fig. 29; pl. 21). Where present, the intervening Saint Marys aquifer underlies the Saint Marys confining unit from the eastern half of the upper Chesapeake Bay across most of the Delmarva Peninsula and offshore, and along a second narrow belt to the south from eastern Isle of Wight County through central city of Suffolk (fig. 31; pl. 22). In addition, the Calvert confining unit is not present to the southwest, where the Saint Marys confining unit is underlain by the Piney Point aquifer across eastern Charles City County, most of the eastern two-thirds of Surry County, easternmost Sussex and Southampton Counties, the western half of Isle of Wight County, and westernmost city of Suffolk (pl. 4, secs. ED–ED', FD–FD'; pl. 5, all secs.). Farther west beyond where the Piney Point aquifer pinches out, the Saint Marys confining unit is underlain by the Nanjemoy-Marlboro confining unit. Distinction between the Saint Marys confining unit and Nanjemoy-Marlboro confining unit can be obscured here, where both confining units thin progressively toward the Fall Zone and their borehole geophysical log signatures become indiscernible.

The maximum altitude of the Saint Marys confining unit is near the western margin across the northern half of the Fall Zone (fig. 32; pl. 23). Borehole geophysical logs from north to south indicate altitudes of 156 ft in northern Caroline County, declining to 80 ft along the Pamunkey River in eastern Hanover County, then increasing to 158 ft in eastern Henrico County. The Saint Marys confining unit is extrapolated updip a few miles or less westward across the northern Fall Zone before pinching out against the Potomac confining zone at altitudes of approximately 160 ft or less. Some sediments of the Saint Marys and(or) Eastover Formations possibly extending a short distance farther west are included with the Potomac confining zone. Across the southern Fall Zone, the Saint Marys confining unit pinches out along the western margin at altitudes generally between 0 ft and 50 ft (pl. 4, sec. FD-FD'; pl. 5, secs. GD–GD', ID–ID'). Because of its relative proximity to land surface, the Saint Marys confining unit is extensively truncated across the northern part of the western margin along major segments of the valleys of the Potomac, Rappahannock, Mattaponi, Pamunkey, Chickahominy, James, and Nottoway



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

- ▢ Extent of Saint Marys confining unit
- ▨ Incised area of confining unit
- - - *-500* — Structural contour—Approximate altitude of top of Saint Marys confining unit. Dashed where inferred. Contour interval is 25 feet. Datum is NGVD 29
- — Fault
- • Borehole location

Figure 32. Approximate altitude and configuration of the top of the Saint Marys confining unit in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 23.)

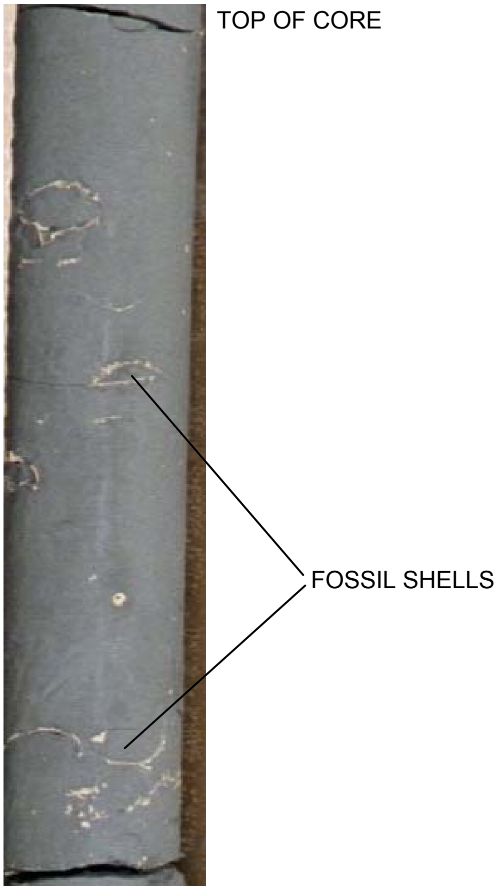


Figure 33. Marine sediments of late Miocene age from the Saint Marys Formation in the North core, borehole local number 59H 4, in Mathews County, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and interval is between approximately 235 and 236 feet below land surface. Variably fossiliferous, silty clay constitutes the major part of the Saint Marys confining unit. Consistency is markedly plastic. Similarly fine-grained lower part of the Eastover Formation of late Miocene age constitutes the remaining part of the Saint Marys confining unit. Fossil shells are more concentrated at other locations but generally are suspended in fine-grained sediments, except across a sandy basal interval typically of only a few feet or less. Greater basal-interval thicknesses across limited extents to the far south and northeast constitute the Saint Marys aquifer.

Rivers and some of their tributaries (fig. 32; pl. 23). An erosional remnant, or outlier, is present along the western margin between the James and Appomattox Rivers in eastern Chesterfield County. In addition, an internal opening or “window” is projected along the axis of the upper Chesapeake Bay, where the entire thickness of the Saint Marys confining unit has been eroded to create an incised area across the Saint Marys aquifer (fig. 31; pl. 22).

The Saint Marys confining unit is overlain across most of its eastern and southern extents by the Yorktown-Eastover aquifer (fig. 34; pl. 24), including the lower reaches of Northern Neck, Middle Peninsula, York-James Peninsula, most of Chesapeake Bay and the Virginia Eastern Shore, and all areas south of the James River. Beyond the extent of the Yorktown-Eastover aquifer to the northwest, the surficial aquifer overlies the remainder of the Saint Marys confining unit and represents the uppermost part of the confined ground-water system across uplands along the middle and upper reaches of Northern Neck, Middle Peninsula, York-James Peninsula, and most of the northern Fall Zone.

Extensively incised areas are projected along major segments of the Potomac and Rappahannock Rivers, with more localized areas along the Mattaponi, Pamunkey, Chickahominy, James, and Nottoway Rivers and some of their tributaries (fig. 32; pl. 23), where the Saint Marys confining unit crops out across the steepest slopes but is mostly covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer. In addition and because of its relative proximity to land surface, the top of the Saint Marys confining unit has been widely sculpted by erosion across the uplands overlain by the surficial aquifer, as indicated by structural contours that reflect the present-day topography. Thinning of the Saint Marys confining unit where it is overlain by the surficial aquifer possibly enhances hydraulic connections between the confined and unconfined ground-water systems, particularly along the main stem of the Potomac River where a relatively broad area is incised by almost the entire river channel. Confined-unconfined hydraulic connections are further enhanced across the “window” along the upper Chesapeake Bay, where the entire thickness of the Saint Marys confining unit has been eroded.

In addition to the uplands overlain by the surficial aquifer, erosion has sculpted parts of the top of the Saint Marys confining unit that are overlain by the Yorktown-Eastover aquifer farther east and south, as indicated by structural contours that reflect partly the present-day topography but also additional features (fig. 32; pl. 23). Some eroded paleochannels underlie and correspond to segments of the present-day Rappahannock, York, Chickahominy, James, Nansemond, and Nottoway Rivers. Additional paleochannels, however, transect present-day drainage divides. Among these, the paleochannel that corresponds to the York River extends southward beyond the river and across the lower York-James Peninsula and terminates at the James River. In addition, another paleochannel trends north across the central part of the city of Chesapeake and into a localized basin that opens to the northeast toward Norfolk. From here, a third paleochannel trends northeast across the mouth of Chesapeake Bay and deepens to more than 200 ft at the southern tip of the Virginia Eastern Shore.

The Saint Marys confining unit dips generally eastward across its entire extent (fig. 32; pl. 23). The Saint Marys confining unit is as thick as approximately 100–150 ft across the middle to lower reaches of Northern Neck and Middle Peninsula and extending eastward across the northern part of the Virginia Eastern Shore (pl. 3, secs. BD–BD', CD–CD'; pl. 4, sec. DD–DD'), the middle reach of the York-James Peninsula (pl. 4, sec. ED–ED'), and south of the James River eastward through the city of Suffolk (pl. 4, sec. FD–FD'; pl. 5, all secs.), where altitudes are as deep as approximately –150 ft to –300 ft. The Saint Marys confining unit thickens farther eastward to approximately 200–300 ft across the northern and western outer parts of the Chesapeake Bay impact crater (pl. 4, secs. DD–DD', ED–ED'; pl. 7, sec. ES–ES') and thins across the inner part of the crater (pl. 4, sec. DD–DD'; pl. 7, sec. GS–GS'). A thickness of 179 ft at altitudes –434 ft to –613 ft along the inner margin of the crater at Kiptopeke (Attachment 1, borehole local number 63F 50) results from incision into the top of the Saint Marys confining unit of a paleochannel interpreted to extend across the mouth of Chesapeake Bay (fig. 32; pl. 23). A thickness of 115 ft at altitudes from –211 ft to –326 ft across the central uplift at Cape Charles (Attachment 1, borehole local number 62G 24) results from substantial shallowing of the top of the underlying Calvert confining unit (see "Calvert Confining Unit").

Across the southern outer part of the crater and southward across the city of Chesapeake and Virginia Beach, the Saint Marys confining unit thickens to as much as approximately 400–500 ft at altitudes generally as deep as –200 ft to –700 ft (pl. 5, all sections; pl. 7, secs. FS–FS', GS–GS'). The Saint Marys confining unit is extrapolated eastward offshore (fig. 32; pl. 23) and, based on previous studies, southward into North Carolina (Winner and Coble, 1996) and northward into Maryland (Vroblesky and Fleck, 1991).

The displacements that are attributed to faults across the top surfaces of the underlying hydrogeologic units are not evident in the Saint Marys confining unit. The faults that are upwardly traceable through the underlying units do not correspond to variations in the top of the Saint Marys confining unit, which exhibits a wholly distinct distribution that is attributed here to erosional sculpting. Displacements along the faults generally decrease upward and possibly are too small across the top of the Saint Marys confining unit to be indiscernible on the borehole geophysical logs. Alternatively, the faults could terminate completely within the Saint Marys confining unit. As a third possibility, appreciable displacements that may exist internally along the faults within the Saint Marys confining unit may have been beveled off by erosion across its top surface. The paleochannel corresponding to the present-day Nansemond River is aligned with one of the underlying faults (pl. 5, sec. GD–GD'). Other paleochannels may be aligned along an altogether different set of faults, which either are not discernible or do not exist in the underlying hydrogeologic units. In the latter case, some unknown mechanism would be required to affect a redistribution of fault propagation. By whatever means, a substantial continuation of fault activity, in some form, is apparent from local-scale structural anomalies associated with the Chesapeake Bay impact crater and exhibited by the overlying Yorktown Formation (Powars and Bruce, 1999). In addition, faulting in general may be far more widespread and ubiquitous throughout the Virginia Coastal Plain than discerned herein (see "Limitations"), at least within proximity of the crater if not more extensively.

Recognition

Penetration of the top of the Saint Marys confining unit in boreholes generally is noted by silty and clayey, glauconitic and phosphatic, fine-grained quartz sands of the Eastover Formation that contrast with the coarse-grained overlying sediments of the Yorktown-Eastover aquifer and the surficial aquifer to the northwest beyond the extent of the Yorktown-Eastover aquifer. Where present, the Yorktown-Eastover aquifer commonly grades transitionally downward to the Saint Marys confining unit with a successive decrease in the shell content of the Eastover Formation sediments. Contact between the two hydrogeologic units can be determined from borehole geophysical-log interpretation. A generally sharp contact is present where the Saint Marys confining unit is overlain by the surficial aquifer and exhibits a marked change in lithology and color. Cuttings of Eastover Formation sediments were observed during this study to exhibit colors varying most commonly among dark gray (5Y 4/1), greenish gray (5G 5/1 and 10Y 5/1), and dark greenish gray (5GY 4/1). Sediments of the underlying Saint Marys Formation that generally compose most of the thickness of the Saint Marys confining unit were observed to be similar in color to those of the Eastover Formation, varying most commonly among grayish brown (2.5Y 5/2), dark greenish gray (10Y 4/1), and greenish gray (10Y 5/1 and 10GY 5/1). Because of their distinctly clayey texture (fig. 33), cuttings of Saint Marys Formation sediments can form elongated ribbons depending on drilling speed and fluid weight, whereas cuttings of Eastover Formation sediments are more commonly chip shaped. In addition, pyrite, lignite, and mica can be observed commonly in Saint Marys Formation sediments by hand lens or the unaided eye.

Through the entire Saint Marys confining unit, drilling response generally is smooth, and the rate of advancement is moderate. Shells can be sufficiently concentrated across some intervals to produce mild chatter in drilling response. In addition, large amounts of shell material originating from the overlying Yorktown-Eastover aquifer commonly continue to be flushed from the borehole in drilling fluid. Mild grittiness can be produced by the basal sands and shells across the lowermost few feet or less of the Saint Marys confining unit.

On borehole electric logs (see "Borehole Geophysical-Log Network") the Saint Marys confining unit generally exhibits a relatively flat signature typical of fine-grained marine sediments. Saint Marys Formation sediments can exhibit some moderate and generally isolated peaks resulting from interbedded shells (fig. 4). In addition, some electric logs exhibit thick shell intervals of as much as a few tens of feet in Eastover Formation sediments within the Saint Marys confining unit. Such intervals can appear similar to those in the overlying Yorktown-Eastover aquifer but can be distinguished by a smoother drilling response and the prevalence of fine-grained cuttings, which indicates that the shells probably are supported in a fine-grained matrix. Correlation of drilling response and cuttings with electric logs can, in some instances, be critical in determining the position of the contact between the Saint Marys confining unit and Yorktown-Eastover aquifer. Gamma logs generally exhibit a uniformly elevated response across the clayey Saint Marys Formation sediments but may include a moderate gamma peak at the base resulting from phosphate in the basal sands. Eastover Formation sediments exhibit a varied gamma response from differences in clay content. The Saint Marys confining unit can be indistinct on both electric and gamma logs where it is in direct contact with adjacent, similarly fine-grained confining units.

Hydrologic Aspects

The Saint Marys confining unit is an extensive hydrogeologic unit that regionally impedes horizontal ground-water flow. Where the Saint Marys aquifer is present, vertical leakage occurs between it and the overlying Yorktown-Eastover aquifer through the Saint Marys confining unit. Across much of its extent, the Saint Marys confining unit is directly underlain by the Calvert confining unit, through both of which leakage takes place primarily between the overlying Yorktown-Eastover aquifer and underlying Piney Point aquifer. Beyond the extent of the Yorktown-Eastover aquifer to the northwest, leakage through the Saint Marys and Calvert confining units occurs primarily between the overlying surficial aquifer and underlying Piney Point aquifer. North of the James River and across the Chesapeake Bay impact crater, the Saint Marys and Calvert confining units have a combined thickness of as much as several hundred feet, which imposes an effective hydraulic separation between the relatively shallow surficial and Yorktown-Eastover aquifers and the much deeper Piney Point and other aquifers. South of the James River and the crater, the Saint Marys confining unit is as much as approximately 500 ft thick and is the primary control on deep leakage because of the sharp thinning of the Calvert confining unit.

Vertical hydraulic conductivity values from the permeameter samples of the Saint Marys confining unit vary by two orders of magnitude between 0.000034 and 0.0023 ft/d (table 1), possibly as a result of the degree of fracturing in the samples. The single Eastover Formation sample is distinctly coarse grained and has a porosity of 32 percent, compared to the three fine-grained Saint Marys Formation samples having porosities ranging from 47 to 54 percent (table 1). Published values of vertical hydraulic conductivity produced by laboratory analyses of sediment core vary over two orders of magnitude from 0.0000028 to 0.000415 ft/d (Harsh and Laczniak, 1990, and Laczniak and Meng, 1988, respectively; table 2) across a lower range than the vertical hydraulic values obtained during this study. The uppermost core-analysis value was apparently applied by Harsh and Laczniak (1990) during ground-water model calibration, possibly on the basis of its being the most representative value of the effective vertical hydraulic conductivity of the Saint Marys confining unit at the regional scale.

Yorktown-Eastover Aquifer

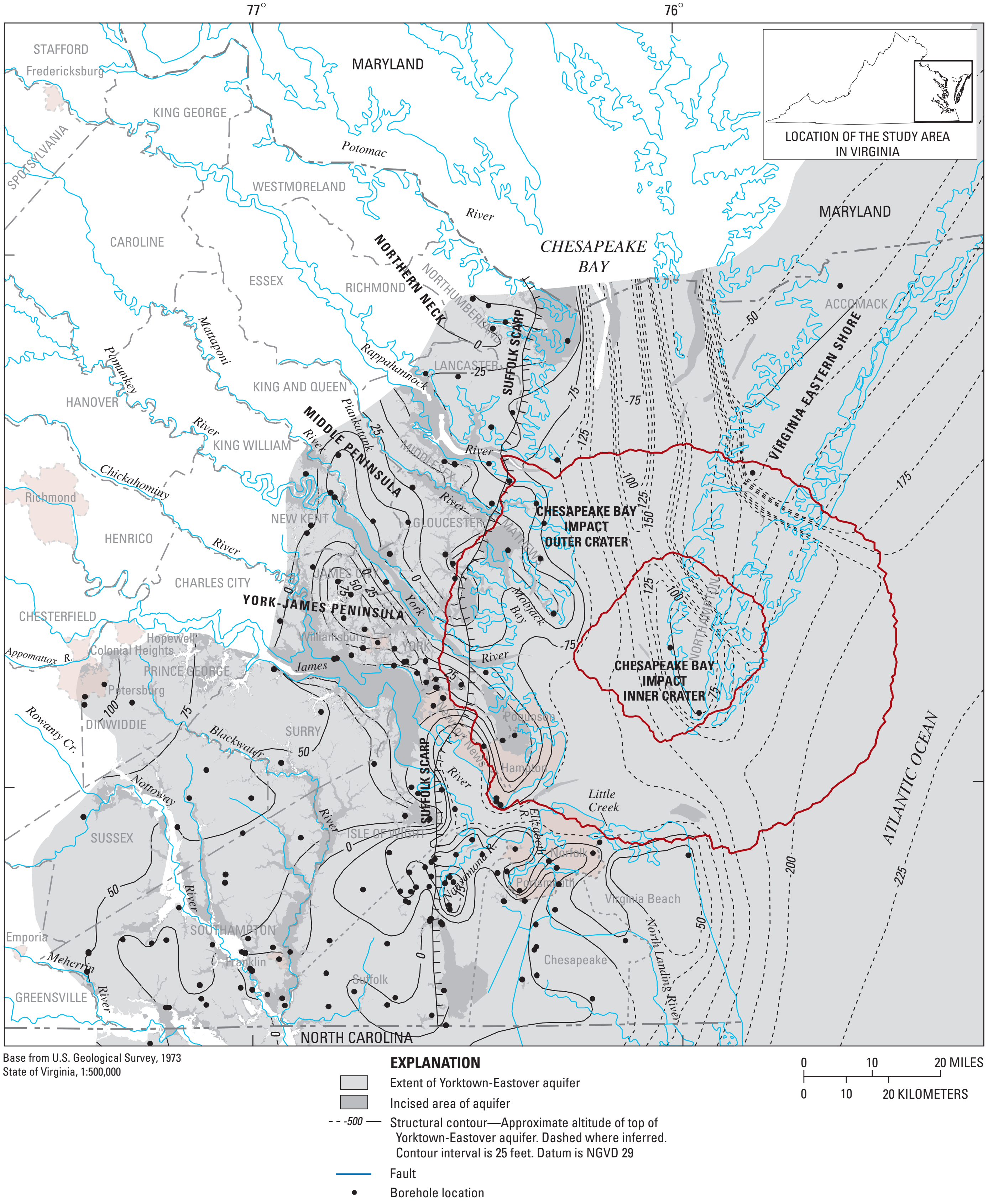
The Yorktown-Eastover aquifer is widespread, relatively shallow, and the second most heavily used source of ground water in the Virginia Coastal Plain. The Yorktown-Eastover aquifer extends across most of the Virginia Coastal Plain except for all or parts of several northwestern counties (fig. 34; pl. 24), and is as thick as a few hundred feet at depths of equal magnitude. The Yorktown-Eastover aquifer is stratigraphically above the Saint Marys confining unit across most of its extent (fig. 3), except for the southern Fall Zone where it is above either the Nanjemoy-Marlboro confining unit or the Potomac confining zone. The Yorktown-Eastover aquifer is a major source of both public and private water supplies in the eastern part of the Virginia Coastal Plain.

Geologic Relations

The upper part of the Yorktown-Eastover aquifer consists of estuarine to marine, variably textured, glauconitic, phosphatic, and fossiliferous quartz sands (fig. 35) and interbedded silts and clays of the Yorktown Formation of Pliocene age (fig. 3). The lower part consists of abundantly fossiliferous sands of the Eastover Formation of late Miocene age. In addition, some localized areas across the uppermost part of the Yorktown-Eastover aquifer to the far southeast possibly include coarse-grained sediments of the Chowan River Formation of late Pliocene age. The uppermost fine-grained sediments of the Chowan River Formation are included as a minor part of the Yorktown confining zone (see section “Yorktown Confining Zone”).

The Yorktown and Eastover Formations compose varying amounts of the Yorktown-Eastover aquifer. Although only the Eastover Formation is included at some locations, the Yorktown Formation generally is more regionally dominant. The lower part of the Eastover Formation consists primarily of silty and clayey fine-grained sands and is not considered part of the Yorktown-Eastover aquifer but instead is included as part of the Saint Marys confining unit (see “Saint Marys Confining Unit”). Likewise, fluvial-deltaic sediments that are possibly contemporary with the Yorktown Formation and mantle the land surface along the Fall Zone and parts of several northwestern counties are considered part of the surficial aquifer (see “Surficial Aquifer”).

The Yorktown-Eastover aquifer is considered to be a heterogeneous aquifer (see “Hydrogeologic-Unit Classification”). Discontinuous and locally variable fine-grained sediments are interbedded with coarse-grained sediments. Particularly, sediments of the Yorktown Formation exhibit sharp contrasts in composition and texture across small distances as a result of fluctuation among estuarine to marine depositional environments from alternate emergence and submergence during



Base from U.S. Geological Survey, 1973
State of Virginia, 1:500,000

EXPLANATION

▭ Extent of Yorktown-Eastover aquifer

▨ Incised area of aquifer

- - -500 —— Structural contour—Approximate altitude of top of Yorktown-Eastover aquifer. Dashed where inferred. Contour interval is 25 feet. Datum is NGVD 29

—— Fault

• Borehole location

Figure 34. Approximate altitude and configuration of the top of the Yorktown-Eastover aquifer in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours depicting paleochannels beneath Chesapeake Bay and Virginia Eastern Shore inferred from Mixon (1985) and D.L. Powars, U.S. Geological Survey, written commun., 2004, and extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 24.)

Figure 35. Marine sediments of late Miocene age from the Eastover Formation in the North core, borehole local number 59H 4, in Mathews County, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and interval is between approximately 91 and 92 feet below land surface. Abundantly fossiliferous, medium- to coarse-grained sand constitutes lower part of the Yorktown-Eastover aquifer. Similarly fossiliferous part of the Yorktown Formation of early to late Pliocene age constitutes most of the remaining part of the Yorktown-Eastover aquifer. Fossil shells of the Eastover Formation are distinguished from those of the Yorktown Formation by inclusion of the distinctly pearly lustered mollusk *Isognomon maxillata*.

the Pliocene Epoch. Thus, the Yorktown-Eastover aquifer is hydraulically continuous on a regional scale but can exhibit local discontinuities where flow is impeded by fine-grained interbeds.

Designation of the Yorktown and Eastover Formations as composing a distinct Yorktown-Eastover aquifer was made in previous studies of part or all of the Virginia Coastal Plain (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designations were made for equivalent sediments in studies in adjacent States during approximately the same period—the Upper Chesapeake aquifer in Maryland (Vroblesky and Fleck, 1991) and the Yorktown aquifer in North Carolina (Winner and Coble, 1996). In various other studies, an aquifer was designated that consists of sediments belonging to the Pamunkey and(or) Chesapeake Groups or their equivalents, of which the Yorktown and Eastover Formations are only parts. Conversely, the Yorktown-Eastover aquifer on the Virginia Eastern Shore was subdivided into upper, middle, and lower aquifers with intervening confining units (Richardson, 1994), primarily in support of development of a ground-water flow model.

In the previous studies of the entire Virginia Coastal Plain (Meng and Harsh, 1988; Harsh and Laczniak, 1990), the surficial fluvial-deltaic sediments that are possibly contemporary with the Yorktown Formation were included as part of an alternately confined and unconfined Yorktown-Eastover aquifer. The estuarine-to-marine sediments to the east and south composed the confined part, whereas the surficial fluvial-deltaic sediments to the northwest composed the unconfined part. By contrast, the latter sediments are considered herein as part of the surficial aquifer (see “Surficial Aquifer”). Although both sediments probably are contemporaneous and thereby stratigraphically correlative, they are not hydraulically continuous. The surficial sediments occupy a structurally uplifted position from which they are separated from the subsurficial sediments and are connected hydraulically most directly with other younger surficial sediments.

Structural Configuration

The Yorktown-Eastover aquifer is underlain by the Saint Marys confining unit (fig. 32; pl. 23) across most of the Virginia Coastal Plain. Beyond the western margin of the Saint Marys confining unit along the southern Fall Zone, the Yorktown-Eastover aquifer is partly underlain by the Nanjemoy-Marlboro confining unit across western Prince George County (fig. 20; pl. 16). Southward beyond the extent of the Nanjemoy-Marlboro confining unit, the Yorktown-Eastover aquifer is underlain by the Potomac confining zone across central and western Sussex County and western Southampton County (fig. 10; pl. 9).

The maximum altitude of the Yorktown-Eastover aquifer is near the western extent across the southern half of the Fall Zone (fig. 34; pl. 24). Borehole geophysical logs from north to south indicate altitudes of 112 ft at Petersburg, declining gradually to 48 ft in far western Southampton County. The Yorktown-Eastover aquifer is extrapolated westward of these locations to pinch out against either the Potomac confining zone or the basement at altitudes of approximately 120 ft or less. The Yorktown-Eastover aquifer does not extend north of the upstream one-third of the James River. Hence, the northern part of its western margin lies to the east across lower reaches of Northern Neck and middle reaches of the Middle and York-James Peninsulas. Here, the Yorktown-Eastover aquifer pinches out at approximately 0 ft (pl. 3, secs. BD–BD', CD–CD'; pl. 4, secs. DD–DD', ED–ED'). Truncation of the western margin of the Yorktown-Eastover aquifer is projected along the valleys of essentially the entire lengths of the Nottoway and Meherrin Rivers in Virginia, and along smaller segments of the Rappahannock and James Rivers and their tributaries and the axis of the upper Chesapeake Bay.

The Yorktown-Eastover aquifer is overlain across most of its extent by the Yorktown confining zone (fig. 36; pl. 25). Locally incised areas are projected across parts of Chesapeake Bay and along all of the major rivers and some of their tributaries (fig. 34; pl. 24), where the Yorktown-Eastover aquifer crops out across the steepest slopes but is mostly covered by several feet or more of flood-plain, terrace, and channel-fill sediments that compose the surficial aquifer. Additional incised areas are projected across some low-lying areas west and south of Chesapeake Bay, where the presence of the Yorktown confining zone is variable (see “Yorktown Confining Zone”). The accuracy of projections of these incised areas is limited by the topographic relations that were assumed in making the projections and by the inherent indistinctness of the Yorktown confining zone (see “Limitations”). The presentation herein serves primarily as an approximation to convey the general nature of the configuration and likely differs from conditions that could be observed locally. The Yorktown-Eastover aquifer probably subcrops directly beneath the surficial aquifer at numerous locations across the low-lying areas. Conversely, isolated outliers of the intervening Yorktown confining zone likely are equally numerous. Locally variable incised contacts between the Yorktown-Eastover aquifer and the overlying surficial aquifer across low-lying areas could create a potentially complex array of hydraulic connections between the confined and unconfined ground-water systems.

In addition to projected incised areas, the top of the Yorktown-Eastover aquifer has been sculpted widely by erosion, as indicated by structural contours that reflect partly the present-day topography but also additional features (fig. 34; pl. 24). Paleochannels underlie and correspond to segments of the Rappahannock, York, James, and Elizabeth Rivers, and Little Creek in northwestern Virginia Beach. Another paleochannel corresponds approximately to the Nansemond River but lies to the northwest by approximately 3 miles. A paleochannel in the underlying Saint Marys confining unit corresponds more directly to the alignment of the Nansemond River, which possibly migrated locally during the Pliocene Epoch. In addition, three large paleochannels as much as 200 ft deep and extending across several tens of miles are inferred from geologic maps across Chesapeake Bay and the Virginia Eastern Shore (Mixon, 1985; D.L. Powars, U.S. Geological survey, written commun., 2004). The paleochannels were formed by a staged southward migration of the Susquehanna River in association with the formation of the Delmarva Peninsula (see “Quaternary Period”).

The Yorktown-Eastover aquifer generally dips eastward across its entire extent (fig. 34; pl. 24). The Yorktown-Eastover aquifer is less than 50 ft thick across most of the lower reaches of Northern Neck and middle reaches of the Middle Peninsula, but thickens eastward beneath the upper Chesapeake Bay and the northern part of the Virginia Eastern Shore to approximately 150 to 250 ft, at altitudes between approximately –50 ft and –300 ft (pl. 3, secs. BD–BD', CD–CD'; pl. 4, sec. DD–DD'). Substantial thinning, or complete truncation in one area, is present along three ancestral Susquehanna paleochannels. Farther south, the Yorktown-Eastover aquifer broadens to the west and is approximately 50 to 100 ft thick across most of the York-James Peninsula (pl. 4, sec. ED–ED'). The Yorktown-Eastover aquifer locally thickens to 192 ft where it has backfilled and masked a paleochannel in the top of the underlying Saint Marys confining unit that is interpreted to extend across the lower York-James Peninsula (Attachment 1, borehole local number 58F 82). Similarly at the Kiptopeke core hole (Attachment 1, borehole local number 63F 50), the Yorktown-Eastover aquifer is thickest at 364 ft (pl. 7, sec. GS–GS'), where it has backfilled a paleochannel that is interpreted to extend across the mouth of Chesapeake Bay. South of the James River, the Yorktown-Eastover aquifer generally is less than 50 ft thick across most areas from the Fall Zone eastward to the Suffolk scarp, but thickens abruptly farther east to 100 ft or more toward the Atlantic coast (pl. 5, all secs.). The Yorktown-Eastover aquifer is extrapolated eastward offshore and, based on previous studies, southward into North Carolina (Winner and Coble, 1996) and northeastward across a small part of Maryland (Vroblesky and Fleck, 1991).

As with the Saint Marys confining unit, the upwardly traceable faults through the underlying hydrogeologic units are not apparent in the Yorktown-Eastover aquifer, which exhibits wholly distinct variations that are attributed herein to erosional sculpting (see “Saint Marys Confining Unit”). As noted for the Saint Marys confining unit, paleochannels and other apparently erosional features of the Yorktown-Eastover aquifer possibly are focused along a different set of faults, and a substantial continuation of fault activity in some form is apparent from local-scale structural anomalies associated with the Chesapeake Bay impact crater (Powars and Bruce, 1999).

Recognition

Penetration of the top of the Yorktown-Eastover aquifer in boreholes generally is noted by coarse-grained, commonly glauconitic and very fossiliferous quartz sands (fig. 35) of the Yorktown Formation, which composes the upper part of the aquifer. These sands contrast with the fine-grained sediments of the overlying Yorktown confining zone or, in its absence, with commonly iron-stained and gravelly quartz sands of the overlying surficial aquifer, which is generally devoid of shell material. Sand-dominated intervals of the Yorktown-Eastover aquifer typically exhibit moderate grittiness in drilling response. Cuttings are returned by drag bit as chips, which were observed during this study to exhibit colors varying among greenish gray (10Y 5/1, 10GY 5/1, 5G 5/1), dark gray (5Y 4/1), and dark greenish gray (5GY 4/1). In addition, abundantly fossiliferous intervals can produce pronounced chatter during drilling and return disaggregated material ranging from biofragmental sands (shell hashes) to whole shells. The most shell-rich intervals generally coincide areally with the Suffolk scarp and are associated with sinkholes resulting from dissolution of shell material. Loss of drilling-fluid circulation commonly occurs because of excessive fluid infiltration into the shells across the wall of the borehole. By contrast, fine-grained clayey or silty interbeds typically exhibit a relatively smooth drilling response and a moderate to rapid rate of advancement. At greater depth, shells from the Eastover Formation, which composes the lower part of the Yorktown-Eastover aquifer, can be recognized by the presence of the distinctly pearly lustered mollusk *Isognomon maxillata*.

Depending on the rate of advancement and drilling-fluid weight and circulation, large amounts of shell material from the Yorktown-Eastover aquifer can remain unflushed from the borehole for some period during subsequent deepening into underlying hydrogeologic units. The shells gradually circulate out with drilling fluid leaving the borehole and thereby become mixed with cuttings originating from the drilled interval. Without recognition of the persistence of the shell material, accurate interpretation of the resulting disparate assemblage of lithologic components in cuttings can be obscured. Particularly, determination of the top of the Saint Marys confining unit that underlies most of the Yorktown-Eastover aquifer is commonly dependent on correlation of drilling response with electric logs.

On borehole electric logs of the Yorktown-Eastover aquifer (see “Borehole Geophysical-Log Network”), distinct and abundantly fossiliferous intervals can exhibit sharp multiple peaks in succession, whereas sand-dominated intervals exhibit lobate signatures. Commonly, shells and sands are closely associated where their individual signatures can transition into more of a blocky signature with some variations resulting from interbedding with silts and(or) clays (fig. 4). Lower parts of the Eastover Formation that compose part of the Saint Marys confining unit exhibit shell intervals on some electric logs but also are distinguished by a smooth drilling response, which indicates that the shells probably are supported in a fine-grained matrix. Gamma logs of the Yorktown-Eastover aquifer generally exhibit a low response from shells and(or) sands, but fine-grained interbeds can produce moderately elevated responses.

Hydrologic Aspects

The Yorktown-Eastover aquifer is an extensive hydrogeologic unit that functions as a pathway for ground-water flow across much of the Virginia Coastal Plain. The Yorktown-Eastover aquifer also is second in importance to the Potomac aquifer as a ground-water supply resource. Yields of 10–30 gal/min are common from water-supply wells, and some large production wells produce from 75 gal/min to as much as 300 gal/min on the Virginia Eastern Shore.

Vertical hydraulic conductivity values of three permeameter samples from the Yorktown-Eastover aquifer range over an order of magnitude from 0.00062 to 0.0022 ft/d (table 1). The sample having the lower value has finer-grained sediment than the other two. Porosity varies from 43 to 53 percent (table 1). Published values of horizontal hydraulic conductivity of the Yorktown-Eastover aquifer resulting from well specific-capacity tests or derived from ground-water model calibration range across three orders of magnitude from 0.7 to 353 ft/d (Laczniak and Meng, 1988; table 2). The range of specific-capacity test values encompasses the single value of 14.7 ft/d derived by model calibration (Harsh and Laczniak, 1990; table 2). Higher values possibly reflect a preponderance of coarse-grained and(or) shelly sands, and lower values represent more silty and medium-grained sands. The vertical hydraulic conductivity values of permeameter samples are less than the published horizontal hydraulic conductivity values partly because of anisotropy but also because samples of highly conductive but structurally incompetent shell-rich sediments could not be collected viably. Values resulting from some specific-capacity tests or derived from calibration of ground-water models probably are more representative of the effective hydraulic conductivity of the Yorktown-Eastover aquifer at the regional scale.

The Yorktown-Eastover aquifer during 2002 produced an estimated 13 percent of the ground water used in the Virginia Coastal Plain, at a rate of 17 Mgal/d (table 3). A rate of 5.9 Mgal/d was reported to the DEQ by regulated industrial, municipal, and commercial users, and unregulated domestic use was estimated at a rate of 11 Mgal/d. Regulated withdrawal declined slightly during 2003 to a rate of 5.4 Mgal/d; consequently, total withdrawal declined to 16 Mgal/d from the Yorktown-Eastover aquifer, but the relative contribution of the aquifer to the total withdrawal in the Virginia Coastal Plain remained essentially unchanged.

The Yorktown-Eastover aquifer is a significant water supply in areas where it is sufficiently thick and permeable to produce appreciable well yields, generally east of the Suffolk scarp. Here, the Saint Marys and Calvert confining units are as much as several hundred feet thick and impose an effective hydraulic separation from underlying aquifers that are much deeper and contain brackish to saline water. Hence, across much of the rapidly growing area of Hampton Roads, the Yorktown-Eastover aquifer locally provides a major part of the public supply of freshwater to small towns and businesses. More broadly, it also provides supplies for crop and livestock production operations, landscape maintenance, and low-density residential development. On the Virginia Eastern Shore, ground water is the sole water-supply source because surface-water supplies do not exist. Because the surficial aquifer is vulnerable to contamination from widespread agricultural activities, most of the water is supplied from the Yorktown-Eastover aquifer. Continued development of the Yorktown-Eastover aquifer has prompted concerns about saltwater intrusion, however, because of hydraulic connectivity to brackish and saline surface-water bodies.

Unregulated withdrawals from the Yorktown-Eastover aquifer generally are dispersed across rural areas. A random sample of domestic well records from county health departments indicates that the Yorktown-Eastover aquifer supplies unregulated withdrawals to more than 50 percent of the wells constructed since approximately 1985 across the lower reaches of the Middle Peninsula and York-James Peninsula, the cities of Chesapeake and Virginia Beach, and the counties of Prince George, Sussex, and Surry (Jason Pope, U.S. Geological Survey, written commun., 2005). On the Virginia Eastern Shore, the Yorktown-Eastover aquifer is estimated to supply all domestic wells in Accomack County and 70 percent of the domestic wells in Northampton County. The Yorktown-Eastover aquifer supplies approximately 10 percent of the domestic wells across the remainder of its extent.

Yorktown Confining Zone

The Yorktown confining zone is widespread and shallow, and locally impedes ground-water flow in the Virginia Coastal Plain. The Yorktown confining zone extends across most of the Virginia Coastal Plain except for all or parts of several northwestern counties (fig. 36; pl. 25). The Yorktown confining zone is as thick as several tens of feet at depths of equal magnitude. The Yorktown confining zone is stratigraphically above the Yorktown-Eastover aquifer (fig. 3), and approximates a transition to the overlying surficial aquifer.

Geologic Relations

The Yorktown confining zone generally is defined locally as the uppermost silt and(or) clay that is interbedded with glauconitic, phosphatic, and fossiliferous quartz sands of the estuarine to marine Yorktown Formation of Pliocene age (fig. 3), or with fossiliferous sands of the Eastover Formation of late Miocene age at some locations where the Yorktown Formation is absent. In addition, some localized areas across the far southeastern part of the Yorktown confining zone possibly include the uppermost fine-grained sediments of the Chowan River Formation of late Pliocene age. Any underlying coarse-grained sediments of the Chowan River Formation are included as a minor part of the Yorktown-Eastover aquifer (see "Yorktown-Eastover Aquifer").

Designation of the Yorktown confining zone accounts for variable configurations and, in some cases, indistinguishable relations that can exist between the underlying Yorktown-Eastover aquifer and the overlying surficial aquifer. Both the Yorktown-Eastover aquifer and the surficial aquifer are heterogeneous aquifers (see "Hydrogeologic-Unit Classification"). Discontinuous and locally variable sediments exhibit sharp contrasts in composition and texture across small distances as a result of fluctuation among marine, estuarine, and fluvial-deltaic depositional environments from alternate emergence and submergence during the Pliocene Epoch and Quaternary Period. Fine-grained interbeds composing the Yorktown confining zone are positioned across the top of the Yorktown Formation and locally impede leakage between the Yorktown-Eastover aquifer and the overlying surficial aquifer. The interbeds are discontinuous, however, and were correlated across relatively large distances as great as several miles or more between borehole locations. As a result, the Yorktown confining zone as mapped probably encompasses coarse-grained sediments of the Yorktown Formation and(or) overlying formations that are locally in direct contact at many locations where no interbeds exist. Thus, the Yorktown confining zone does not represent a distinct contact surface, but rather approximates a transition from the Yorktown-Eastover aquifer to the surficial aquifer.

Designation of a Yorktown confining unit was made in previous studies of part or all of the Virginia Coastal Plain (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designations were made to equivalent sediments in studies in adjacent States during approximately the same period—the Upper Chesapeake confining unit in Maryland (Vroblesky and Fleck, 1991) and the Yorktown confining unit in North Carolina (Winner and Coble, 1996). In various other studies, an aquifer was designated that consists of sediments belonging to the Pamunkey and(or) Chesapeake Groups or their equivalents, of which the Yorktown Formation is only a part. Conversely, upper, middle, and lower Yorktown-Eastover confining units were designated whereby the Yorktown-Eastover aquifer was subdivided on the Virginia Eastern Shore (Richardson, 1994), primarily in support of development of a ground-water flow model. In addition, the Yorktown confining unit was locally subdivided in York County to include the Cornwallis Cave aquifer and confining unit (Brockman and Richardson, 1992).

Although it was acknowledged in these earlier studies that the Yorktown confining unit does not represent a single fine-grained interbed, it was either expressed or implied that interbeds within the designated interval are of sufficient density across a continuous expanse to function hydraulically as a regional barrier to flow. By contrast, it was observed during this study that fine-grained intervals in boreholes in Yorktown Formation sediments appear to be primarily of local extent and do not represent a confining unit overlying the Yorktown-Eastover aquifer.

In the previous studies of the Virginia Coastal Plain (Meng and Harsh, 1988; Harsh and Laczniak, 1990), sediments of the Bacons Castle Formation of late Pliocene age and the upper part of the Yorktown Formation were designated as composing the Yorktown confining unit. The Bacons Castle Formation is a surficial deposit that mantles the land surface across areas of intermediate altitude extending across a 20- to 30-mi wide, southwest-northeast trending belt along the southern Fall Zone and middle reaches of Northern Neck and the York-James and Middle Peninsulas. With inclusion of the Bacons Castle Formation, the eastward subsurface part of the Yorktown confining unit was extended updip to crop

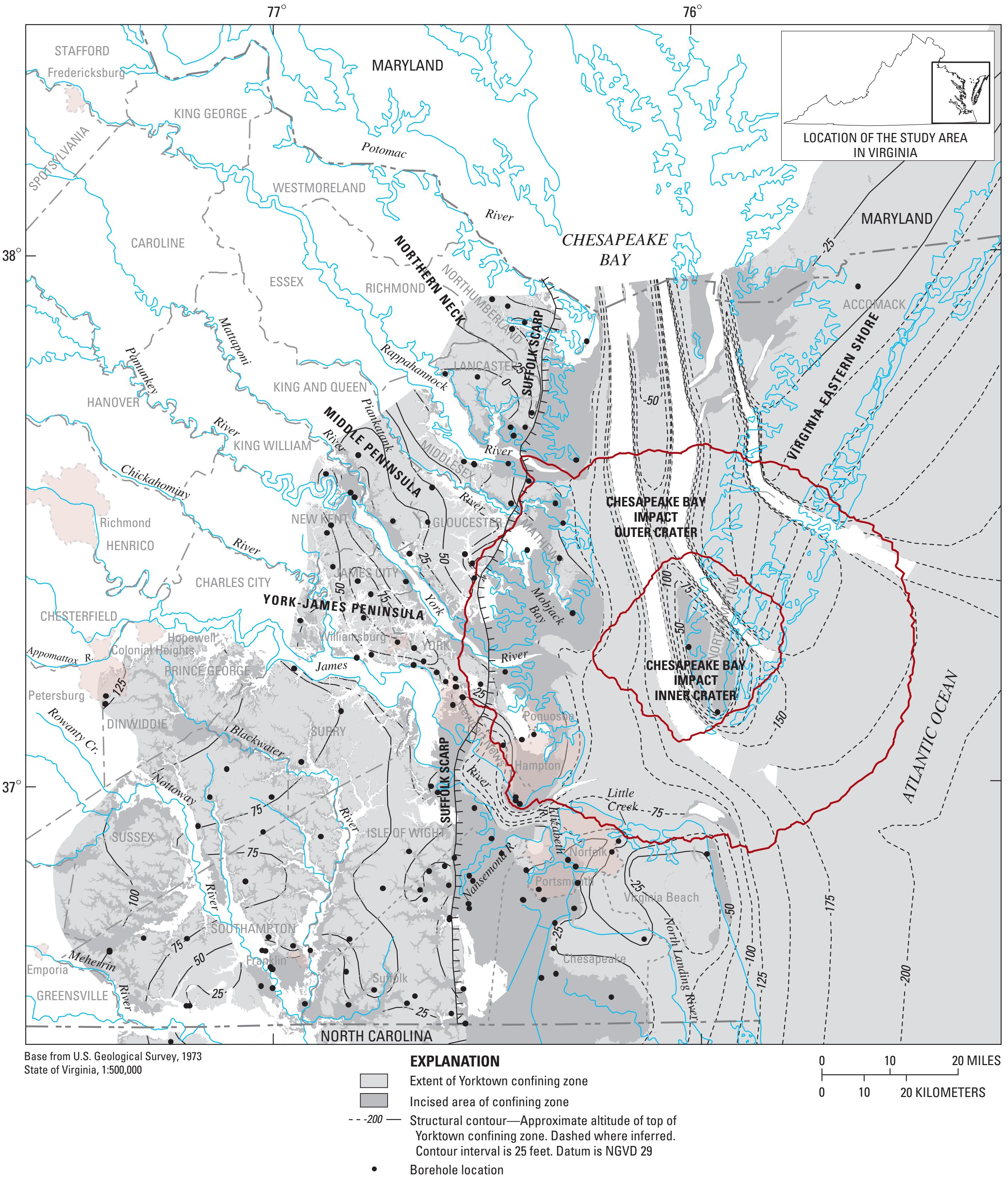


Figure 36. Approximate altitude and configuration of the top of the Yorktown confining zone in the Virginia Coastal Plain. (Location of the Chesapeake Bay impact crater is from Powars and Bruce (1999). Structural contours depicting paleochannels beneath Chesapeake Bay and Virginia Eastern Shore inferred from Mixon (1985) and D.L. Powars, U.S. Geological Survey, written commun., 2004, and extrapolated beyond borehole locations are inferred on the basis of eastward dip offshore. Further details are shown on plate 25.)

out toward the west. The centrally located outcrop belt of the Yorktown confining unit areally separated the subsurficial confined part of the Yorktown-Eastover aquifer to the east from the surficial unconfined part to the west. By contrast, the surficial sediments of the Bacons Castle Formation are not included herein as part of the Yorktown confining zone but rather are considered as part of the surficial aquifer (see "Surficial Aquifer"). The water table is within the Bacons Castle Formation with other surficial sediments that are hydraulically continuous across the entire Virginia Coastal Plain and jointly function as a distinct surficial aquifer.

Structural Configuration

The Yorktown confining zone is underlain across its entire extent by the Yorktown-Eastover aquifer (fig. 34; pl. 24). The maximum altitude of the Yorktown confining zone is near the western margin across the southern half of the Fall Zone (fig. 36; pl. 25). Borehole geophysical logs from north to south indicate altitudes of 140 ft at Petersburg, declining slightly to 110 ft in far western Southampton County. The Yorktown confining zone is extrapolated westward of these locations to pinch out against either the Potomac confining zone or the basement at altitudes of approximately 150 ft or less. The Yorktown confining zone does not extend northward from the upstream one-third of the James River. Hence, the northern part of the western margin lies to the east across lower reaches of Northern Neck and middle reaches of the Middle and York-James Peninsulas where the Yorktown confining zone pinches out at an altitude of a few tens of feet or less (pl. 3, secs. BD–BD', CD–CD'; pl. 4, secs. DD–DD', ED–ED'). From its western margin, the Yorktown confining zone generally dips eastward across its entire extent (fig. 36; pl. 25). The thickness of the Yorktown confining zone is variable and ranges from less than 50 ft across many areas to between 50 and 100 ft in others (pls. 3–7, all secs.).

The Yorktown confining zone has been widely sculpted by erosion because of its proximity to land surface. Structural contours across the lower reaches of Northern Neck and middle reaches of the Middle and York-James Peninsulas reflect the present-day topography (fig. 36; pl. 25). In addition, significant thinning or complete truncation is projected in many areas. The western margin of the Yorktown confining zone is extensively truncated across long segments of the major river valleys and many of their tributaries. Several internal openings or "windows" and more expansive incised areas are projected across an arcuate belt extending across low-lying areas of upper Chesapeake Bay and its western shore and south across eastern Isle of Wight County and the city of Suffolk and much of the city of Chesapeake. The presence of the Yorktown confining zone likely is highly variable. The accuracy of the projections of these areas is limited by the topographic relations that were assumed in making the projections and by the inherent indistinctness of the Yorktown confining zone (see "Limitations"). The presentation herein serves primarily as an approximation to convey the general nature of the configuration and likely differs from conditions that could be observed locally. The Yorktown-Eastover aquifer probably subcrops directly beneath the surficial aquifer at numerous locations across low-lying areas. Conversely, isolated outliers of the intervening Yorktown confining zone likely are equally numerous. Locally variable, incised contacts between the Yorktown-Eastover aquifer and the overlying surficial aquifer across low-lying areas could create a potentially complex array of hydraulic connections between the confined and unconfined ground-water systems.

Farther east, the Yorktown confining zone is truncated along three large paleochannels as much as 200 ft deep and extending across several tens of miles across Chesapeake Bay and the Virginia Eastern Shore (fig. 36; pl. 25) that are inferred from geologic maps (Mixon, 1985; D.L. Powars, U.S. Geological Survey, written commun., 2004). The surficial aquifer directly overlies incised parts of the Yorktown-Eastover aquifer along paleochannels that were formed by a staged southward migration of the Susquehanna River in association with the formation of the Delmarva Peninsula (see "Quaternary Period"). Additional localized areas of incision and truncation are projected across the southern tip of the Virginia Eastern Shore and southward across the mouth of Chesapeake Bay and northern Virginia Beach. The Yorktown confining zone is extrapolated eastward offshore and, based on previous studies, southward into North Carolina (Winner and Coble, 1996) and northeastward across a small part of Maryland (Vroblesky and Fleck, 1991).

Recognition

Penetration of the top of the Yorktown confining zone in boreholes generally is noted by the first fine-grained clayey or silty interbed or group of interbeds across the top of the Yorktown Formation that contrast with more coarse-grained sediments of the overlying surficial aquifer and underlying Yorktown-Eastover aquifer. Drilling response generally is smooth and quiet with a moderate to rapid rate of advancement.

Coarse-grained, commonly glauconitic and very fossiliferous quartz sands of the Yorktown or Eastover Formations that underlie the uppermost fine-grained interbed(s) mark the top of the Yorktown-Eastover aquifer (see "Yorktown-Eastover Aquifer"). Sediments of the surficial aquifer likely directly overlie the Yorktown-Eastover aquifer at many locations where no intervening interbeds are present. In addition, fine-grained sediments can be interbedded within several formations that compose the surficial aquifer (see "Surficial Aquifer"). Such configurations can be clearly discerned in core or in rare outcrops but generally are more obscure based solely on drill cuttings and(or) borehole geophysical logs. As a result, the Yorktown confining zone is, in most instances, designated on geophysical logs as an interval that is transitional from the recognizable adjacent hydrogeologic units (fig. 4). The Yorktown confining zone generally exhibits a flat signature on electric logs and a moderately elevated response on gamma logs. Differentiation across the interval of fine-grained interbeds of the Yorktown Formation from some sediments of overlying formations can be obscured because the log signatures commonly are indistinct, especially where the different interbeds are relatively thin.

Hydrologic Aspects

Although the Yorktown confining zone is regionally extensive, it impedes ground-water flow primarily at a local scale. No permeameter samples of the Yorktown confining zone were collected during this study. Published values of vertical hydraulic conductivity of the Yorktown confining zone determined by analyses of sediment core range across two orders of magnitude from 0.000013 to 0.0039 ft/d (Richardson, 1994, and Harsh and Laczniak, 1990, respectively; table 2), and encompass a single value of 0.000864 ft/d derived by model calibration (Hamilton and Larson, 1988: table 2). The range of values possibly reflects variations among clayey and silty interbeds. Leakage can be impeded substantially where interbeds are present. Interbeds are discontinuous, however, and greater leakage takes place where interbeds do not exist. The Yorktown confining zone does not represent a lithologically uniform mass of sediment through which leakage is enhanced as a result of having overall relatively large vertical hydraulic conductivity, and description as a leaky confining unit is not conceptually accurate.

Given the nature of the Yorktown confining zone, the surficial aquifer and underlying Yorktown-Eastover aquifer are closely associated hydrologically. The likely numerous, locally incised and truncated areas across the Yorktown confining zone result in the surficial and Yorktown-Eastover aquifers being in close, vertical proximity or direct contact. Hence, a potentially complex but extensively developed array of hydraulic connections links the unconfined and confined ground-water systems. By contrast, the Saint Marys and Calvert confining units that underlie the Yorktown-Eastover aquifer each represent a lithologically uniform mass of sediment through which leakage is impeded regionally, and together are as much as several hundred feet thick across much of the Virginia Coastal Plain. Hence, the eastern part of the surficial aquifer and the Yorktown-Eastover aquifer can be viewed jointly as composing a shallow, generally semi-confined ground-water system that is distinct and hydraulically separated from the significantly deeper, wholly confined system.

Surficial Aquifer

The surficial aquifer is a widespread, shallow, and moderately used source of ground water in the Virginia Coastal Plain. The surficial aquifer mantles the land surface across the entire Virginia Coastal Plain and is as thick as several tens of feet at depths of equal magnitude. The surficial aquifer is stratigraphically above the Yorktown confining zone across most of its extent (fig. 3), except in the northwest where it primarily overlies either the Saint Marys or Calvert confining units. The surficial aquifer provides mostly domestic water supplies and also serves as the primary entryway for recharge to the entire ground-water system.

Geologic Relations

The surficial aquifer is composed of a series of primarily fluvial-deltaic and estuarine, variably textured quartz sands and gravels with interbedded silts and clays (fig. 37) that range in age from late Pliocene through Quaternary (fig. 3). Sediments of differing ages occupy a step-like succession of terraces separated by intervening scarps, with those in areas of high to intermediate altitude generally of Pliocene age and those at low altitude of Quaternary age (see “Oligocene, Miocene, and Pliocene Epochs” and “Quaternary Period”).

Mantling broad areas of western uplands are fluvial-deltaic sediments, possibly contemporary with the Yorktown Formation, that straddle the Fall Zone and widen progressively northward across the upper reaches of Northern Neck and the York-James and Middle Peninsulas. Eastward and across areas of intermediate altitude are diverse fluvial-deltaic, estuarine, tidal-flat, and shallow-marine variably colored clayey silts and silty fine sands of the Bacons Castle Formation, which extends across a 20- to 30-mi wide, southwest-northeast trending belt along the southern Fall Zone and middle reaches of Northern Neck and the York-James and Middle Peninsulas. Farther east across broad areas of low altitude stretches a relatively thin veneer of variably colored and textured interbedded gravels, sands, silts, clays, and peat of Pliocene to Pleistocene age (Windsor, Charles City, Chuckatuck, Shirley, and Tabb Formations) landward of Chesapeake Bay (undifferentiated in fig. 3) and their stratigraphic equivalents on the Virginia Eastern Shore. These sediments extend across southeastern Virginia, the lower reaches of Northern Neck and the York-James and Middle Peninsulas, and areas to the east. Lastly, channels, flood plains, and terraces of present-day rivers and streams, Chesapeake Bay, and the Atlantic coast are mantled by sediments of Holocene age composed of modern alluvial, colluvial, estuarine, marsh, swamp, and dune deposits.

The surficial aquifer is a heterogeneous aquifer (see “Hydrogeologic-Unit Classification”). Discontinuous and locally variable fine-grained sediments are interbedded with the more coarse-grained sediments. Several formations exhibit sharp contrasts in sediment composition and texture across small distances as a result of fluctuation among fluvial, deltaic, and estuarine depositional environments from alternate emergence and submergence during the Pliocene Epoch and Quaternary Period. Thus, the surficial aquifer is hydraulically continuous on a regional scale but locally can exhibit discontinuities where flow is impeded by fine-grained interbeds.

Sediments of Pliocene through Quaternary age were designated in previous studies of part or all of the Virginia Coastal Plain as the Columbia aquifer (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990; fig. 3). Similar designation was

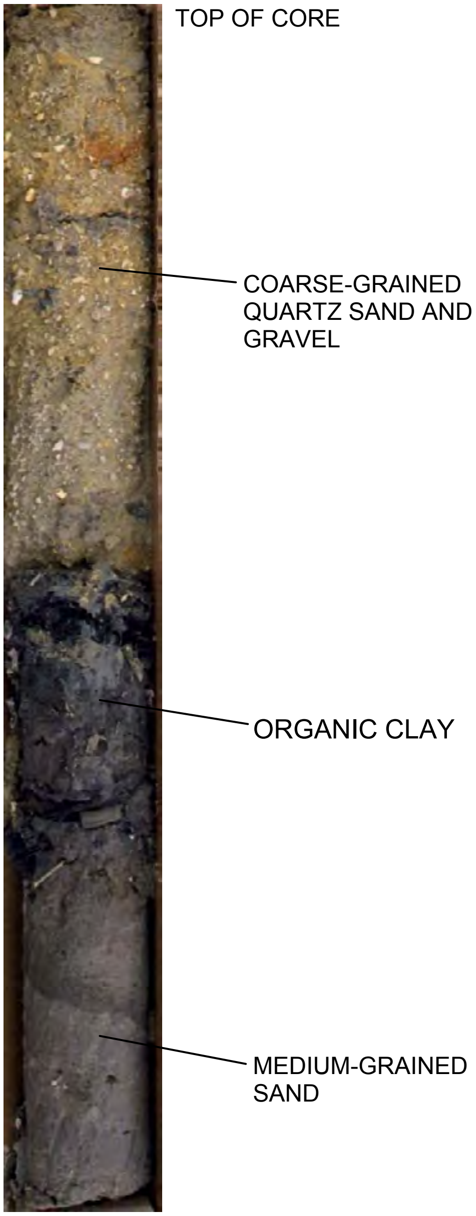


Figure 37. Fluvial and estuarine sediments of late Pleistocene age from the Tabb Formation in the North core, borehole local number 59H 4, in Mathews County, Virginia (borehole location shown on plate 1). Core diameter is approximately 2 inches, and interval is from land surface to a depth of approximately 2 feet. Iron stained, coarse-grained quartz sand and gravel across upper part of section, and medium-grained sand across bottom of section, constitute surficial aquifer. Organic clay across middle of section contains fossil plant material and is interbedded within surficial aquifer. The surficial aquifer more broadly encompasses similarly variable sediments of a series of fluvial-deltaic and estuarine formations of late Pliocene to Quaternary age that are hydrologically closely associated and mantle the land surface across the entire Virginia Coastal Plain.

made to roughly equivalent sediments in studies in adjacent States during approximately the same period—the surficial aquifer in Maryland (Vroblesky and Fleck, 1991) and in North Carolina (Winner and Coble, 1996). In addition, some sediments of equivalent age were subdivided locally in York County to include the Cornwallis Cave aquifer and confining unit (Brockman and Richardson, 1992).

In the previous studies of the entire Virginia Coastal Plain (Meng and Harsh, 1988; Harsh and Laczniak, 1990), the surficial fluvial-deltaic sediments that are possibly contemporary with the Yorktown Formation were included as part of an alternately confined and unconfined Yorktown-Eastover aquifer. The estuarine-to-marine sediments to the east and south composed the confined part, whereas the surficial fluvial-deltaic sediments to the northwest composed the unconfined part. By contrast, the former sediments are considered herein as the wholly confined Yorktown-Eastover aquifer (see “Yorktown-Eastover Aquifer”). Although both sediments probably are contemporaneous and thereby stratigraphically correlative, they are not hydraulically continuous. The surficial sediments occupy a structurally uplifted position from which they are separated from the subsurficial sediments and are most directly connected hydraulically with other younger surficial sediments.

Structural Configuration

The surficial aquifer is underlain by the Yorktown confining zone across most of the Virginia Coastal Plain south of the James River, and across the lower to middle reaches of Northern Neck, the Middle and York-James Peninsulas, and eastward (fig. 36; pl. 25). The presence of the Yorktown confining zone is variable across incised areas that are projected across some low-lying areas west and south of Chesapeake Bay (see “Yorktown Confining Zone”), where the surficial aquifer probably directly overlies the Yorktown-Eastover aquifer at numerous locations. The surficial aquifer also directly overlies incised parts of the Yorktown-Eastover aquifer where the Yorktown confining zone is truncated along three large paleochannels as much as 200 ft deep and extending across several tens of miles across Chesapeake Bay and the Virginia Eastern Shore (pl. 3, secs. BD–BD', CD–CD'; pl. 4, secs. DD–DD', ED–ED'; pl. 7, secs. FS–FS', GS–GS'), and which are inferred from geologic maps (Mixon, 1985; D.L. Powars, U.S. Geological Survey, written commun., 2004). Progressively upstream along the westernmost paleochannel, further truncation is projected where the surficial aquifer directly overlies an incised area of the Saint Marys confining unit (fig. 32; pl. 23) and the Saint Marys aquifer (fig. 31; pl. 22).

To the northwest beyond the margin of the Yorktown confining zone, the surficial aquifer is underlain mostly by the Saint Marys confining unit along the northern Fall Zone and across the upper reaches of Northern Neck and the Middle and

York-James Peninsulas (fig. 32; pl. 23). Beyond the northwestern margin of the Saint Marys confining unit, the surficial aquifer is underlain by the Calvert confining unit across most of King George County, northern Caroline County, and the far eastern corners of Stafford and Spotsylvania Counties (fig. 29; pl. 21). The surficial aquifer also is underlain by many of the deeper hydrogeologic units across numerous locally incised areas along the major rivers and some of their tributaries and along various segments of the Fall Zone, which are individually described elsewhere in this report in the sections on each of the hydrogeologic units. Although the deeper hydrogeologic units crop out along sparse cut banks of major rivers, they are otherwise almost entirely covered by the surficial aquifer.

The top of the surficial aquifer essentially is equivalent to the land surface, which grades from rolling terrain and deeply incised stream valleys in the northwest to gently rolling-to-level terrain, broad stream valleys, and extensive wetlands in the east and south. Altitude ranges from higher than 200 ft across some western uplands to 0 ft along the Atlantic coast. Broad uplands bound the basins of major rivers, including the Potomac, Rappahannock, Piankatank, Mattaponi, Pamunkey, York, Chickahominy, James, Appomattox, Blackwater, Nottoway, Meherrin, Nansemond, Elizabeth, and North Landing. Lowlands consisting of terraces, flood plains, and wetlands occupy the valley floors. The sediments that compose the surficial aquifer extend westward of the Fall Zone and beyond the Virginia Coastal Plain as erosional caps and outliers (fig. 2), which are hydraulically continuous with saprolite and other surficial deposits that form the surficial aquifer of the Piedmont.

The surficial aquifer is as thick as several tens of feet beneath some western uplands but generally thins eastward across areas of low altitude to a few tens of feet or less (pls. 3–7, all secs.). Notable exceptions to the eastward thinning include paleochannels, some parts of Chesapeake Bay, and some areas of the Virginia Eastern Shore and to the far southeast. The saturated thickness of the surficial aquifer is determined by the position of the water table, which fluctuates seasonally and over drought cycles but typically ranges from a few tens of feet below land surface beneath uplands to within a few feet or less of land surface beneath lowlands.

Recognition

Other than the sparse outcrops of deeper hydrogeologic units that are primarily along the cut banks of major rivers, sediments directly at the land surface constitute the surficial aquifer. Lithologic composition and texture, however, can vary considerably among different areas and vertically at a given location (fig. 37). Very coarse quartz sands and gravels, along with cobbles and boulders extend across broad areas of western uplands that straddle the Fall Zone and widen progressively northward across the upper reaches of Northern Neck and the York-James and Middle Peninsulas. Variably textured but generally fine-grained sands and interbedded clayey silts are present eastward across areas of intermediate altitude that extend across a 20- to 30-mi wide, southwest-northeast trending belt along the southern Fall Zone and middle reaches of Northern Neck and the York-James and Middle Peninsulas. Additional variably textured and interbedded gravels, sands, silts, clays, and peat are present farther east across broad areas of low altitude that extend across southeastern Virginia, the lower reaches of Northern Neck and the York-James and Middle Peninsulas, and areas to the east. Diverse alluvial, colluvial, estuarine, marsh, swamp, and dune deposits are present along channels, flood plains, and terraces of present-day rivers and streams, Chesapeake Bay, and the Atlantic coast. Some areas in proximity to the coast can exhibit moderate amounts of shell material, which is sparse or absent elsewhere.

Across the Virginia Coastal Plain, sand-dominated intervals of the surficial aquifer exhibit moderate grittiness in drilling response, and cuttings are returned generally in a wholly disaggregated state. In addition, relatively bright colors are commonly exhibited from pronounced iron staining and were observed during this study to include yellow (10YR 7/6 and 8/6), olive yellow (2.5Y 6/6), reddish yellow (7.5YR 6/6 and 7/8), brownish yellow (10YR 6/6), red (10R 4/6), weak red (5R 5/4), yellowish red (5YR 5/6), and dark reddish brown (5YR 3/4). Fine-grained clayey or silty interbeds typically exhibit a relatively smooth drilling response and moderate to rapid rate of advancement. Cuttings are returned as “pea-sized” chips that generally have dull colors and, in this study, included white (5Y 8/1, 5YR 8/1), light brownish gray (10YR 6/2), very pale brown (10YR 7/4), gray (5Y 6/1), and dark gray (5Y 4/1).

The surficial aquifer generally is obscured on borehole electric logs because the baseline of measurement response across the shallowest several tens of feet shifted beyond the scale of most of the logs, which were generated using analog equipment as paper strip charts. Hence, a relatively greater reliance on lithologic information from drillers’ logs and(or) cuttings descriptions, and on gamma logs where available, is necessary to discern the position of the surficial aquifer. The surficial aquifer generally exhibits a low response on gamma logs, which in many instances contrasts with the moderately elevated response of the underlying Yorktown confining zone and(or) Yorktown-Eastover aquifer.

Hydrologic Aspects

The surficial aquifer is an extensive hydrogeologic unit that functions as a pathway for ground-water flow across much of the Virginia Coastal Plain. The surficial aquifer also is a moderately and widely used ground-water supply resource, primarily for private domestic and agricultural use. Yields of a few to as much as 10 gal/min or more can be obtained from water-supply wells in favorable settings.

A single permeameter sample of the surficial aquifer had a vertical hydraulic conductivity of 0.45 ft/d (table 1), which is exceeded only by two samples of sands of the Potomac aquifer. The surficial aquifer sample also is the most coarse grained of all the permeameter samples and has a well-sorted texture, although the porosity of 35 percent is within the range of the other samples. Published values of horizontal hydraulic conductivity of the surficial aquifer resulting from well specific-capacity tests and slug tests or derived from ground-water model calibration, range across four orders of magnitude from 0.0084 to 170 ft/d (McFarland, 1997, and Laczniak and Meng, 1988, respectively; table 2). Higher values probably reflect a preponderance of coarse-grained sands, and lower values reflect more silty and medium-grained sands. The vertical hydraulic conductivity of the permeameter sample is toward the low end of the published horizontal hydraulic conductivity values partly because of anisotropy but also because samples of highly conductive but structurally incompetent sands and gravels could not be collected viably. Higher values resulting from some well tests or derived from calibration of ground-water models probably are more representative of the effective hydraulic conductivity of the surficial aquifer at the regional scale.

The surficial aquifer during 2002 produced an estimated 4 percent of the ground water used in the Virginia Coastal Plain at a rate of 5.8 Mgal/d (table 3). A rate of only 0.56 Mgal/d was reported to the DEQ by regulated industrial, municipal, and commercial users, and the remaining unregulated domestic use was estimated to be 5.2 Mgal/d. An identical rate for regulated withdrawal was reported during 2003, and the relative contribution of the surficial aquifer to the total withdrawal from the Virginia Coastal Plain remained essentially unchanged.

A random sample of domestic well records from county health departments indicates that the surficial aquifer supplies unregulated withdrawals to as many as 50 percent or more of the wells constructed since approximately 1985 across the northwestern part of the Virginia Coastal Plain, which is beyond the margin of the Yorktown-Eastover aquifer (Jason Pope, U.S. Geological Survey, written commun., 2005). By contrast, to the south and east, no more than approximately 25 percent of the wells are supplied by the surficial aquifer because the Yorktown-Eastover aquifer provides a more viable and nearly as easily developed supply.

The surficial aquifer is an important water supply in areas where it is sufficiently thick and permeable to produce appreciable well yields, primarily for low-density residential development, crop and livestock production, and landscape maintenance. As a result of continual recharge, the surficial aquifer contains freshwater across virtually its entire extent, except possibly some limited areas in direct proximity to the coast. In widespread domestic use across most rural areas are 24- to 40-in diameter bored wells, typically several tens of feet deep and cased with segmented concrete pipe. In addition, older residences along low-lying areas adjacent to some major rivers commonly have 1- to 2-in diameter jetted wells only a few tens of feet deep or less and cased with perforated galvanized steel pipe. Because the position of the water table fluctuates seasonally and over drought cycles, wells in the surficial aquifer are relatively prone to going dry on a periodic basis depending on production demand and decreasing well efficiency with age. As an additional consideration, most rural residences are served by on-site septic systems that discharge to the surficial aquifer, and wells are best sited in upgradient locations to avoid contamination. On the Virginia Eastern Shore, ground water is the sole source water supply because surface-water supplies do not exist. Because the surficial aquifer is vulnerable to contamination from widespread agricultural activities, most of the water is supplied from the underlying Yorktown-Eastover aquifer.

In addition to serving as a ground-water supply resource, the surficial aquifer performs a unique function in the ground-water-flow system. Recharge to the entire ground-water system of the Virginia Coastal Plain occurs primarily by way of the surficial aquifer. The water table is within the surficial aquifer. Although the surficial aquifer is widely unconfined, locally confined or perched conditions can exist where fine-grained interbeds are present. Water infiltrates to the water table from precipitation at the land surface. Because of the humid temperate climate, recharge on average exceeds evapotranspiration. Part of the excess water is kept in storage, thereby elevating the water table above streams and other surface-water bodies. The configuration of the water table is subparallel to the land surface, with the hydraulic gradient toward the streams. As additional infiltration reaches the water table, most of the water flows through the surficial aquifer to discharge into streams and maintain base flow (fig. 2). Based on an estimated water-table recharge rate of 10 inches per year (in/yr), rates of discharge directly to streams from 7.6 to 9.5 in/yr were simulated in a series of local-scale ground-water flow models (McFarland, 1997, 1999). Depending on the location of entry to the water table, water can take from as short as a few hours to as long as a few decades to flow through the surficial aquifer to a receiving stream. Both the quantity and quality of discharging ground water can be critical to the viability of ecosystems associated with streams and other surface-water bodies. Its proximity to land surface makes the surficial aquifer of primary concern for degradation of water quality as a result of human activities.

A relatively small amount of water from the surficial aquifer does not discharge directly to streams but rather leaks downward into deeper hydrogeologic units. Downward leakage occurs primarily beneath upland areas, where hydraulic gradients generally are downward. Beneath lowland areas and in proximity to streams and other surface-water bodies, hydraulic gradients are upward, and many of the hydrogeologic units that underlie the surficial aquifer are at or near land surface where they have been incised at various locations (pls. 8–25). As a result, some of the water from downward leakage beneath uplands laterally flows short distances and leaks back upward to discharge to nearby streams (fig. 2). Rates of downward leakage of as much as 2.4 in/yr were simulated in a series of local-scale ground-water-flow models (McFarland, 1997, 1999), with accompanying rates of upward leakage and subsequent stream discharge of as much as 1.8 in/yr. Rates of the remaining water entering the deep regional-flow system were relatively uniform, between

0.5 in/yr and 0.6 in/yr. Because the lowlands function as discharge zones, little or no direct recharge to the regional-flow system occurs at outcrops or other near-surface parts of the hydrogeologic units.

Because of the slow rate at which water leaks from the surficial aquifer into the deep regional-flow system, most of the confined aquifers of the Virginia Coastal Plain contain water as old as several tens of thousands of years (Nelms and others, 2003). This water eventually re-enters the surficial aquifer by upward leakage across downgradient areas to the east (fig. 2) or discharges directly to estuaries or the Atlantic Ocean. The surficial aquifer is in contact with underlying hydrogeologic units across a patchwork of overlapping unit margins beneath uplands and across numerous locally incised areas along major rivers, some of their tributaries, and adjacent to and beneath Chesapeake Bay. As a result, the spatial distribution and rate of both downward and upward leakage potentially are highly variable and controlled by a complex array of hydraulic connections between the confined and unconfined ground-water systems.

Summary and Conclusions

Ground water is heavily used in the Coastal Plain of eastern Virginia, at a regional rate generally exceeding 100 Mgal/d. As a result, ground-water levels have declined during much of the past century by as much as 200 ft at some major pumping centers, and flow gradients have been altered creating the potential for saltwater intrusion. The Virginia Department of Environmental Quality (DEQ) relies on continual advancement of the knowledge of Coastal Plain geology and hydrology to manage the ground-water resource. A descriptive hydrogeologic framework and a digital computer model of the ground-water-flow system developed during the U.S. Geological Survey (USGS) Regional Aquifer-System Analysis (RASA) program in the early and middle 1980s were adopted by the DEQ during the 1990s to evaluate the potential effects of current and proposed withdrawals. Further understanding has since been gained by the USGS and DEQ discovery of the Chesapeake Bay impact crater, which underlies lower Chesapeake Bay and adjacent areas, and by determination of other geological relations. Accordingly, a refined framework has been developed that provides a new regional hydrogeologic perspective by incorporating emerging findings and an advanced level of detail on the ground-water system. This refined hydrogeologic framework is being applied by the USGS to a revised ground-water-flow model that will enable the DEQ to address ongoing ground-water withdrawal by incorporating present-day hydrologic conditions and projecting potential future conditions.

The hydrogeologic framework is a resource for ground-water development and management activities in that it provides enhanced geologic understanding of the Virginia Coastal Plain in a hydrologic context. A seaward-thickening wedge of extensive, eastward-dipping strata of largely unconsolidated sediments overlies a bedrock basement and is classified into a series of 19 hydrogeologic units. Geophysical logs, lithologic descriptions, and mineralogic, paleontologic, textural, and hydrologic analyses of sediment core, drill cuttings, and(or) drillers' logs were interpreted from a regional network of 403 boreholes. Each hydrogeologic unit encompasses a volume of sediment that occupies a specific position and has a distinct function in the ground-water-flow system. Aquifers are designated as primary pathways of ground-water flow and, in part, as water-supply resources. Aquifers are further distinguished as either homogeneous or heterogeneous, based on the degree and nature of spatial variation in sediment texture and composition. Confining units are designated as regionally impeding ground-water flow. Primarily vertical leakage occurs though confining units between adjacent aquifers. Additionally and as new interpretation, confining zones are designated to approximate the variable configurations and indistinguishable relations between heterogeneous aquifers and adjacent hydrogeologic units. Flow is only locally impeded across confining zones.

The extent and configuration of each of the hydrogeologic units are presented in a series of hydrogeologic sections and structural contour maps. Correlations across borehole locations are augmented by published and unpublished geologic and hydrogeologic maps, sections, and outcrop descriptions. Additionally, areas of partial incision or complete truncation of the hydrogeologic units along river valleys and adjacent to and beneath Chesapeake Bay were projected by using geographic information system (GIS) methods. Each hydrogeologic unit is described in detail, including its geologic relations, structural configuration, recognition during drilling operations, and hydrologic aspects. Each description serves individually as a stand-alone reference on the hydrogeologic unit, but relations with other hydrogeologic units also are discussed to provide a system-wide perspective.

The Virginia Coastal Plain hydrogeologic framework discussed herein adheres to earlier interpretations and nomenclature where appropriate, but also includes alternative or wholly new interpretations where warranted by recent geological advancements and broadly expanded hydrogeologic data that provide greater detail and accuracy. In stratigraphically upward sequence, findings of particular importance include the following:

1. Fluvial-deltaic coarse sands and gravels of Early Cretaceous age compose the Potomac aquifer, which is as much as hundreds to thousands of feet deep and is the primary ground-water supply resource of the Virginia Coastal Plain. The Potomac aquifer is designated herein as a single aquifer rather than the subdivided lower, middle, and upper Potomac aquifers as previously designated. The heterogeneous Potomac aquifer contains fine-grained interbeds that are spatially highly variable and inherently discontinuous. Interbeds are not of sufficient density across a continuous expanse to function as regional

barriers to ground-water flow among distinct and vertically separated volumes of Potomac Formation sediments. The Potomac confining zone is designated to approximate a transition from the Potomac aquifer to overlying hydrogeologic units.

2. Part of the Potomac aquifer within the outer part of the recently discovered Chesapeake Bay impact crater consists of megablock beds of Potomac Formation sediments that essentially are undeformed internally but bounded by widely separated faults that possibly have decreased hydraulic conductivity locally (see item 9 below). The Potomac aquifer is entirely truncated across the inner crater. Desalinization of brackish ground water from the Potomac aquifer along the landward margin of the crater is an important recent development.

3. Recently determined geologic relations of variable sediments of Late Cretaceous age that are present only south of the James River form the basis for new or revised hydrogeologic-unit designations that include the upper Cenomanian confining unit, the Virginia Beach aquifer and confining zone, and the Peedee aquifer and confining zone. Marine, well-sorted glauconitic sands compose the Virginia Beach aquifer, which is a locally important ground-water supply resource in southeastern Virginia. Some generally coarse-grained but as yet poorly known fluvial-deltaic sediments compose the Peedee aquifer, which possibly extends slightly into Virginia from its more regional extent in North Carolina.

4. Marine, glauconitic, shelly sands of late Paleocene age compose the Aquia aquifer, which is regionally extensive but only a minor ground-water supply resource. Generally similar, but finer-grained sediments of late Paleocene to early Eocene age compose the overlying Nanjemoy-Marlboro confining unit. Both hydrogeologic units are truncated along the margin of the Chesapeake Bay impact crater.

5. Sediments of late Eocene age compose three newly designated confining units that overlie the Potomac aquifer within the Chesapeake Bay impact crater. These confining units include, from bottom to top, the impact-generated, lithologically distinctive but highly variable Exmore clast and Exmore matrix confining units and the marine, clayey Chickahominy confining unit. The three confining units collectively impede ground-water flow across the crater.

6. The Piney Point aquifer is composed of marine, partly shelly and calcified glauconitic sands of early Eocene to middle Miocene age that belong to a closely associated but spatially variable group of several geologic formations. The Piney Point aquifer is regionally extensive, overlying most of the Chesapeake Bay impact crater and beyond, but is only locally significant as a ground-water supply resource across the middle reaches of Northern Neck and the Middle and York-James Peninsulas.

7. Marine fine sands and silts of the Calvert confining unit of middle Miocene age are mostly overlain by marine clayey silts of the Saint Marys confining unit of late Miocene age, which result in a combined thickness of as much as several hundred feet that effectively separates the underlying Piney Point aquifer and deeper aquifers from overlying shallow aquifers. The two confining units are separated across two limited areas by marine shelly sands of the intervening Saint Marys aquifer of late Miocene age. One area, mostly beneath the city of Suffolk, is indicated by newly determined geologic relations. In this area, the Saint Marys aquifer is a largely unused resource but represents a limited potential alternative supply to parts of the deep Potomac aquifer that have high fluoride concentrations. The second area, underlying the Virginia Eastern Shore and indicated by only two boreholes, contains brackish water.

8. Marine shelly sands of late Miocene to late Pliocene age compose the Yorktown-Eastover aquifer, which is regionally extensive and the second most heavily used ground-water supply resource. The Yorktown-Eastover aquifer generally is no more than 200 ft deep. The Yorktown confining zone approximates a transition to the overlying surficial aquifer, which is composed of fluvial-deltaic and estuarine, variably textured sediments belonging to several geologic formations of late Pliocene to Holocene age that collectively extend across the entire land surface. The surficial aquifer is a moderately used resource. The Yorktown-Eastover aquifer and eastern part of the surficial aquifer are widely in close vertical proximity or direct contact, and are closely associated across complex and extensive hydraulic connections. These aquifers thereby jointly compose a shallow, generally semiconfined ground-water system across the eastern part of the area that is distinct and hydraulically separated from the deeper system by thick, underlying confining units.

9. Closely spaced displacements, generally of a few tens of feet, across the tops of most hydrogeologic units are attributed to vertical faults that extend from basement upward through most of the overlying hydrogeologic units. Disruption of depositional intergranular structure by movement along fault zones likely has decreased hydraulic conductivity locally in the generally incompetent sediments. The Chickahominy confining unit possibly is unique in exhibiting localized fluid flow in open fractures. Some hydrogeologic units are partly to wholly truncated where displacements are relatively large, resulting in lateral flow barriers or flow con-

duits. Faults are potentially widespread and ubiquitous, particularly in association with the Chesapeake Bay impact crater, but are not recognized in areas where sparse borehole data do not provide adequate spatial control.

10. The tops of the Saint Marys confining unit and overlying Yorktown-Eastover aquifer and Yorktown confining zone are widely sculpted by erosion. Structural contours represent present-day topography and other features, including buried paleochannels aligned with major rivers and Chesapeake Bay or, alternatively, transecting modern drainage divides. Fault displacements in underlying hydrogeologic units probably extend internally within these hydrogeologic units, but their top surfaces have been beveled by erosion. Additionally, erosion across the land surface along the valleys of major rivers and their tributaries has truncated and modified the margins of and partly incised underlying hydrogeologic units. As a result, the surficial aquifer is in contact with a patchwork of underlying hydrogeologic units, resulting in a complex array of hydraulic connections between the confined and unconfined ground-water systems.

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Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
50E 1	37.103333	-77.550000	219	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	83
50F 1	37.165278	-77.510000	189	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	134
50J 1	37.602222	-77.550000	274	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	206
50K 1	37.626389	-77.500000	214	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	164
50K 2	37.632222	-77.510000	229	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	169
50M 1	37.989722	-77.510000	209	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	159
50M 28	37.968889	-77.540000	209	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	205
50N 1	38.018611	-77.500000	229	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	167
51B 1	36.688890	-77.385000	115	95	48	—	—	—	—	—	—	—	—	—	—	—	—	—	—	24	6	nd
51B 3	36.685830	-77.385280	123	110	56	nd	—	—	—	—	—	—	nd	—	—	—	—	—	—	22	10	-130
51B 4	36.652220	-77.389170	125	nd	51	—	—	—	—	—	—	—	—	—	—	—	—	—	—	11	-3	nd
51D 1	36.943330	-77.399170	75	—	65	nd	—	—	—	—	—	—	nd	—	—	—	—	—	—	nd	25	-33
51F 7	37.169720	-77.396110	170	140	110	—	—	—	—	—	—	—	nd	—	—	—	—	—	—	88	52	6
51F 8	37.155000	-77.397780	157	127	107	—	—	—	—	—	—	—	nd	—	—	—	—	—	—	83	53	nd
51G 1	37.279167	-77.410000	56	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6
51G 3	37.345560	-77.377780	180	—	—	83	—	—	—	—	—	—	33	—	—	—	—	—	—	16	2	-155
51G 7	37.351389	-77.405556	167	—	—	123	—	—	—	—	—	—	65	—	—	—	—	—	—	nd	nd	nd
51H 5	37.472780	-77.376390	140	—	—	—	—	110	—	—	—	—	—	—	—	—	—	—	—	nd	86	-76
51H 92	37.421944	-77.446944	102	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<50
51H 93	37.421944	-77.446944	102	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<65
51H 94	37.421944	-77.446944	102	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<77
51H130	37.422222	-77.450000	102	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	93
51H131	37.422500	-77.450000	104	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	91
51H192	37.486670	-77.402500	160	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	99	44	nd
51J 8	37.551670	-77.388060	140	—	—	103	—	71	—	—	—	—	52	—	—	—	—	—	—	36	30	-80
51J 9	37.611390	-77.389720	170	—	—	120	—	64	—	—	—	—	54	—	—	—	—	—	—	7	-4	-50
51J 10	37.513890	-77.380000	155	—	—	134	—	93	—	—	—	—	77	46	—	—	—	—	—	36	24	nd
51J 11	37.513610	-77.382500	155	—	—	117	—	90	—	—	—	—	77	33	—	—	—	—	—	28	23	nd
51J 12	37.541940	-77.379170	150	—	—	103	—	77	—	—	—	—	57	—	—	—	—	—	—	30	24	-117
51K 6	37.693056	-77.420000	202	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-4
51K 14	37.638333	-77.470000	179	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	144
51K 15	37.633611	-77.430000	184	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-46
51K 16	37.676667	-77.460000	134	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	53
51M 1	37.977778	-77.490000	199	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	149
51M 2	37.980556	-77.490000	199	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	149
51M 3	37.980000	-77.490000	204	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	140

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.–Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
51M 4	37.980278	-77.490000	199	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	145
51M 6	37.772500	-77.500000	184	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	132
51M 7	37.881940	-77.463890	135	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	95
51M 8	37.882222	-77.460000	117	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	67
51M 9	37.888611	-77.470000	69	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	49
51M 10	37.884444	-77.460000	74	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	54
51M 11	37.888056	-77.460000	69	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-106
51M 18	37.969720	-77.430280	110	—	—	—	—	—	—	—	—	—	99	60	—	—	—	—	—	nd	nd	nd
51N 1	38.016940	-77.406390	200	—	—	nd	—	nd	—	—	—	—	nd	nd	—	—	—	—	—	32	16	-136
51N 2	38.026110	-77.490280	220	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	140
51P 4	38.248330	-77.421110	75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	30	-35	-275
51Q 1	38.372220	-77.375560	185	—	—	—	—	—	—	—	—	—	145	117	—	—	—	—	—	6	-22	nd
51Q 19	38.330280	-77.418890	200	—	—	—	—	—	—	—	—	—	152	100	—	—	—	—	—	66	58	nd
51Q 20	38.286940	-77.433060	150	—	—	—	—	—	—	—	—	—	—	110	—	—	—	—	—	62	20	-277
51Q 23	38.280560	-77.459720	60	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	33	-76	-170
52A 1	36.569440	-77.252220	44	nd	nd	nd	—	—	—	—	—	—	nd	—	—	—	—	—	—	6	-70	nd
52A 2	36.569440	-77.251940	42	nd	nd	nd	—	—	—	—	—	—	nd	—	—	—	—	—	—	1	-69	nd
52B 3	36.712500	-77.305560	110	80	21	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-4	-14	nd
52E 2	37.083610	-77.362220	140	—	—	—	—	—	—	—	—	—	130	—	—	—	—	—	—	nd	95	nd
52F 1	37.221111	-77.290000	131	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-39
52F 5	37.159170	-77.284440	141	nd	90	nd	—	—	—	—	—	—	nd	—	—	—	—	—	—	60	27	nd
52F 7	37.192500	-77.351110	142	nd	112	—	—	—	—	—	—	—	nd	—	—	—	—	—	—	68	26	-110
52F 8	37.203890	-77.362500	130	nd	nd	—	—	—	—	—	—	—	nd	—	—	—	—	—	—	54	14	nd
52G 1	37.300278	-77.278333	50	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<-250
52G 24	37.341940	-77.333330	71	—	—	—	—	—	—	—	—	—	52	—	—	—	—	—	—	nd	42	nd
52G 26	37.348890	-77.268610	5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-12	-23	nd
52G 29	37.367220	-77.267220	4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-43	nd
52H 3	37.493330	-77.353060	152	—	—	114	—	86	—	—	—	—	—	—	—	—	—	—	—	—	54	-66
52H 5	37.443890	-77.355000	142	—	—	97	—	77	—	—	—	—	54	40	—	—	—	—	—	32	22	nd
52H 8	37.483060	-77.367500	145	—	—	120	—	100	—	—	—	—	—	—	—	—	—	—	—	77	65	-113
52H 9	37.481940	-77.367500	140	—	—	115	—	nd	—	—	—	—	nd	—	—	—	—	—	—	nd	90	-76
52H 11	37.413333	-77.252500	125	—	—	97	—	86	—	—	—	—	38	nd	—	—	—	—	—	nd	nd	nd
52H 15	37.392220	-77.361670	85	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	nd	38	nd
52H 17	37.427220	-77.370830	135	—	—	—	—	103	—	—	—	—	—	—	—	—	—	—	—	nd	81	nd
52J 4	37.530830	-77.311940	168	—	—	158	—	80	—	—	—	—	60	37	—	—	—	—	—	8	-4	nd
52J 12	37.520000	-77.276940	160	—	—	105	—	73	—	—	—	—	54	-14	—	—	—	—	—	-37	-41	-430

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.–Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are <u>underlined</u>; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
52J 17	37.612220	-77.341670	170	—	—	115	—	76	—	—	—	—	49	14	—	—	—	—	—	-23	-32	nd
52J 18	37.544440	-77.360280	150	—	—	125	—	67	—	—	—	—	35	24	—	—	—	—	—	-8	-38	nd
52J 20	37.595830	-77.370000	140	—	—	124	—	57	—	—	—	—	28	4	—	—	—	—	—	-29	-34	-175
52J 22	37.594720	-77.368060	140	—	—	120	—	67	—	—	—	—	37	14	—	—	—	—	—	-6	-11	-172
52J 23	37.547500	-77.363610	150	—	—	124	—	70	—	—	—	—	28	6	—	—	—	—	—	-10	-22	nd
52J 25	37.550000	-77.339720	160	—	—	109	—	77	—	—	—	—	58	25	—	—	—	—	—	7	-2	nd
52J 26	37.536940	-77.359440	145	—	—	115	—	70	—	—	—	—	37	27	—	—	—	—	—	-1	-23	nd
52J 30	37.509440	-77.322220	160	—	—	116	—	77	—	—	—	—	61	39	—	—	—	—	—	20	12	nd
52J 35	37.521390	-77.350560	160	—	—	123	—	81	—	—	—	—	67	24	—	—	—	—	—	15	3	<-140
52J 48	37.545000	-77.371944	160	—	—	123	—	81	—	—	—	—	48	37	—	—	—	—	—	33	23	-138
52J 49	37.520278	-77.334444	155	—	—	115	—	75	—	—	—	—	—	—	—	—	—	—	—	35	12	nd
52J 50	37.519722	-77.365000	165	—	—	nd	—	110	—	—	—	—	90	47	—	—	—	—	—	34	25	nd
52J 52	37.508889	-77.342222	35	—	—	108	—	76	—	—	—	—	—	—	—	—	—	—	—	46	20	nd
52J 53	37.517778	-77.265556	153	—	—	nd	—	63	57	—	—	—	44	-25	—	—	—	—	—	-67	-78	-413
52J 54	37.589440	-77.276940	190	—	—	112	—	68	—	—	—	—	57	-6	—	—	—	—	—	-52	-96	nd
52K 5	37.653000	-77.373000	195	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<-127
52K 6	37.654170	-77.362780	180	—	—	133	—	82	—	—	—	—	60	-15	—	—	—	—	—	-34	-54	nd
52K 9	37.707780	-77.366940	170	—	—	124	—	83	—	—	—	—	52	5	—	—	—	—	—	-22	-32	nd
52K 10	37.625280	-77.296940	190	—	—	115	—	81	—	—	—	—	48	-46	—	—	—	—	—	-66	-73	nd
52K 11	37.686110	-77.354170	185	—	—	135	—	85	—	—	—	—	54	-1	—	—	—	—	—	-35	-70	nd
52K 14	37.628060	-77.300280	190	—	—	124	—	88	—	—	—	—	57	-36	—	—	—	—	—	-53	-59	nd
52L 4	37.768060	-77.278610	60	—	—	—	—	nd	—	—	—	—	32	-30	—	—	—	—	—	-62	-112	nd
<u>52L 10</u>	37.756111	-77.348889	105	—	—	80	—	65	—	—	—	—	60	-23	—	—	—	—	—	-44	-69	-255
52M 2	37.900560	-77.318060	105	—	—	nd	—	nd	—	—	—	—	nd	25	—	—	—	—	—	-7	-103	nd
52N 13	38.104170	-77.279720	180	nd	nd	156	nd	140	—	nd	nd	nd	74	30	nd	nd	nd	nd	nd	nd	nd	nd
52N 14	38.018330	-77.356110	145	—	—	nd	—	nd	—	—	—	—	129	75	—	—	—	—	—	13	nd	nd
52N 15	38.096670	-77.305830	230	—	—	147	—	136	—	—	—	—	80	50	—	—	—	—	—	-10	-58	nd
52N 16	38.056390	-77.346390	205	—	—	145	—	111	—	—	—	—	99	78	—	—	—	—	—	11	-43	nd
52P 8	38.180000	-77.292500	205	—	—	—	—	145	—	—	—	—	60	1	—	—	—	—	—	-97	-105	nd
52P 9	38.148890	-77.329170	160	—	—	—	—	148	—	—	—	—	88	10	—	—	—	—	—	-80	-140	nd
52P 10	38.143000	-77.354000	222	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-444
53A 3	36.584440	-77.198060	40	26	17	2	—	—	—	—	—	—	nd	—	—	—	—	—	—	-32	-77	nd
53A 4	36.584720	-77.204170	39	26	18	1	—	—	—	—	—	—	nd	—	—	—	—	—	—	-34	-74	-411
53A 6	36.516670	-77.240560	120	59	34	nd	—	—	—	—	—	—	nd	—	—	—	—	—	—	6	-64	nd
53B 3	36.705000	-77.237220	103	nd	26	14	—	—	—	—	—	—	-2	-10	—	—	—	—	—	-26	-42	nd
53B 6	36.711670	-77.204170	95	75	15	0	—	—	—	—	—	—	nd	-2	—	—	—	—	—	-20	nd	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.—Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
53B 9	36.627306	-77.125139	90	nd	32	18	—	—	—	—	—	—	7	1	—	—	-4	-8	nd	-30	-68	nd
53C 1	36.772780	-77.174440	105	nd	45	15	—	—	—	—	—	—	nd	-20	—	—	—	—	nd	-49	-57	nd
53D 3	36.978610	-77.150560	95	85	66	30	—	—	—	—	—	—	16	3	—	—	—	—	—	-6	-20	-444
53D 5	36.925000	-77.177780	90	nd	52	20	—	—	—	—	—	—	—	2	—	—	—	—	—	-5	-38	-426
53D 9	36.925000	-77.177780	90	76	50	28	—	—	—	—	—	—	21	6	—	—	—	—	—	0	-26	nd
53G 2	37.325560	-77.211940	35	—	—	—	—	—	—	—	—	—	-5	-27	—	—	—	—	—	-70	-103	nd
53G 13	37.351390	-77.193330	75	—	—	43	—	35	19	—	—	—	5	-39	—	—	—	—	—	-89	-127	nd
53G 15	37.334170	-77.190000	20	—	—	—	—	—	—	—	—	—	-20	-36	—	—	—	—	—	-91	-133	nd
53G 17	37.336670	-77.190000	20	—	—	—	—	—	—	—	—	—	-34	-52	—	—	—	—	—	-92	-132	nd
53G 21	37.336940	-77.205560	20	—	—	—	—	—	—	—	—	—	nd	nd	—	—	—	—	—	-91	-103	nd
53J 7	37.516110	-77.233060	130	—	—	90	—	nd	28	—	—	—	10	-38	—	—	—	—	—	-90	-98	-510
53J 17	37.537233	-77.202569	155	—	—	89	—	—	43	—	—	—	26	-64	—	—	—	—	—	-97	-146	nd
53K 17	37.728330	-77.144170	160	—	—	120	—	46	22	—	—	—	-32	-86	—	—	—	—	—	-162	-198	nd
53K 18	37.637500	-77.130560	30	—	—	—	—	15	-16	—	—	—	-34	-92	—	—	—	—	—	-162	-168	nd
53K 21	37.649440	-77.248890	160	—	—	94	—	62	—	—	—	—	28	-58	—	—	—	—	—	-83	-95	-395
53L 2	37.761110	-77.155830	140	—	—	100	—	39	-18	—	—	—	-44	-108	—	—	—	—	—	-182	-244	nd
53M 1	37.989440	-77.241390	89	—	—	—	—	79	—	—	—	—	59	-16	—	—	—	—	—	nd	nd	nd
53P 4	38.238330	-77.154440	180	—	—	—	—	127	64	—	—	—	36	-58	—	—	—	—	—	-134	-230	nd
53P 8	38.177220	-77.187220	35	—	—	—	—	—	—	—	—	—	15	-51	—	—	—	—	—	-120	-141	nd
53Q 7	38.292500	-77.245280	150	—	—	—	—	141	—	—	—	—	74	34	—	—	—	—	—	-40	nd	nd
53Q 9	38.329170	-77.236390	45	—	—	—	—	—	—	—	—	—	—	25	—	—	—	—	—	-52	-115	nd
54A 1	36.622780	-77.029440	35	15	5	-5	—	—	—	—	—	—	-18	-24	—	—	-33	-102	-132	-165	-175	nd
54A 2	36.616940	-77.041110	52	nd	nd	nd	—	—	—	—	—	—	nd	-16	—	—	-33	-114	-137	-168	-183	nd
54A 3	36.589170	-77.110000	100	nd	26	6	—	—	—	—	—	—	nd	-2	—	—	-12	-20	—	-31	-48	nd
54A 4	36.600560	-77.121390	97	nd	17	-1	—	—	—	—	—	—	nd	-18	—	—	-26	-32	—	-43	-57	nd
54A 5	36.618610	-77.003330	25	6	-10	-18	—	—	—	—	—	—	-24	-39	—	—	-53	-93	-132	nd	nd	nd
54B 1	36.654170	-77.003060	19	0	-20	-34	—	—	—	—	—	—	-52	-64	—	—	-95	-109	-126	-181	-203	nd
54B 2	36.657780	-77.007500	23	8	-20	-33	—	—	—	—	—	—	nd	-46	—	—	-73	-93	-128	-173	-187	<-602
54B 6	36.654170	-77.003610	20	8	-18	-38	—	—	—	—	—	—	-46	-56	—	—	-98	-112	-132	-188	-202	<-740
54B 7	36.701110	-77.013610	43	nd	nd	-6	—	—	—	nd	nd	nd	-17	-44	—	—	—	—	-62	-82	-181	nd
54B 16	36.698330	-77.044170	27	nd	nd	11	—	—	—	—	—	—	-21	-34	—	—	—	—	-47	-78	-115	nd
54B 18	36.703060	-77.095280	50	nd	30	6	—	—	—	—	—	—	-12	-18	—	—	—	—	nd	-28	-69	nd
54B 22	36.688330	-77.020000	27	8	4	-4	—	—	-43	—	—	—	-50	-56	—	—	—	—	-75	nd	nd	nd
54B 24	36.689170	-77.026940	29	12	5	-2	—	—	-36	—	—	—	-41	-51	—	—	—	—	-65	-112	-157	nd
54B 25	36.686110	-77.020280	25	nd	8	-3	—	—	-41	—	—	—	-50	-60	—	—	—	—	-72	-123	-172	nd
54B 26	36.714170	-77.012220	81	65	20	-2	—	—	-31	—	—	—	-37	-41	—	—	—	—	-52	-71	-110	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.—Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
54C 2	36.819720	-77.066940	115	85	39	-7	—	—	—	—	—	—	-25	-32	—	—	—	—	—	-38	-59	nd
54C 4	36.835830	-77.065000	115	nd	35	-5	—	—	—	—	—	—	-29	-39	—	—	—	—	—	-45	-62	nd
54D 1	36.979170	-77.005830	110	78	58	-5	—	—	—	—	—	—	-31	-50	—	—	—	—	—	-98	-112	-620
54D 5	36.913333	-77.024444	91	68	47	26	—	—	—	—	—	—	—	-38	—	—	—	—	—	-46	-89	nd
54E 7	37.032220	-77.110560	110	80	64	39	—	—	—	—	—	—	nd	25	—	—	—	—	—	2	-58	nd
54G 10	37.332220	-77.097780	35	—	—	—	—	15	-23	—	—	—	-49	-95	—	—	—	—	—	-135	-142	-565
54H 11	37.499440	-77.043330	63	—	—	19	—	10	-18	—	—	—	-87	-129	—	—	—	—	—	-163	-194	nd
54H 13	37.496940	-77.122500	110	—	—	85	—	53	24	—	—	—	-40	-100	—	—	—	—	—	-151	-158	nd
54J 4	37.535280	-77.114440	160	—	—	104	—	57	16	—	—	—	-26	-109	—	—	—	—	—	-158	-171	nd
54J 9	37.605000	-77.093060	5	—	—	—	—	—	-16	—	—	—	-79	nd	—	—	—	—	—	nd	nd	nd
54J 10	37.602500	-77.050560	50	—	—	35	—	9	-23	—	—	—	-90	-142	—	—	—	—	—	-172	nd	nd
54K 16	37.727780	-77.023610	29	—	—	nd	—	nd	-38	—	—	—	-105	-176	—	—	—	—	—	-224	-249	nd
54K 17	37.688060	-77.013610	130	—	—	95	—	10	-30	—	—	—	-104	-178	—	—	—	—	—	-230	-285	nd
54L 6	37.785280	-77.105000	42	—	—	nd	—	nd	-34	—	—	—	-54	-118	—	—	—	—	—	-216	-234	nd
54L 10	37.794170	-77.090830	52	—	—	—	—	36	-27	—	—	—	-42	nd	—	—	—	—	—	nd	nd	nd
54N 2	38.035560	-77.053610	160	—	—	120	—	70	30	—	—	—	-10	-134	—	—	—	—	—	nd	nd	nd
54P 3	38.169440	-77.038610	180	—	—	112	—	80	31	—	—	—	-6	-160	—	—	—	—	—	-280	-324	nd
54P 4	38.146940	-77.026670	105	—	—	86	—	nd	21	—	—	—	-39	-157	—	—	—	—	—	-283	nd	nd
54Q 9	38.298610	-77.048610	25	—	—	—	—	7	-5	—	—	—	-15	-115	—	—	—	—	—	-252	-278	nd
54Q 10	38.332500	-77.053890	20	—	—	—	—	8	—	—	—	—	nd	-88	—	—	—	—	—	-222	-266	nd
54Q 11	38.340000	-77.087780	140	—	—	—	—	110	—	—	—	—	-7	-74	—	—	—	—	—	-212	-320	nd
54R 3	38.378330	-77.063060	110	—	—	—	—	72	—	—	—	—	-8	-83	—	—	—	—	—	-230	-272	nd
55A 1	36.601944	-76.933333	22	nd	-3	-16	—	—	-39	—	—	—	-51	-63	—	—	-84	-110	-170	-251	-254	nd
55A 3	36.608889	-76.966944	18	nd	-6	-28	—	—	-33	—	—	—	-40	-62	—	—	-79	-104	-148	-204	-218	nd
55A 5	36.588361	-76.926833	15	0	-36	-47	—	—	-53	—	—	—	-60	-72	—	—	-87	-136	-169	nd	nd	nd
55B 13	36.713000	-76.909000	33	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<-837
55B 26	36.731389	-76.908056	27	nd	nd	nd	—	—	-62	—	—	—	-69	-86	—	—	—	—	-104	-173	-208	nd
55B 28	36.737500	-76.903889	37	nd	nd	-23	—	—	-65	—	—	—	-75	-95	—	—	—	—	-103	-157	-213	nd
55B 36	36.690278	-76.913333	37	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<-811
55B 59	36.646111	-76.894444	20	nd	nd	nd	—	—	-70	—	—	—	-78	-88	—	—	-112	-116	-168	-257	-284	nd
55B 60	36.683611	-76.913333	25	nd	nd	-10	—	—	-56	—	—	—	-68	-77	—	—	—	—	-108	-233	-249	<-805
55B 63	36.689167	-76.914167	30	16	6	-20	—	—	-62	—	—	—	-70	-90	—	—	—	—	-124	-216	-244	nd
55B 64	36.675833	-76.940556	34	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	<-348
55B 65	36.675833	-76.940556	34	nd	-7	-46	—	—	-50	—	—	—	-58	-78	—	—	—	—	-114	-186	-204	nd
55B 74	36.697458	-76.954722	91	61	1	-31	—	—	-43	—	—	—	-56	-67	—	—	—	—	-90	-168	-216	nd
55C 12	36.768056	-76.888333	15	nd	nd	nd	—	—	-69	—	—	—	-83	-109	—	—	—	—	-121	-174	-210	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.—Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
55D 5	36.904167	-76.888889	90	69	32	9	—	—	-69	—	—	—	-79	-125	—	—	—	—	—	-142	-158	nd
55E 1	37.045833	-76.935000	108	80	46	-2	—	—	-66	—	—	—	-73	-95	—	—	—	—	—	-149	-202	nd
55F 20	37.222500	-76.951667	90	70	55	-24	—	—	-58	—	—	—	-80	-113	—	—	—	—	—	-178	-205	nd
55G 4	37.312500	-76.936944	35	27	8	-40	—	—	-59	—	—	—	-101	-152	—	—	—	—	—	-186	-194	nd
55H 1	37.407778	-76.937500	10	—	—	-35	—	-54	-60	—	—	—	-124	-168	—	—	—	—	—	-219	-233	nd
55J 15	37.589722	-76.876111	90	60	10	-29	—	-59	-79	—	—	—	-163	-220	—	—	—	—	—	-250	-365	nd
55L 2	37.825000	-76.944440	170	—	—	130	—	2	-59	—	—	—	-122	nd	—	—	—	—	—	nd	nd	nd
55N 2	38.006670	-76.982780	141	—	—	96	—	43	-26	—	—	—	-83	-185	—	—	—	—	—	-303	-338	nd
55P 3	38.189440	-76.925280	21	—	—	1	—	-14	-39	—	—	—	-89	-199	—	—	—	—	—	-321	-361	nd
55P 4	38.186110	-76.916940	25	—	—	—	—	-15	-47	—	—	—	-81	-205	—	—	—	—	—	-329	nd	nd
55P 5	38.186110	-76.918060	24	—	—	—	—	-16	-46	—	—	—	-80	-204	—	—	—	—	—	-330	-372	nd
55Q 6	38.258610	-76.975000	15	—	—	—	—	-8	-39	—	—	—	-69	-201	—	—	—	—	—	-319	-331	nd
56A 1	36.586389	-76.824722	35	21	-28	-35	—	—	-60	—	—	—	-92	-105	—	—	-140	-179	-219	-332	-339	nd
56A 9	36.607000	-76.874000	80	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-908
56A 10	36.562500	-76.783889	45	nd	nd	nd	-73	-93	-104	—	—	—	-120	-136	—	—	-152	-229	-250	-391	-407	nd
56A 11	36.614722	-76.765000	80	62	7	-6	-79	-110	-121	—	—	—	-138	-154	—	—	-173	-204	-242	-381	-396	nd
56B 1	36.686944	-76.763056	84	nd	nd	nd	—	-108	-118	—	—	—	-134	-148	—	—	—	—	-159	-285	-345	nd
56B 9	36.649167	-76.829444	85	29	-23	-38	—	—	-70	—	—	—	-99	-123	—	—	-148	-159	-213	-307	-344	nd
56B 12	36.710467	-76.821825	85	55	-10	-35	—	—	-87	—	—	—	-100	-133	—	—	—	—	-160	-275	-282	nd
56F 8	37.241389	-76.810556	18	—	1	-19	—	-77	-90	—	—	—	-149	-204	—	—	—	—	—	-234	-258	nd
56F 16	37.242778	-76.804167	30	25	0	-20	—	-78	-95	—	—	—	-158	-211	—	—	—	—	—	-239	-258	nd
56F 42	37.142222	-76.840833	110	75	60	14	—	—	-82	—	—	—	-123	-202	—	—	—	—	—	-241	-256	nd
56F 52	37.248178	-76.768833	60	44	10	-78	—	-110	-114	—	—	—	-165	-221	—	—	—	—	—	-260	-264	nd
56G 6	37.318060	-76.786670	120	70	57	-24	—	-97	-104	—	—	—	-170	-232	—	—	—	—	—	-260	-279	nd
56G 61	37.354167	-76.817778	126	nd	nd	32	—	-69	-82	—	—	—	-138	-192	—	—	—	—	—	-232	-245	nd
56G 65	37.363333	-76.769444	100	nd	nd	-23	—	-102	-114	—	—	—	-173	-228	—	—	—	—	—	-258	-302	nd
56G 66	37.363056	-76.769444	100	83	62	-2	—	-101	-112	—	—	—	-162	-230	—	—	—	—	—	-262	-301	nd
56G 68	37.310278	-76.794722	109	nd	nd	nd	—	-103	-115	—	—	—	-181	-241	—	—	—	—	—	-275	-307	nd
56H 25	37.414167	-76.859167	103	41	-13	-27	—	-58	-67	—	—	—	-129	-186	—	—	—	—	—	-219	-231	nd
56H 38	37.386667	-76.801667	106	83	74	-7	—	-84	-90	—	—	—	-154	-206	—	—	—	—	—	-248	-272	nd
56H 39	37.386944	-76.801667	105	83	74	4	—	-87	-93	—	—	—	-151	-205	—	—	—	—	—	-245	-276	nd
56H 42	37.492500	-76.863611	97	47	3	-13	—	-57	-77	—	—	—	-143	-191	—	—	—	—	—	-225	-237	nd
56H 46	37.492500	-76.863611	94	63	3	-8	—	-60	-80	—	—	—	-138	-193	—	—	—	—	—	-224	-236	nd
56H 48	37.478611	-76.873889	118	48	-4	-16	—	-56	-72	—	—	—	-130	-174	—	—	—	—	—	-222	-240	nd
56J 5	37.546110	-76.808330	27	7	-24	-32	—	-74	-85	—	—	—	-159	-251	—	—	—	—	—	-285	-343	nd
56J 13	37.554720	-76.817780	27	9	-29	-49	—	-64	-84	—	—	—	-153	-236	—	—	—	—	—	-277	-304	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.–Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
56J 16	37.625560	-76.799170	25	5	-30	-39	—	-83	-97	—	—	—	-179	-263	—	—	—	—	—	-297	-369	nd
56L 5	37.827780	-76.759440	10	—	—	nd	—	nd	-132	—	—	—	-210	nd	—	—	—	—	—	nd	nd	nd
56L 6	37.875000	-76.851110	11	—	—	6	—	-5	-92	—	—	—	-169	nd	—	—	—	—	—	nd	nd	nd
56M 17	37.910830	-76.859440	28	—	—	18	—	2	-82	—	—	—	-142	-234	—	—	—	—	—	-314	-332	nd
56M 19	37.960000	-76.770280	135	—	—	69	—	-7	-123	—	—	—	-199	-297	—	—	—	—	—	-403	-449	nd
56N 7	38.087780	-76.791670	145	—	—	108	—	7	-107	—	—	—	-151	-283	—	—	—	—	—	-372	-425	nd
56N 8	38.092780	-76.821110	150	—	—	110	—	27	-86	—	—	—	-136	-282	—	—	—	—	—	-354	-400	nd
56P 2	38.169440	-76.869440	137	—	—	106	—	30	-63	—	—	—	-113	-240	—	—	—	—	—	-355	nd	nd
56P 3	38.153890	-76.837780	130	—	—	55	—	14	-96	—	—	—	-155	-282	—	—	—	—	—	nd	nd	nd
57A 1	36.602222	-76.668611	72	33	-11	-38	-114	-154	-169	—	—	—	-196	-211	—	—	-250	-272	-326	-431	-476	nd
57A 6	36.603056	-76.669167	73	nd	nd	-39	-114	-153	-172	—	—	—	-195	-211	—	—	-249	-260	-345	-427	-470	nd
57A 7	36.588792	-76.688178	57	27	15	-40	-116	-153	-169	—	—	—	-185	-195	—	—	-238	-287	-332	nd	nd	nd
57B 1	36.670278	-76.729444	65	nd	nd	-27	—	-132	-137	—	—	—	-156	-182	—	—	—	—	-201	-338	-382	nd
57B 2	36.704444	-76.687778	73	nd	-19	-41	-147	-156	-175	—	—	—	-201	-232	—	—	—	—	-252	-355	-384	nd
57B 3	36.733333	-76.763056	77	nd	nd	nd	—	—	-125	—	—	—	-141	-164	—	—	—	—	-176	-283	-295	nd
57B 6	36.713333	-76.653611	55	nd	nd	nd	-155	-181	-186	—	—	—	-205	-239	—	—	—	—	-267	-346	-387	nd
57B 7	36.722500	-76.625833	60	nd	nd	nd	-170	-199	-203	—	—	—	-222	-258	—	—	—	—	-279	-412	-441	nd
57C 12	36.781944	-76.636389	78	nd	-38	-82	-149	-182	-190	—	—	—	-212	-248	—	—	—	—	-277	-344	-365	nd
57C 15	36.802222	-76.631111	52	nd	-73	-101	-170	-206	-212	—	—	—	-232	-277	—	—	—	—	-310	-352	-363	nd
57C 16	36.838611	-76.634722	50	30	-46	-99	-166	-207	-214	—	—	—	-238	-278	—	—	—	—	-314	-332	-350	nd
57C 17	36.802778	-76.655833	40	16	-57	-86	-149	-184	-192	—	—	—	-206	-247	—	—	—	—	-274	-326	-338	nd
57C 22	36.784167	-76.643611	74	38	30	-63	-159	-194	-199	—	—	—	-225	-257	—	—	—	—	-281	-360	-379	nd
57C 29	36.803333	-76.730556	60	nd	nd	-61	—	—	-134	—	—	—	-157	-198	—	—	—	—	-238	-275	-284	nd
57C 32	36.806297	-76.743878	81	33	-45	-66	—	—	-135	—	—	—	-155	-203	—	—	—	—	-226	-247	-277	nd
57D 3	36.990833	-76.632778	50	nd	nd	-110	—	-212	-219	—	—	—	-233	-279	—	—	—	—	—	-289	-296	nd
57D 15	36.997500	-76.631111	40	nd	nd	-92	—	-202	-209	—	—	—	-224	-272	—	—	—	—	—	-280	-289	nd
57D 16	36.998611	-76.629167	35	-5	-35	-96	—	-215	-221	—	—	—	-236	-283	—	—	—	—	—	-292	-298	nd
57D 20	36.875556	-76.682222	50	40	-59	-100	-141	-166	-179	—	—	—	-203	-239	—	—	—	—	—	-260	-290	nd
57D 29	36.945308	-76.644047	56	—	41	-116	—	-180	-196	—	—	—	-218	-264	—	—	—	—	—	-282	-298	nd
57D 30	36.945300	-76.644028	60	—	45	-110	—	-181	-192	—	—	—	-211	-258	—	—	—	—	—	-279	-292	nd
57E 10	37.043333	-76.716389	85	nd	14	-37	—	—	-152	—	—	—	-175	-215	—	—	—	—	—	-261	-268	nd
57F 2	37.239167	-76.641111	85	nd	nd	-52	—	-192	-214	—	—	—	-252	-320	—	—	—	—	—	-360	-380	nd
57F 4	37.165556	-76.699167	36	nd	nd	-29	—	-152	-159	—	—	—	-194	-265	—	—	—	—	—	-290	-339	nd
57F 7	37.228611	-76.668889	53	45	-5	-68	nd	-176	-196	—	—	—	-219	-301	—	—	—	—	—	-340	-363	nd
57F 8	37.235000	-76.645278	73	52	43	-55	—	-185	-207	—	—	—	-253	-308	—	—	—	—	—	-349	-364	nd
57F 30	37.236667	-76.638611	80	—	45	-56	—	-192	-214	—	—	—	-256	-318	—	—	—	—	—	-342	-346	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.—Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
57G 1	37.296944	-76.738333	92	—	65	-24	—	-129	-144	—	—	—	-192	-265	—	—	—	—	—	-296	-298	nd
57G 21	37.260556	-76.668333	80	62	30	-16	—	-169	-192	—	—	—	-226	-300	—	—	—	—	—	-340	-352	nd
57G100	37.261944	-76.742500	105	nd	25	-19	—	-127	-138	—	—	—	-171	nd	—	—	—	—	—	nd	nd	nd
57G104	37.297967	-76.720711	89	nd	nd	-19	nd	-118	-133	—	—	—	-179	-250	—	—	—	—	—	-280	-284	nd
57G105	37.271775	-76.706656	81	71	47	-18	nd	-145	-161	—	—	—	-201	-273	—	—	—	—	—	-303	-311	nd
57H 6	37.386110	-76.687220	50	32	-43	-74	—	-144	-168	—	—	—	-222	-296	—	—	—	—	—	-342	-362	nd
57H 17	37.498060	-76.634720	80	23	-2	-25	—	-152	-194	—	—	—	-260	-364	—	—	—	—	—	-431	nd	nd
57H 20	37.439170	-76.678330	6	-5	-13	-30	nd	-130	-167	—	—	—	-226	-315	—	—	—	—	—	-365	-405	nd
57J 3	37.500000	-76.716670	51	17	-25	-49	—	-127	-137	—	—	—	-205	-297	—	—	—	—	—	-330	-390	nd
57M 5	37.955280	-76.671110	112	—	—	nd	—	-48	-172	—	—	—	-244	-336	—	—	—	—	—	-462	-544	nd
57M 7	37.953610	-76.673330	87	—	—	20	—	nd	nd	—	—	—	nd	nd	—	—	—	—	—	nd	nd	nd
57N 3	38.075000	-76.675000	120	—	—	80	—	-42	-163	—	—	—	-216	-332	—	—	—	—	—	nd	nd	nd
57P 1	38.148610	-76.672780	10	—	—	2	—	-44	-151	—	—	—	-194	-378	—	—	—	—	—	-460	-514	nd
57P 3	38.126670	-76.731390	32	—	—	18	—	-27	-120	—	—	—	-174	-308	—	—	—	—	—	-404	-452	nd
58A 2	36.568889	-76.583333	56	38	24	-103	—	-204	-217	—	—	—	-249	-273	—	—	-286	-414	-440	-550	-576	-1874
58A 75	36.550833	-76.550556	40	10	-4	-127	—	-249	-254	—	—	—	-273	-310	—	—	-320	-361	-425	-577	-654	nd
58A 76	36.615278	-76.555556	33	15	7	-133	-253	-261	-266	—	—	—	-275	-292	—	—	-305	-389	-417	-570	-580	nd
58B 1	36.744167	-76.543056	22	nd	nd	-104	—	-267	-270	—	—	—	-288	-331	—	—	—	—	-345	-451	-460	nd
58B 10	36.744722	-76.562500	20	nd	-25	-77	-238	-249	-254	—	—	—	-268	-320	—	—	—	—	-333	-441	-450	nd
58B 11	36.741111	-76.558889	20	nd	17	-94	-239	-251	-254	—	—	—	-268	-319	—	—	—	—	-332	-443	-451	nd
58B 12	36.734167	-76.553056	20	nd	nd	-92	-248	-258	-265	—	—	—	-274	-323	—	—	—	—	-335	-452	-461	nd
58B115	36.747778	-76.587222	30	13	8	-90	-219	-231	-235	—	—	—	-259	-306	—	—	—	—	-321	-440	-452	nd
58B270	36.721667	-76.615278	35	nd	nd	-68	-183	-205	-208	—	—	—	-228	-269	—	—	—	—	-284	-410	-444	nd
58B277	36.747718	-76.587179	30	—	10	-92	-219	-233	-237	—	—	—	-262	-306	—	—	—	—	-323	-446	-451	nd
58C 1	36.776389	-76.542222	20	8	-88	-133	—	-252	-257	—	—	—	-285	-330	—	—	—	—	-345	-427	-432	nd
58C 2	36.848611	-76.598056	87	29	-47	-146	-192	-223	-234	—	—	—	-256	-323	—	—	—	—	-329	-355	-361	nd
58C 3	36.830000	-76.540000	8	0	-78	-168	-243	-257	-263	—	—	—	-283	-345	—	—	—	—	-358	-410	-421	nd
58C 7	36.810556	-76.619167	43	nd	-47	-86	-180	-211	-219	—	—	—	-236	-291	—	—	—	—	-310	-352	-356	nd
58C 8	36.871667	-76.525000	22	nd	-38	-152	-256	-269	-280	—	—	—	-301	-365	—	—	—	—	-380	-396	-403	nd
58C 10	36.768056	-76.540000	24	-29	-89	-139	—	-249	-255	—	—	—	-282	-325	—	—	—	—	-341	-420	-429	nd
58C 11	36.750278	-76.585833	35	-5	-52	-87	-215	-228	-232	—	—	—	-255	-301	—	—	—	—	-317	-449	-458	nd
58C 16	36.751944	-76.584167	32	nd	-41	-86	-217	-230	-233	—	—	—	-254	-303	—	—	—	—	-320	-448	-455	nd
58C 17	36.768611	-76.540000	24	nd	-87	-138	—	-246	-257	—	—	—	-284	-327	—	—	—	—	-344	-423	-432	nd
58C 34	36.866111	-76.501944	12	nd	nd	-180	—	-302	-310	—	—	—	-327	-341	—	—	—	—	-352	-463	-481	nd
58C 44	36.830833	-76.582778	68	nd	-57	-160	-205	-230	-237	—	—	—	-253	-319	—	—	—	—	-332	-354	-372	nd
58C 46	36.858333	-76.582500	50	nd	-53	-140	-192	-218	-229	—	—	—	-250	-318	—	—	—	—	-327	-352	-363	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.–Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
58C 51	36.817778	-76.551389	20	nd	-75	-184	-239	-256	-260	—	—	—	-279	-335	—	—	—	—	-348	-404	-410	nd
58C 52	36.753333	-76.576944	10	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-1678
58C 67	36.811667	-76.588611	83	43	-29	-129	-170	-192	-197	—	—	—	-215	-282	—	—	—	—	-293	-330	-349	nd
58C 68	36.790556	-76.598889	60	nd	nd	-158	-189	-202	-205	—	—	—	-226	-276	—	—	—	—	-292	-413	-427	nd
58C 69	36.820278	-76.531111	8	0	-95	-180	-256	-270	-275	—	—	—	-293	-355	—	—	—	—	-369	-430	-440	nd
58C 70	36.863867	-76.572258	25	nd	nd	-153	-208	-237	-247	—	—	—	-267	-331	—	—	—	—	-342	-362	-370	nd
58C 76	36.864017	-76.574392	26	6	-22	-157	-208	-236	-246	—	—	—	-267	-330	—	—	—	—	-340	-361	-365	nd
58D 6	36.994167	-76.558333	22	nd	-45	-121	-191	-214	-254	—	—	—	-269	-322	—	—	—	—	—	-346	-361	nd
58D 7	36.986667	-76.613889	35	-5	-33	-121	—	-218	-227	—	—	—	-242	-295	—	—	—	—	—	-319	-325	nd
58D 9	36.957500	-76.527500	15	5	-101	-151	-233	-257	-281	—	—	—	-297	-385	—	—	—	—	—	-409	-431	nd
58D 20	36.939075	-76.586497	40	—	30	-132	—	-215	-230	—	—	—	-247	nd	nd	nd	nd	nd	nd	nd	nd	nd
58F 3	37.188889	-76.615000	22	nd	nd	-106	—	-210	-230	—	—	—	-288	-342	—	—	—	—	—	-362	-376	nd
58F 18	37.237500	-76.594167	40	—	4	-101	—	-201	-230	—	—	—	-260	-339	—	—	—	—	—	-417	-425	nd
58F 38	37.213890	-76.614440	42	21	-8	-70	—	-211	-234	—	—	—	-268	-320	—	—	—	—	—	-353	nd	nd
58F 50	37.202222	-76.569722	55	27	21	-124	—	-210	-269	-280	-376	—	—	—	—	—	—	—	—	-431	-473	nd
58F 81	37.166944	-76.554444	35	nd	nd	-125	—	-226	-277	-307	—	—	—	—	—	—	—	—	—	nd	-397	nd
58F 82	37.191389	-76.510556	56	36	26	-166	—	-255	-339	-414	-591	—	—	—	—	—	—	—	—	-665	-698	nd
58F 83	37.166389	-76.553889	37	1	-6	-127	—	-229	-280	-307	—	—	—	—	—	—	—	—	—	-381	-397	nd
58F 84	37.167222	-76.554167	33	-1	-7	-131	—	-228	-281	-312	—	—	—	—	—	—	—	—	—	-399	-408	nd
58F 85	37.166667	-76.553611	35	nd	nd	-129	—	-224	-277	-315	—	—	—	—	—	—	—	—	—	-387	-401	nd
58F 86	37.166667	-76.554444	39	nd	nd	-130	—	-228	-281	-310	—	—	—	—	—	—	—	—	—	-386	-393	nd
58F 87	37.166667	-76.554444	38	nd	nd	-126	—	-223	-279	-304	—	—	—	—	—	—	—	—	—	nd	-395	nd
58F 88	37.177778	-76.588333	34	nd	nd	-114	—	-209	-254	-318	—	—	—	—	—	—	—	—	—	-382	-387	nd
58F 90	37.186389	-76.570278	35	21	11	-119	—	-209	-266	-294	-369	—	—	—	—	—	—	—	—	-428	-461	nd
58F 91	37.186667	-76.570278	36	18	-2	-118	—	-212	-265	-294	-382	—	—	—	—	—	—	—	—	-410	-457	nd
58F 92	37.178611	-76.588056	29	nd	nd	-114	—	-207	-251	-316	—	—	—	—	—	—	—	—	—	nd	-384	nd
58F 95	37.186389	-76.569722	34	19	10	-116	—	-209	-265	-292	-374	—	—	—	—	—	—	—	—	-422	-470	nd
58F127	37.196944	-76.592778	51	33	24	-112	—	-200	-246	-273	—	—	nd	-333	—	—	—	—	—	-345	-361	nd
58F183	37.152308	-76.576672	30	20	-11	-119	—	-206	-255	-292	—	—	—	—	—	—	—	—	—	-374	-381	nd
58H 4	37.391940	-76.523890	75	40	39	-135	—	-261	-315	-346	-532	-579	—	—	—	—	—	—	—	-631	-650	nd
58H 5	37.420560	-76.529440	70	0	-10	-143	—	-244	-307	-337	-535	-579	—	—	—	—	—	—	—	-648	-665	nd
58H 9	37.437780	-76.547500	68	51	38	-117	—	-231	-297	-334	-518	-545	—	—	—	—	—	—	—	-624	-630	nd
58H 11	37.431761	-76.547467	37	nd	nd	-123	—	-248	-309	-349	-587	-634	—	—	—	—	—	—	—	-1,137	-1,143	nd
58J 5	37.608330	-76.523890	40	24	-5	-48	—	-160	-230	—	—	—	-358	-446	—	—	—	—	—	-456	-466	nd
58J 7	37.612220	-76.548060	75	48	4	-39	—	-149	-227	—	—	—	-339	-443	—	—	—	—	—	-455	-461	nd
58J 8	37.606110	-76.522500	55	32	3	-38	—	-159	-231	—	—	—	-357	-453	—	—	—	—	—	-472	-476	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.–Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
58J 9	37.606110	-76.522500	60	33	8	-36	—	-152	-222	—	—	—	-348	-446	—	—	—	—	—	-468	-477	nd
58J 11	37.564440	-76.624440	110	48	26	-40	—	-119	-174	—	—	—	-253	-384	—	—	—	—	—	-443	-462	nd
58K 6	37.638330	-76.578330	22	nd	nd	nd	—	-128	-202	—	—	—	-277	-411	—	—	—	—	—	-430	-448	nd
58K 11	37.625830	-76.555560	22	nd	nd	-42	—	-142	-218	—	—	—	-321	-436	—	—	—	—	—	-458	-474	nd
58K 19	37.633060	-76.581940	80	nd	nd	-22	—	-119	-198	—	—	—	-274	-407	—	—	—	—	—	-424	-431	nd
58K 20	37.664170	-76.594440	12	nd	nd	nd	—	-127	-198	—	—	—	-291	-428	—	—	—	—	—	-446	-460	nd
58L 7	37.772220	-76.513890	90	-5	-26	-42	—	-140	-230	—	—	—	-330	-466	—	—	—	—	—	-494	-510	nd
58L 8	37.778060	-76.591670	10	-8	-21	-36	—	-110	-194	—	—	—	-313	-443	—	—	—	—	—	-460	-472	nd
58M 6	37.965830	-76.522780	95	—	—	36	—	-85	-215	—	—	—	-320	nd	—	—	—	—	—	nd	nd	nd
58N 3	38.027780	-76.566670	20	—	—	nd	—	nd	-171	—	—	—	-256	nd	—	—	—	—	—	nd	nd	nd
58N 4	38.088890	-76.580560	15	—	—	nd	—	nd	-174	—	—	—	-253	nd	—	—	—	—	—	nd	nd	nd
58N 5	38.017500	-76.533060	11	—	—	nd	—	-63	-208	—	—	—	-287	nd	—	—	—	—	—	nd	nd	nd
59C 1	36.836667	-76.428611	10	—	-30	-150	—	-322	-344	—	—	—	-363	-369	—	—	—	—	-381	-508	-531	nd
59C 2	36.802222	-76.387500	16	nd	nd	-166	—	-352	-367	—	—	—	-387	-423	—	—	—	—	-446	-552	-582	nd
59C 7	36.784167	-76.414167	21	nd	nd	-99	—	-317	-330	—	—	—	-354	-373	—	—	—	—	-396	-522	-543	nd
59C 13	36.871667	-76.463056	16	-1	-42	-194	—	-324	-330	—	—	—	-344	-360	—	—	—	—	-383	-473	-492	nd
59C 14	36.840278	-76.406111	16	-12	-68	-158	—	-339	-360	—	—	—	-377	-380	—	—	—	—	-394	-508	-522	nd
59C 28	36.783889	-76.415278	21	1	-13	-111	—	-330	-341	—	—	—	-366	-386	—	—	—	—	-407	-530	-547	nd
59C 32	36.783056	-76.413056	21	6	-19	-108	—	-330	-344	—	—	—	-366	-385	—	—	—	—	-407	-533	-553	nd
59C 33	36.803056	-76.377500	10	-30	-88	-177	—	-371	-387	—	—	—	-408	-442	—	—	—	—	-467	-580	-598	nd
59D 1	36.881944	-76.386389	15	—	-5	-127	—	-345	-373	—	—	—	-387	-391	—	—	—	—	-403	-493	-507	nd
59D 2	36.899722	-76.487778	10	-9	-29	-176	—	-294	-304	—	—	—	-320	-382	—	—	—	—	-410	-490	-518	nd
59D 20	36.977778	-76.430556	20	2	-65	-170	—	-333	-378	-418	-584	-596	—	—	—	—	—	—	—	-746	-772	nd
59D 23	36.970833	-76.429722	11	nd	nd	-180	—	nd	-407	-453	-653	-665	—	—	—	—	—	—	—	-759	-781	nd
59D 24	36.970833	-76.429722	11	-17	-66	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
59D 25	36.965431	-76.420036	19	4	-60	-167	—	-361	-377	-438	-562	-571	—	—	—	—	—	—	—	-650	-666	nd
59E 5	37.093889	-76.378611	9	nd	nd	-132	—	-388	-442	-586	-736	-852	—	—	—	—	—	—	—	-1,424	-1,438	-2,053
59E 6	37.086389	-76.415000	12	9	4	-124	—	-357	-409	-519	-671	-776	—	—	—	—	—	—	—	nd	nd	nd
59E 31	37.095633	-76.385822	8	-2	-4	-129	—	-398	-445	-590	-764	-894	—	—	—	—	—	—	—	-1,445	-1,457	-2,047
59E 32	37.075533	-76.458514	27	-58	-93	-184	—	-328	-372	-455	-590	—	—	—	—	—	—	—	—	-615	-667	nd
59F 2	37.214170	-76.452220	10	0	-40	-119	—	-254	-350	-427	nd	nd	—	—	—	—	—	—	—	nd	nd	nd
59H 4	37.444720	-76.398330	15	6	-7	-152	—	-291	-411	-492	-719	-791	—	—	—	—	—	—	—	-1,162	-1,169	nd
59J 5	37.592500	-76.439170	25	nd	nd	-108	—	-179	-303	-355	—	—	—	—	—	—	—	—	—	-490	-507	nd
59J 6	37.533610	-76.436670	56	2	-40	-114	—	-244	-384	-408	-551	-560	—	—	—	—	—	—	—	-649	-674	nd
59J 11	37.575000	-76.394440	25	-20	-59	-108	—	-242	-406	-429	-559	-571	—	—	—	—	—	—	—	nd	nd	nd
59J 13	37.608060	-76.442780	20	5	-60	-102	—	-178	-298	-348	—	—	—	—	—	—	—	—	—	-486	-516	nd

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.–Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
59K 17	37.661390	-76.430000	15	0	nd	nd	—	-178	-295	—	—	—	-388	-512	—	—	—	—	—	-529	-539	nd
59K 18	37.676670	-76.437220	24	4	-31	-60	—	-172	-283	—	—	—	-386	-504	—	—	—	—	—	-521	-526	nd
59K 19	37.703330	-76.385830	75	30	-53	-71	—	-171	-313	—	—	—	-393	-539	—	—	—	—	—	-572	-588	nd
59K 27	37.676670	-76.401390	54	19	nd	-66	—	-167	-306	—	—	—	-410	-532	—	—	—	—	—	-546	-579	nd
59L 5	37.874170	-76.401110	75	21	0	-15	—	-137	-271	—	—	—	-371	nd	—	—	—	—	—	nd	nd	nd
59L 6	37.862500	-76.431940	85	35	-13	-29	—	-151	-278	—	—	—	-383	-539	—	—	—	—	—	-555	-562	nd
59M 7	37.918890	-76.479440	93	43	3	-12	—	-108	-243	—	—	—	-351	nd	—	—	—	—	—	nd	nd	nd
59M 8	37.905000	-76.441670	89	32	1	-13	—	-128	-255	—	—	—	-361	-497	—	—	—	—	—	-532	-555	nd
59M 9	37.931110	-76.468060	46	—	—	12	—	-108	-243	—	—	—	nd	nd	—	—	—	—	—	nd	nd	nd
60B 1	36.636389	-76.372778	17	6	-15	-106	—	-378	-390	—	—	—	-397	-415	-437	-479	-505	-557	-588	nd	nd	nd
60B 2	36.696944	-76.338611	12	nd	-34	-147	—	-418	-430	—	—	—	-442	-463	—	—	-476	-512	-561	-727	-731	nd
60B 3	36.643333	-76.338056	16	-6	-28	-137	—	-385	-407	—	—	—	-425	-434	-452	-531	-574	-600	-645	-803	-807	nd
60B 19	36.739722	-76.339444	9	-13	-29	-131	—	-409	-418	—	—	—	-431	-454	—	—	-471	-484	-507	-645	-649	nd
60B 20	36.690833	-76.342778	16	-24	-34	-150	—	-411	-421	—	—	—	-435	-458	—	—	-476	-505	-569	-727	-734	nd
60C 1	36.846111	-76.290278	12	-8	-35	-164	—	-465	-495	—	—	—	-524	-533	—	—	—	—	-547	nd	nd	nd
60C 4	36.846111	-76.290278	12	nd	nd	nd	—	-459	-492	—	—	—	-513	-528	—	—	—	—	-543	-708	-731	nd
60C 6	36.814722	-76.285833	10	-24	-52	-143	—	-459	-481	—	—	—	-508	-522	—	—	—	—	-541	-709	-729	nd
60C 7	36.854167	-76.321389	10	nd	nd	-127	—	-403	-430	—	—	—	-448	-453	—	—	—	—	-472	-617	-649	nd
60C 25	36.858611	-76.308056	5	-5	-51	-143	—	-421	-443	—	—	—	-465	-473	—	—	—	—	-505	-623	-648	nd
60C 40	36.783889	-76.365556	20	7	-10	-166	—	-366	-389	—	—	—	-401	-431	—	—	-451	-462	-484	-582	-604	nd
60C 53	36.766536	-76.294139	15	-6	-63	-160	—	-465	-476	—	—	—	-494	-509	—	—	-523	-530	-571	-718	-725	nd
60G 5-7	37.325280	-76.292780	4	-4	-21	-154	—	-335	-508	-701	-919	-1,126	—	—	—	—	—	—	—	-1,751	-1,756	-2,322
60H 5	37.428610	-76.321940	7	-16	-69	nd	—	nd	nd	nd	nd	nd	nd	nd	—	—	—	—	—	nd	nd	nd
60H 6	37.495000	-76.313330	5	-35	-77	nd	—	nd	nd	nd	nd	nd	nd	nd	—	—	—	—	—	nd	nd	nd
60J 1	37.532780	-76.330560	10	-12	-50	-134	—	-238	-422	-444	-580	-590	—	—	—	—	—	—	—	-684	-706	nd
60J 7	37.613890	-76.281940	4	-18	-92	-144	—	-225	-428	-441	-518	-533	—	—	—	—	—	—	—	-593	-617	nd
60L 21	37.838890	-76.253330	11	-12	-16	-97	—	-189	-375	—	—	—	-439	-593	—	—	—	—	—	-613	-683	nd
61A 12	36.598144	-76.208575	13	3	-28	-119	—	-521	-531	—	—	—	-549	-587	-603	-696	-783	-791	-840	-1,000	-1,012	nd
61B 11	36.707500	-76.129722	15	-59	-73	-177	—	-600	-612	—	—	—	-638	-651	-673	-740	-776	-793	-848	-1,042	-1,053	nd
61C 2	36.872500	-76.204167	13	nd	nd	-142	—	-551	-597	-650	-669	—	—	—	—	—	—	—	—	-732	-751	nd
61C 3	36.872500	-76.204167	7	-55	-63	-144	—	-555	-599	-629	-671	—	—	—	—	—	—	—	—	-766	-769	nd
61C 4	36.872500	-76.204167	7	nd	nd	-145	—	-554	-601	-649	-681	—	—	—	—	—	—	—	—	-763	-740	nd
61D 2	36.892500	-76.188056	25	-33	-93	-212	—	-607	-655	-691	-822	—	—	—	—	—	—	—	—	-925	-958	nd
61D 4	36.890278	-76.194444	24	nd	nd	-215	—	-595	-643	-668	-780	—	—	—	—	—	—	—	—	-834	-863	nd
61D 5	36.906944	-76.180556	11	nd	nd	-201	—	-632	-687	-724	-911	—	—	—	—	—	—	—	—	-1,160	-1,179	nd
62G 24	37.259077	-76.018353	11	-4	-86	-211	—	-326	-935	-987	-1,152	-1,308	—	—	—	—	—	—	—	nd	nd	-3,000

Attachment 1. Aquifer, confining-unit, and confining-zone top-surface altitudes interpreted from borehole geophysical logs and ancillary data in the Coastal Plain of Virginia.–Continued

[Borehole numbers refer to locations on plate 1; numbers of cored boreholes are in **bold**; numbers of boreholes with detailed cuttings logs are underlined; —, not present; nd, not definitive]

Borehole number	Latitude (decimal degrees)	Longitude (decimal degrees)	Top-surface altitude, in feet																			
			Land surface	Yorktown confining zone	Yorktown-Eastover aquifer	Saint Marys confining unit	Saint Marys aquifer	Calvert confining unit	Piney Point aquifer	Chickahominy confining unit	Exmore matrix confining unit	Exmore clast confining unit	Nanjemoy-Marlboro confining unit	Aquia aquifer	Peedee confining unit	Peedee aquifer	Virginia Beach confining zone	Virginia Beach aquifer	Upper Cenomanian confining unit	Potomac confining zone	Potomac aquifer	Basement bedrock
63C 1	36.866667	-75.980833	20	-26	-36	-228	—	-700	-837	—	—	—	-862	-866	—	—	-888	-897	-932	-1,074	-1,096	nd
63F 50	37.135278	-75.952222	10	-14	-70	-434	—	-613	-934	-1,077	-1,279	-1,291	—	—	—	—	—	—	—	—	—	nd
64J 14	37.585556	-75.819167	30	nd	-99	-242	-490	-731	-930	-984	-1,179	nd	—	—	—	—	—	—	—	nd	nd	nd
66M 23	37.936111	-75.605000	6	-42	-64	-340	-496	-652	-848	-1,025	—	—	—	—	—	—	—	—	—	-1,173	-1,292	nd
CA Fd 85	38.376667	-76.431667	106	—	—	35	—	-134	-219	—	—	—	-320	-472	—	—	—	—	—	-584	-676	nd
SM Bc 39	38.434722	-76.717222	165	—	—	79	—	-13	-68	—	—	—	-93	-295	—	—	—	—	—	-457	-477	nd
SM Dd 72	38.273889	-76.659444	115	—	—	54	—	-3	-102	—	—	—	-199	-316	—	—	—	—	—	-453	-493	nd

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