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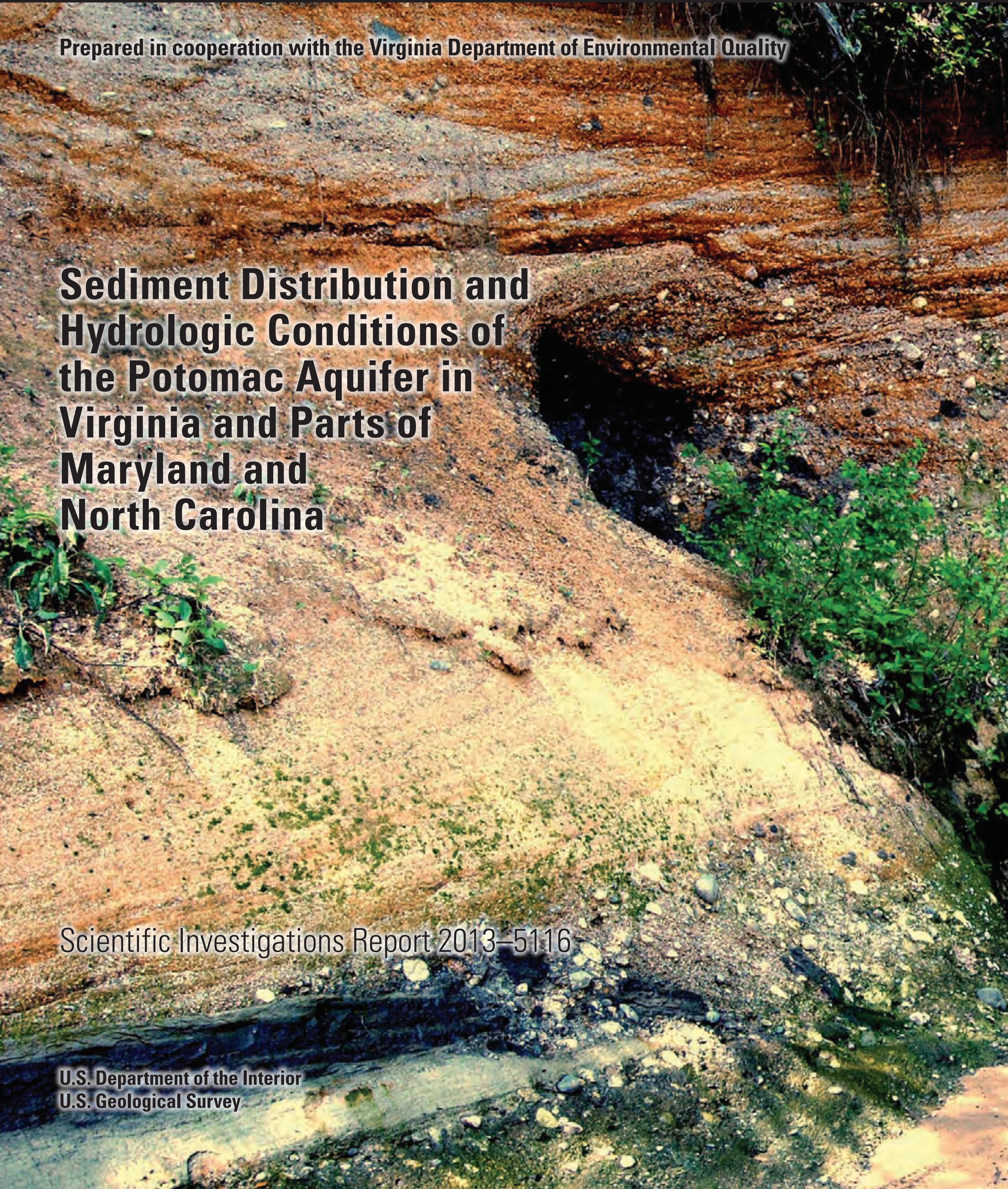
Sediment Distribution and Hydrologic Conditions of the Potomac Aquifer in Virginia and Parts of Maryland and North Carolina

Scientific Investigations Report 2013–5116

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



Cover. Outcrop of Potomac aquifer sediments at Drewry's Bluff on the James River, approximately 7 miles downstream from Richmond, Virginia. Typical sediment lithologies are locally diverse and complexly distributed. At top, coarse-grained quartzo-feldspathic sands are cross bedded and iron stained. Near center, a black 2-foot wide angular rip-up boulder of organic-rich clay is flanked by quartzite gravel. Underlying tan medium-grained quartz sand is weakly bedded. At bottom, beds of black organic-rich clay and white kaolinized feldspar sand are broken and truncated by quartzite gravel.

The outcrop is one of a series of sparse exposures of Potomac aquifer sediments, limited and localized along most of the Fall Zone in Virginia to incised major rivers. The bluff forms a 90-foot escarpment along the cut bank of the James River on the outside of a meander bend. The location during the Civil War was the site of Fort Darling, a major Confederate garrison and artillery installation that blocked Union advance along the James River toward the Richmond Capitol, and which is now part of the National Park Service Richmond Battlefields Park. Site access courtesy of Tim Mount, National Park Service.

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SALLY JEWELL, Secretary

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U.S. Geological Survey, Reston, Virginia: 2013

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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)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
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)
	Aquifer hydraulic properties	
per foot (/ft)	3.2808	per meter (/m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

All photographs are by the author.

Sediment Distribution and Hydrologic Conditions of the Potomac Aquifer in Virginia and Parts of Maryland and North Carolina

By E. Randolph McFarland

Abstract

Sediments of the heavily used Potomac aquifer broadly contrast across major structural features of the Atlantic Coastal Plain Physiographic Province in eastern Virginia and adjacent parts of Maryland and North Carolina. Thicknesses and relative dominance of the highly interbedded fluvial sediments vary regionally. Vertical intervals in boreholes of coarse-grained sediment commonly targeted for completion of water-supply wells are thickest and most widespread across the central and southern parts of the Virginia Coastal Plain. Designated as the Norfolk arch depositional subarea, the entire sediment thickness here functions hydraulically as a single interconnected aquifer. By contrast, coarse-grained sediment intervals are thinner and less widespread across the northern part of the Virginia Coastal Plain and into southern Maryland, designated as the Salisbury embayment depositional subarea. Fine-grained intervals that are generally avoided for completion of water-supply wells are increasingly thick and widespread northward. Fine-grained intervals collectively as thick as several hundred feet comprise two continuous confining units that hydraulically separate three vertically spaced subaquifers. The subaquifers are continuous northward but merge southward into the single undivided Potomac aquifer. Lastly, far southeastern Virginia and northeastern North Carolina are designated as the Albemarle embayment depositional subarea, where both coarse- and fine-grained intervals are of only moderate thickness. The entire sediment thickness functions hydraulically as a single interconnected aquifer. A substantial hydrologic separation from overlying aquifers is imposed by the upper Cenomanian confining unit.

Potomac aquifer sediments were deposited by a fluvial depositional complex spanning the Virginia Coastal Plain approximately 100 to 145 million years ago. Westward, persistently uplifted granite and gneiss source rocks sustained a supply of coarse-grained sand and gravel. Immature, high-gradient braided streams deposited longitudinal bars and channel fills across the Norfolk arch subarea. By contrast, across the Salisbury and Albemarle embayment subareas, mature, medium- to low-gradient meandering streams deposited medium- to coarse-grained channel fills and point bars segregated from fine-grained overbank deposits. The Virginia depositional complex merged northward across the Salisbury embayment subarea with another complex in Maryland. Here, additional sediments were received from schist source rocks that underwent three cycles of initial uplift and rapid erosion followed by crustal stability and erosional leveling.

Because of the predominance of coarse-grained sediments, transmissivity, hydraulic conductivity, and regional velocities of lateral flow through the Potomac aquifer are greatest across the Norfolk arch depositional subarea, but decrease progressively northward with increasingly fine-grained sediments. Confining units hydraulically separate the Potomac aquifer from overlying aquifers, as indicated by large vertical hydraulic gradients. By contrast, most of the Potomac aquifer internally functions hydraulically as a single interconnected aquifer, as indicated by uniformly small vertical gradients. Most fine-grained sediments within the aquifer do not hydraulically separate overlying and underlying coarse-grained sediments. Across the Salisbury embayment depositional subarea, however, hydraulic separation among the vertically spaced subaquifers is imposed by the intervening confining units.

The Potomac aquifer is the largest and most heavily used source of groundwater in the Virginia Coastal Plain. Water-level declines as great as 200 feet create the potential for saltwater intrusion. Conventional stratigraphic correlation has been generally ineffective at accurately characterizing complexly distributed fluvial sediments that compose the Potomac aquifer. Consequently, the aquifer's internal hydraulic connectivity and overall hydrologic function have not been well understood. Water-supply planning and development efforts have been hampered, and interpretations of regulatory criteria for allowable water-level declines have been ambiguous.

An investigation undertaken during 2010–11 by the U.S. Geological Survey, in cooperation with the Virginia Department of Environmental Quality, provides a comprehensive regional description of the spatial distribution of Potomac aquifer sediments and their relation to hydrologic conditions. Altitudes and thicknesses of 2,725 vertical sediment intervals represent the spatial distribution of Potomac aquifer sediments in the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina. Sediment intervals are designated as either dominantly coarse or fine grained and were determined by interpretation of geophysical logs and ancillary information from 456 boreholes. Sediment-interval and borehole summary statistical data indicate regional trends in sediment lithology and stratigraphic continuity, upon which three structurally based and hydrologically distinct sediment depositional subareas are designated. Broad patterns of sediment deposition over time are inferred from published sediment pollen-age data. Discrepancies in previously drawn hydrostratigraphic relations between southeastern Virginia and northeastern North Carolina are partly resolved based on borehole geophysical logs and a recently documented geologic map and corehole. A conceptual model theorizes the depositional history of the sediments and geologically accounts for their distribution. Documented pumping tests of the Potomac aquifer at 197 locations produced 336 values of transmissivity and 127 values of storativity. Based on effective aquifer thicknesses, 296 values of sediment hydraulic conductivity and 113 values of sediment specific storage are calculated. Vertical hydraulic gradients are calculated from 9,479 pairs of water levels measured between November 17, 1953, and October 4, 2011, in 129 closely spaced pairs of wells.

Borehole sediment-interval and related data provide a means to achieve high yielding production wells in the Potomac aquifer by site-specific targeting of drilling operations toward water-bearing coarse-grained sand and gravel. Advance knowledge of the potential of different parts of the aquifer also aids in planning optimal groundwater-development areas. Depositional subareas further provide a possible context for resource management. Current (2013) regulatory limits on water-level declines are relative to top surfaces of subdivided upper, middle, and lower Potomac aquifers across the entire Virginia Coastal Plain, but have the potential to exceed the same limit relative to a single undivided Potomac aquifer. By contrast, designation of the sediments as a single aquifer in the Norfolk arch and Albemarle embayment subareas—and as a series of vertically spaced subaquifers and intervening confining units in the Salisbury embayment subarea—best reflects understanding of the Potomac aquifer and can avoid the potential for excessive water-level declines. Simulation modeling to evaluate effects of groundwater withdrawals could be designed similarly, including vertical discretization and (or) zonation of the Potomac aquifer based on depositional subareas and a geostatistical distribution of aquifer properties derived from borehole sediment-interval data. Further resource-management information needs extend beyond the developed part of the Potomac aquifer, particularly across the Northern Neck and Middle Peninsula where only the shallowest part of the aquifer is known, and include structural aspects such as faults, basement bedrock, and the Chesapeake Bay impact crater.

Introduction

Groundwater in the Atlantic Coastal Plain Physiographic Province in eastern Virginia (fig. 1) is a heavily used resource. The rate of groundwater withdrawal is estimated to have been close to zero during the late 1800s, but increased continuously during the 20th century. By 2003, withdrawal rates from Coastal Plain aquifers in Virginia totaled approximately 117 million gallons per day (Mgal/d) (Heywood and Pope, 2009). As a result, groundwater levels have declined by as much as 200 feet (ft) near large withdrawal centers. Flow gradients have been reversed from a previously seaward direction to a landward direction, creating the potential for saltwater intrusion. Increasing withdrawals are likely, which could result in further water-level declines and intrusion potential.

To manage the groundwater resource, the Virginia Department of Environmental Quality (VA DEQ) regulates groundwater withdrawals throughout the Virginia Coastal Plain. Withdrawals greater than 300,000 gallons per month must be approved under the VA DEQ Groundwater Withdrawal Permit Program, which requires groundwater users to submit withdrawal-related information that is needed to evaluate the potential effects of the withdrawals on the aquifer system.

The VA DEQ relies on a sound scientific understanding of Virginia Coastal Plain geology and hydrology to make groundwater-management decisions. The U.S. Geological Survey (USGS) has been advancing knowledge of the geology and hydrology of the Virginia Coastal Plain since the beginning of the 20th century. A widely recognized description of the hydrogeology of the Virginia Coastal Plain resulted from the USGS Regional Aquifer-System Analysis (RASA) and related investigations completed during the 1980s. A hydrogeologic framework was developed (Meng and Harsh, 1988) to provide a basis for construction of a digital computer model of groundwater flow (Harsh and Laczniak, 1990). Although originally developed as a means for scientific analysis of the aquifer system, the RASA framework and model were adopted in an updated form by the VA DEQ as an aid in managing the groundwater resource (McFarland, 1998) and currently (2013) are used to evaluate the potential effects of existing and proposed withdrawals.

Following the USGS RASA investigation and related efforts, additional findings provided a basis for major changes in the description of hydrogeologic conditions, with the most significant being discovery of the largest known meteor-impact crater in the United States buried beneath the lower Chesapeake Bay (Powars and Bruce, 1999; Powars, 2000). Knowledge of the impact crater and other recently recognized geologic relations led to a complete redefinition of the aquifer system, including a refined hydrogeologic framework (McFarland and Bruce, 2006), a revised digital computer model of the groundwater-flow system (Heywood and Pope, 2009), and an updated description of groundwater chemical quality (McFarland, 2010). Large amounts of new information were synthesized to provide a refined regional perspective

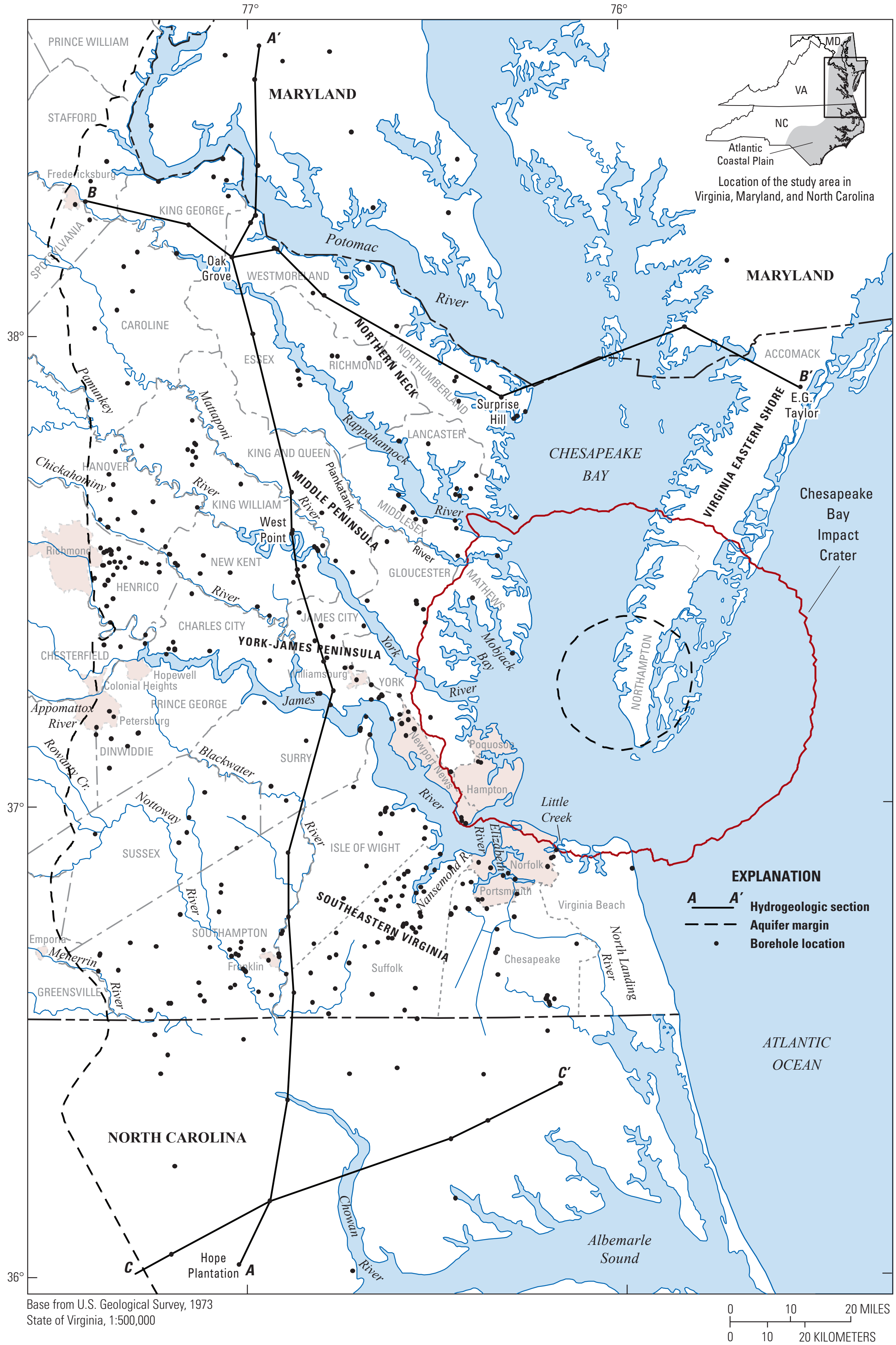


Figure 1. Locations of boreholes and hydrogeologic sections of the Potomac aquifer in Virginia and parts of Maryland and North Carolina, and of the Chesapeake Bay impact crater (from Powars and Bruce, 1999). Further details are shown on plate 1. Hydrogeologic sections are shown in figure 17.

tailored toward meeting the future needs of water-resource management.

The above works provide the most current and comprehensive understanding of the geologic relations, configuration, composition, and hydrologic aspects of a stratified series of 19 aquifers, confining units, and confining zones (collectively termed hydrogeologic units) that compose the Virginia Coastal Plain aquifer system (fig. 2). Among these, the Potomac aquifer is the largest and most heavily used source of groundwater. The Potomac aquifer extends across the entire Virginia Coastal Plain except for the inner part of the Chesapeake Bay impact crater. The aquifer is several thousand feet thick and occupies the lowermost stratigraphic position within the hydrogeologic framework (figs. 2 and 3) (McFarland and Bruce, 2006). Approximately three-fourths of the groundwater used in the Virginia Coastal Plain is produced from the Potomac aquifer at a rate of approximately 90 Mgal/d (Heywood and Pope, 2009) to supply major industries, many towns and cities, and low density residential developments in rural areas. Industrial withdrawals at the two largest pumping centers in the Virginia Coastal Plain are from the Potomac aquifer, resulting in two regional cones of depression that have water-level declines as great as 200 ft. The cones of depression dominate the hydraulic head distribution across most of the aquifer system (Heywood and Pope, 2009). Additional large withdrawals from the Potomac aquifer are located in metropolitan areas along the middle and lower reaches of the York-James Peninsula and southeastern Virginia, many for municipally operated public water systems. At some systems along the western margin of the Chesapeake Bay impact crater, desalinization of brackish groundwater is being developed to address growing demands. Additionally, numerous withdrawals from the Potomac aquifer supply diverse commercial, agricultural, community, and individual domestic uses across most of the Virginia Coastal Plain (Pope and others, 2008).

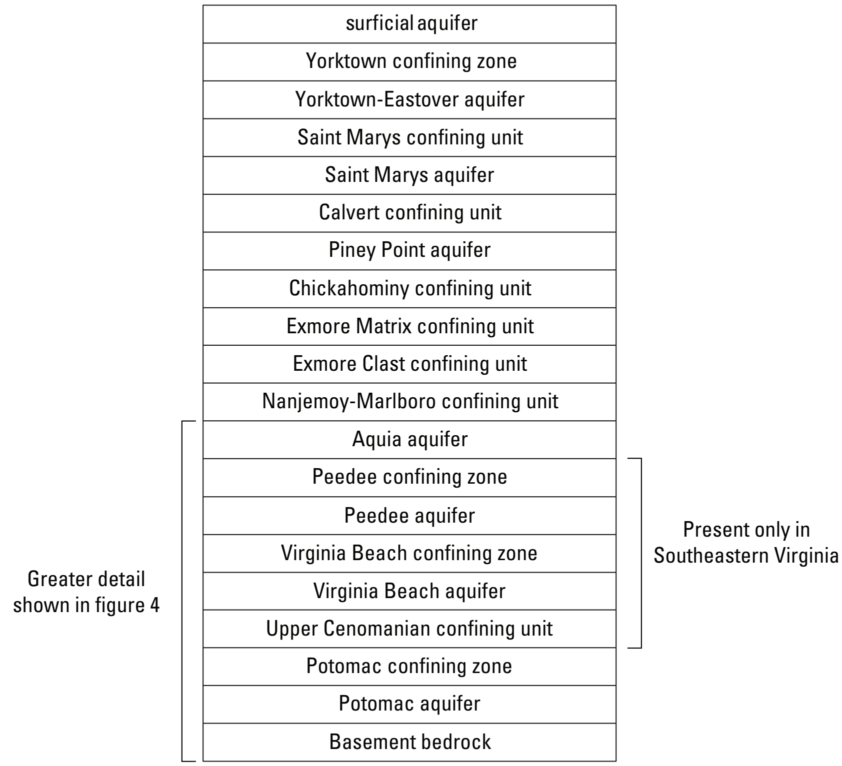


Figure 2. Simplified stratigraphic relations among hydrogeologic units of the Virginia Coastal Plain (adapted from McFarland and Bruce, 2006). Associations among some hydrogeologic units that cross stratigraphic boundaries are not shown.

The spatial distribution of Potomac aquifer sediments determines the internal hydraulic connectivity and overall hydrologic function of the aquifer within the Virginia Coastal Plain aquifer system. Conventional stratigraphic correlation, however, has been generally ineffective at accurately characterizing the sediment distribution across much of Virginia. The Potomac aquifer consists of fluvial sediments of varied compositions that are complexly distributed. Sediments of differing textures contrast sharply and commonly are highly interbedded. Individual beds typically extend only short distances of several hundred feet or less. Numerous studies of groundwater in the Virginia Coastal Plain designated these sediments as a single Potomac aquifer or equivalent, until the USGS RASA investigation subdivided them into upper, middle, and lower Potomac aquifers separated by intervening confining units (Meng and Harsh, 1988). Subdivision of the Potomac aquifer was necessary for development of a groundwater-flow model (Harsh and Laczniak. 1990). The aquifer was vertically discretized into separate model layers that were needed to simulate vertical flow within the aquifer system and were combined into a single groundwater-flow model of the entire North Atlantic Coastal Plain (Leahy and Martin, 1993). Subsequently, data collected from a large number of additional boreholes have indicated that hydraulically effective confining units are not widely present (McFarland and Bruce, 2006). Thus, a single Potomac aquifer currently (2013) is considered to function across a continuous expanse at the regional scale, but can locally exhibit discontinuities where flow is impeded by fine-grained beds.

The complex spatial distribution of contrasting Potomac aquifer sediments has hindered a full understanding of its internal hydraulic connectivity and overall hydrologic function within the Virginia Coastal Plain aquifer system. Moreover, hydrogeologic characterization of the Potomac aquifer is necessary for water-resource management for two reasons. First, water-supply planning and development efforts in Virginia are hampered by uncertainty associated with the design and siting of production wells in the heterogeneous

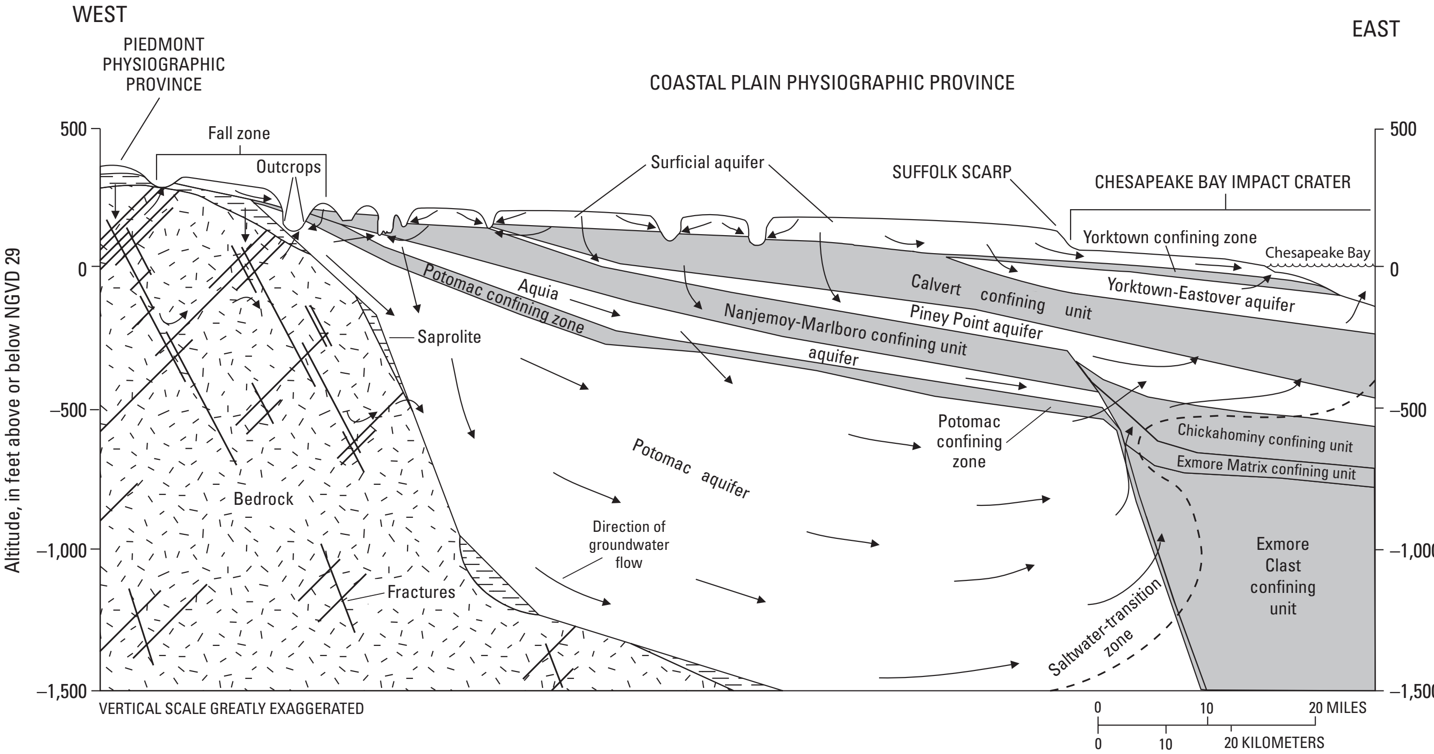


Figure 3. Generalized hydrogeologic section and directions of predevelopment groundwater flow in the Virginia Coastal Plain (altitude relative to National Geodetic Vertical Datum of 1929) (from McFarland and Bruce, 2006).

sediments of the Potomac aquifer. Well drillers, environmental consultants, and water-resource managers have short-term, practical needs for local scale information to facilitate construction of water-supply wells in the Potomac aquifer. Effective design of high yielding wells requires site-specific targeting of productive water-bearing beds composed of coarse-grained sand and gravel, and avoidance of low yielding fine-grained beds. Production-well drilling projects, however, are currently undertaken without the potential benefit of an organized and easily used source of information on water-bearing beds that are intercepted by existing boreholes. As a result, borehole advancement often entails a largely uncharted exploration of conditions specific to each drilling site. Project designs that incorporate advanced knowledge of likely target depths for well completion would more effectively optimize drilling operations and reduce costs. More broadly, water-resource planners require a means to identify optimal areas for groundwater development. Understanding broad trends in the composition of Potomac aquifer sediments is contingent upon distinguishing areas dominated by relatively dense concentrations of coarse-grained beds from concentrations of fine-grained beds.

A second need for water-resource management is designation of the sediments either as a single aquifer or a series of multiple aquifers, which has bearing on the regulation of groundwater withdrawal in Virginia. The VA DEQ limits water-level declines resulting from regulated withdrawals to no more than 80 percent of the difference between an estimate of the water level before development and the top of the aquifer being withdrawn. This criterion currently (2013) is applied relative to the subdivided upper, middle, and lower Potomac aquifers as delineated by the USGS RASA investigation. Many withdrawals, however, would likely exceed the limit for the same criterion relative to a single undivided Potomac aquifer because the top of the aquifer generally is higher than those of the earlier designated middle and lower aquifers. More fundamentally underlying the regulatory criterion, a general understanding of how the spatial distribution of contrasting sediments controls internal hydraulic connectivity within the Potomac aquifer is needed to determine the overall function of the aquifer system.

To address these needs, an investigation was undertaken by the USGS in cooperation with the VA DEQ during 2010–11 to provide a comprehensive regional description of the Potomac aquifer in the Virginia Coastal Plain. Existing groundwater data were compiled and analyzed to characterize the spatial distribution of Potomac aquifer sediments and interpret their relation to hydrologic conditions.

Purpose and Scope

The Potomac aquifer is characterized here to address information needs for water-resource management in the Virginia Coastal Plain. Both specific information to support water-supply planning and development and a broadened perspective to understand the hydrologic function of the

Potomac aquifer are provided. First, a generalized description is given to discuss various hydrogeologic designations of the Potomac aquifer, its configuration, and distribution of groundwater flow.

Next, a detailed geologic characterization of the Potomac aquifer is presented. Reader familiarity with basic geologic terminology and processes is assumed. Lithologies and associated depositional processes of fluvial sediments composing the Potomac aquifer are described. The spatial distribution of aquifer sediments is then presented in the form of altitudes and thicknesses of vertical sediment intervals intercepted by existing boreholes located in the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina. Sediment intervals are designated as either dominantly coarse or fine grained, as determined from interpretations of borehole geophysical logs and ancillary information. Borehole sediment-interval data are presented in maps and hydrogeologic sections, and tabulated in digital data-spreadsheet files. Trends among sediment intervals and borehole summary statistical data are examined to infer broad contrasts between parts of the Potomac aquifer dominated by either coarse- or fine-grained sediments. Three hydrologically distinct depositional subareas are designated on the basis of relations among sediment texture, stratigraphic continuity, and regional structure. Sediment-age relations are discussed, and a new conceptual model is introduced to theorize the depositional history of the sediments and to geologically account for sediment distribution.

Various hydrologic conditions are related to the spatial distribution of Potomac aquifer sediments. Hydraulic properties of the sediments are analyzed from documented aquifer pumping tests and are related to contrasting lateral groundwater velocities inferred from published groundwater age-dating studies. In addition, vertical hydraulic connectivity among sediments within the Potomac aquifer and with overlying aquifers is characterized on the basis of vertical hydraulic gradients calculated from water levels measured in closely spaced pairs of wells.

Relevance of the above information to water-resource management is discussed. Guidance is provided for using borehole sediment-interval data to target productive water-bearing beds for construction of water-supply wells in the Potomac aquifer and to identify optimal parts of the aquifer for groundwater development. In addition, various aspects of the sediment distribution are examined with regard to the regulation of groundwater withdrawal and evaluating its effects and further information needs.

Description of the Study Area

The Virginia Coastal Plain occupies an area of approximately 13,000 square miles (mi^2) (fig. 1). The climate is temperate and humid, with annual precipitation of more than 40 inches (in.; National Weather Service, 1996). The region generally is 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 six counties (Gloucester, Isle of Wight, James City, Southampton, Surry, and York) and 10 cities (Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Williamsburg, Chesapeake, Suffolk, and Virginia Beach). The latter three cities are large—comparable to the counties in land area—and include rural as well as urban land uses. The remainder 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 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 major rivers including the Potomac, Rappahannock, York, James (fig. 1), and others. Lowlands consisting of terraces, floodplains, and wetlands occupy valley floors and are flanked by broad uplands along basin boundaries. Relict erosional scarps associated with the rivers bound the uplands and lowlands (Johnson and Ramsey, 1987), but are obscured in places by the present-day tributary drainage pattern. Land-surface altitude ranges from over 300 ft across some western uplands to 0 ft along the Atlantic coast.

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. Distinct landmasses defined by the estuarine rivers include, from north to south, the Northern Neck, Middle Peninsula, York-James Peninsula, and southeastern Virginia (fig. 1). Chesapeake Bay separates these parts of the Virginia Coastal Plain to the west from the Virginia Eastern Shore to the east.

Geologic Setting

The Coastal Plain is underlain by a seaward-thickening wedge of regionally extensive, generally eastward-dipping strata of unconsolidated to partly consolidated sediments of Cretaceous, Tertiary, and Quaternary age that unconformably overlie a basement of consolidated bedrock (fig. 3). The sediment wedge extends from Cape Cod, Massachusetts, southward to the Gulf of Mexico and offshore to the Continental Shelf. Sediment thickness in Virginia ranges from 0 ft at its western margin to more than 6,000 ft along the Atlantic coast. 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 Ocean in response to changes in sea level. A thick sequence of nonmarine strata primarily of Cretaceous age is overlain by a thinner sequence of marine strata of Tertiary age, which is in turn overlain by a veneer of nearly flat-lying terrace and floodplain deposits primarily of Quaternary age.

Coastal Plain sediments in Virginia were further affected during the Tertiary Period by the impact of an asteroid or comet near the mouth of the present-day Chesapeake Bay (Powars and Bruce, 1999). The buried Chesapeake Bay impact crater is greater than 50 miles (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 as deep as basement bedrock. Subsequent sediment deposition has buried crater-fill sediments 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) (fig. 3), 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 adjacent to the Piedmont is designated as the Fall Zone. Numerous falls and rapids are present in streams where gradients increase across the transition from resistant bedrock onto more easily eroded sediments. From the Fall Zone, the Piedmont bedrock slopes eastward beneath the sediment wedge to constitute the basement that underlies the Coastal Plain. The Fall Zone encompasses a belt several miles wide with an intricate configuration of surface exposures of sediment and bedrock. Streams have eroded through Coastal Plain sediments to expose Piedmont bedrock in their valley floors, whereas interstream divides are capped by uneroded sediments overlying the bedrock (Mixon and others, 1989).

Groundwater Conditions

Sediments of the Virginia Coastal Plain are represented by a hydrogeologic framework of aquifers, confining units, and confining zones, collectively termed hydrogeologic units (fig. 2) (McFarland and Bruce, 2006). Permeable sediments that act as regionally extensive conduits for groundwater flow are designated as aquifers, and less permeable sediments that partly restrict flow are designated as confining units. Less distinct transitional intervals between aquifers and confining units are termed confining zones. Parts of some aquifers provide a widely used supply of water in Virginia.

A complex history of sediment deposition has produced numerous lateral variations in lithology. Consequently, the positions of hydrogeologic-unit margins do not coincide, and their areal distribution has a complex, overlapping “patchwork” configuration. In particular, some units pinch out westward toward the Fall Zone (fig. 3), where the vertical sequence of sediments varies widely compared to other parts of the Coastal Plain. In addition, major discontinuities among units are present along the margin of the Chesapeake Bay impact crater. None of the hydrogeologic units extends across the entire Virginia Coastal Plain.

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

Groundwater in the Coastal Plain is recharged principally by precipitation that infiltrates the land surface and percolates to the water table. Most of the unconfined groundwater flows relatively short distances and discharges to nearby streams, but a small amount leaks downward to recharge the deeper confined aquifers (fig. 3) primarily along the Fall Zone and beneath surface-drainage divides between major river valleys. 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 bedrock imposes a relatively impermeable underlying boundary. Localized flow interactions are theorized to occur between bedrock fractures and the overlying sediments, but the extent and magnitude of these interactions are not well known.

Because of the stratification of the Coastal Plain sediments, horizontal hydraulic conductivity generally is greater than vertical hydraulic conductivity. Hence, flow through the confined aquifers is primarily lateral in the down-dip direction to the east (fig. 3) toward large withdrawal centers and major discharge areas along large rivers and the Atlantic coast. Contrasting density between freshwater and saltwater to the east causes the confined groundwater to discharge by upward leakage across intervening confining units. In addition, hydraulic boundaries along the Chesapeake Bay impact crater have been theorized to cause a lateral divergence of flow to either side of the impact crater (McFarland, 2010).

Methods of Investigation

Altitudes and thicknesses were determined for 2,725 vertical sediment intervals within the Potomac aquifer that are designated as either dominantly coarse or fine grained. Geophysical logs and descriptions of sediment cuttings and cores were interpreted from 456 boreholes located in the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina (fig. 1; pl. 1). Borehole geophysical logs and ancillary information were obtained from records at the USGS Virginia Water Science Center, a dataset provided by the Maryland Geological Survey (MGS), and a North Carolina Department of Natural Resources (NCDNR) Web site at *http://www.ncwater.org/Data_and_Modeling/Ground_Water_Databases/logaccess.php*. Sediment intervals were determined from all geophysical logs that span the Potomac aquifer in the revised hydrogeologic framework (McFarland and Bruce, 2006), as well as additional logs obtained since the framework was completed.

Hydraulic properties of Potomac aquifer sediments were analyzed from results of 197 aquifer pumping tests documented in diverse sources. Values of vertical hydraulic gradient were calculated from 9,479 pairs of water levels measured between November 17, 1953, and October 4, 2011, in 129 closely spaced pairs of wells. Historical water-level data were obtained from the USGS National Water Inventory System (NWIS) for Virginia, Maryland, and North Carolina, and from the NCDNR Web site at *http://www.ncwater.org/Data_and_Modeling/Ground_Water_Databases/wellaccess.php*. Vertical gradients between wells open to the Potomac aquifer were distinguished from gradients between wells in the Potomac aquifer and wells in overlying aquifers.

Description of the Potomac Aquifer

Potomac aquifer sediments have been described using various geologic and hydrogeologic designations. The Potomac aquifer exhibits distinct structural and hydrologic features. Flow through the Potomac aquifer is a function of relations among sediment hydraulic properties, recharge and discharge areas, and hydrologic boundaries and stresses.

Hydrogeologic Designations

Coastal Plain sediments exhibit widely varying compositions and stratigraphic relations as a result of long and complex depositional histories. The sediments have been designated by numerous studies as geologic formations or groups of formations to characterize their depositional history and as hydrogeologic units (such as aquifers and confining units) to characterize their transmission and storage of water. Because the composition of the sediments is closely related to their depositional history and hydraulic properties, corresponding names have traditionally been used to designate both geologic formations and closely related hydrogeologic units, although their boundaries commonly do not exactly coincide. Stratigraphic relations that result from the depositional history of the sediments must be considered conjunctively with their hydraulic properties to provide context and impose constraints on interpretations of their hydraulic connectivity.

McGee (1886) is widely cited as having made the first designation of the Potomac Formation for sediments of fluvial origin that crop out along the western margin of the Coastal Plain in Virginia and Maryland. Because outcrops of the Potomac Formation are relatively sparse in Virginia, descriptions of the Potomac Formation are not included in many surficial geologic maps and similar studies of the Virginia Coastal Plain. Numerous subsurface studies, however, have designated these sediments as the Potomac Formation, Potomac Group, Potomac aquifer, or principal artesian aquifer (Clark and Miller, 1912; Sanford, 1913; Cederstrom, 1939, 1941, 1943, 1945a, 1945b, 1946a, 1946b, 1957, 1968; Sinnott, 1969b; Commonwealth of Virginia, 1973, 1974; Teifke, 1973; Virginia State Water Control Board, 1973; Brown and Cosner, 1974; Lichtler and Wait, 1974; Cosner, 1975, 1976; Siudyla and others, 1977; Ellison and Masiello, 1979; Newton and Siudyla, 1979; Harsh, 1980; Hopkins and others, 1981; Larson, 1981; Siudyla and others, 1981; Wigglesworth and others, 1984).

Common among all of the above studies, Potomac Formation sediments were designated as a single aquifer. By contrast, the USGS RASA investigation and several closely collaborative studies divided these sediments in Virginia into upper, middle, and lower Potomac aquifers separated by intervening confining units (fig. 4) (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Meng and Harsh, 1988; Harsh and Laczniak, 1990). Subdivision of the Potomac aquifer was largely based on a single, then recently completed, corehole at Oak Grove in Westmoreland County (Reinhardt and others, 1980) (fig. 1). This corehole was heavily relied on as the type stratigraphic section to define the sediment sequence for the entire Virginia Coastal Plain across areas more than 100 mi to the south. Designation of the confining units that separate the subdivided aquifers was based on stratigraphic correlation among vertical intervals theorized to contain relatively dense concentrations of local-scale beds rather than regionally extensive fine-grained beds. Correlated intervals were viewed as functioning hydraulically across a continuous expanse as regional barriers to flow between intervening coarse-grained sand and gravel of the three aquifers. No explicit account was made, however, of the depositional history and related processes that would have concentrated the fine-grained sediments that constitute the confining units.

The same subdivision of the sediments was made by integrated RASA investigations by the USGS in Maryland and North Carolina (fig. 4). In Maryland, continuity was inferred between the Patapsco aquifer and the upper and middle Potomac aquifers in Virginia, and the Patuxent aquifer and lower Potomac aquifer (Vroblesky and Fleck, 1991). The same relation has been more recently applied (Drummond, 2007). In North Carolina, continuity was inferred between the upper Cape Fear aquifer and the upper Potomac aquifer in Virginia, the lower Cape Fear aquifer and middle Potomac aquifer, and the lower Cretaceous aquifer and lower Potomac aquifer (Winner and Coble, 1996). Similar designations were made in Delaware, New Jersey, and New York, and subsequently a single hydrogeologic framework was developed for the entire North Atlantic Coastal Plain (Trapp, 1992).

Subdivision of the Potomac aquifer facilitated each of the integrated RASA investigations to vertically discretize the aquifer for development of a series of groundwater-flow models of the Coastal Plain in Virginia, Maryland, and North Carolina (Harsh and Laczniak, 1990; Fleck and Vroblesky, 1996; Giese and others, 1997). Modeling techniques of that time required the designation of separate aquifers to enable representation as separate model layers in order to simulate vertical flow within the aquifer system. Moreover, a uniform aquifer classification was used among the integrated studies for the layers to be combined into a single groundwater-flow model of the entire North Atlantic Coastal Plain (Leahy and Martin, 1993).

Following the USGS RASA investigations, the hydrogeologic framework of the Virginia Coastal Plain was revised (McFarland and Bruce, 2006) to explicitly represent newly discovered features of the aquifer system, including the Chesapeake Bay impact crater (Powars and Bruce, 1999), the James River structural zone, and other geologic relations in southeastern Virginia (Powars, 2000). A revised groundwater-flow model (Heywood and Pope, 2009) and hydrochemical characterization (McFarland, 2010) that was based on the revised framework indicated that the entire aquifer system is strongly affected by the impact crater, which has a major influence on groundwater flow and the saltwater-transition zone.

The revised hydrogeologic framework (McFarland and Bruce, 2006) designates a single Potomac aquifer in Virginia on the basis that laterally continuous and hydraulically effective confining units within Potomac Formation sediments are not widely present. A large number of additional boreholes revealed many locations where previously designated confining-unit intervals include predominantly coarse-grained sediment. Moreover, both coarse- and fine-grained beds commonly exhibit highly variable thicknesses and large vertical offsets across relatively short distances, which do not align with any consistent regional structural trend. Conventional stratigraphic correlation to delineate regionally continuous, lithologically uniform volumes of sediment within the Potomac aquifer is generally ineffective in Virginia. Most concentrations of fine-grained beds are of local extent of several miles or less. Hydraulic evidence further indicates that Potomac Formation sediments function as a single aquifer. Potentiometric surfaces mapped for the separate upper, middle, and lower Potomac aquifers (Hammond and others, 1994a, b, c) are broadly similar and do not indicate widespread large vertical hydraulic gradients that would result if confining units were regionally continuous (see section “Vertical Hydraulic Connectivity”). The most recent groundwater-flow model (Heywood and Pope, 2009) represents the single Potomac aquifer in Virginia with multiple model layers, which simulate vertical gradients and flow within the aquifer without requiring subdivision into multiple aquifers.

The most recent hydrogeologic characterizations of the Virginia Coastal Plain (McFarland and Bruce, 2006; Heywood and Pope, 2009; McFarland, 2010) are followed here and consider the Potomac aquifer in Virginia to consist of all lower Cretaceous to lowermost upper Cretaceous fluvial sediments of the Potomac Formation (fig. 4). Both undisrupted Potomac Formation sediments of 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 are designated as composing the Potomac aquifer. Also tentatively included here are lowermost lower Cretaceous fluvial sediments of the Waste Gate Formation that directly overlie basement bedrock along the Atlantic coast (Hansen, 1982, 1984).

Configuration

The top surface of the Potomac aquifer in Virginia slopes generally to the east (fig. 5). Offshore from the Atlantic coast, the sediments extend beneath the present-day Continental Shelf to terminate at the Continental Slope. Both onshore and offshore sediments are partly to wholly excavated within the Chesapeake Bay impact crater. Fault-bounded megablocks consisting of Potomac Formation sediments are currently designated (McFarland and Bruce, 2006) to compose the Potomac aquifer within the partially excavated outer part of the impact crater. Little information currently exists, however, on the spatial distribution and hydrologic effects of megablock bounding faults, as well as possible internal disruption of sediments within megablocks. Rotation and (or) overturning of megablocks is indicated by an inverted sequence of sediment pollen-age zones exhibited among samples of sediment core from borehole 58F 50 located in the city of Newport News (see section “Sediment Pollen-Age Zonation”). Faulting and other structural features also likely extend an unknown distance beyond the impact crater across a more widespread disruption zone. A small number of faults have been mapped by other studies and (or) inferred by large vertical offsets among hydrologic-unit contacts between closely spaced boreholes (fig. 5). Potentially many more faults remain unknown. Within the inner impact crater, the Potomac aquifer is wholly excavated to create a structural window to underlying basement bedrock. Crater-fill sediments that are designated as other hydrogeologic units directly overlie bedrock within the inner impact crater.

The bottom surface of the Potomac aquifer in Virginia coincides with the top surface of basement bedrock, which thereby forms the lower boundary of the Potomac aquifer and the entire Coastal Plain aquifer system (fig. 3). Thin intervals of saprolite formed from weathered bedrock are preserved in places. The bedrock slope is generally to the east, but the slope is steeper than that of the top of the Potomac aquifer, which has resulted in an eastward-thickening wedge shape. Bedrock exhibits an undulating configuration that results from adjacent major structural features (fig. 6). The broadly uplifted area across the central and southern parts of the Virginia Coastal Plain is known as the Norfolk arch. Structurally lower adjacent areas are known as the Salisbury embayment to the north and the Albemarle embayment to the south. Further details of the composition and structural features of bedrock are among the least well known aspects of the aquifer system. Bedrock is commonly assumed to be impermeable relative to the overlying sediments, but some permeable zones may exist where Mesozoic-age sedimentary basins are present. The spatial distribution and hydrologic effects of faults and fractures that likely pervade bedrock are also largely unknown.

The Potomac aquifer is closest to land surface along the Fall Zone. Outcrops of Potomac Formation sediments in Virginia are areally extensive only north of Fredericksburg (Mixon and others, 1989) along a relatively broad belt that extends northward into Maryland. Westernmost Potomac

AGE DESIGNATIONS				GEOLOGIC INVESTIGATIONS			
				ATLANTIC COASTAL PLAIN	NORTH CAROLINA	VIRGINIA	MARYLAND
ERA	PERIOD	EPOCH	POLLEN ZONE	Owens and Gohn, 1985	Weems and others, 2009	Powars and Bruce, 1999; Powars, 2000	Drummond, 2007; Hansen, 1982, 1984
Cenozoic	Tertiary	late Paleocene	not used	not used	Aquia Formation		
		early Paleocene			Jericho Run Formation	Brightseat Formation	
Mesozoic	Cretaceous	Late	VII and younger	sequence 6	Peedee Formation[2]	clayey silty sand[3]	Monmouth Group
				sequence 5		organic-rich clay[3]	
					Donoho Creek		Matawan Group
				sequence 4	Caddin Formation	glauconitic quartz sand[3]	
			?[1]		Sheperd Grove Formation		Magothy Formation
			V	sequence 3	Pleasant Creek Formation	Red Beds	not identified
					Cape Fear Formation	glauconitic sand	
			IV	sequence 2	Clubhouse Formation	upper Cenomanian Beds	
			III	sequence 1	not identified	Potomac Formation	Patapsco Formation
		Early	II				
			I		Patuxent Formation		Arundel Formation
							Patuxent Formation
			pre-I				Waste Gate Formation
	Jurassic	undifferentiated		basement			
	Triassic						
Paleozoic Proterozoic							

[1]Stratigraphic position of transition from zone V to zone VII in Virginia is uncertain.
[2]Presence inferred from Sohl and Owens (1991).
[3]Age relation of units in Virginia younger than pollen zone V to units in adjacent States is uncertain.
[4]Not recognized in Lautier (1998).
[5]Absent in Virginia in Lautier (1998).
[6]Not recognized in Drummond (2007).
[7]Subdivided into upper and lower units in Drummond (2007).

Figure 4. Expanded geohydrostratigraphic chart of sediments of Cretaceous through early Tertiary age in the Virginia Coastal Plain and

HYDROGEOLOGIC INVESTIGATIONS					
NORTH CAROLINA	VIRGINIA				MARYLAND
Winner and Coble, 1996; Lautier, 1998; Gellici and Lautier, 2010	Meng and Harsh, 1988	Harsh and Laczniak, 1990	Hamilton and Larson, 1988; Laczniak and Meng, 1988	McFarland and Bruce, 2006	Vroblesky and Fleck, 1991; Drummond, 2007
Beaufort aquifer	Aquia aquifer				Aquia-Rancocas aquifer
Peedee confining unit[3]	Brightseat confining unit	upper Potomac confining unit	upper Potomac confining unit	Peedee confining zone	upper Brightseat confining unit
	Brightseat aquifer				Brightseat aquifer[6]
		confining unit 5	Peedee confining unit		Lower Brightseat confining unit[6]
Peedee aquifer[3]		aquifer 5	Peedee aquifer	Peedee aquifer	Severn aquifer[6]
Black Creek confining unit[4]	upper Potomac confining unit	confining unit 4	Virginia Beach confining unit	Virginia Beach confining zone	Severn confining unit[6]
Black Creek aquifer[3]					Matawan aquifer[6]
					Magothy confining unit[6]
					Magothy aquifer
upper Cape Fear confining unit					Patapsco confining unit[7]
		aquifer 4	Virginia Beach aquifer	Virginia Beach aquifer	
				upper Cenomanian confining unit	
upper Cape Fear aquifer	upper Potomac aquifer	Brightseat-upper Potomac aquifer	Upper Potomac aquifer	Potomac confining zone	Patapsco aquifer[7]
lower Cape Fear confining unit[5]	middle Potomac confining unit			Potomac aquifer	
lower Cape Fear confining unit	middle Potomac aquifer				
lower Cretaceous confining unit[4]	lower Potomac confining unit				Potomac confining unit
lower Cretaceous aquifer	lower Potomac aquifer				Patuxent aquifer
basement					

adjacent parts of Maryland and North Carolina.

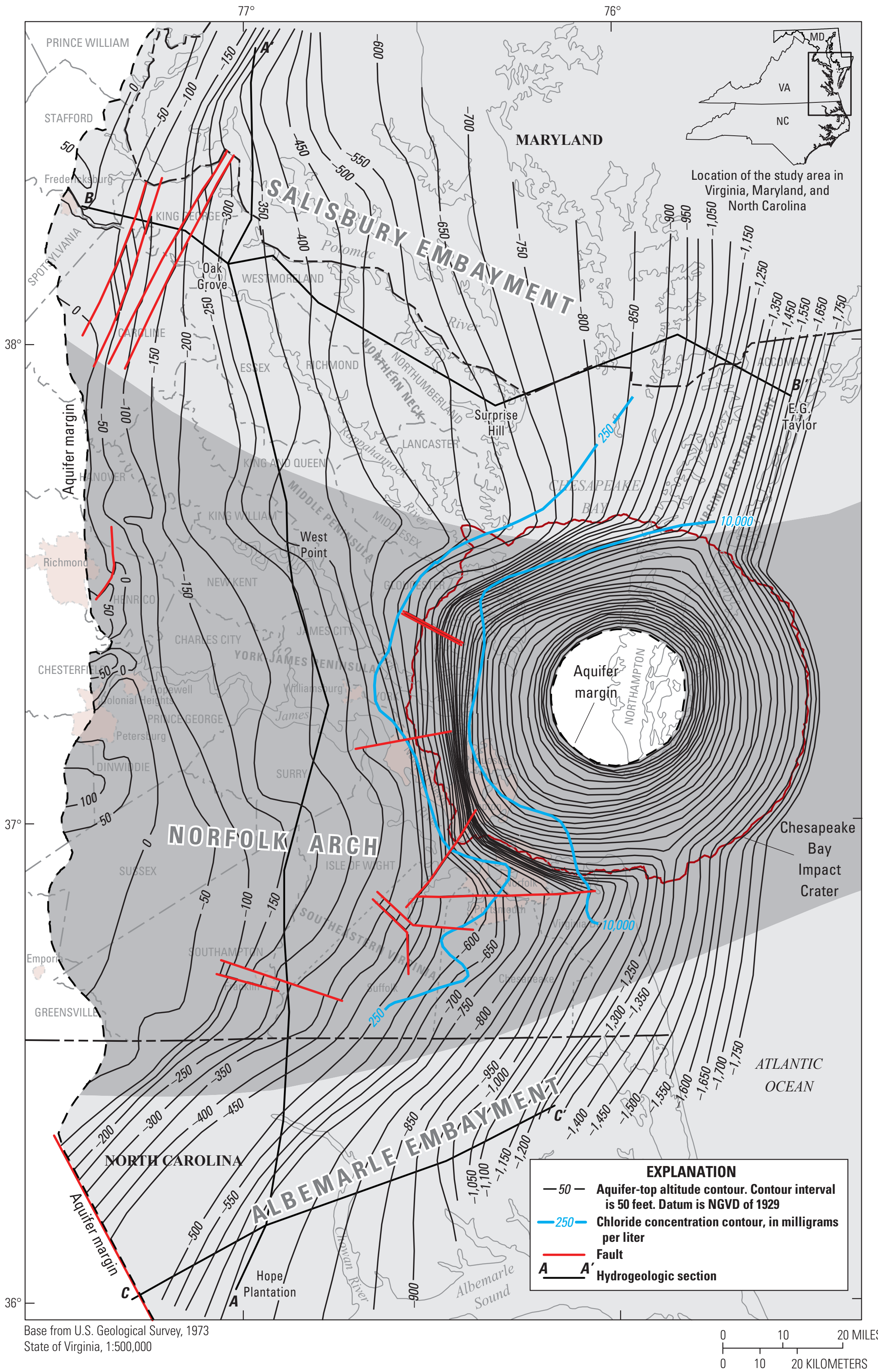


Figure 5. Approximate altitude and groundwater chloride concentration of the top of the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Adapted from McFarland and Bruce (2006) and McFarland (2010). Location of Chesapeake Bay impact crater from Powars and Bruce (1999). Hydrogeologic sections shown in figure 17.

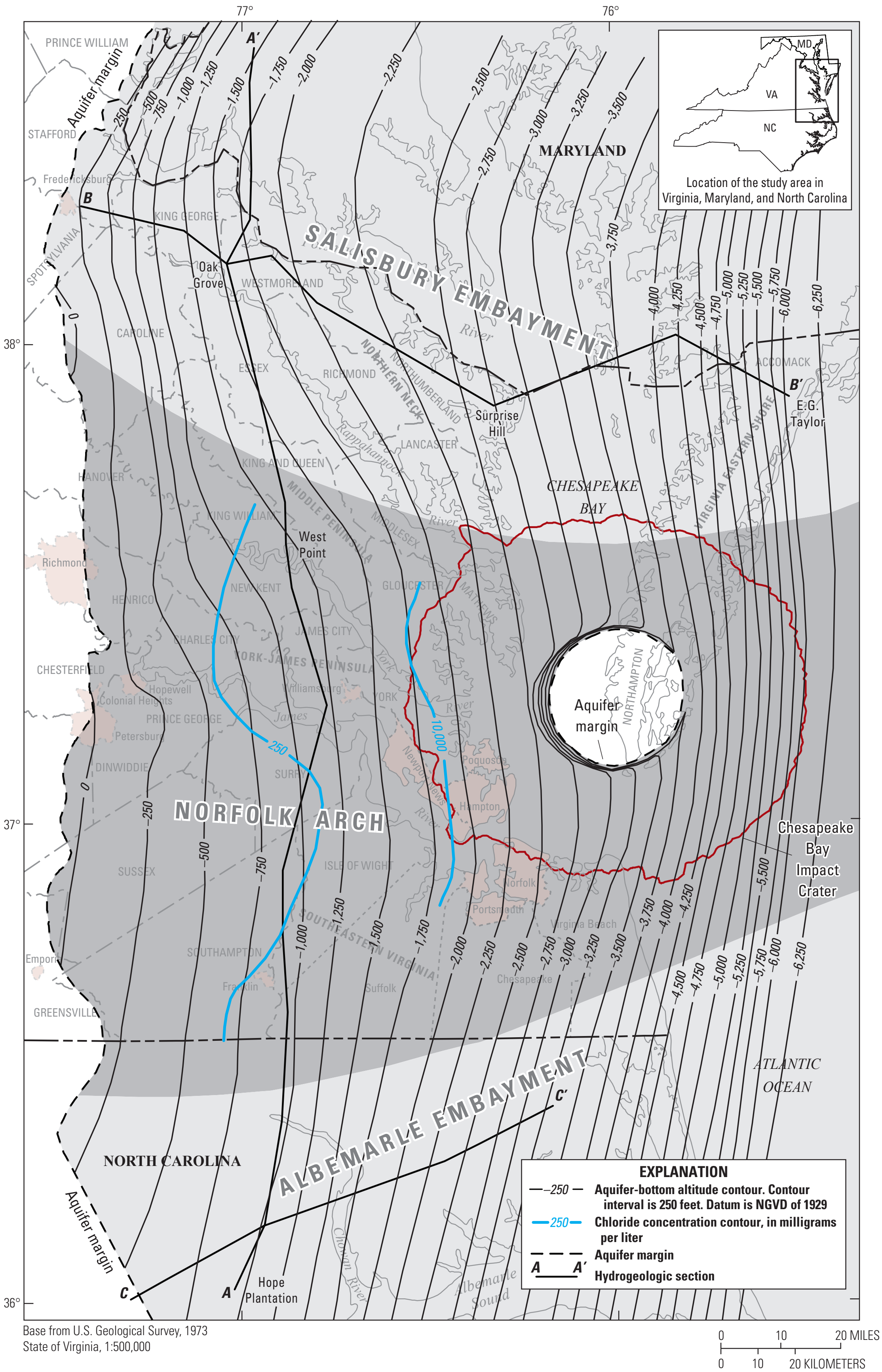


Figure 6. Approximate altitude and groundwater chloride concentration of the bottom of the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Adapted from McFarland and Bruce (2006) and McFarland (2010). Location of Chesapeake Bay impact crater from Powars and Bruce (1999). Hydrogeologic sections shown in figure 17.

Formation sediments span upland areas to form caps overlying basement bedrock, within which the water table is positioned to constitute the unconfined surficial aquifer. Along most of the Fall Zone in Virginia south of Fredericksburg, however, the Potomac aquifer pinches out westward below land surface against basement bedrock (fig. 3). Consequently, outcrops are very sparse and limited to localized narrow cut banks of incised major rivers (see report cover photograph).

Compaction of sediments within the Potomac aquifer and overlying hydrogeologic units resulted in subsidence of land surface across the Virginia Coastal Plain. Across the Chesapeake Bay impact crater, ongoing subsidence has been induced by compaction of crater-fill sediments and settling of megablocks since the impact event took place (Powars and Bruce, 1999). As a result, overlying post-impact sediments are downwarped across the impact crater, and land-surface topography has developed a series of seaward-facing scarps that coincide closely with the crater rim. The formation and alignment of Chesapeake Bay also may have resulted from redirection of regional surface drainage toward the impact crater. More widely, sediment compaction and land subsidence across most of the Coastal Plain in Virginia and beyond has been inferred to result from large groundwater withdrawals primarily from the Potomac aquifer (Pope and Burby, 2004). Rates of subsidence, however, have only been directly measured at two locations during 1980–96.

Much of the Potomac aquifer contains fresh groundwater, dominated most widely by sodium cations and bicarbonate anions (McFarland, 2010). Toward Chesapeake Bay and the Atlantic coast, however, groundwater dominated by elevated concentrations of sodium cations and chloride anions forms the saltwater-transition zone, a major regional boundary for the freshwater part of the aquifer system. The saltwater-transition zone in Virginia protrudes abnormally landward across the Chesapeake Bay impact crater. Curved and closely spaced contours of groundwater chloride concentration across the top of the Potomac aquifer (fig. 5) reflect how the saltwater-transition zone within the upper part of the Potomac aquifer and overlying sediments is steeply sloping, warped, and mounded across the impact crater. Conversely, widely spaced chloride-concentration contours across the bottom of the Potomac aquifer (fig. 6) reflect that at greater depth the saltwater-transition zone slopes more broadly landward. The saltwater-transition zone is further affected by discrete, vertically inverted zones across which salty groundwater overlies fresh groundwater (fig. 3), resulting in a three-dimensionally convoluted configuration.

Flow

Because of its varied sediment texture, the Potomac aquifer is classified as a heterogeneous aquifer (McFarland and Bruce, 2006). Hydraulic conductivity of coarse-grained sand and gravel is large, whereas that of fine-grained sand, silt, and clay is considerably smaller. Groundwater flows mostly through beds of sand and gravel and is relatively stagnant in fine-grained beds. At the regional scale, the Potomac aquifer is considered to function hydraulically across a continuous expanse, but locally can exhibit discontinuities where flow is impeded by fine-grained beds.

Model simulation (Heywood and Pope, 2009) indicates that prior to the onset of large withdrawals, groundwater flowed through the Potomac aquifer generally eastward from recharge areas along its western margin to discharge areas along Chesapeake Bay and the Atlantic Ocean (fig. 7). Hydraulic heads above sea level across much of the east resulted in upward leakage from the Potomac aquifer through overlying sediments (fig. 3). Flow also was laterally diverted around a large stagnant zone across low-permeability sediments within the Chesapeake Bay impact crater (see section “Configuration”). By contrast, as of 2003 and to the present (2013), flow through the Potomac aquifer has been greatly affected by numerous, large, and widespread groundwater withdrawals that have been imposed for much of the previous century. The steepest depressions in hydraulic head are near the largest production wells, but broader regional depressions span the entire aquifer system (fig. 8). Consequently, flow has been redirected landward to create the potential for saltwater intrusion. In addition, head decline in the Potomac aquifer is greater than in overlying aquifers, thereby inducing downward leakage throughout most of the aquifer system (see section “Vertical Hydraulic Connectivity”). Stagnant conditions persist, however, within the impact crater.

Both prior to and since the onset of large withdrawals, steep hydraulic gradients indicate that recharge of the Potomac aquifer is focused along its western margin (figs. 7 and 8). The configuration of the Potomac aquifer, however, largely precludes direct infiltration from land surface along most of its western margin in Virginia. Other than north of Fredericksburg, outcrops of the Potomac aquifer in Virginia exist only along a few narrow cut banks of incised major rivers (fig. 3), which function as local discharge areas. Conversely, infiltration is received primarily at the water table positioned in overlying sediments beneath adjacent uplands. Of an estimated 10 inches per year (in/yr) of recharge at the water table along the Fall Zone, approximately 9 in/yr travels only a relatively short distance before discharging to nearby streams and rivers (McFarland, 1997, 1999). Only the remaining 1 in/yr is not intercepted by localized flow and discharge and, subsequently, is entrained in the regional flow system as recharge to deeper, downgradient parts of the Potomac aquifer.

Prior to large groundwater withdrawals, dense salty groundwater along the coast induced eastward flowing fresh groundwater to leak upward and discharge (fig. 3). Dispersive mixing between fresh and salty groundwater took place across a density gradient along the saltwater-transition zone. Major withdrawals from the Potomac aquifer, however, include large capacity production wells currently located within the saltwater-transition zone that supply brackish groundwater to desalination facilities. Consequently, monitoring of saltwater

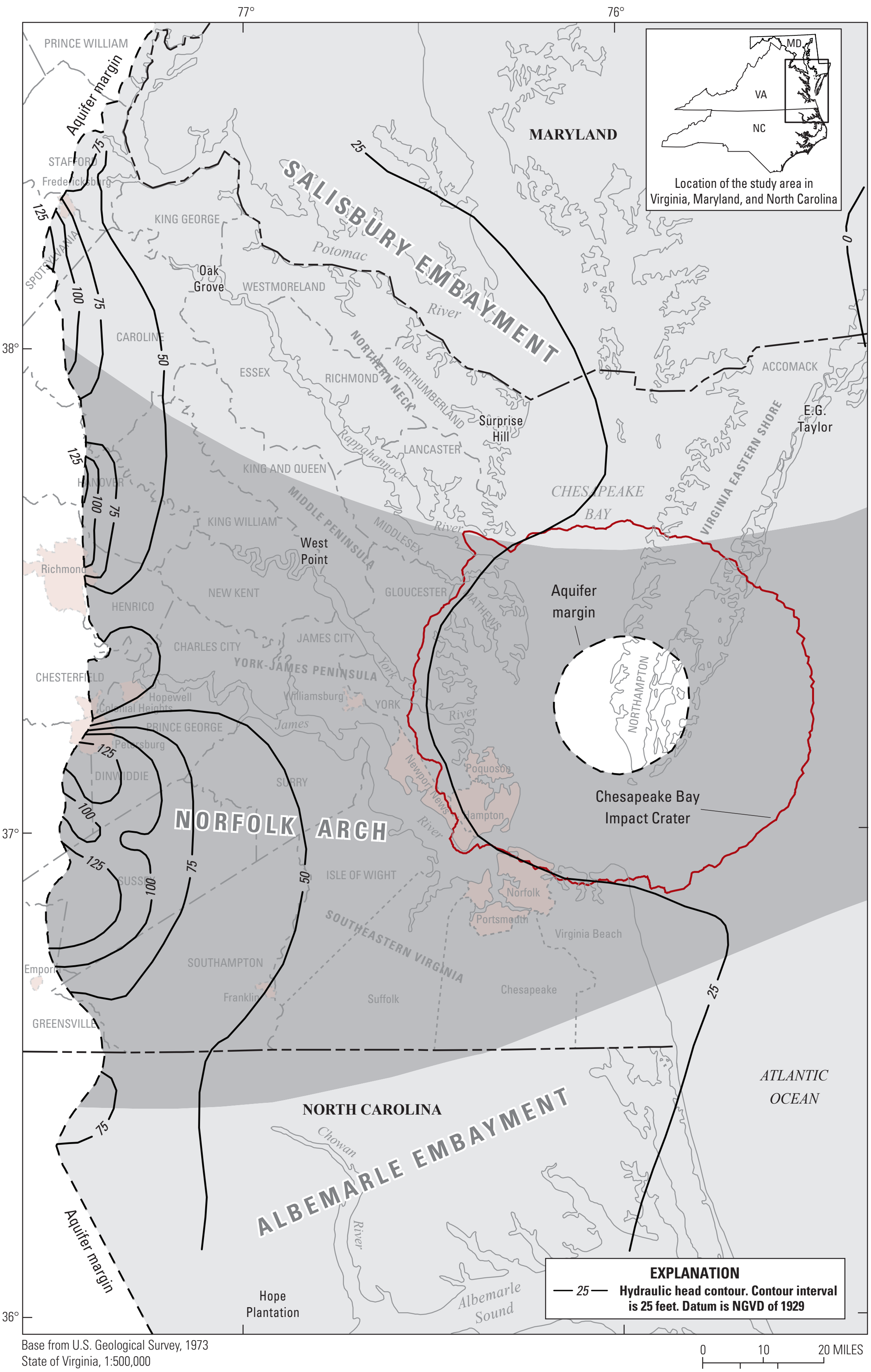


Figure 7. Simulated pre-development hydraulic head in the Potomac aquifer in Virginia and adjacents parts of Maryland and North Carolina (from Heywood and Pope, 2009). Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

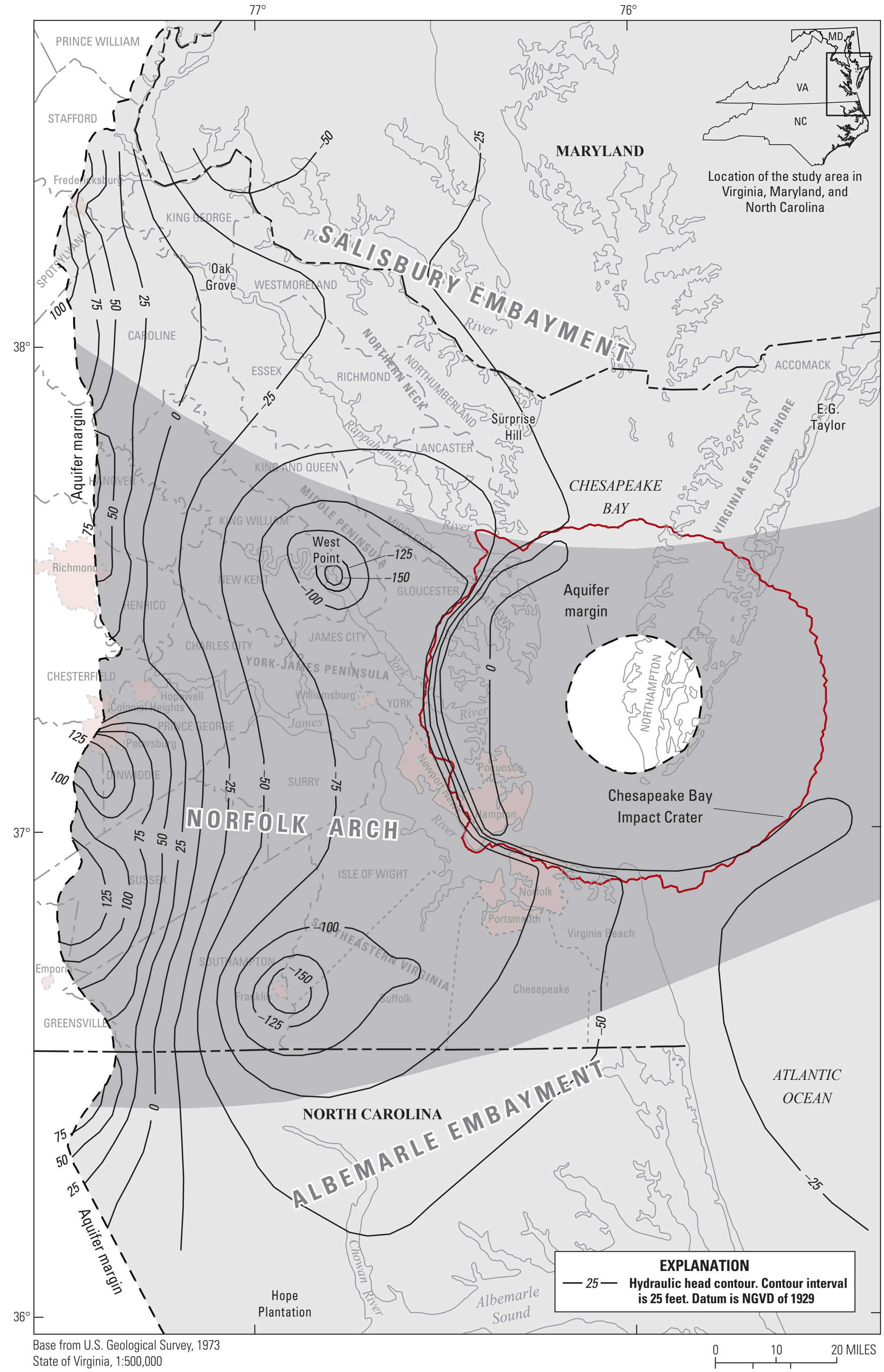


Figure 8. Simulated hydraulic head during 2003 in the Potomac aquifer in Virginia and parts of Maryland and North Carolina (from Heywood and Pope, 2009). Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

intrusion is critical to detect salinity increases above brackish concentrations.

The configuration of the saltwater-transition zone resulted from dynamic interactions between fresh and salty groundwater over geologically substantial periods of time (McFarland and Bruce, 2005; Sanford and others, 2009; McFarland, 2010). Predominantly marine conditions have existed across most of the Virginia Coastal Plain over the past approximately 65 million years (m.y.) since the beginning of the Tertiary Period. Seawater has been repeatedly emplaced within parts of the Potomac aquifer and other hydrogeologic units from recurrent inundation by the Atlantic Ocean. The most recent regionwide series of inundations likely emplaced seawater within much of the Coastal Plain sediments during the Pliocene Epoch, approximately 2.6 to 5.3 million years ago (Ma). Sea level has since fluctuated at lower levels, but ultimately declined as low as 390 to 470 ft below that of present day during the most recent glacial maximum of the Pleistocene Epoch from 18,000 to 21,000 years ago (Peltier, 1994; Bradley, 1999). With emergence of the land surface, recharge resumed to emplace fresh groundwater and displace the saltwater-transition zone eastward, probably to beyond its current position. Seawater was at least partly retained, however, within low-permeability sediments filling the Chesapeake Bay impact crater. Fresh groundwater flushed seawater from around the impact crater in a complex three-dimensional fashion, laterally bifurcating to the north and south, and vertically focusing along discrete preferential pathways to produce inverted salinity zones. With renewed sea-level rise from approximately 18,000 years ago to the present, modern seawater is reentering the sediments, and the saltwater-transition zone is migrating westward to merge with older saltwater in crater-fill sediments. Eastward flow of fresh groundwater has continued, but has been progressively stalled, truncated, and overridden by the westward migrating saltwater-transition zone.

The configuration of the saltwater-transition zone remains largely as it was prior to the onset of large groundwater withdrawals because flow velocities are very slow, and groundwater has not yet been displaced over regionally appreciable distances in response to the withdrawals. Instead, withdrawn water has primarily been released from storage. Velocities of fresh groundwater that flows laterally through the Potomac aquifer vary regionally as a result of differences in the texture and associated hydraulic conductivity of aquifer sediments (see section “Hydraulic Conductivity”). Estimates of lateral flow velocity have been based on ages of groundwater relative to the time of recharge, as determined among different parts of the Potomac aquifer using an array of geochemical tracers. In Virginia, a lateral flow velocity of approximately 10 feet per year (ft/yr) is apparent from ages of groundwater samples collected from wells in the Potomac aquifer located in southeastern Virginia across the Norfolk arch (Nelms and others, 2003). Ages of water samples collected from wells located farther north in Virginia into the Salisbury embayment indicate a slower velocity of approximately 4 ft/yr. Yet slower velocities are indicated in Maryland (Plummer and others, 2012), ranging from approximately 3 ft/yr near upgradient recharge areas to 0.1 ft/yr downgradient. Lateral velocities likely are slowed, and fresh groundwater flow is stalled progressively downgradient as upward leakage through thick low-permeability sediments overlying the Potomac aquifer is induced by the saltwater-transition zone. Lateral flow velocities correspond to groundwater ages ranging from tens of thousands of years in Virginia to millions of years in Maryland. Thus, most of the Potomac aquifer contains fresh groundwater that was emplaced long before the most recent glacial maximum.

Sediment Distribution of the Potomac Aquifer

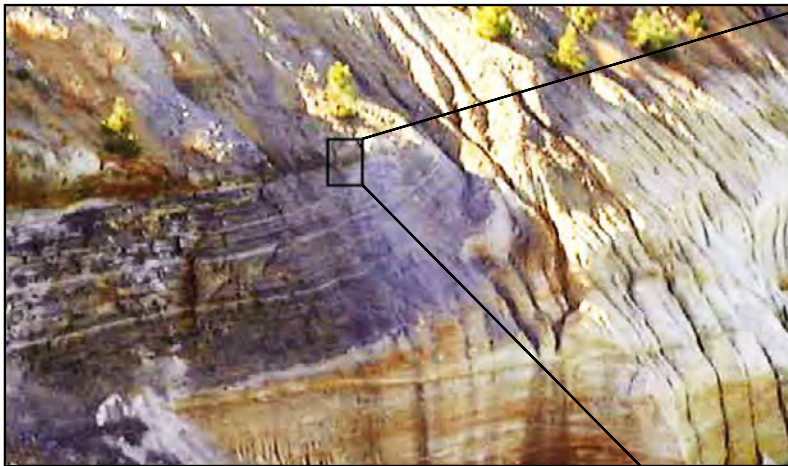
The Potomac aquifer is composed of fluvial sediments that exhibit distinct characteristics resulting from complex, locally dynamic, and regionally evolving depositional environments. Spatial distribution of the sediment is represented by borehole-interval data based on interpretations of geophysical logs and ancillary information. Regional trends among the sediment intervals are analyzed to describe and geologically account for the distribution of sediments by theorizing their depositional history and related processes.

Lithologic and Depositional Characteristics

“Lithology,” as used in this report, refers to (1) composition, including mineralogy of sediment grains, along with other components such as fossil shells and organic material, and (2) grain size distribution or texture. Potomac aquifer sediments consist of coarse-grained quartz and feldspar sand and gravel, interbedded with fine-grained sand, silt, and clay (see photograph on report cover; fig. 9*A–D*). Sediment lithology is locally variable and complexly distributed. Sediments of different compositions and textures contrast sharply and are highly interbedded, and individual beds extend only short distances typically several hundred feet or less.

Sediments of the Potomac aquifer in Virginia are of fluvial origin. Sediment deposition in fluvial environments is locally dynamic. Coarse-grained sand and gravel are deposited under high energy conditions along relatively narrow stream channels and adjacent bars (fig. 10). Fine-grained sand, silt, and clay are deposited under low energy conditions across broad floodplains, swamps, and other overbank areas away from channels. Rapid currents within the stream channels allow only the coarsest sediments to settle out, keeping finer sediments in suspension. At high flood stages, however, water spreads beyond the channels across overbank areas where it loses velocity, depositing fine-grained sand, silt, and clay. In addition, channels and bars shift laterally over time as a result of differential erosion of stream banks, as well as punctuated realignments during individual floods that rapidly cut new

A



B

Figure 9. Examples of sediment lithologies. (*A*) Relation between coarse- and fine-grained sediments of the Potomac aquifer exposed at a sand and gravel operation near Petersburg, Virginia. Clay bed (center left) is approximately 10 feet thick and surrounded by coalescing, predominantly massive beds of coarse-grained sand and gravel. (*B*) Tough, dense, organic-rich clay is nearly impermeable and is in sharp contact with friable water-bearing fieldspathic sand. Length of pick is 22 inches.

C ***D*** ***E***

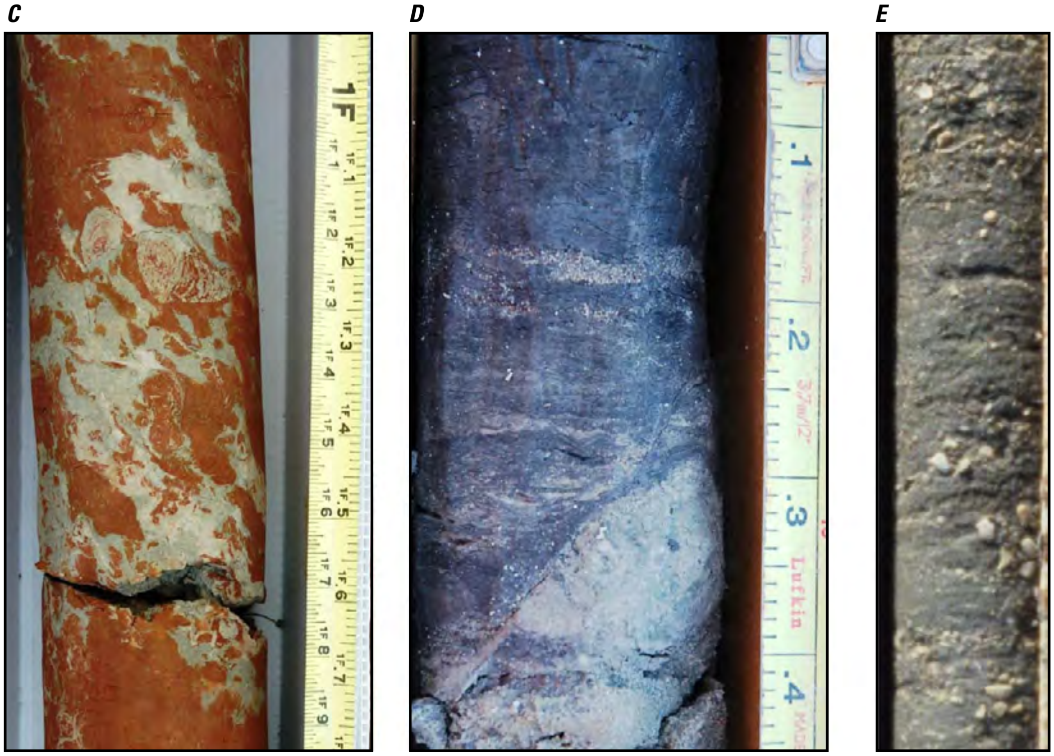


Figure 9—Continued. Examples of sections of drill core. Core diameters range from approximately 2 to 4 inches, and major scale divisions are in tenths of feet where shown. Corresponding geophysical-log signatures are shown in figure 11, and borehole locations are shown on plate 1. (*C*) Massive smectitic clay of the Potomac aquifer, typical of paleosol floodplain deposits, at a depth of approximately 125 feet in borehole 54C 10 at Sebrell, Virginia. Lithology is varibly colored and commonly mottled as shown. (*D*) Micaceous and variably sandy organic-rich clay of the Potomac aquifer, typical of freshwater swamp deposits, at depth of approximately 795 feet in borehole 60L 22 at Surprise Hill, Virginia. Note lenticular and wavy fine interbedding of sand and clay. (*E*) Near-shore marine, glaucontitic and micaceous, sandy and clayey silt of the upper Cenomanian confining unit, at depth of approximately 585 feet in borehole 58A 76 at Dismal Swamp, Virginia. Note finely interbedded biofragmental sands and shells that include the diagnostic *Exogyra woolmani.*

F

Figure 9—Continued. (*F*) Relation between the Potomac aquifer and overlying Aquia aquifer exposed at a sand and gravel operation near Petersburg, Virginia. Weathered material has been scraped from surface of quarry wall across center of photograph to reveal sediment color and composition. Light material at bottom is predominantly quarzitic coarse-grained sand and gravel that constitute the Potomac aquifer. Contact with dark glauconitic medium-grained sand of the Aquia aquifer is at position "1." Aquifer-on-aquifer contact is lacking intervening fine-grained sediments that function as a confining unit to hydraulically separate the aquifers. Overlying intervals with contacts at positions "2," "3," and "4" exhibit three distinct phases of sediment networking during deposition of Aquia aquifer sediments that incorporate underlying gravel and cobbles from the Potomac aquifer. Such intervals are likely widespread across much of the Virginia Coastal Plain and complicate distinguishing the aquifers from signatures on borehole geophysical logs.

channel segments across previous overbank areas. As deposition proceeds over periods of decades to millennia, locally variable arrays of relict channel and bar deposits develop, overlapping with relict overbank deposits.

Distinct variations in the morphologies and sediment lithologies of channel, bar, and overbank deposits develop as fluvial environments evolve regionally over millennia. Newly formed depositional systems in proximity to actively eroding sediment-source areas are composed of localized networks of immature braided streams that undergo frequent, large magnitude, but short duration fluctuations in streamflow. Complexly overlapping and coalescing longitudinal bars and channel fills are dominated by coarse-grained sands and gravels, with mineralogies that relatively directly reflect those of source rocks. With erosional leveling of sediment-source areas, older depositional systems are composed of mature, medium- to low-gradient meandering streams. Seasonal large magnitude flows and localized overbank flooding are followed by relatively long intervening periods of stable base flow. Channel fills and point bars of medium- to coarse-grained sands are segregated from large amounts of fine-grained sediments that form various overbank deposits, including floodplains, swamps, and abandoned channels such as oxbow lakes. Sediment mineralogies are progressively dominated by clays produced by chemical weathering of source rocks.

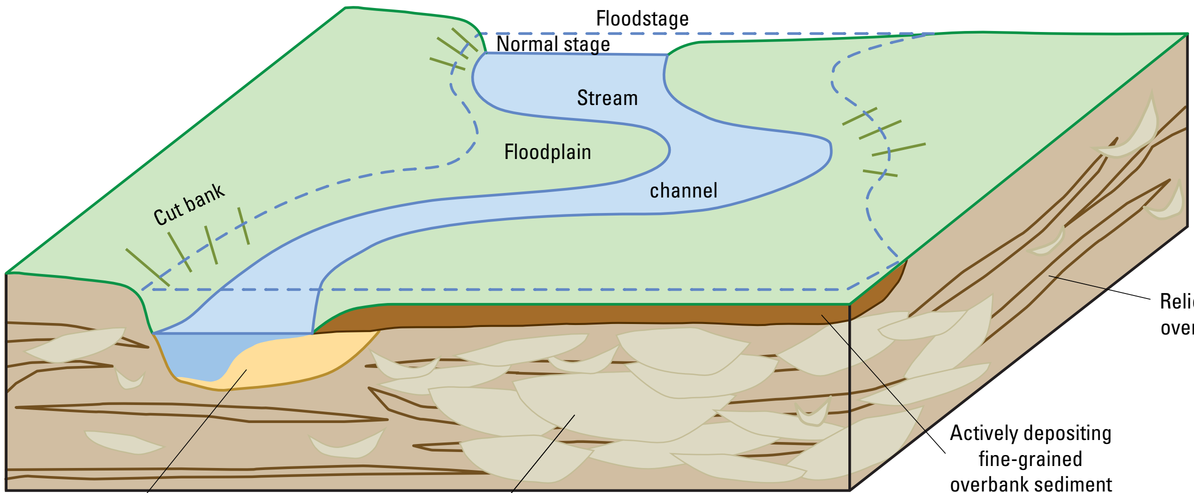


Figure 10. Simplified and generalized fluvial sedimentary depositional environment. Coarse-grained sediments are deposited under high flow-energy conditions in proximity to stream channels. Fine-grained sediments are deposited under low flow-energy conditions farther from stream channels. Variations in deposit distributions and geometries among streams of differing maturity are described in text. Coalescing concentrations of coarse-grained deposits (front right) comprise major water-bearing intervals within the Potomac aquifer, which are sparse in parts of the aquifer dominated by fine-grained deposits (front left and rear right).

Large fluvial depositional systems can consist of several or more individual drainage basins that change configuration substantially over geologic time. Moreover, within a large depositional system, immature braided streams in proximity to sediment-source areas can transition gradationally downgradient to mature meandering streams farther from source areas. Distal parts of the system adjacent to coastal areas can merge with subareal deltas, featuring broad networks of distributary streams and extensive, perennially inundated interstream marshes and bays.

Fluvial sediments of the Potomac aquifer were deposited over a period of approximately 45 m.y. and are overlain by younger sediments of mostly marine origin (for example, fig. 9*E* and *F*). Marine sediment lithologies differ from fluvial sediments and commonly include components such as glauconite, phosphate, and shells and other fossil material. In contrast to the locally dynamic conditions of fluvial environments, marine environments are broadly stable. Marine sediments of relatively uniform lithology are widely deposited across large areas of the Continental Shelf. Hence, many of the sediments overlying the Potomac aquifer can be reliably correlated stratigraphically across distances of tens of miles or more.

Across the central and northern parts of the Virginia Coastal Plain, the Potomac aquifer is overlain by medium-grained, glauconitic marine sand of the Aquia aquifer (fig. 9*F*). Intervening fine-grained sediments that function as a confining unit to hydraulically separate the two aquifers are localized and discontinuous in many places, and wholly absent elsewhere, which results in direct aquifer-on-aquifer contact. Moreover, reworking of Potomac aquifer sediments into overlying intervals of the Aquia aquifer is likely widespread and complicates distinguishing the two aquifers solely from signatures on borehole geophysical logs. Interpretive uncertainty associated with this stratigraphic relation is represented by a transitional interval designated as the Potomac confining zone (McFarland and Bruce, 2006). By contrast, across the southernmost part of the Virginia Coastal Plain, the Potomac aquifer is overlain by fine-grained, shelly marine sands of the upper Cenomanian confining unit (fig. 9*E*), which is readily distinguishable from borehole geophysical-log signatures. The upper Cenomanian confining unit imposes a substantial hydraulic separation between the Potomac aquifer and overlying sediments (see section “Hydrostratigraphy of Cretaceous Age Sediments in Southeastern Virginia and Northeastern North Carolina”).

Borehole Sediment Intervals

The spatial distribution of fluvial sediments that compose the Potomac aquifer in the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina is represented by vertical intervals intercepted by a network of 456 boreholes that penetrate the aquifer (fig. 1; pl. 1). Diagnostic signatures of borehole geophysical logs were used (fig. 11), along with descriptions of sediment cuttings and core, to determine altitudes and thicknesses of 2,725 vertical intervals designated as either dominantly coarse or fine grained.

Most boreholes are represented by electrical logs (fig. 11) consisting of vertical profiles across the borehole of electrical resistivity and spontaneous potential that vary generally in response to sediment texture. A small number of boreholes are represented by electromagnetic induction logs that are similarly interpreted. Many boreholes are further represented by natural gamma logs, which vary in response to sediment mineralogies having different concentrations of radioactive elements.

Geophysical-log signatures of Potomac aquifer sediments generally reflect several distinct lithologies. Sediment intervals designated as coarse grained represent medium- to coarse-grained channel and bar sands and gravels (see photograph on report cover; fig. 9*A* and *B*), which are commonly targeted for completion of water-supply wells. The natural gamma signature (fig. 11) is generally low (to the left), reflecting the predominance of quartz, but can be slightly increased across some beds if potassium feldspar is sufficiently concentrated. Cross bedding is commonly exhibited in outcrop and sediment core. Blocky resistivity and spontaneous potential log signatures indicate massive bedding, whereas tapered signatures indicate fining-upward graded bedding. Thick distinct bedding sequences of either type are rarely preserved, however, because the sediments were frequently reworked by alternating erosion and re-deposition under locally dynamic fluvial conditions. Hence, many coarse-grained intervals probably represent multiple stacked remnants of bedding sequences that have been partly beveled by erosion.

Sediment intervals designated as fine grained are generally avoided for completion of water-supply wells and are commonly preserved either in bedded form or as rip-up clasts (see photograph on report cover). Varied geophysical-log signatures reflect different lithologies. Massive clays exhibit distinctively flat and low resistivity and spontaneous potential signatures, commonly several tens of feet or more in thickness, along with increased natural gamma (fig. 11) resulting from clay minerals with relatively large concentrations of radioactive elements. Such signatures on many logs represent widespread, dense, and commonly multicolored, smectitic

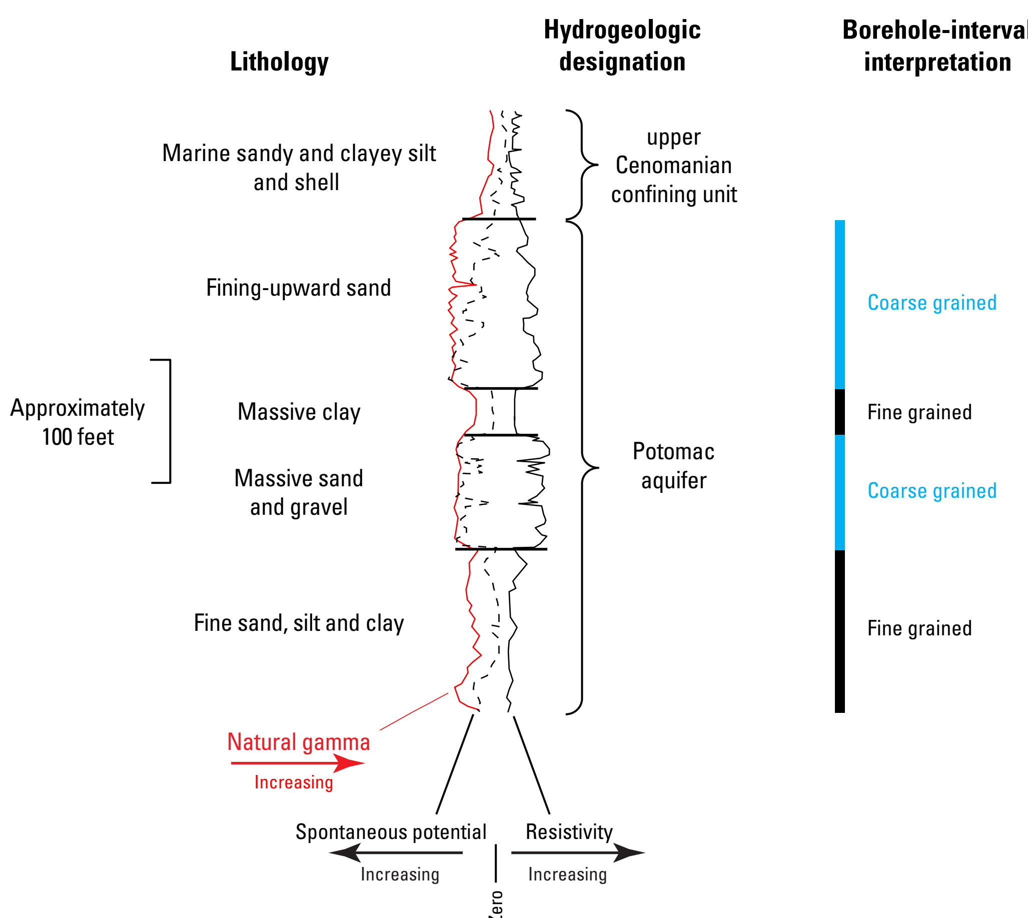


Figure 11. Generalized composite electric and gamma borehole geophysical logs. Diagnostic log signatures distinguish contrasting lithologies of the Potomac aquifer and overlying upper Cenomanian confining unit.

paleosols of floodplains (fig. 9*C*). Aggregated soil structure and root traces are commonly exhibited in sediment core, along with sharply contrasting mottled colors that result from burrowing followed by post-depositional weathering. Other massive clays were formed by in-situ kaolinization of feldspathic sands, which can be distinguished in sediment core by the presence of preserved sand-grain nuclei and an absence of soil-related features. Mineralogic analyses of core samples indicate the transported floodplain clays to be composed predominantly of smectitie and illite, whereas in situ interstitial clays are predominantly kaolinite (Reinhardt and others, 1980).

Other sediment intervals designated as fine grained represent micaceous silts and fine sands interbedded with black organic-rich clays (fig. 9*A*, *B*, and *D*). These intervals exhibit variable geophysical-log signatures among resistivity, spontaneous potential, and natural gamma (fig. 11), reflecting small scale variations among the proportions of the different textures. These sediments were deposited in freshwater swamps and abandoned stream channels such as oxbow lakes. Sediment core and cuttings commonly include readily visible plant fragments and lignite along with more finely disseminated organic matter.

Coarse-grained sediment intervals were distinguished from fine-grained intervals by identifying log signatures of prominent thickness and magnitude (fig. 11). Productive water-bearing beds composed of coarse sand and gravel are capable of yielding water at rates from several to multiple tens of gallons per minute (gal/min) or greater, depending on well-construction characteristics. Designated coarse-grained intervals are thereby suitable for completing wells to supply water for uses ranging from domestic and other limited demands to large commercial, municipal, and industrial operations. Conversely, fine-grained intervals primarily represent fine sand, silt, and clay that are generally not suitable for well completion, but within which small amounts of coarse-grained sediment can be interbedded. As designated, both coarse- and fine-grained intervals can encompass multiple individual coarse- or fine-grained beds and, thus, are relatively generalized.

Coarse- and fine-grained borehole sediment intervals are tabulated in a digital data-spreadsheet file (Attachment 1). The spreadsheet “borehole_summary” lists each borehole by number and includes ancillary information followed by summary statistical data for the intervals in each borehole, including the mean thicknesses of coarse- and fine-grained intervals and the percentage of the total length of each borehole composed of coarse-grained sediments (see section “Regional Lithologic Trends”). These data are followed by altitudes of the top and bottom surfaces of confining units where present (see sections “Depositional Subareas” and “Hydrostratigraphy of Cretaceous Age Sediments in Southeastern Virginia and Northeastern North Carolina”). Individual coarse- and fine-grained sediment-interval top and bottom altitudes and thicknesses in each borehole are listed in the spreadsheets “coarse-grained_intervals” and “fine-grained_intervals,” respectively.

Borehole sediment-interval data are subject to limitations. Most boreholes terminate partway along their lowermost sediment interval, the bottom altitude of which is unknown and designated as “not determined” (Attachment 1). Some interval top altitudes are likewise designated in boreholes that are only partly spanned by geophysical logs. In both instances, individual interval thicknesses are “not determined.” Mean interval thicknesses are also “not determined” for boreholes that do not intercept at least one entire interval. Percentages of the total length of each borehole composed of coarse-grained sediments are “not determined” for boreholes that do not intercept at least one entire coarse-grained and one entire fine-grained interval.

Coarse- and fine-grained borehole sediment-interval data are graphically presented by six sectional views (pl. 2). The sections are referenced to map areas (pl. 1) consisting of six corresponding north-to-south oriented belts that are indexed to USGS 7.5-minute series topographic quadrangle maps. Each section area spans two quadrangles from east to west and from 8 to 21 quadrangles from north to south. Sediment intervals are projected onto each section from the boreholes located within the corresponding section area. In addition, traces of the top surfaces of the Potomac aquifer and basement bedrock across the updip and downdip boundaries of each sectional area are projected onto the sections.

Regional Lithologic Trends

Broad trends among borehole sediment intervals were examined to describe the spatial distribution of Potomac aquifer sediments. Visual examination of the sediment intervals indicates a generally northward-fining/southward-coarsening trend that corresponds with major structural features of the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina (pl. 2; fig. 12). A predominance of coarse-grained intervals is apparent across the Norfolk arch, and fine-grained intervals predominate across the Salisbury embayment.

Summary statistical data for the sediment intervals in each borehole corroborate the visually apparent trend. Values of borehole mean coarse-grained interval thickness generally are greater across the Norfolk arch than the adjacent Salisbury and Albemarle embayments (fig. 13). Mean coarse-grained intervals thicker than 80 ft are almost exclusively within the area of the Norfolk arch. In addition, coarse-grained intervals thicken eastward across the Norfolk arch. Almost all mean intervals thicker than 120 ft are along an eastward belt that spans from near West Point to the south-southeast through the northern part of the city of Suffolk. The eastward thickening coarse-grained intervals coincide with eastward thickening of the Potomac aquifer.

As a corollary to the above, values of borehole mean fine-grained interval thickness generally are less across the Norfolk arch than the adjacent Salisbury and Albemarle embayments (fig. 14). Mean fine-grained intervals of 20 ft

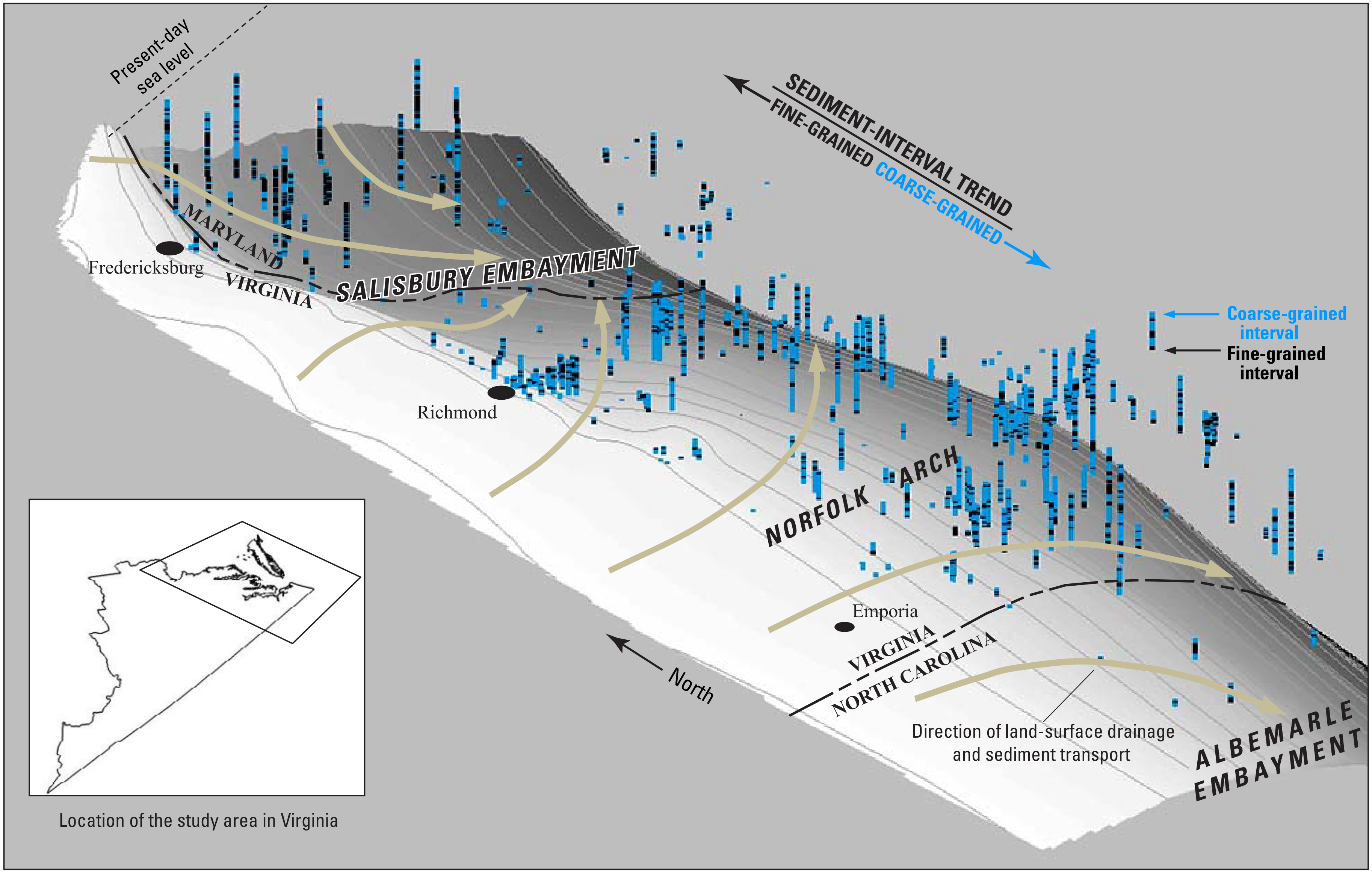


Figure 12. Coarse-grained (blue) and fine-grained (black) borehole sediment intervals in the Potomac aquifer, basement bedrock top surface (shaded and contoured), and inferred directions of land-surface drainage and sediment transport (tan arrows) in the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina during the early to earliest late Cretaceous period between approximately 100 and 145 million years ago. View is to the northeast at an approximately 45-degree downward angle (see inset). Vertical exaggeration is 75 times. Basement bedrock dips to the east and exhibits an undulating configuration between the uplifted Norfolk arch and downwarped Salisbury and Albemarle embayments. A visually apparent trend indicates predominantly coarse-grained sediment intervals southward overlying the Norfolk arch and fine-grained sediment intervals northward overlying the Salisbury embayment.

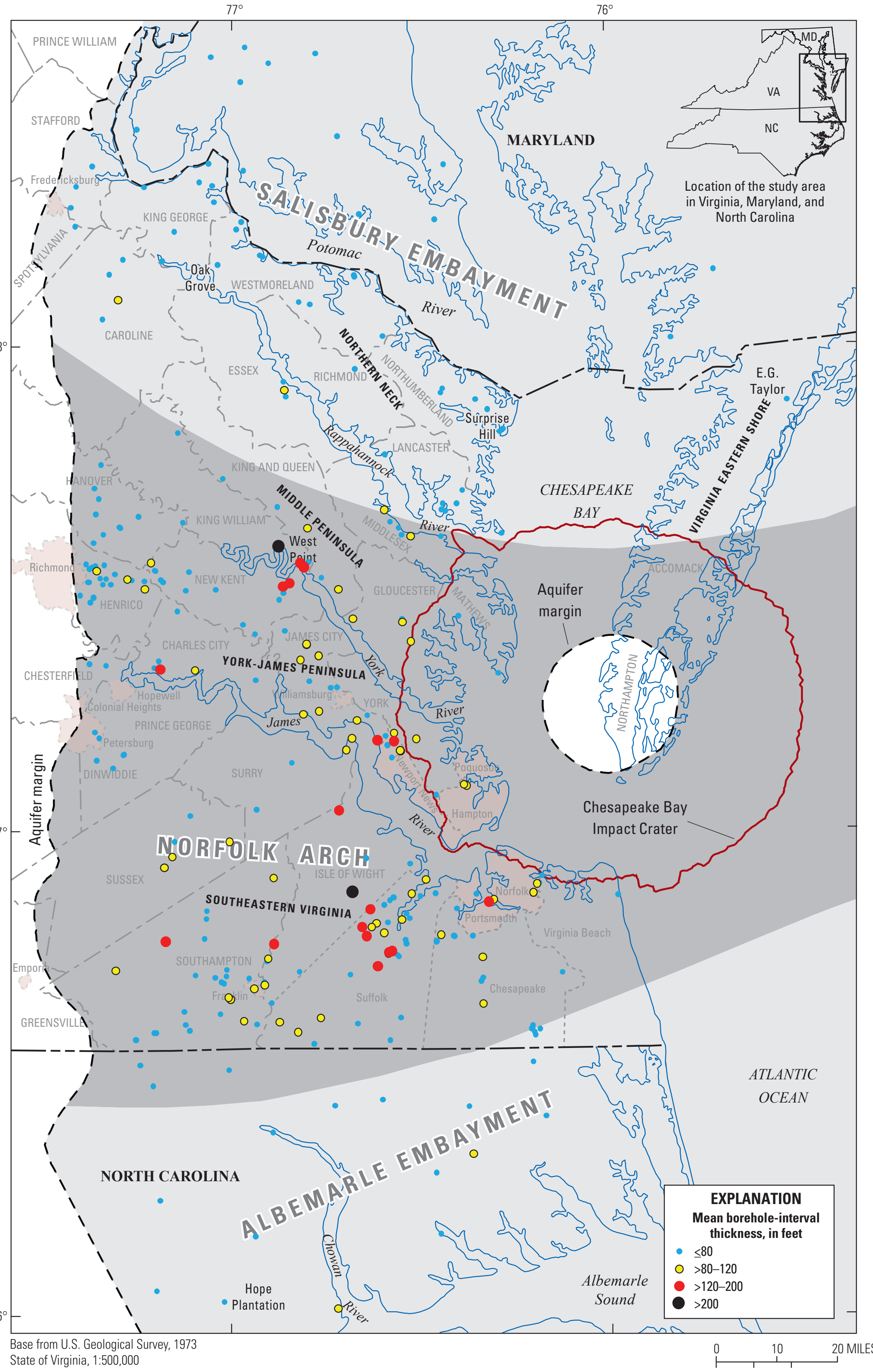


Figure 13. Mean borehole-interval thicknesses composed of coarse-grained sediment of the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Coarse-grained intervals generally are thicker across the Norfolk arch than elsewhere. Most boreholes do not penetrate entire aquifer thickness (see figure 35). Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

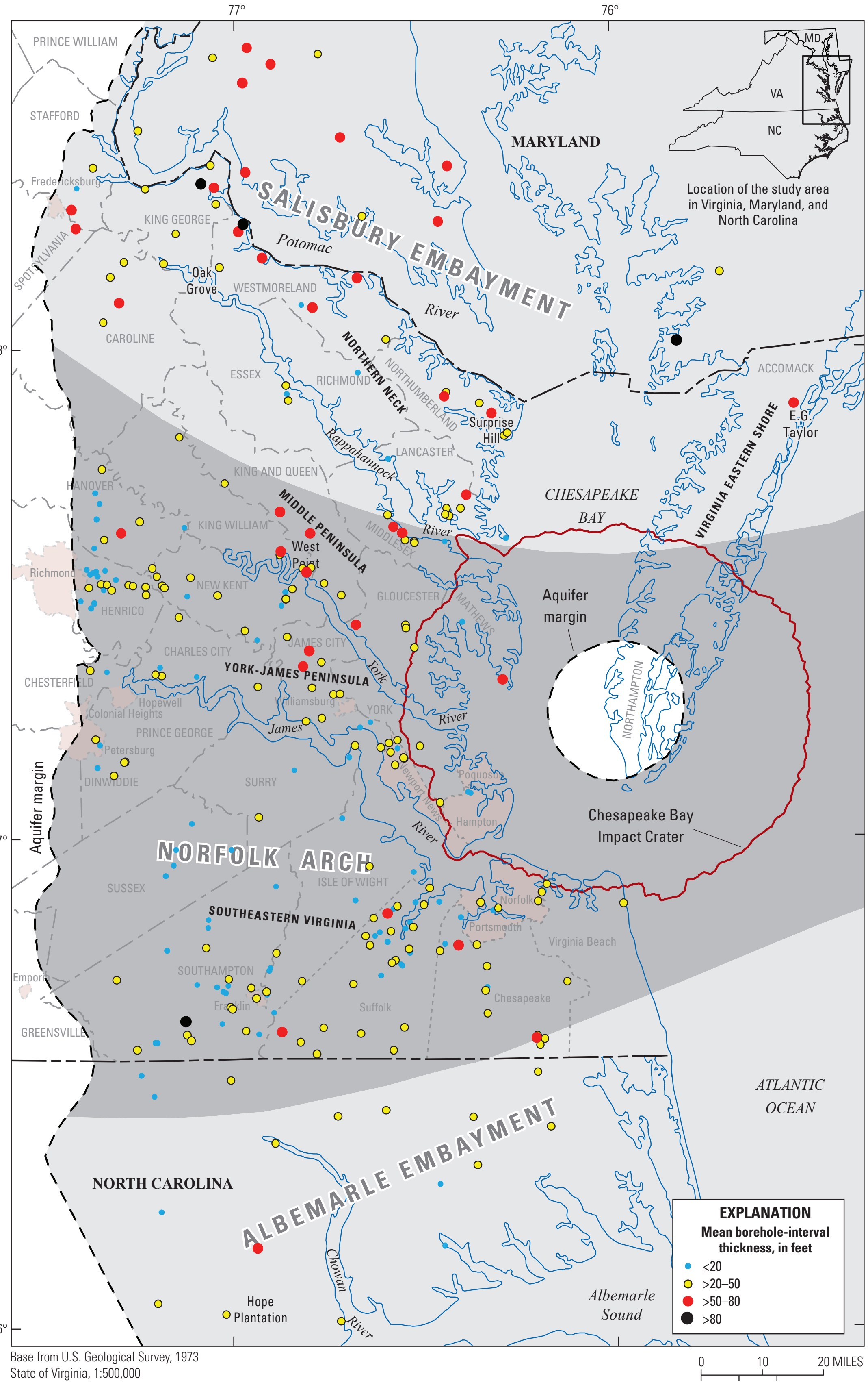


Figure 14. Mean borehole-interval thicknesses composed of fine-grained sediment of the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Fine-grained intervals generally are thinner across the Norfolk arch than elsewhere. Most boreholes do not penetrate entire aquifer thickness (see figure 35). Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

or thinner are almost exclusively within the area of the Norfolk arch. Fine-grained intervals also thicken eastward across the Norfolk arch, coinciding with eastward thickening of the Potomac aquifer. By contrast, across the Salisbury embayment, mean fine-grained intervals thicker than 50 ft are common in boreholes located throughout the aquifer, including parts of the aquifer to the far west. Most mean intervals thicker than 80 feet, however, are aligned in proximity to the axis of the Salisbury embayment.

Based on the above trends, the thicknesses of coarse- and fine-grained sediment intervals broadly contrast between the Norfolk arch and the Salisbury and Albemarle embayments. Percentages of the total length of each borehole composed of coarse-grained sediments (fig. 15) represent the relative dominance of coarse- and fine-grained sediments across the major structural features independent of the eastward thickening of the aquifer. On this basis, coarse-grained sediments are widely more dominant across the Norfolk arch than the adjacent embayments. Borehole lengths composed of greater than 80 percent coarse-grained sediments are almost exclusively within the area of the Norfolk arch. Moreover, boreholes with greater than 85 percent coarse-grained sediments span most of the area of the Norfolk arch, including areas of the arch to the far west.

Bedding sequences of coarse-grained sediments, distinguished where preserved from geophysical-log signatures as either massive or graded (fig. 11), also differ between the Norfolk arch and the Salisbury and Albemarle embayments (fig. 16). Thick (40 ft or greater) graded-bedding sequences are generally widespread, whereas thick sequences of massive bedding are present only across the Norfolk arch.

Depositional Subareas

Thicknesses and relative dominance of coarse- and fine-grained sediments composing the Potomac aquifer broadly contrast across major structural features of the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina. Accordingly, three hydrologically distinct sediment depositional subareas are designated here (figs. 12–17)—the Norfolk arch, Salisbury embayment, and Albemarle embayment—on the basis of regional trends in sediment lithology and stratigraphic continuity.

Norfolk Arch

The Norfolk arch depositional subarea occupies the central and southern parts of the Virginia Coastal Plain, extending from the upper York-James and lower Middle Peninsulas southward through southeastern Virginia to the North Carolina line. Coarse-grained sediment intervals are among the thickest and most widespread within the Potomac aquifer and exhibit massive as well as graded bedding where distinct sequences are preserved. Both coarse- and fine-grained intervals thicken eastward, but coarse-grained sediments dominate the entire subarea. Stratigraphic correlation among sediment intervals is ineffective at the regional scale, however, because of widely varying thicknesses and large vertical offsets among closely spaced intervals and lack of their alignment to any consistent regional structural trend. Thus, the entire sediment thickness functions hydraulically as a single interconnected aquifer (see section "Vertical Hydraulic Connectivity").

Salisbury Embayment

The Salisbury embayment depositional subarea occupies the northern part of the Virginia Coastal Plain, extending from the upper Middle Peninsula and lower Northern Neck northward into southern Maryland. Coarse-grained sediment intervals within the Potomac aquifer are thinner and less widespread than in the Norfolk arch subarea and exhibit predominantly graded bedding where distinct sequences are preserved. Conversely, fine-grained sediment intervals are increasingly thick and widespread northward.

Unique to the Salisbury embayment subarea are two continuous confining units that are delineated here (figs. 17–21) on the basis of stratigraphic correlation. The confining units encompass fine-grained borehole sediment intervals collectively as thick as several hundred feet and are consistently aligned to a regional structural trend having a generally north-south strike and eastward dip. Thin localized coarse-grained intervals intersected by some boreholes are included where enclosed between thick fine-grained intervals.

The confining units approximately correspond to those mapped in southern Maryland (Drummond, 2007). From southern Maryland, the confining units correlate into Virginia to boreholes located along the northernmost Northern Neck and Virginia Eastern Shore. Positions of the southern margins of the confining units, however, are uncertain across the southernmost part of the Salisbury embayment subarea because no boreholes there are deep enough to intercept the confining units. Farther south, deep boreholes located along the northernmost part of the Norfolk arch subarea exhibit widely varying thicknesses and large vertical offsets among fine-grained intervals, which consequently cannot be correlated with the confining units to the north. Moreover, margins of the confining units are likely indistinct because of regionally gradational changes in fluvial depositional conditions over time. The confining units are inferred to extend across most of the Salisbury embayment subarea, based on the likelihood that mature meandering streams spanned the concave basement bedrock surface in the southern part of the subarea (see section "Deposition Over Time"). Far southeastern parts of the confining units possibly are also truncated by the Chesapeake Bay impact crater.

The confining units hydraulically separate coarse-grained sediments within the Salisbury embayment subarea into three vertically spaced subaquifers—the upper, middle, and lower Potomac aquifers (fig. 17, sections *A–A′* and *B–B′*). Vertical flow between the subaquifers is impeded by the confining units. The subaquifers are continuous northward with aquifers in southern Maryland, designated from shallowest to deepest

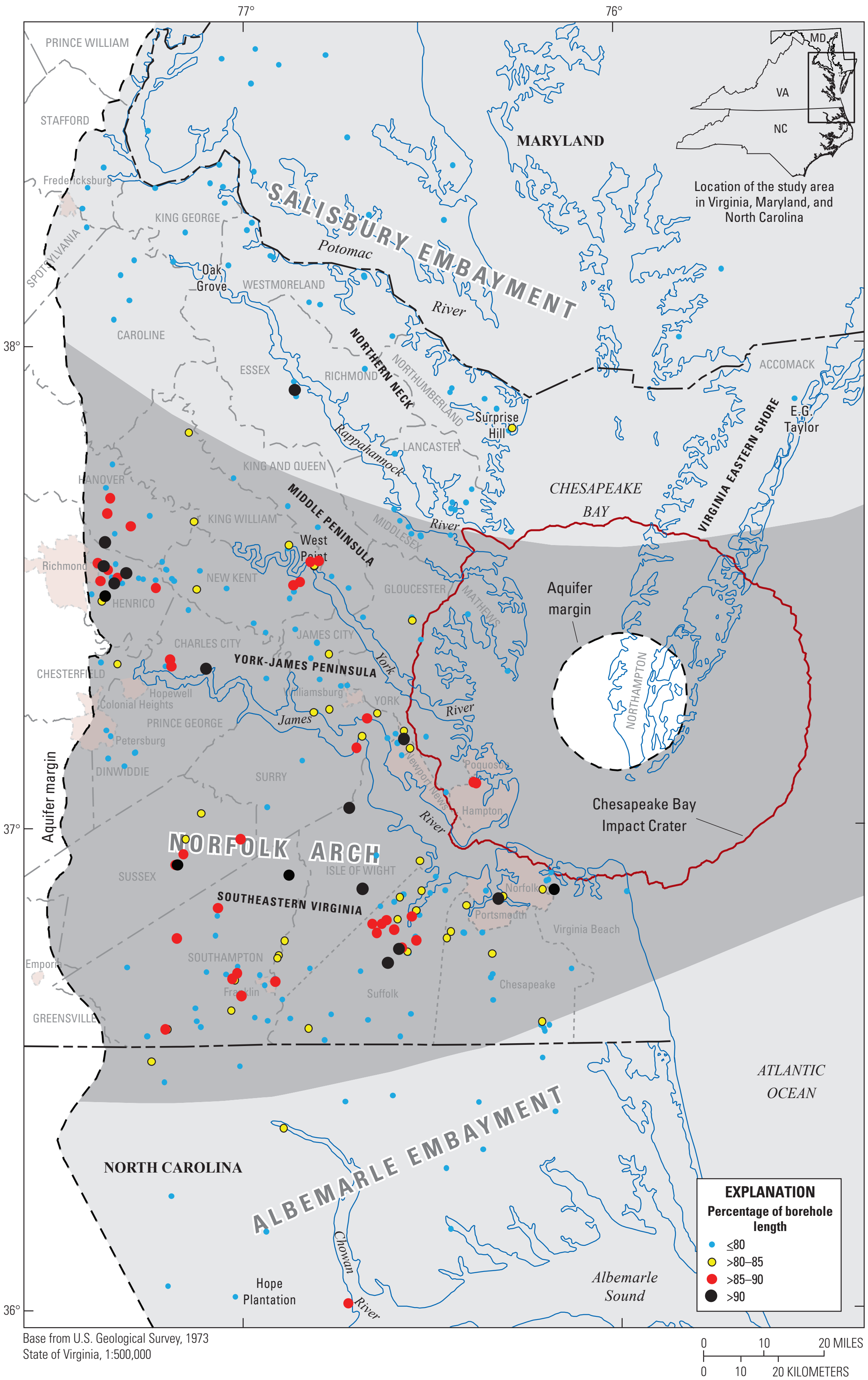


Figure 15. Percentages of borehole lengths composed of coarse-grained sediment of the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Coarse-grained sediments are more dominant across the Norfolk arch than elsewhere. Most boreholes do not penetrate entire aquifer thickness (see figure 35). Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

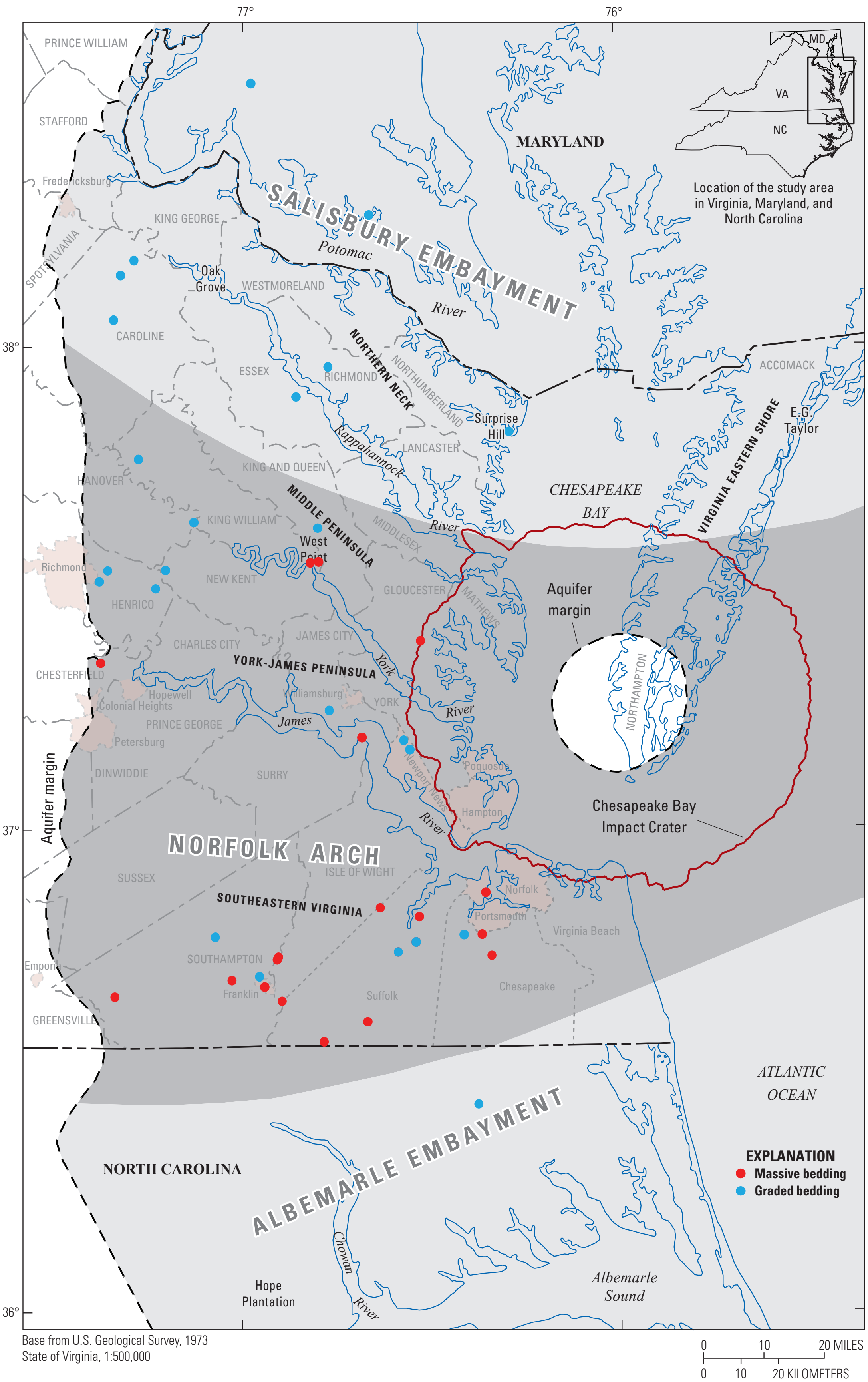


Figure 16. Borehole intervals of 40 feet or greater thickness exhibiting preserved massive or graded bedding among coarse-grained sediments of the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Massive bedding is exhibited only across the Norfolk arch. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

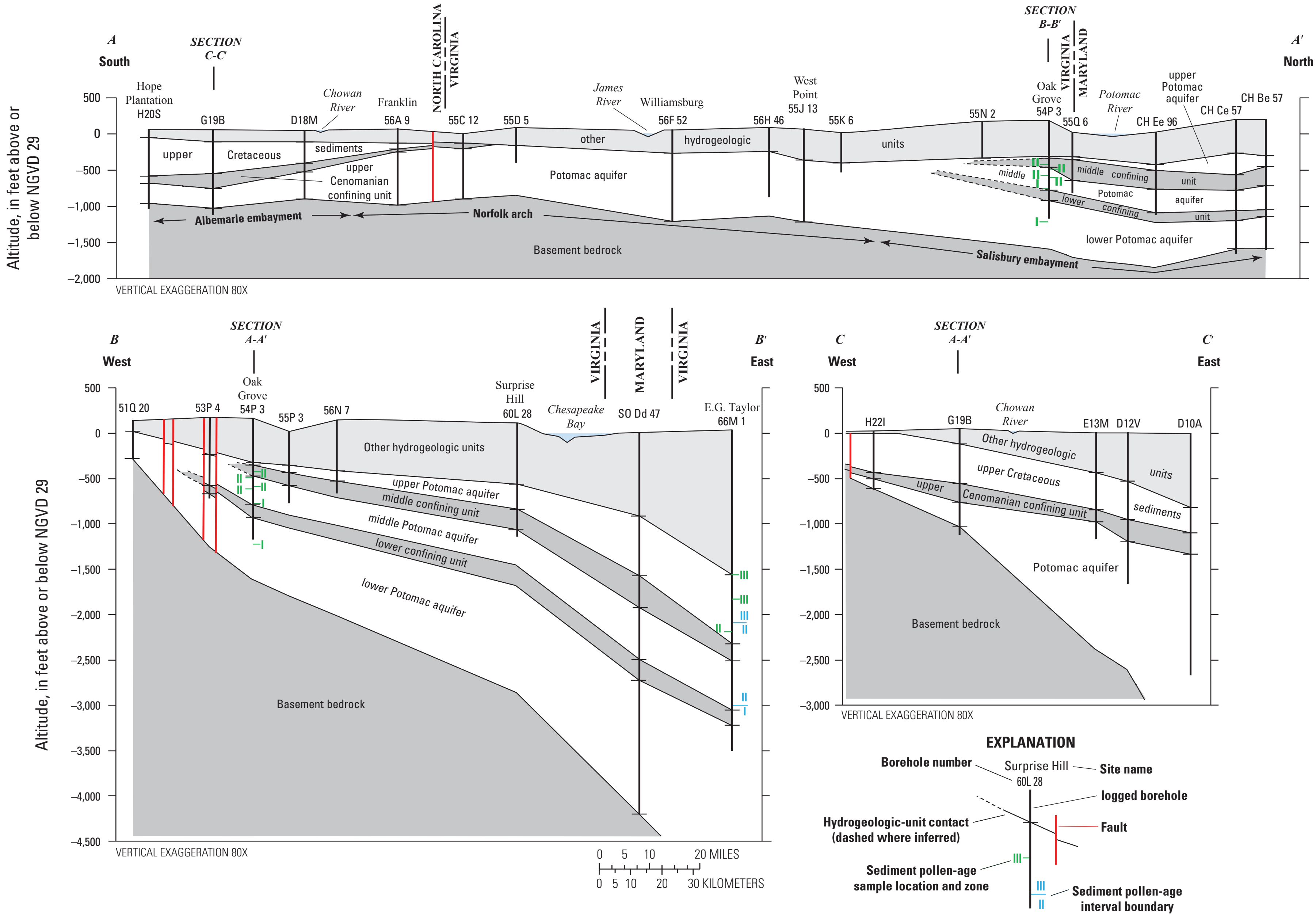


Figure 17. Hydrogeologic sections of the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina. Section locations are shown in figure 1. Additional sediment pollen-age information is shown in figures 22–23 and table 1. In much of Virginia, the Potomac aquifer is composed of mostly coarse-grained sediments across the Norfolk arch (section *A–A′* center). Fine-grained confining units that subdivide the Potomac aquifer are limited to the Salisbury embayment in Maryland and northern most Virginia (sections *A–A′* right and *B–B′*). The Potomac aquifer in North Carolina and southernmost Virginia is hydraulically separated from overlying upper Cretaceous sediments by the upper Cenomanian confining unit (sections *A–A′* left and *C–C′*) and truncated against basement bedrock by a fault (section *C–C′* left).

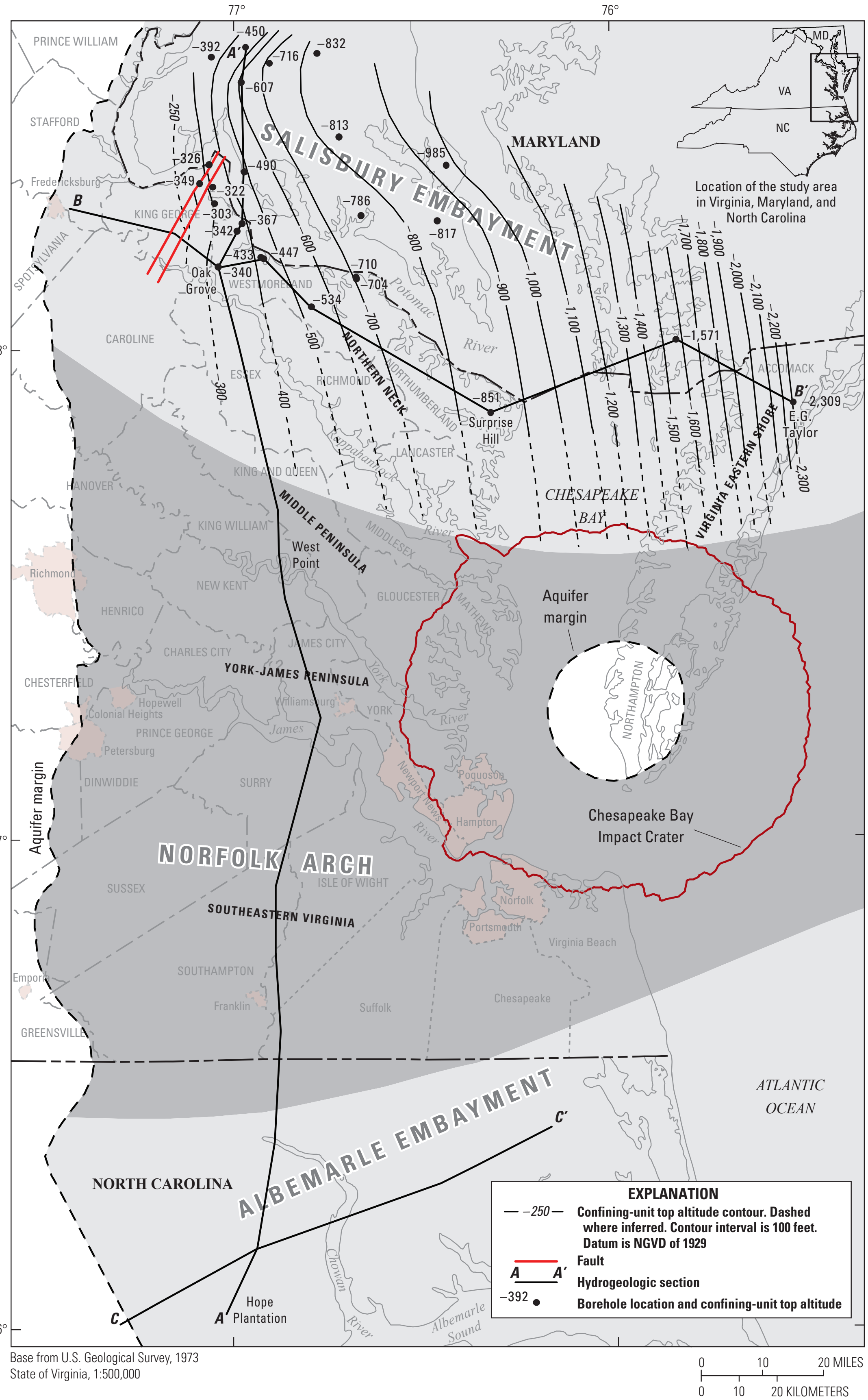


Figure 18. Approximate altitude and configuration of the top of the middle confining unit in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999). Hydrogeologic sections shown in figure 17.

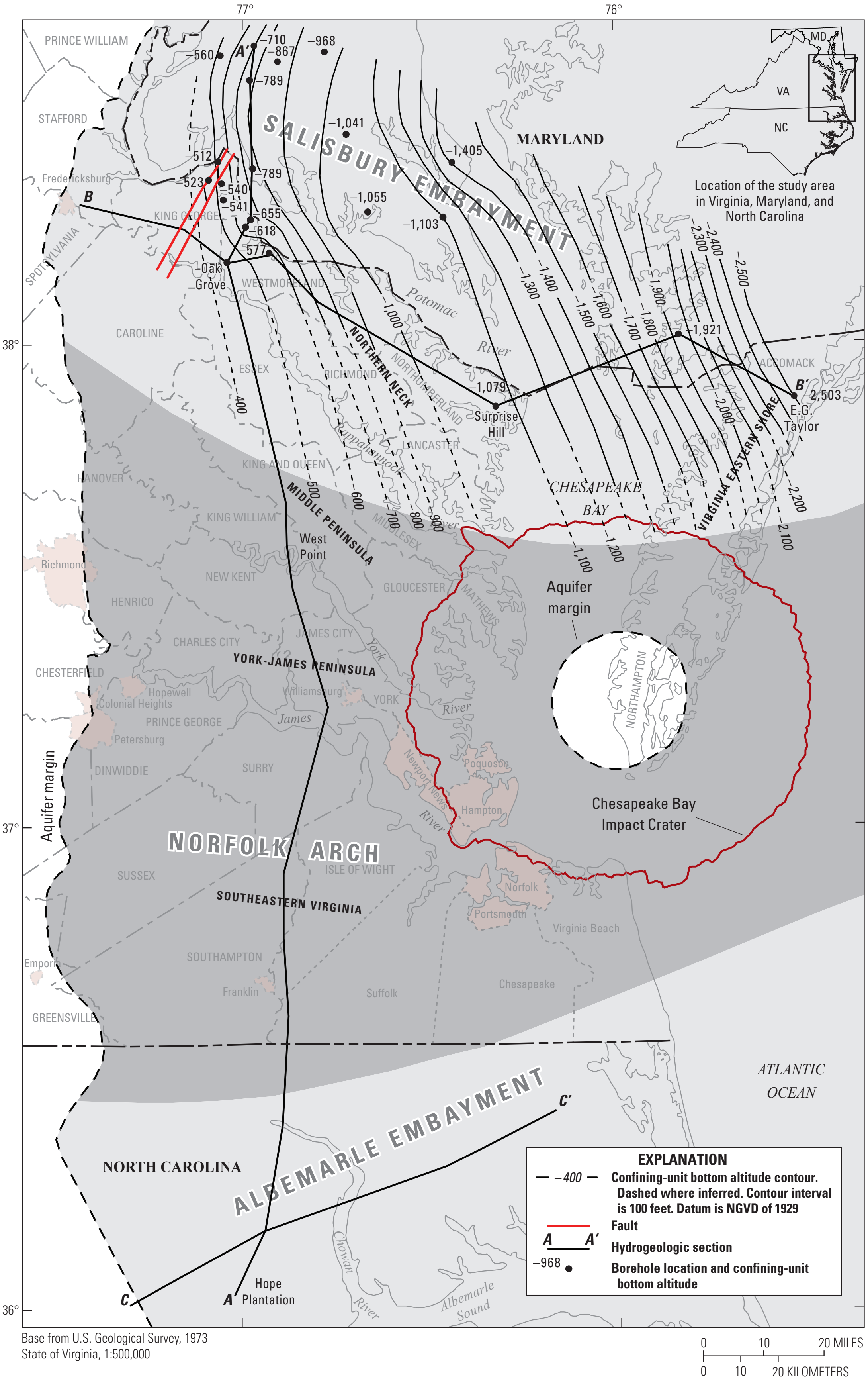


Figure 19. Approximate altitude and configuration of the bottom of the middle confining unit in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999). Hydrogeologic sections shown in figure 17.

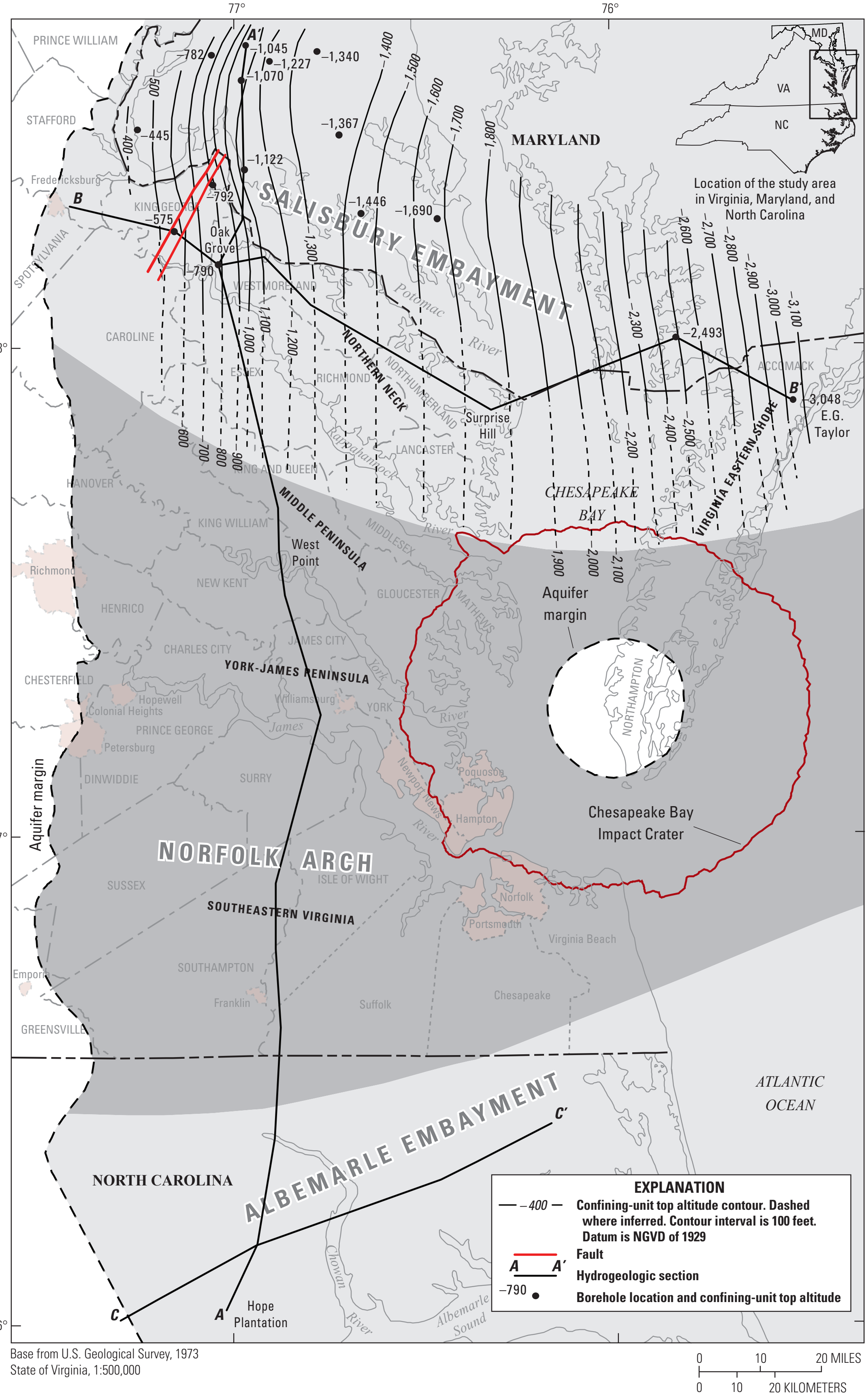


Figure 20. Approximate altitude and configuration of the top of the lower confining unit in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999). Hydrogeologic sections shown in figure 17.

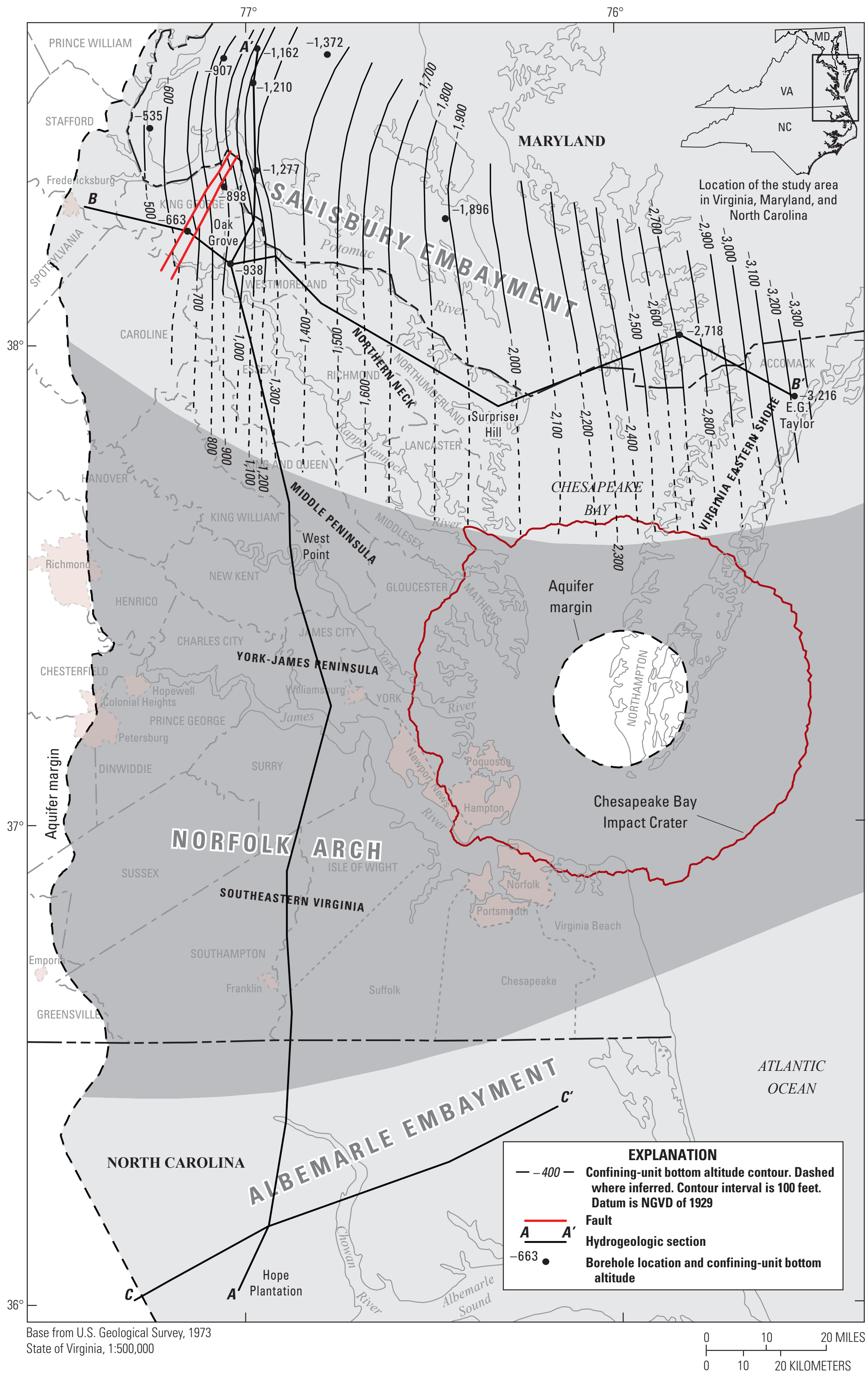


Figure 21. Approximate altitude and configuration of the bottom of the lower confining unit in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999). Hydrogeologic sections shown in figure 17.

as the upper Patapsco, lower Patapsco, and Patuxent (Drummond, 2007). The subaquifers merge southward into the Norfolk arch subarea, where the entire thickness of the undivided sediments functions hydraulically as a single interconnected aquifer (see section "Vertical Hydraulic Connectivity").

The distinction made here between divided and undivided parts of the Potomac aquifer in Virginia provides a new understanding from previous hydrogeologic designations of the aquifer sediments. Designation of upper, middle, and lower Potomac aquifers throughout the Virginia Coastal Plain by the USGS RASA investigation (Meng and Harsh, 1988) relied heavily on a single corehole at Oak Grove in Westmoreland County (Reinhardt and others, 1980) as a type stratigraphic section to widely define the sediment sequence across areas more than 100 miles to the south (see section "Hydrogeologic Designations"). The Oak Grove corehole is designated as borehole 54P 3 (pl. 1, Attachment 1) and is among the boreholes interpreted here to intercept confining units (figs. 17–21). Thus, the stratigraphic section of the Oak Grove core is generally representative of the sequence of Potomac aquifer sediments across areas to the north and east, but probably less than 30 mi to the south.

Albemarle Embayment

The Albemarle embayment depositional subarea occupies only a small part of the Virginia Coastal Plain, extending from far southeastern Virginia southward and southwestward across northeastern North Carolina. Coarse-grained sediment intervals within the Potomac aquifer are thinner and less widespread than in the Norfolk arch subarea. Unlike the Salisbury embayment subarea, however, delineation of confining units by stratigraphic correlation among fine-grained sediment intervals is ineffective. Fine-grained intervals are of only moderate thicknesses and lack alignment to a consistent regional structural trend. Thus, the entire sediment thickness functions hydraulically as a single interconnected aquifer regionally.

The configuration of the Albemarle embayment subarea contrasts with that of the Salisbury embayment subarea. The Albemarle embayment structurally represents a 100-mi southwestward elongation of the southern limb of the Norfolk arch. The top surface of basement bedrock exhibits a planar and evenly southeastward sloping configuration (figs. 6 and 12), which continues with the northeastern limb of the Cape Fear arch farther south. By contrast, the shape of the Salisbury embayment is distinctly concave. Despite the relatively open structural configuration of the Coastal Plain in northeastern North Carolina, the term embayment has been used traditionally—but possibly inappropriately—to account for a pronounced progradation of sediments far to the east across the Continental Shelf (Owens and Gohn, 1985). The more closed configuration of the Salisbury embayment possibly was more conducive to accumulation of thick fine-grained sediments (see section "Conceptual Depositional Model"). In addition, the supply of fine-grained sediments to the Salisbury embayment was probably enhanced by a relatively large proportion of clay minerals produced from schist source rocks by chemical weathering (see section "Deposition Over Time").

Sediment Age Relations

The spatial distribution of sediments composing the Potomac aquifer resulted from an approximately 45-m.y. history of deposition within complex, locally dynamic, and regionally evolving fluvial environments (see section "Lithologic and Depositional Characteristics"). Accordingly, further understanding of the distribution of the sediments can be inferred from differences among their ages.

Sediment Pollen-Age Zonation

Numerous analyses of fossil pollen have been undertaken during much of the past century as a means to estimate the relative timing of sediment deposition. Since the rise of terrestrial plants on Earth, pollen has been continually produced in large quantities and dispersed globally through the atmosphere. Subsequently, pollen incorporated within some sedimentary deposits has been preserved through geologic time. Distinctions among pollen morphologies associated with the evolution of plant species have been chronologically systematized and applied to many sedimentary sequences worldwide.

Within the Atlantic Coastal Plain of North America, pollen-age zones of Cretaceous age designated pre-zone I through VII (from oldest to youngest) have been related to sediment ages, designated geologic formations and hydrogeologic units, and interpreted depositional environments (fig. 4). A pre-zone I pollen age was inferred for the Waste Gate Formation (Hansen, 1982, 1984). Dominantly massive bedded, coarse-grained feldspathic sediments directly overlying basement bedrock along the Atlantic coast were interpreted to have been deposited by immature braided streams. Fluvial and deltaic sediments of the Patuxent and Arundel Formations of Maryland were inferred to be of zone I pollen age and of the Patapsco Formation to be of zone II pollen age (Doyle and Robbins, 1977; Reinhardt and others, 1980). Zone III and younger sediments were further interpreted to be of estuarine to marginal marine origin. The USGS RASA investigation inferred pollen ages of lower Potomac aquifer sediments to be pre-zone I and zone I, middle aquifer sediments to be zone II, and upper aquifer sediments to be zones III and IV (Meng and Harsh, 1988).

A fundamental regional perspective was established by a comprehensive analysis of the entire Atlantic Coastal Plain (Owens and Gohn, 1985), in which six depositional sedimentary sequences were described as spanning the Cretaceous Period. The Potomac Formation in Virginia represents the first depositional sequence, consisting of early Cretaceous to earliest late Cretaceous age, primarily fluvial sediments of pre-zone I through zone III pollen ages. These sediments span the entire Coastal Plain in Virginia and northward through

Maryland, Delaware, and New Jersey, but extend southward only across northeastern North Carolina and are absent farther south. Younger near-shore marine sediments of the second depositional sequence are not part of the Potomac Formation, but are present only farther north in Maryland and from far southeastern Virginia into northeastern North Carolina. All remaining younger depositional sequences are entirely absent from Virginia, southern Maryland, and northeastern North Carolina.

Potomac Formation sediments have been delineated to be of zone I pollen age across the entire Virginia Coastal Plain, but in the northern and southern parts of the Virginia Coastal Plain, the Potomac Formation also includes two separate overlying wedge-shaped masses of zone II pollen age (Powars, 2000). A thin overlying interval of glauconitic marine sediments of zone III pollen age was further theorized to be present in far southeastern Virginia. These sediments were identified in only one borehole and, although designated as part of the Potomac Formation, have not been included as part of the Potomac aquifer. Overlying sediments of zones IV and V pollen ages were also identified in far southeastern Virginia but were designated as other formations. Following these delineations, samples of sediment penetrated by borehole 58F 50 in proximity to the Chesapeake Bay impact crater (pl. 1) were analyzed to reveal an inverted sequence among pollen zones I, II, and III, indicating overturning of a megablock (see section "Configuration").

A unique hydrologic application of sediment pollen-age analysis was undertaken in northern Delaware, where the Potomac Formation has not been subdivided because of the lack of continuity among its highly interbedded sediments (Benson, 2006). Samples of sediment determined to have pollen ages ranging from zones I through III were stratigraphically correlated to broadly distinguish early Cretaceous age from late Cretaceous age parts of the Potomac Formation. Hydraulically continuous time-stratigraphic layers were then extrapolated from the pollen-age boundaries throughout the Potomac Formation on the basis of correlations of geophysical-log "marker" beds. This analysis was constrained, however, by the required assumption that coarse-grained sediments are subordinate to and fully enclosed within aerially extensive, time-synchronous fine-grained sediments. The time-stratigraphic layers formed the basis for representing the sediments in a digital groundwater-flow model as three distinct layers separated by the pollen-zone boundaries, but without intervening confining units.

Published pollen-age data representing zones pre-I through III were compiled from some of the above and additional studies (table 1). The data represent pollen ages described for sediments penetrated by several boreholes at widely spaced locations in the Virginia Coastal Plain and southern Maryland. Similar data for northeastern North Carolina are not readily available. Sediment pollen ages were either determined directly by microscopic examination of sediment samples or were inferred by the cited studies for designated intervals within boreholes. Subdivisions among relative ages of some pollen zone II sediments are denoted, from oldest to youngest, by letter designations A, B, or C.

Published sediment pollen-age data were used to delineate the approximate configuration of two surfaces within the Potomac aquifer that represent boundaries between sediments of zone I and zone II ages, and between zone II and zone III ages (figs. 22 and 23). Pollen-zone age-boundary surface altitudes at each borehole location were approximately bracketed vertically, on the basis of published sediment-sample and borehole-interval pollen ages. Potomac aquifer sediments that probably are within megablocks disrupted by the Chesapeake Bay impact crater were not included because they do not reflect the sediment-age distribution resulting from original deposition. Boundary-surface altitude contours were then broadly interpolated between the boreholes. Much of the area is generally lacking extensive time-synchronous fine-grained sediments, however, that were relied on to constrain boundary-surface delineation in northern Delaware (Benson, 2006). In addition, boundary-surface contours were projected across the excavated part of the impact crater where originally deposited Potomac aquifer sediments have been removed.

Pollen-zone age-boundary surfaces broadly represent the sediment-age distribution within the Potomac aquifer. Designated depositional subareas are not segregated by the boundary surfaces. Thus, the regional trend of coarse- and fine-grained sediments among the depositional subareas widely transgresses sediment-age boundaries. Within the Salisbury embayment subarea, however, the two confining units (figs. 17–21) are approximately aligned with the boundary surfaces.

Hydrostratigraphy of Cretaceous Age Sediments in Southeastern Virginia and Northeastern North Carolina

Across the central and northern parts of the Virginia Coastal Plain, the stratigraphic relation between the Potomac aquifer and the overlying Aquia aquifer is represented by a transitional interval designated as the Potomac confining zone (McFarland and Bruce, 2006) (see section "Lithologic and Depositional Characteristics"). Farther south, other sediments of late Cretaceous age separate the Potomac and Aquia aquifers (figs. 2 and 4). The late Cretaceous age sediments have been alternatively interpreted by various studies. The lowermost among these sediments were most recently designated geologically in Virginia as the upper Cenomanian beds (Powars, 2000), and subsequently designated hydrogeologically as the upper Cenomanian confining unit (McFarland and Bruce, 2006).

The upper Cenomanian confining unit represents a major hydrologic upper boundary on the Potomac aquifer in southeastern Virginia and imposes a substantial hydraulic separation between the Potomac aquifer and overlying late Cretaceous age sediments of the Virginia Beach aquifer (McFarland and Bruce, 2006). Sediment cores exhibit glauconitic and micaceous fine shelly sands of near-shore marine origin (fig. 9*E*) of pollen-zone IV age (Powars, 2000) (fig. 4). On the

Table 1. Published pollen-zone ages of sediment composing the Potomac aquifer of the Virginia Coastal Plain and adjacent parts of Maryland.

[Depths are in feet below land surface; borehole numbers and names refer to locations shown in figures 22–23; horizontal datum is referenced to the North American Datum of 1927; altitudes are in feet referenced to the National Geodetic Vertical Datum of 1929; sample – pollen age determined by microscopic examination of sediment; interval – pollen age inferred by cited study for designated borehole interval; NASA, National Aeronautics and Space Administration]

Pollen zone	Designation type	Depth
Calis and Drummond, 2008		
borehole CA Db 96 – Prince Frederick latitude 38.5456 longitude –76.5950 altitude 152		
III	sample	1,000 – 1,015
II or III	sample	1,235 – 1,240
II-B	sample	1,340 – 1,360
II-B	sample	1,440 – 1,460
II-B	sample	1,520 – 1,540
I	sample	1,590 – 1,610
borehole SM Dd 72 – Paw Paw Hollow latitude 38.2739 longitude –76.6594 altitude 115		
II-B or C	sample	600 – 620
II-B or C	sample	720 – 740
II-B	sample	950 – 970
II-A	sample	1,110 – 1,130
II-A	sample	1,130 – 1,150
II-A	sample	1,330 – 1,350
I	sample	1,550 – 1,570
I	sample	1,570 – 1,590
I	sample	1,590 – 1,610
Doyle and Robbins, 1977		
borehole 66M 1 – E.G. Taylor latitude 37.8842 longitude –75.5169 altitude 42		
III	interval	1,564 – 2,127*
II	interval	2,127 – 3,045*
II	interval	2,440 – 2,888
I	interval	3,045 – 4,682*
pre-I	interval	4,682 – 6,272*
pre-I and lowest I	interval	5,128 – 6,086
III	sample	1,616
III	sample	1,860
II-B or C	sample	2,214
lowest I	sample	4,470
Edwards and others, 2010		
borehole 59E 32 – Watkins Elementary School latitude 37.0755 longitude –76.4585 altitude 27		
III	interval	645 – 721.8
II-C	interval	721.8 – 985.3
III	sample	692.8
II-C	sample	772.4
II-C	sample	879.7
II-C	sample	902.8

Table 1. Published pollen-zone ages of sediment composing the Potomac aquifer of the Virginia Coastal Plain and adjacent parts of Maryland.—Continued

[Depths are in feet below land surface; borehole numbers and names refer to locations shown in figures 22–23; horizontal datum is referenced to the North American Datum of 1927; altitudes are in feet referenced to the National Geodetic Vertical Datum of 1929; sample – pollen age determined by microscopic examination of sediment; interval – pollen age inferred by cited study for designated borehole interval; NASA, National Aeronautics and Space Administration]

Pollen zone	Designation type	Depth
Fleck and Wilson, 1990		
borehole CH Be 57 – Smallwood Drive latitude 38.6183 longitude –76.9656 altitude 212.26		
II-B	sample	635
borehole CH Bf 144 – Pinefield Production latitude 38.6536 longitude –76.8506 altitude 202.29		
II-C or III	sample	624 – 625
II-C or III	sample	881 – 882
borehole CH Bf 149 – coreholes latitude 38.6508 longitude –76.8803 altitude 210		
III	sample	526.9
II-C	sample	537.3
II-B	sample	577.9
II-B	sample	606
N.O. Fredericksen, U.S. Geological Survey, oral commun., 2001		
borehole 56F 55 – James City Service Authority BGD-1B latitude 37.2483 longitude –76.7691 altitude 57		
III	sample	483.8 – 487
Fredericksen and others, 2005		
borehole 59E 31 – NASA Langley latitude 37.0956 longitude –76.3858 altitude 8		
I	sample	1,464.7
Powars, 2000		
borehole 58A 76 – Dismal Swamp latitude 36.6153 longitude –76.5556 altitude 33		
III	interval	593 – 728
II	interval	728 – 1,383
I	interval	1,383 – 1,827
borehole 61B 11 – Fentress latitude 36.7075 longitude –76.1297 altitude 15		
III	sample	1,055
III	sample	1,303
Reinhardt and others, 1980		
borehole 54P 3 – Oak Grove latitude 38.1694 longitude –77.0386 altitude 180		
II-B	sample	596.5
II-B	sample	660
II-B	sample	756
II-B	sample	781
upper I or basal I-A	sample	950
I	sample	1,398

*Based on regional correlation.

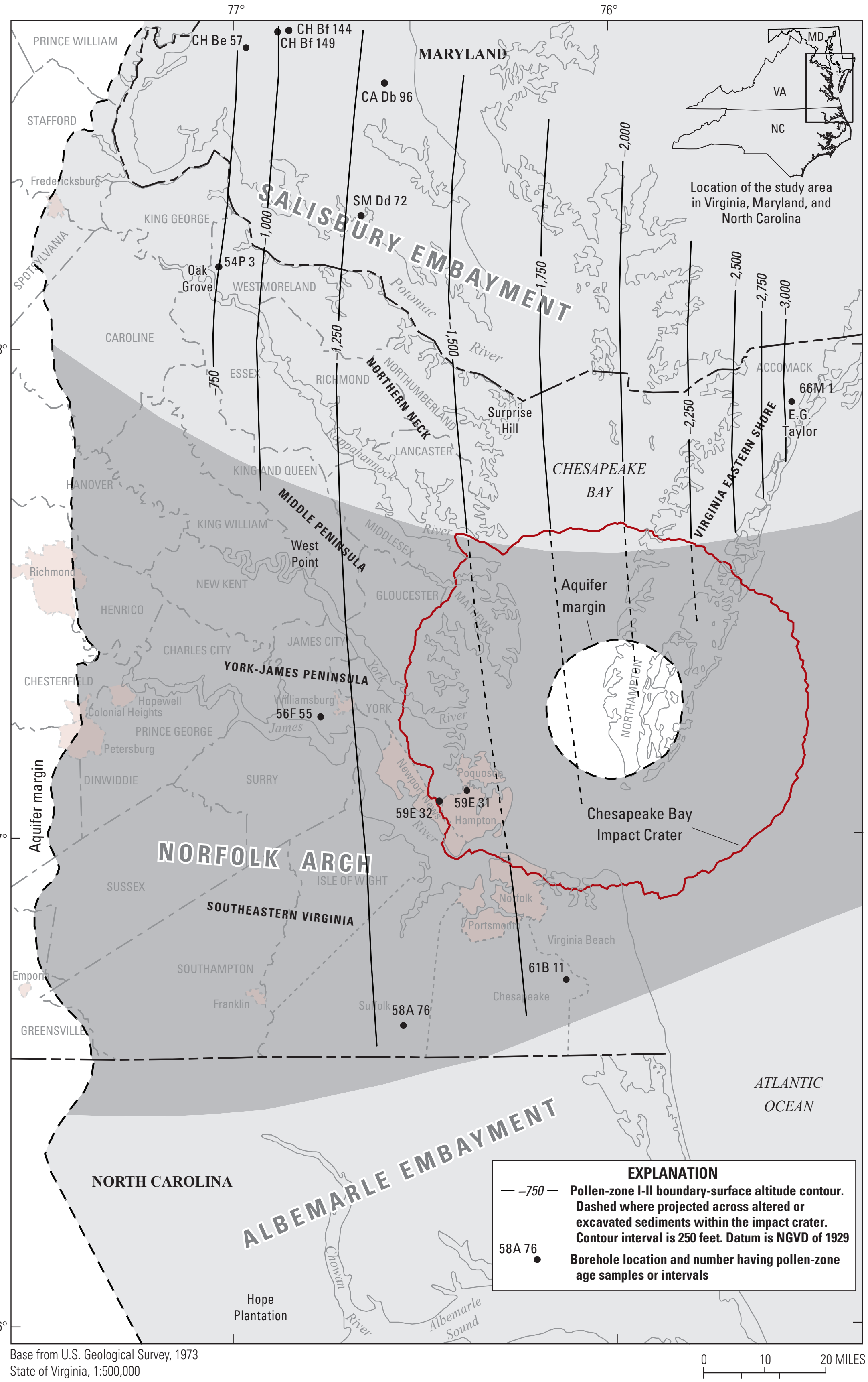
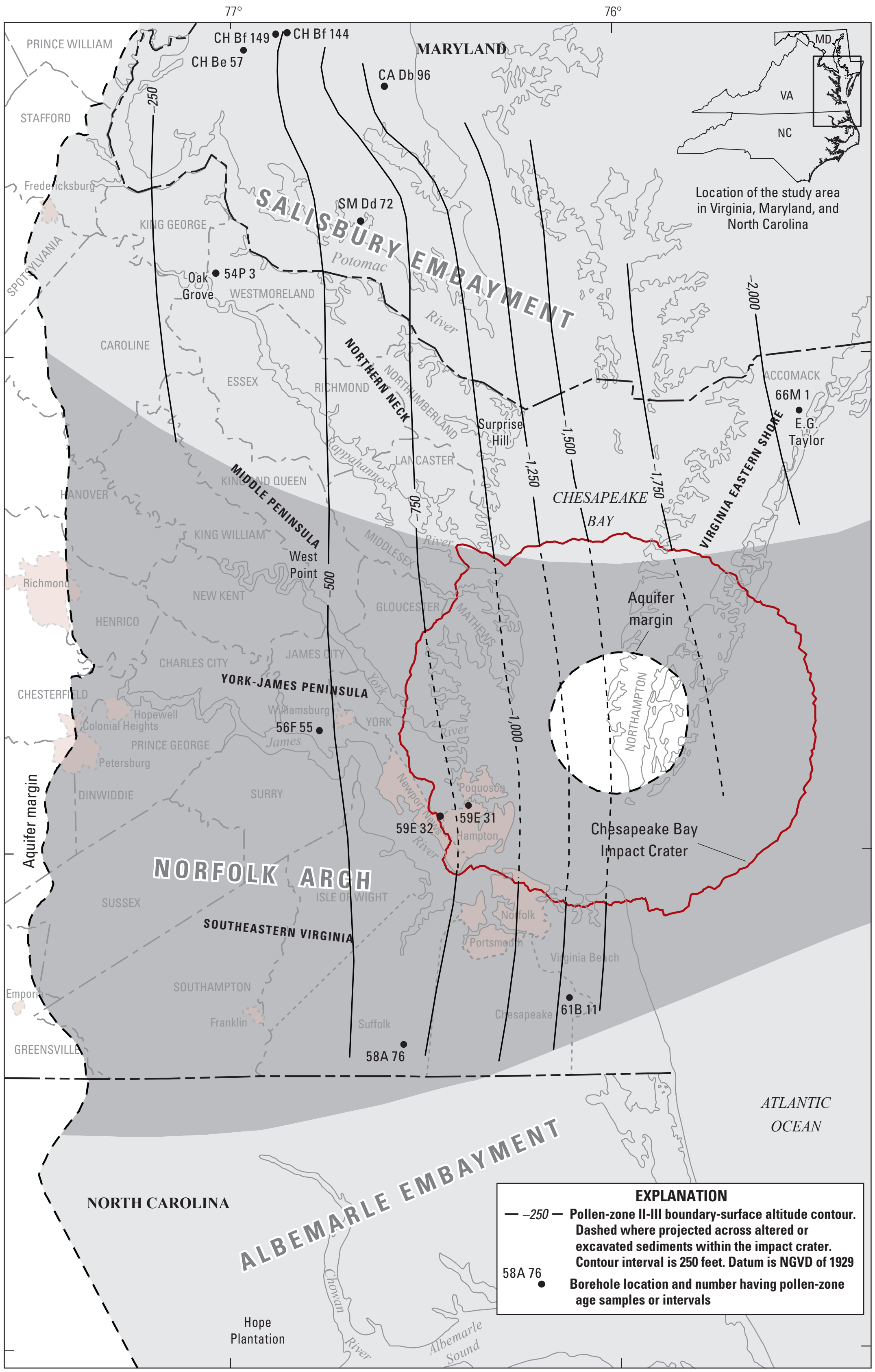


Figure 22. Approximate altitude and configuration of the pollen-zone I-II boundary surface in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).



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

0 10 20 MILES
0 10 20 KILOMETERS

Figure 23. Approximate altitude and configuration of the pollen-zone II-III boundary surface in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

basis of lithologic descriptions, these sediments were probably included by the USGS RASA investigation as part of the upper Potomac aquifer (Meng and Harsh, 1988). The sediments are readily identifiable, however, based on a distinctive saw-toothed shaped geophysical-log signature (fig. 11) produced by alternating thin beds of concentrated shells of the mollusk *Exogyra woolmani* as seen in sediment cores.

The upper Cenomanian confining unit previously has been delineated only in southeastern Virginia (McFarland and Bruce, 2006). In northeastern North Carolina, alternate hydrogeologic interpretations have been made of sediments of both early and late Cretaceous age. The USGS RASA investigation considered the upper, middle, and lower Potomac aquifers in Virginia to be continuous in North Carolina with the upper Cape Fear, lower Cape Fear, and lower Cretaceous aquifers, respectively (Winner and Coble, 1996) (fig. 4). Sediments much younger than the Potomac aquifer, however, were included in North Carolina, some as young as pollen-zone VII age. Subsequently, the lower Cape Fear aquifer in North Carolina was considered as continuous with both the middle and lower Potomac aquifers in Virginia (Lautier, 1998). The upper Cape Fear, lower Cape Fear, and lower Cretaceous aquifers were most recently considered as continuous with a single Potomac aquifer in Virginia (Gellici and Lautier, 2010), but were delineated as extending individually across southeastern Virginia and including sediments of pollen-zone IV age and younger.

Apart from these studies, a fundamental geologic perspective was recently established for Cretaceous age sediments in northeastern North Carolina. Sediment lithologic and age relations were determined from a corehole at Hope Plantation (borehole H20S; pl. 1; fig. 1; fig. 17, section *A–A′*) (Weems and others, 2007). Subsequently, geologic mapping of the Roanoke Rapids quadrangle (Weems and others, 2009) extrapolated these relations to some of the same boreholes used by earlier hydrogeologic studies. Immature fluvial sediments of lower Cretaceous age that are continuous with the Potomac aquifer in Virginia are delineated in northeastern North Carolina in the subsurface only and are truncated to the southwest against a fault. Overlying sediments are geologically designated separately as either the Clubhouse Formation or Cape Fear Formation, both of late Cretaceous age and including pollen zones IV and V, respectively (fig. 4). Clubhouse Formation sediments are of marine origin, which separate and distinguish fluvial sediments of the overlying Cape Fear Formation from underlying fluvial sediments continuous with the Potomac aquifer. On the basis of lithologic composition, depositional origin, and sediment-age relations, the Clubhouse Formation in North Carolina is considered here as continuous with—and an extension of—the upper Cenomanian confining unit in southeastern Virginia. No previous hydrogeologic investigations in either State are known to have recognized this relation.

Previously published hydrostratigraphic interpretations among Cretaceous age sediments between southeastern Virginia and northeastern North Carolina are inconsistent with the relations established by Weems and others (2009). A fundamental discrepancy exists in considering late Cretaceous age sediments that compose some aquifers in North Carolina as being continuous with early Cretaceous age sediments of the Potomac aquifer in Virginia. Direct hydraulic connectivity between early and late Cretaceous age sediments is implausible with recognition of the substantial vertical hydrologic boundary imposed by the upper Cenomanian confining unit (see section “Vertical Hydraulic Connectivity”).

In order to partly resolve hydrostratigraphic relations between early and late Cretaceous age sediments, the upper Cenomanian confining unit is delineated here as extending from southeastern Virginia into northeastern North Carolina (figs. 17 and 24). Geophysical logs of boreholes located in northeastern North Carolina generally exhibit the distinctive signature of the upper Cenomanian confining unit, including sediments designated in the Hope Plantation core and subsequently mapped as the Clubhouse Formation (Weems and others, 2007, 2009). The part of the upper Cenomanian confining unit that extends from southeastern Virginia into northeastern North Carolina generally is consistently aligned to the regional strike and dip, although the configuration is unknown toward the coast where no boreholes are deep enough to penetrate into early Cretaceous age sediments.

With recognition of the upper Cenomanian confining unit in northeastern North Carolina, the following relations are apparent:

1. The Potomac aquifer deepens and thins southward from southeastern Virginia into northeastern North Carolina (fig. 17, section *A–A′*) before being truncated to the southwest against a fault (fig. 7; fig. 17, section *C–C′*).

2. The substantial hydraulic separation imposed by the upper Cenomanian confining unit between the Potomac aquifer and overlying sediments in southeastern Virginia continues southward across northeastern North Carolina (see “Vertical Hydraulic Connectivity”).

3. Some late Cretaceous age sediments overlying the upper Cenomanian confining unit in northeastern North Carolina possibly are continuous with the Virginia Beach aquifer in southeastern Virginia.

4. Previous designations of the upper and lower Cape Fear aquifers in northeastern North Carolina include large parts of late Cretaceous age sediments that are not continuous with the Potomac aquifer in southeastern Virginia, but possibly are partly continuous with the Virginia Beach aquifer.

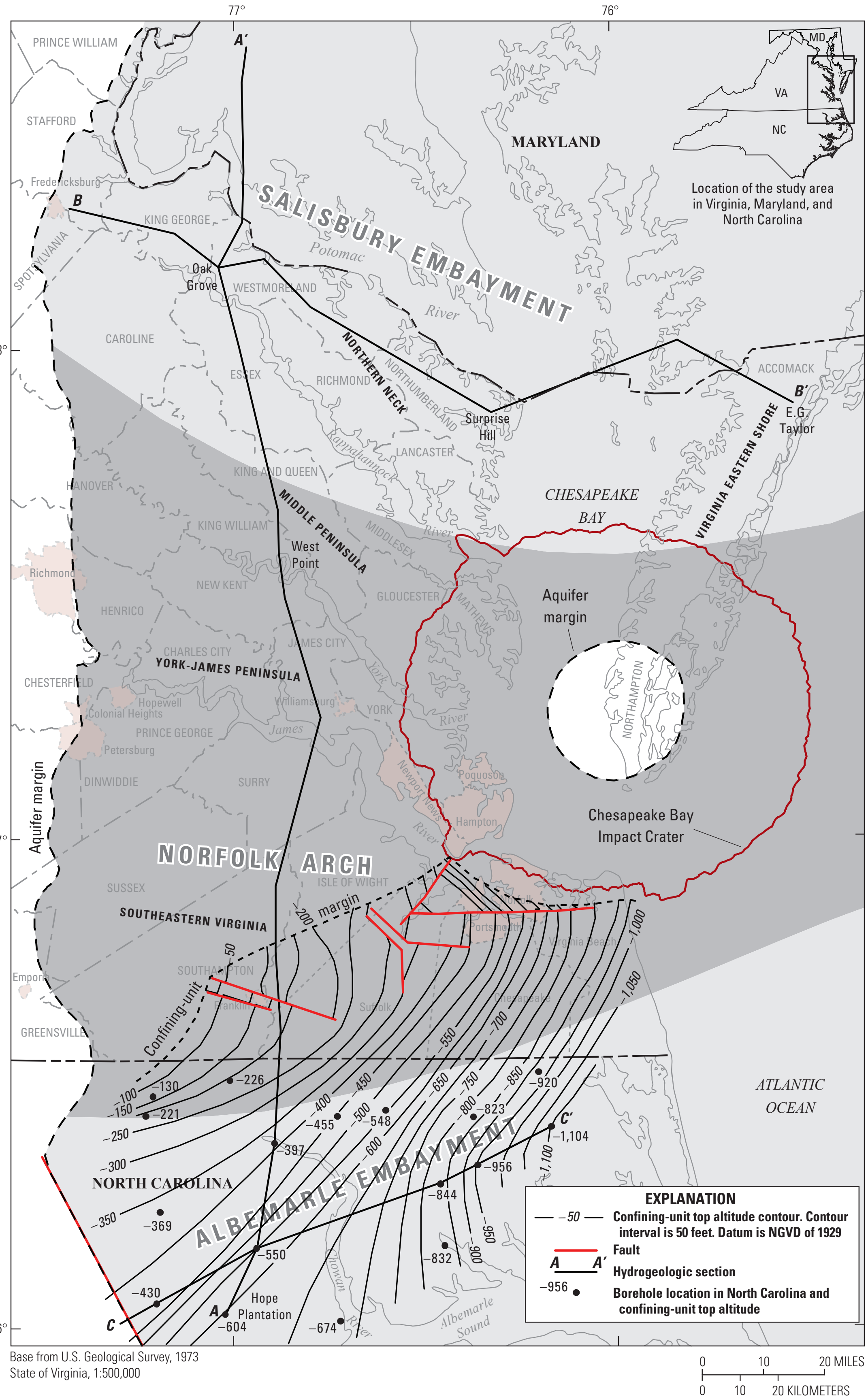


Figure 24. Approximate altitude and configuration of the top of the upper Cenomanian confining unit overlying the Potomac aquifer in Virginia and parts of North Carolina. Configuration in Virginia adapted from McFarland and Bruce (2006). Location of Chesapeake Bay impact crater from Powars and Bruce (1999). Hydrogeologic sections shown in figure 17.

Conceptual Depositional Model

Ages of sediments composing the Potomac aquifer provide an understanding of processes operating over geologic time that resulted in the spatial distribution of coarse- and fine-grained sediments. Following rifting of the supercontinent Pangea during the Triassic and Jurassic Periods, sediments were deposited along the eastern margin of the newly forming North American continent, coinciding with initial opening of the present-day Atlantic Ocean during the early to earliest late Cretaceous Period. Flexure associated with tension of the Earth’s crust resulted in uplift and erosion of bedrock across the Piedmont to the west and downwarp and sediment deposition across the Coastal Plain to the east (fig. 25). Sources of sediment were restricted to areas east of the Blue Ridge Mountains that maintained an unbreached drainage divide from areas farther west until the early Miocene Epoch, based on fission-track dating of zircon sand grains (Naeser, Naeser, Newell, and others, 2004, 2006). Erosional lowering of the Piedmont took place at approximately 0.0008 in/yr as estimated from fission-track dating of apatite sand grains (Naeser, Naeser, Southworth, and others, 2004). Abundant plant fossils and other organic matter in some sediments indicate a relatively heavily vegetated landscape and humid climate.

Spatial Controls

Sediment deposition coincided with geomorphic maturation of the land surface as the form, function, and geographic distribution of streams evolved (see section “Lithologic and Depositional Characteristics”). During transport, coarse- and fine-grained sediments were segregated eastward (fig. 25) by fluctuations in streamflow energy through progressively mature stream morphologies. Coarse-grained sediments were preferentially deposited in proximity to Piedmont source rocks under high energy flow conditions by immature, high gradient braided streams. Much of the fine-grained sediments remained in suspension until transported farther from Piedmont source rocks and eventually were deposited upon entering low energy flow conditions of mature, medium to low gradient meandering streams.

The distribution among coarse- and fine-grained sediments was further affected by structural features of the Continental Margin. The top surface of basement bedrock likely imposed a primary control on the locations of Piedmont sediment-source rocks and on directions of stream drainage and sediment transport. The present-day undulating configuration of arches and embayments (figs. 6, 12, and 17) is theorized to have formed early in the development of the Continental Margin (Owens and Gohn, 1985), possibly as

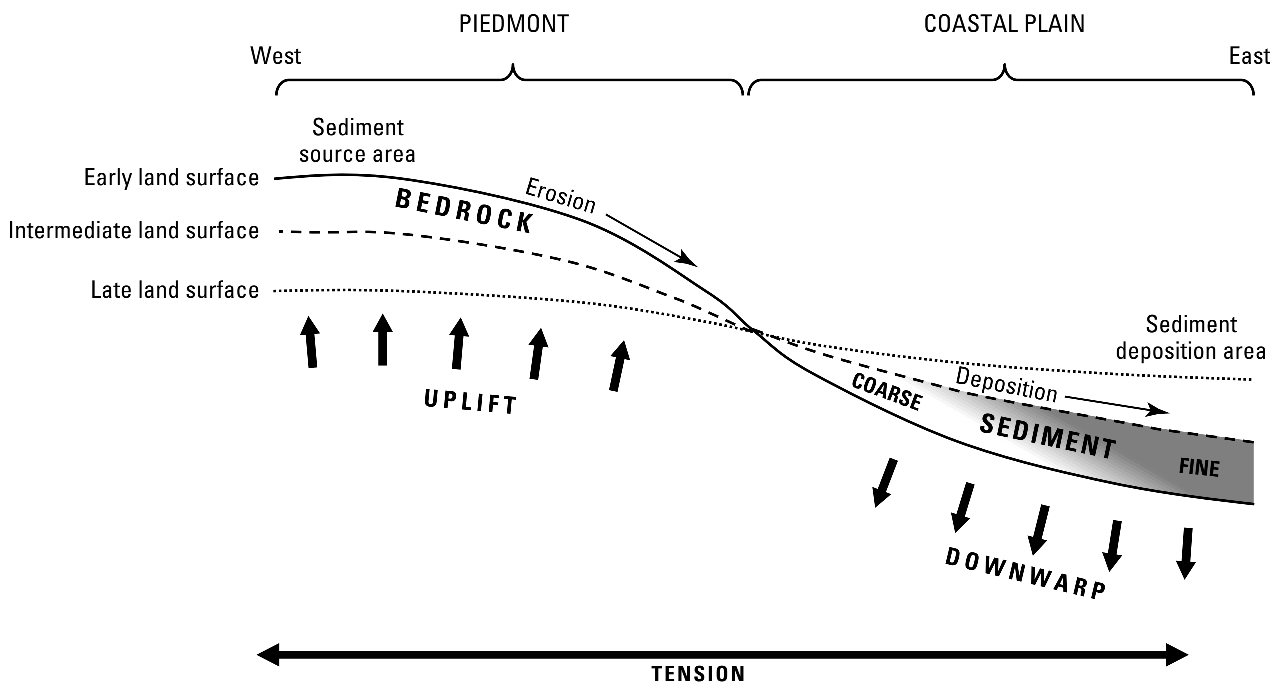


Figure 25. Simplified structural features of the North American Continental Margin during the early to earliest late Cretaceous Period between approximately 100 and 145 million years ago. Lateral tension associated with ongoing widening of the Atlantic Ocean induced crustal flexure that uplifted the westward side of the margin and downwarped the eastward side. Sediment produced by erosion of bedrock in uplifting source areas (corresponding to the present-day Piedmont) was transported eastward by rivers and streams into downwarped depositional areas (corresponding to the present-day Coastal Plain). Ongoing erosion and deposition progressively leveled the land surface.

a result of movement along landward extensions of ocean transform faults (Powars, 2000). Consequently, drainage and sediment transport were not uniform eastward across the entire Coastal Plain, but rather varied in local orientation.

The spatial distribution of early Cretaceous age sediments across the Maryland Coastal Plain has been theorized to result from segregation of coarse- and fine-grained sediments during transport (Hansen, 1969, 1971). A broad regional trend among sediments of the Patuxent and Patapsco Formations was produced by a fluvial depositional complex spanning the Maryland Coastal Plain (fig. 26). The Maryland depositional complex was comparable in size to major present-day depositional systems and possessed a bilaterally symmetric drainage pattern that radiated southward to Virginia and eastward to Delaware. Coarse-grained sediments were deposited by immature braided streams across the center of the complex in proximity to the present-day city of Baltimore. Increasingly fine-grained sediments were transported farther southward toward Virginia and eastward toward Delaware until being deposited by mature meandering streams.

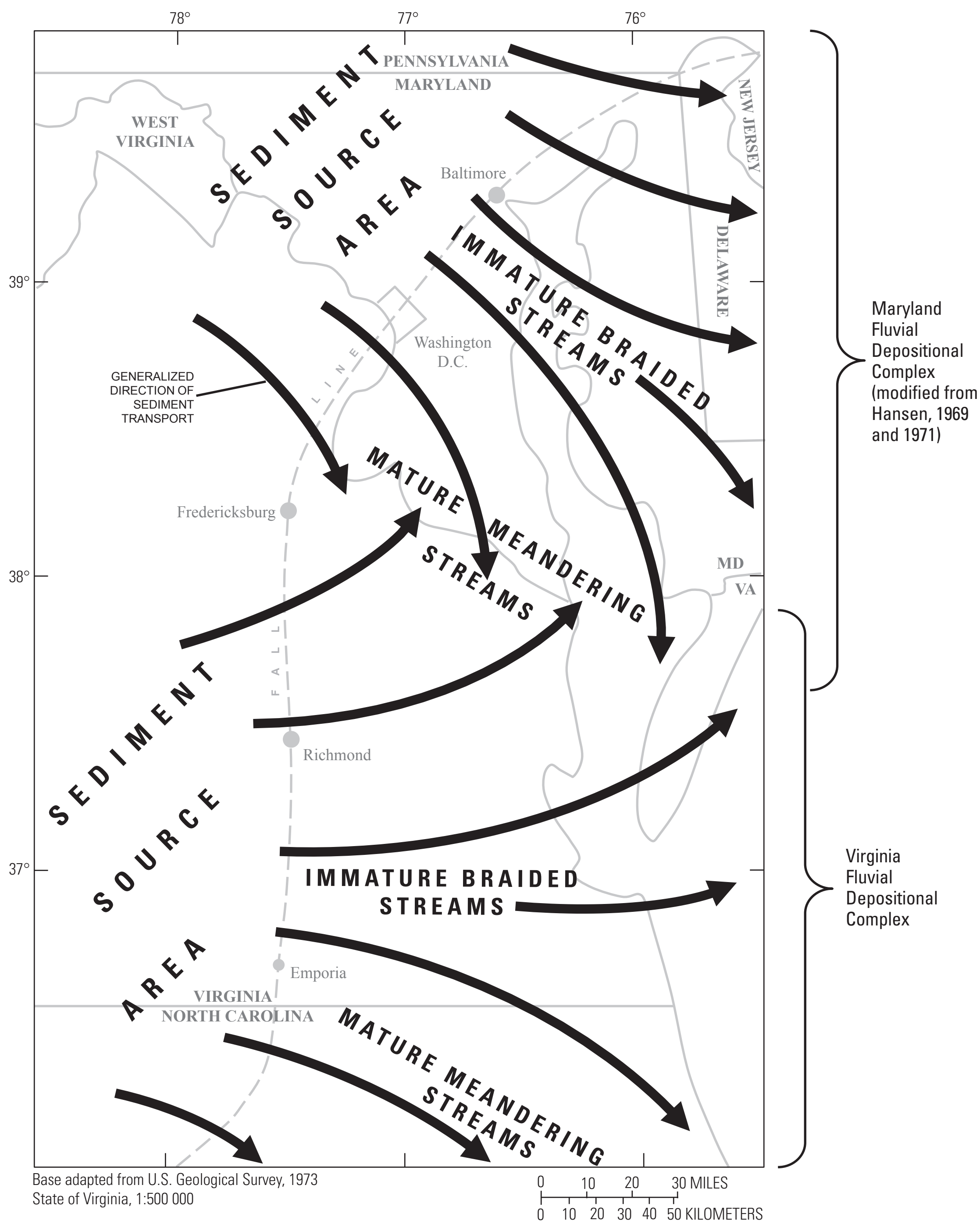


Figure 26. Fluvial depositional complexes of the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina during the early to earliest late Cretaceous Period between approximately 100 and 145 million years ago. Depositional complexes likely consisted of several or more individual drainage basins that changed configuration over time. Predominantly coarse-grained sediments were generally deposited eastward across the central and southern Virginia Coastal Plain under high-energy conditions by immature, high-gradient braided streams in proximity to a persistently uplifted source area. Fine-grained sediments were preferentially transported farther from the source area to the northeast and southeast, and were deposited under low-energy conditions by mature, medium- to low-gradient meandering streams. The depositional complex in Virginia merged northward with another similar depositional complex in Maryland described by Hansen (1969, 1971).

Virginia Fluvial Depositional Complex

A fluvial depositional complex spanning the Virginia Coastal Plain (fig. 26) is theorized here to have produced the spatial distribution of sediments composing the Potomac aquifer in Virginia during the early to earliest late Cretaceous Period between approximately 100 and 145 Ma. The depositional complex represents a southern counterpart to the depositional complex theorized in the Maryland Coastal Plain (Hansen, 1969, 1971). Likewise, these are probably only two of a series of generally eastward oriented depositional complexes that were arrayed from north to south along the entire Atlantic Coastal Plain.

Within the Virginia depositional complex, distinct variations in the morphologies and lithologies of sedimentary deposits are related to the three depositional subareas, which are based on borehole sediment intervals (see section “Depositional Subareas”). The Norfolk arch subarea was in proximity to an uplifted, actively eroding sediment-source area in the Piedmont to the west (fig. 26). Localized networks of immature, high-gradient braided streams deposited complexly overlapping and coalescing longitudinal bars and channel fills dominated by coarse-grained quartz and feldspar sand and gravel. Where not reworked and beveled by erosion, preserved sequences formed both massive and graded bedding. Some concentrations of feldspathic sands eventually weathered in situ to kaolinitic clay.

Both the Salisbury and Albemarle embayment depositional subareas were farther from the sediment-source area in Virginia. Predominantly mature, medium- to low-gradient, broadly meandering streams deposited channel fills and point bars. Graded beds of quartzitic medium- to coarse-grained sand were segregated from fine-grained sediments in overbank deposits. Immature braided streams in the Norfolk arch subarea transitioned progressively downgradient to mature meandering streams in the Salisbury and Albemarle embayment subareas. Likewise, distal parts of the Virginia depositional complex adjacent to coastal areas farthest to the east merged with subareal deltas. Coeval sediments even farther east beneath the present-day Continental Shelf were deposited under marine conditions.

Across the northernmost part of the Virginia Coastal Plain, the Virginia depositional complex likely merged with the southern margin of the Maryland depositional complex. Sediments were received from both depositional complexes at different times and originated from two different source areas located in Virginia and Maryland (fig. 26). Mineralogic analyses of sand grains from Potomac aquifer sediments reflect two distinct dominant Piedmont sediment-source rocks (Glaser, 1969). Erosion of granite and gneiss produced much of the sediments deposited across the central and southern parts of the Virginia Coastal Plain, whereas sediments deposited farther north and into southern Maryland were produced predominantly by erosion of schist.

The southward extent of the Virginia depositional complex is uncertain. Sediment was deposited across the Albemarle embayment depositional subarea by mature, medium- to low-gradient meandering streams onto the evenly sloping basement-bedrock surface that forms an extended southern limb of the Norfolk arch (see section “Albemarle Embayment”). The Virginia depositional complex possibly merged with the northern margin of another depositional complex positioned farther south in proximity to the Cape Fear arch.

Deposition Over Time

Erosion of Piedmont bedrock and deposition of Coastal Plain sediment throughout the Cretaceous Period led to regionwide leveling across the North American Continental Margin for approximately 80 m.y. Areas of sediment deposition broadly alternated, however, in response to differential vertical adjustments of the continental crust (Owens and Gohn, 1985). In Virginia, sediments that compose the Potomac aquifer were deposited only during the early to earliest late Cretaceous Period between approximately 100 and 145 Ma. Sediments deposited during the remainder of the Cretaceous Period in Virginia are preserved only to the far southeast and are not directly hydraulically connected with nor considered part of the Potomac aquifer (see section “Hydrostratigraphy of Cretaceous Age Sediments in Southeastern Virginia and Northeastern North Carolina”).

The Virginia fluvial depositional complex evolved regionally over millennia, during which the configurations of numerous individual drainage basins within the depositional complex probably changed substantially. Across the Norfolk arch and Albemarle embayment subareas, however, the broad pattern of deposition remained relatively fixed over time. Sediment-source rocks primarily of granite and gneiss (Glaser, 1969) in proximity to the Norfolk arch were persistently uplifted, sustaining the supply of coarse-grained feldspathic sediments deposited throughout the period.

By contrast, deposition across the Salisbury embayment subarea probably changed dynamically over time as a result of punctuated adjustments of the Earth’s crust. Unique to the Salisbury embayment subarea, coarse-grained sediments composing three vertically spaced subaquifers are hydraulically separated by thick fine-grained sediments composing two continuous confining units (see section “Salisbury Embayment”). Piedmont rocks supplying sediment to the Maryland depositional complex apparently underwent three distinct cycles, each consisting of initial uplift and rapid erosion followed by crustal stability and progressively slower erosional leveling (fig. 25). Predominantly coarse-grained sediments were generated and deposited during each uplift. Increasingly thick and concentrated fine-grained sediments were subsequently deposited as the source rocks were stabilized and leveled. Accumulation of fine-grained sediments during quiescent periods was also probably enhanced by the predominantly schist source rocks (Glaser, 1969), which generated a relatively large proportion of clay minerals as products of chemical weathering.

Across the southernmost part of the Salisbury embayment subarea, several factors potentially complicated the southern margins of the confining units over time. Alternating overlap between the Virginia and Maryland depositional complexes probably supplied sediments from different source areas at different times. Moreover, as the configurations of individual drainage basins within each depositional complex changed, gradational transitions between immature braided streams and mature meandering streams also shifted. The configuration of basement bedrock, however, possibly imposed a long-term structural control. Whereas immature braided streams broadly spanned the convex bedrock surface across the Norfolk arch subarea, development of mature meandering streams was confined to the structurally closed concave surface within the Salisbury embayment subarea. Consequently, thick, fine-grained sediments accumulated primarily within the Salisbury Embayment subarea most of the time.

Following deposition of fluvial sediments that compose the Potomac aquifer, fine shelly sands of the upper Cenomanian confining unit were deposited under near-shore marine conditions during the part of the late Cretaceous Period corresponding to pollen zone IV (see section "Hydrostratigraphy of Cretaceous Age Sediments in Southeastern Virginia and Northeastern North Carolina"). Sediments of both fluvial and marine origin were deposited during the remainder of the Cretaceous Period and have received various geologic and hydrogeologic designations in Virginia, Maryland, and North Carolina (fig. 4). The original geographic extents of late Cretaceous age sediments, however, are not known. The upper Cenomanian confining unit and overlying aquifers and confining units are preserved only in southeastern Virginia and northeastern North Carolina. Other sediments of late Cretaceous age compose a series of aquifers and confining units in Maryland that pinches out approximately 20 mi north of Virginia, possibly as a result of downwarping and (or) downfaulting of basement bedrock across the Salisbury embayment (Hansen, 1978). Widespread deposition throughout the Virginia Coastal Plain would not be preserved until the beginning of the Tertiary Period.

Hydrologic Conditions of the Potomac Aquifer

The spatial distribution of sediments composing the Potomac aquifer affects groundwater levels, flow, and availability, including hydraulic properties and connectivity within the aquifer and with overlying aquifers. Information on the Potomac aquifer in this report can be applied to support efforts to manage the aquifer as a water resource.

Sediment Hydraulic Properties

Several hydraulic properties of aquifers are determined by sediment composition (Freeze and Cherry, 1979). Hydraulic conductivity (K) describes the ability of sediment to transmit water. It is defined as the volumetric rate of water transmitted through a unit volume of aquifer material resulting from a unit change in hydraulic head and is expressed as length per unit time such as feet per day (ft/d). Coarse-grained sediments have relatively large and interconnected pore spaces and thereby generally have greater hydraulic conductivities than fine-grained sediments. Transmissivity (T) is the volumetric rate produced by the entire thickness of the aquifer (b), equivalent to $K \times b$, and is expressed as area per unit time such as feet squared per day (ft^2/d). Specific storage (S_s) describes the ability of sediment to store water. It is defined as the volume of water taken into or released by a unit volume of aquifer material resulting from a unit change in hydraulic head and is expressed as per length such as per foot (/ft). Fine-grained sediments containing a large percentage of uncompacted clay are relatively compressible and thus can have higher specific storage than coarse-grained sediments. Conversely, compacted clay can have low specific storage. Storativity (S) is the volume taken or released by the entire thickness of the aquifer (b), equivalent to $S_s \times b$, and is unitless.

Hydraulic properties of the Potomac aquifer have been widely measured by aquifer tests. A well completed in the aquifer is pumped at a known rate or rates, while water-level drawdown is measured over time. Water levels can be measured either solely in the pumped production well or in the production well along with one or more unpumped observations wells. For a period following cessation of pumping, water-level recovery can also be measured. A variety of methods has been developed to analyze the water-level drawdown and recovery data to determine values for aquifer transmissivity and storativity. Different analytical methods address specific field conditions and test limitations, and are constrained by various assumptions. Regardless of the analytical method used, values of storativity can only be determined from aquifer tests that include one or more observation wells.

Values of transmissivity and storativity were compiled from documented pumping tests of the Potomac aquifer. Reported test results attributable to specific wells with known locations and construction characteristics were obtained from several sources. Results of many aquifer tests are cited among internal memoranda of the VA DEQ (S.W. Kudlas, Virginia Department of Environmental Quality, written commun., 2010) that document technical evaluations of proposed groundwater withdrawals. Reports compiled by engineering and hydrogeologic consulting firms also document aquifer-test results among other information produced for various groundwater-development projects. Additional aquifer-test results from Virginia and Maryland were obtained from published scientific literature. Similar data for northeastern North Carolina were not readily available. Aquifer-test locations span the Virginia Coastal Plain west of Chesapeake Bay and northward into Maryland, but are sparse across the upper Middle Peninsula and Northern Neck and in Sussex and Surry Counties (fig. 27).

Aquifer-test results are tabulated in a digital data-spreadsheet file (Attachment 2). The file includes study-site or area names, documentation sources, and location information

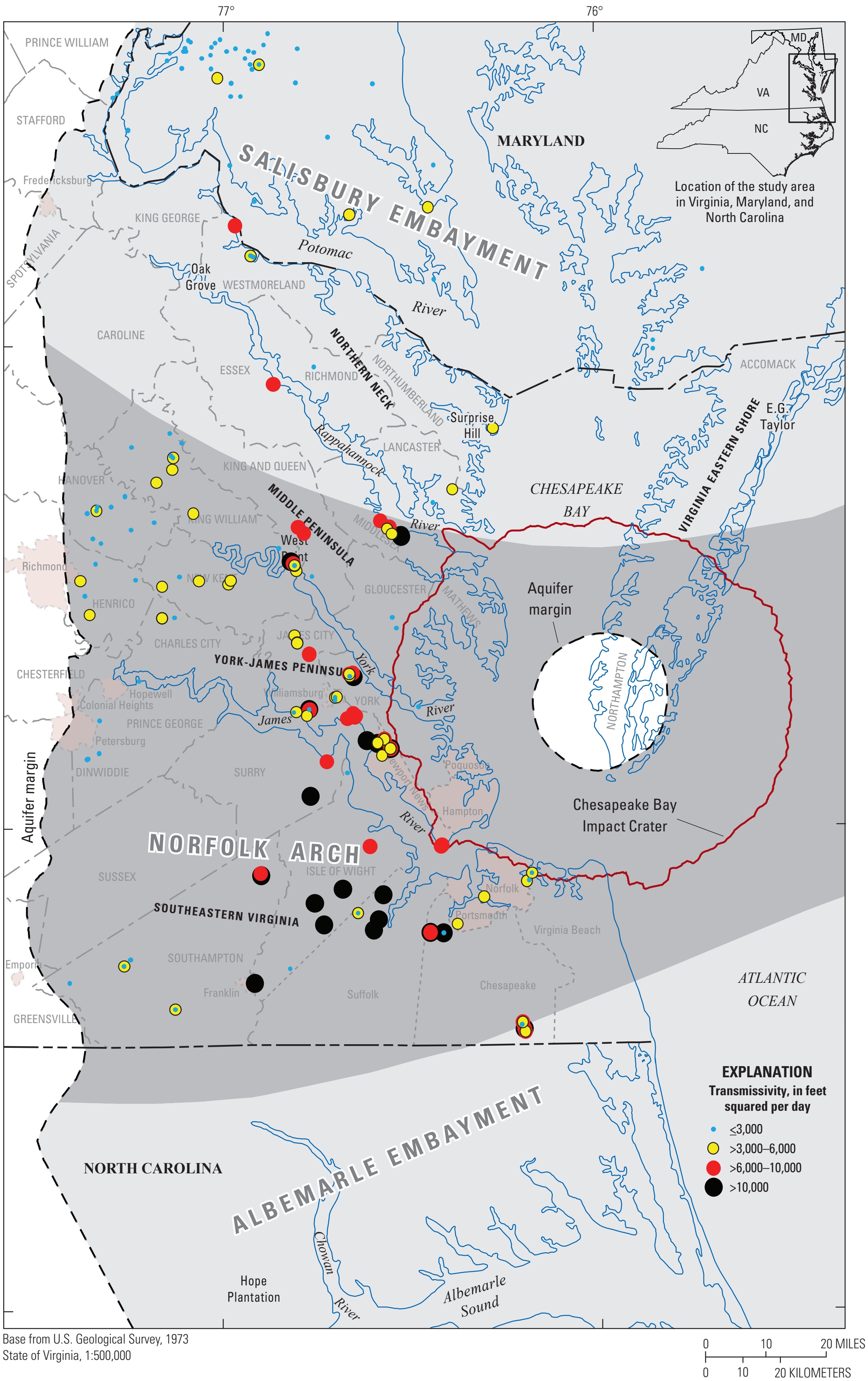


Figure 27. Transmissivity values estimated from aquifer tests in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

for 197 test sites. Production and observation wells are identified by reported number and USGS local well number (where assigned). Rates and durations of pumped discharge are listed where documented. Then listed are 336 values of aquifer transmissivity and 127 values of storativity. More than one aquifer test is reported at some locations, and more than one analytical method and resulting set of hydraulic-property values are reported for some tests. Storativity values are reported only for aquifer tests that included one or more observation wells.

Aquifer-test analytical methods determine values for transmissivity and storativity but not hydraulic conductivity or specific storage. Calculated values for these hydraulic properties are listed, along with supporting information on aquifer thickness, and production-well open intervals and aquifer penetration.

The aquifer tests likely represent only relatively small volumes of aquifer sediments. Pumping rates and durations of aquifer tests were small, having a median discharge rate of 325 gal/min and median duration of 48 hours where specified among constant-rate tests (Attachment 2). Water levels declined only in observation wells within a few hundred feet of production wells, and at greater distances remained static. Hence, drawdowns were generally propagated only short distances through water-bearing beds directly connected to production-well open intervals. Hydraulic stresses probably did not extend vertically through adjacent fine-grained sediments and into water-bearing beds above or below well open intervals.

Transmissivity

Aquifer transmissivity has been related to the sediment distribution of the Maryland fluvial depositional complex (Hansen, 1971) (see section “Conceptual Depositional Model”). Large transmissivity values were correlated with the predominance of coarse-grained sediments across the center of the depositional complex, whereas small values were correlated with increasingly fine-grained sediments toward the margins of the complex.

Similarly, transmissivity is generally aligned among the depositional subareas of the Potomac aquifer designated here. Large transmissivity values broadly correlate with the predominance of coarse-grained sediments across the Norfolk arch subarea, and small values correlate with increasingly fine-grained sediments toward the Salisbury embayment subarea (fig. 27). Almost all transmissivity values greater than 6,000 ft^2/d are within or close to the Norfolk arch subarea. Although the relative proportion of coarse-grained sediments is great throughout the Norfolk arch subarea (fig. 15), transmissivity increases eastward coinciding with thickening of the Potomac aquifer.

Hydraulic Conductivity

Whereas transmissivity is partly a function of aquifer thickness, hydraulic conductivity is an intrinsic property of sediment texture and directly relatable to its distribution. Hydraulic conductivity values can be calculated by dividing transmissivity values by aquifer thickness. Transmissivity values represent the entire thickness of the aquifer, however, only if tested wells fully penetrate the aquifer or—if tested wells are partially penetrating—appropriate analytical methods have been applied. Most open intervals of tested wells are small relative to aquifer thickness. Less than 20 percent of total aquifer thickness is penetrated by all but a few wells, and many wells penetrate no more than 10 percent of the aquifer (fig. 28). Moreover, analytical methods for many of the aquifer tests are not documented. Among those tests having documented analytical methods, only three indicate that well partial penetration is accounted for but do not specify values used for aquifer thickness. Analytical methods that are undocumented for many of the tests probably likewise do not account for well partial penetration.

Because partial penetration is largely unaccounted for by the aquifer tests, 296 values of hydraulic conductivity were calculated (Attachment 2) by dividing reported aquifer-test transmissivity values by the lengths of open intervals in production wells. Open-interval length is assumed to approximate the effective aquifer thickness that was hydraulically stressed during the tests and represented by the transmissivity values. Hydraulic conductivity values were not calculated for 23 wells because open-interval data were not available.

The distribution of hydraulic conductivity of sediments composing the Potomac aquifer is similar to the values of transmissivity, with large values across the Norfolk arch depositional subarea and small values toward the Salisbury embayment subarea (fig. 29). Unlike transmissivity values that increase to the east, however, large hydraulic conductivity values span all of the Norfolk arch subarea. Thus, hydraulic conductivity values are consistently aligned with relative proportions of coarse-grained sediments throughout the Potomac aquifer.

The texture and associated hydraulic conductivity of sediments composing the Potomac aquifer control regional velocities of lateral groundwater flow on the basis of trends in estimated ages of groundwater relative to the time of recharge (see section “Flow”). Assuming a relatively uniform hydraulic gradient and sediment porosity, lateral flow velocity is directly proportional to hydraulic conductivity. Groundwater ages across the Norfolk arch depositional subarea (Nelms and others, 2003) indicate a fast velocity of approximately 10 ft/yr, correlating with high hydraulic conductivity values and the predominance of coarse-grained sediments. Conversely, northward into the Salisbury embayment, progressively slower velocities from approximately 4 ft/yr to 0.1 ft/yr are indicated by groundwater ages including parts of the Potomac aquifer in Maryland (Plummer and others, 2012), correlating with low hydraulic conductivity values and fine-grained sediments.

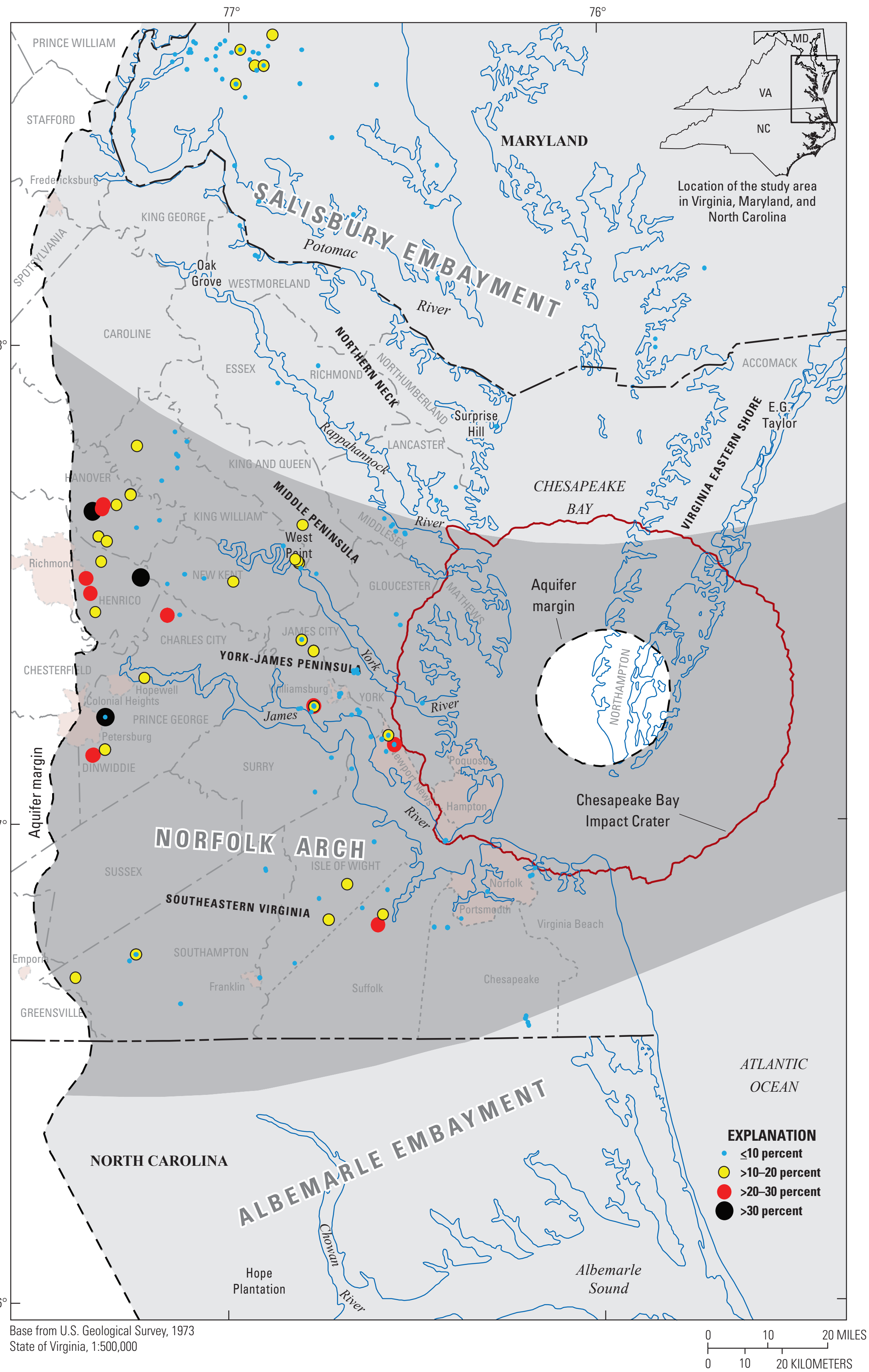


Figure 28. Open-interval lengths of aquifer-tested wells as a percentage of total thickness of the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

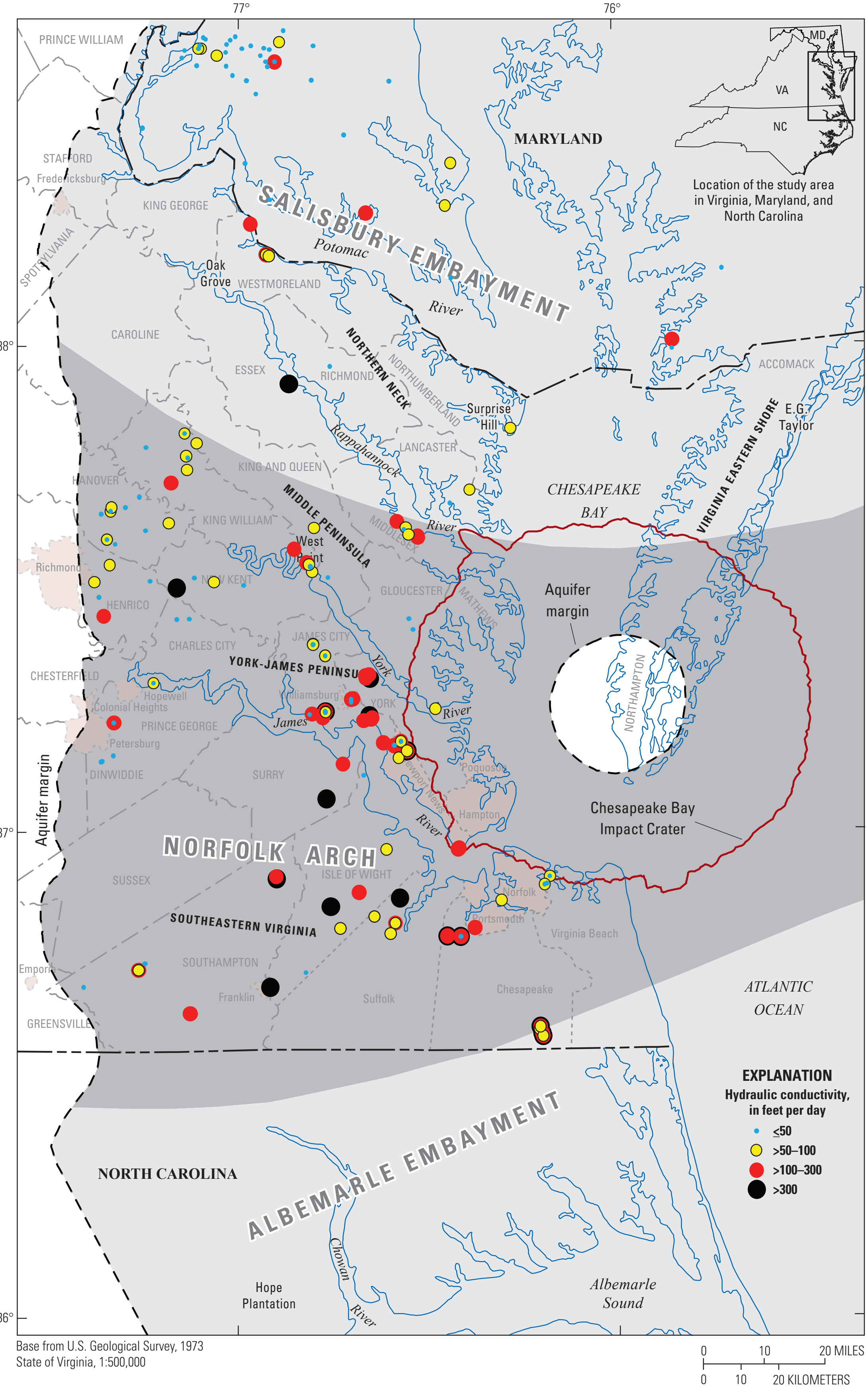


Figure 29. Hydraulic conductivity values of the Potomac aquifer in Virginia and parts of Maryland and North Carolina as calculated from aquifer-test estimates of transmissivity and well open-interval lengths. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

Specific Storage and Storativity

Fewer storativity values are reported for the Potomac aquifer than transmissivity values because observation-well data were not available as required to determine storativity. Almost all storativity values are from aquifer tests located within or close to the Norfolk arch depositional subarea, with the exception of one test located farther north within the Salisbury embayment subarea in Virginia and a small number of additional tests in Maryland (fig. 30). The reported storativity values do not exhibit any discernible regional trend.

Whereas storativity is partly a function of aquifer thickness, specific storage is an intrinsic property of the sediment resulting from its compressibility, and which is relatable to the sediment distribution. Specific storage can be calculated by dividing storativity values by thickness. Accordingly, 113 values of specific storage were calculated (Attachment 2) by dividing reported aquifer-test storativity values by the lengths of open intervals in production wells and were assumed to approximate the effective aquifer thickness that was hydraulically stressed during the tests (see section “Hydraulic Conductivity”). Specific storage values were not calculated for 14 wells because open-interval data were not available.

Specific storage of sediments composing the Potomac aquifer across the Norfolk arch depositional subarea is generally greater than at the few locations with available data in the Salisbury embayment subarea (fig. 31). Lower specific storage toward the Salisbury embayment subarea possibly could result from less compressible sediments there. Many fine-grained sediments within the Potomac aquifer—notably widespread floodplain paleosols and organic-rich swamp deposits (fig. 9*C* and *D*)—are typically dense and highly compacted as a result of deep burial for more than 100 m.y. Pressurized extraction of pore water from core samples of these sediments (McFarland and Bruce, 2005) produced much smaller volumes (as little as an order of magnitude) than samples of younger, overlying and less compacted fine-grained sediments composing other hydrogeologic units. By the same rationale, sediments having the largest specific storage values along the western margin of the Potomac aquifer have been less deeply buried and possibly are less compacted.

Vertical Hydraulic Connectivity

In confined stratified sedimentary aquifer systems such as in the Virginia Coastal Plain, groundwater primarily flows laterally through aquifers with slower vertical flow as leakage across confining units between aquifers (fig. 32). Additionally, across much of the Virginia Coastal Plain, confining-unit leakage is generally downward because widespread water-level declines are greater in the Potomac aquifer than in overlying aquifers (see section “Flow”). In proximity to large production wells, substantial vertical flow within a single aquifer can be locally induced toward the well open interval.

The relations described above are reflected by vertical hydraulic gradients among different parts of the Virginia Coastal Plain aquifer system. Vertical gradients are large across confining units that impose an effective hydraulic separation between aquifers (fig. 32, far left side). Water levels in wells completed in the upper aquifer are substantially higher than those in the lower aquifer. Conversely, vertical gradients away from and unaffected locally by large production wells are generally small within each of the aquifers (fig. 32, left of center), and water levels in closely spaced wells completed at different depths within a single aquifer differ only slightly. By contrast, at locations in proximity to large production wells, vertical gradients can be large within the pumped aquifer (fig. 32, right), and water levels in closely spaced wells completed at different depths can differ substantially.

On the basis of the above information, variations among values of vertical hydraulic gradients within the Virginia Coastal Plain aquifer system indicate effects of contrasting sediment texture on hydraulic connectivity. Large vertical gradients between the Potomac aquifer and overlying aquifers result from an effective hydraulic separation imposed between the aquifers by fine-grained sediments that compose an intervening confining unit or units. Likewise, within parts of the Potomac aquifer not affected locally by large production wells, large vertical gradients across intervals of fine-grained sediments indicate that an effective hydraulic separation is imposed between overlying and underlying coarse-grained sediments. Conversely, fine-grained sediments that are too thin and (or) discontinuous to hydraulically separate overlying and underlying coarse-grained sediments result in small vertical gradients within the Potomac aquifer.

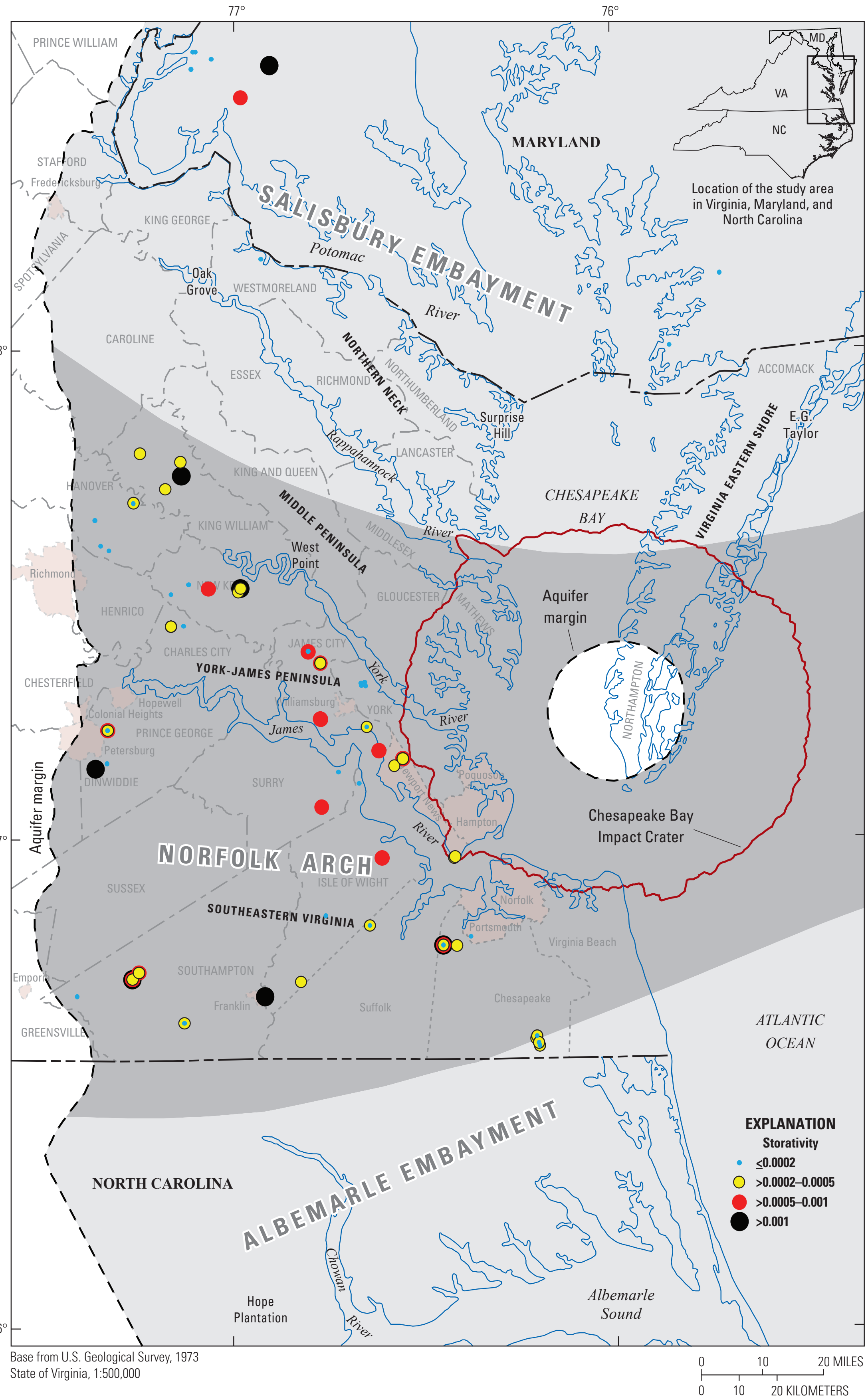


Figure 30. Storativity values estimated from aquifer tests in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

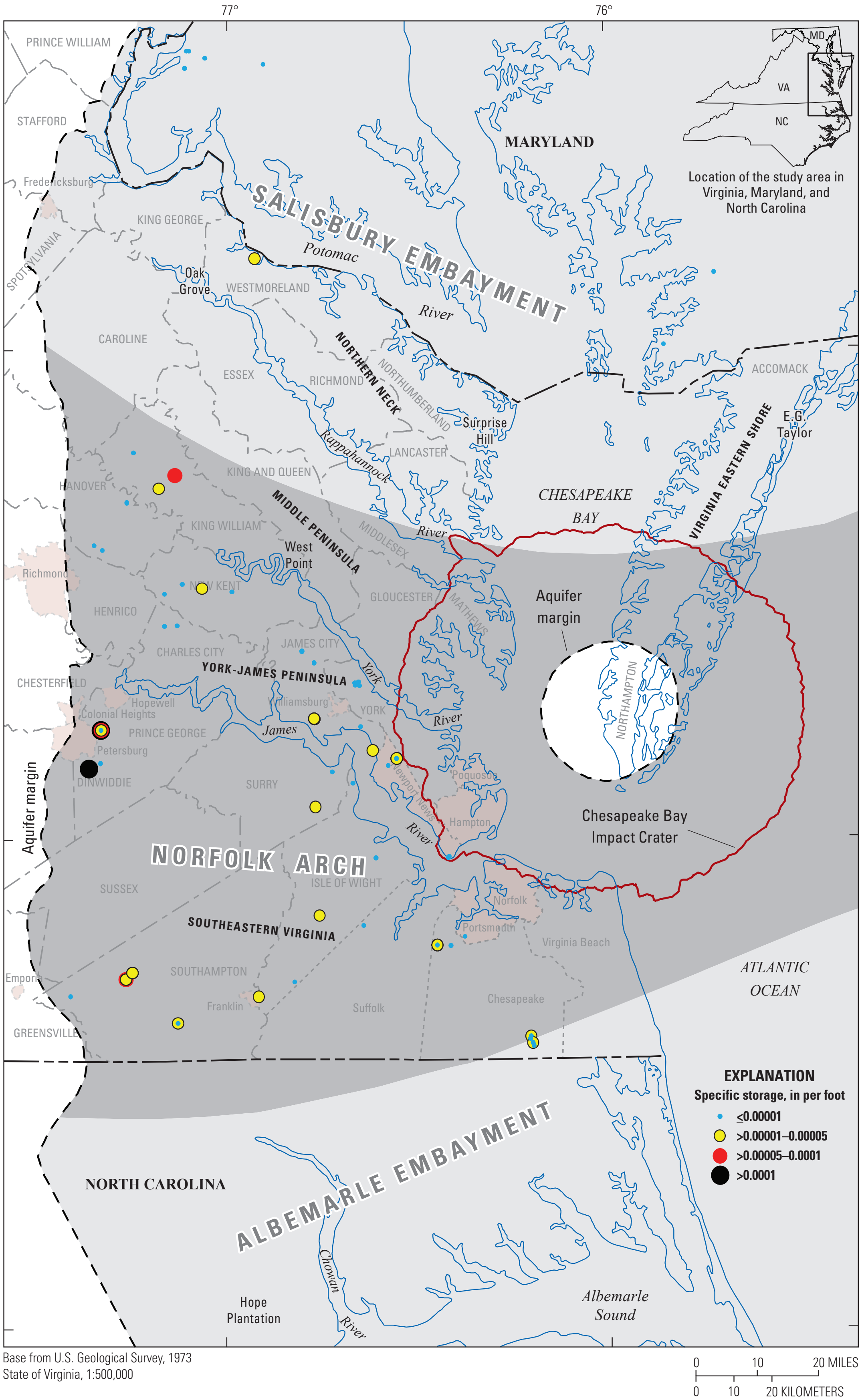


Figure 31. Specific storage of the Potomac aquifer in Virginia and parts of Maryland and North Carolina as calculated from aquifer-test estimates of storativity and well open-interval lengths. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

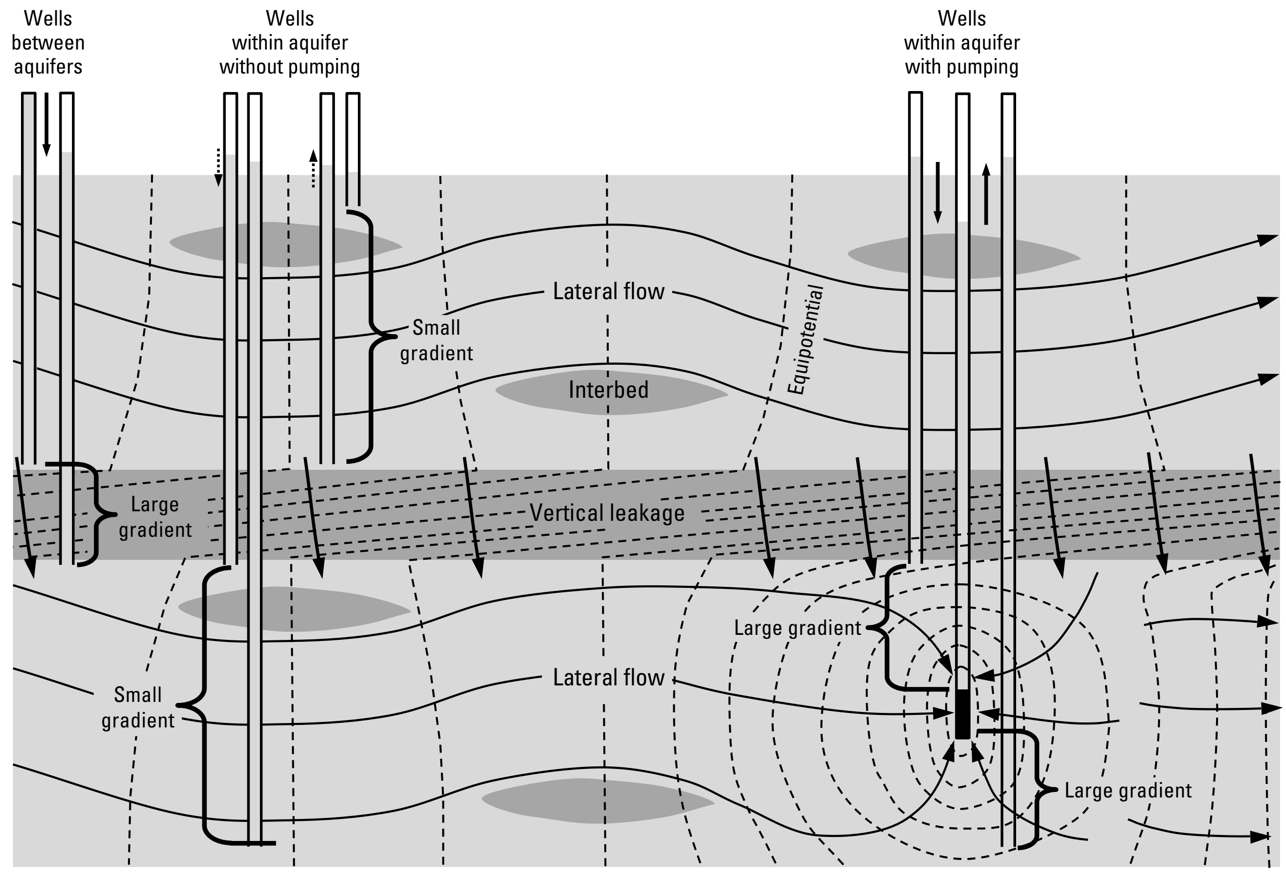


Figure 32. Conceptual sectional flow net of generalized hydraulic head distribution across adjacent aquifers (light gray) separated by a confining unit (dark gray) in the Virginia Coastal Plain. Primarily lateral flow takes place through the aquifers and vertical leakage through the confining unit. A large downward hydraulic gradient exists between the aquifers (far left). Where not in proximity to pumping, small upward and downward hydraulic gradients exist within each aquifer (left of center). Fine-grained interbeds within the aquifers are too discontinuous to impose large vertical hydraulic gradients. In proximity to pumping (right), large upward and downward hydraulic gradients exist within a single aquifer. Effects of boundary conditions are not represented.

Vertical Hydraulic Gradients

Vertical hydraulic gradients were calculated on the basis of water levels measured in wells in the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina. Historical water-level data were obtained from the USGS National Water Inventory System (NWIS) databases for Virginia, Maryland, and North Carolina. These data include water levels measured by the VA DEQ and MGS. Additional water-level data from North Carolina were obtained from the NC DNR Web site at *http://www.ncwater.org/Data_and_Modeling/Ground_Water_Databases/wellaccess.php*.

Vertical hydraulic gradients were calculated as the difference in water-level altitude between closely spaced wells open across different intervals divided by the vertical distance between the open intervals. Resulting gradient values are dimensionless. Water levels were omitted that were

- measured in a single well lacking one or more closely spaced wells,
- measured in pairs of wells having vertically overlapping open intervals,
- measured more than 1 day apart between paired wells,
- dominated by large short-term fluctuations, and probably affected locally by large production wells (based on examination of water levels among wells having adequate lengths of record to support an evaluation), or
- from unconfined parts of the Potomac aquifer receiving recharge by infiltration from the land surface.

A total of 129 pairs of wells were used to calculate 9,479 vertical gradient values based on water levels measured between November 17, 1953, and October 4, 2011. Periods of record among most well pairs are brief, including 24 well pairs with only one set of measurements and 45 well pairs having measurements spanning less than 1 year.

Historical mean vertical hydraulic gradients for each pair of wells were calculated from individual vertical gradient values for each well pair and are tabulated in a digital data-spreadsheet file (Attachment 3). Ancillary information on each pair of wells is followed by summary statistics of individual gradient values for each pair, along with information on the water-level measurement record.

Wells open to the Potomac aquifer are distinguished from wells open to other aquifers on the basis of the most recent hydrogeologic characterization of the Virginia Coastal Plain (McFarland and Bruce, 2006). Historical mean vertical hydraulic gradients within the Potomac aquifer were calculated for 52 pairs of wells having both wells open at different depths within the Potomac aquifer (fig. 33). At these well pairs, 4,954 individual gradient values were calculated from water levels measured between June 25, 1969, and December 29, 2010. Well pairs are sparse across the Northern Neck, upper Middle Peninsula, and in southern Maryland. Only one well pair is located in northeastern North Carolina because most observation wells in North Carolina are open to upper Cretaceous sediments that are recognized here as being distinct from the Potomac aquifer.

Historical mean vertical hydraulic gradients between the Potomac aquifer and overlying aquifers were calculated for 77 pairs of wells having one well open to the Potomac aquifer and the other open to an overlying aquifer (fig. 34). At these well pairs, 4,525 individual gradient values were calculated from water levels measured between November 17, 1953, and October 4, 2011. These well pairs are also sparse across the Northern Neck and upper Middle Peninsula, where water-level measurements are generally lacking, and in southern Maryland where few observation wells are closely spaced. Well pairs located in northeastern North Carolina include wells open to upper Cretaceous sediments recognized here as distinct from sediments of the Potomac aquifer (see section “Hydrostratigraphy of Cretaceous Age Sediments in Southeastern Virginia and Northeastern North Carolina”).

Regional Connectivity Trends

Vertical hydraulic gradients indicate that sediments composing most of the Potomac aquifer in Virginia function hydraulically as a single interconnected aquifer. Vertical gradients within the Potomac aquifer are generally small (fig. 33), with an overall mean among historical well-pair mean gradients of 0.006 downward. Moreover, gradients within most of the Potomac aquifer are neither distinctly upward nor downward, with all values in Virginia between 0.1 upward and 0.1 downward. By contrast, most vertical gradients between the overlying aquifers and the Potomac aquifer are large and downward (fig. 34), with an overall mean among historical well-pair mean gradients of 0.18 downward and values of 29 well-pair mean gradients (38 percent of the total) greater than 0.1 downward. Thus, the Potomac aquifer is hydraulically separated from overlying aquifers by intervening confining units, but most fine-grained sediments within the Potomac aquifer are too thin and discontinuous to hydraulically separate overlying and underlying coarse-grained sediments. Hydraulic continuity of the Potomac aquifer in Virginia has been further indicated by potentiometric surfaces that were mapped for the separate upper, middle, and lower Potomac aquifers of the USGS RASA investigation (Hammond and others, 1994a, b, c). The potentiometric surfaces are broadly similar and do not indicate widespread large vertical gradients.

Data for vertical hydraulic gradients are relatively sparse across the Salisbury embayment depositional subarea and are only available for two locations in Virginia. Within the Potomac aquifer (fig. 33), vertical hydraulic gradients are small at Surprise Hill in Northumberland County, Virginia, which is more than 30 mi from large pumping centers and possibly relatively isolated from widespread water-level declines. Small vertical gradients also exist far to the northwest near the aquifer margin among three well pairs with open intervals that are not separated by confining units. By contrast, several miles to the east in Maryland, large vertical gradients exist among three wells pairs where intervals of fine-grained sediments hydraulically separate overlying and underlying coarse-grained sediments. Pumping and drawdown in the middle part of the Potomac aquifer induces both upward and downward gradients from underlying and overlying parts of the aquifer in which water levels are higher.

Consistent with the above, potentiometric surfaces mapped for the three vertically spaced subaquifers in Maryland (Curtin and others, 2010b, c, d) indicate that the subaquifers are hydraulically separated by intervening confining units (see section “Salisbury Embayment”). Cones of depression beneath pumping centers at different locations within each subaquifer are laterally offset by several miles, resulting in substantial vertical hydraulic gradients between the subaquifers. Hydraulic continuity of the subaquifers in Maryland—and their separation by confining units—also was corroborated by relating observed sediment sand percentages to numerical models of connectivity among individual sand bodies (Drummond, 2007). Hydraulic separation between the subaquifers likely extends into Virginia to the northernmost Northern Neck and Virginia Eastern Shore where the confining units have been identified in boreholes. Data are not adequate, however, to determine how much farther south across the Salisbury embayment depositional subarea the confining units extend and hydraulically separate the subaquifers.

Some vertical gradients between the Potomac aquifer and overlying aquifers in the Salisbury embayment depositional subarea are large and upward (fig. 34). The Potomac aquifer in Maryland is not as heavily developed as in Virginia (Drummond, 2007). The Aquia aquifer, however, is more heavily developed in Maryland and exhibits large and widespread water-level drawdowns (Curtin and others, 2010a). Water levels in parts of the underlying Potomac aquifer are higher than in the Aquia aquifer (Curtin and others, 2010b, c, d).

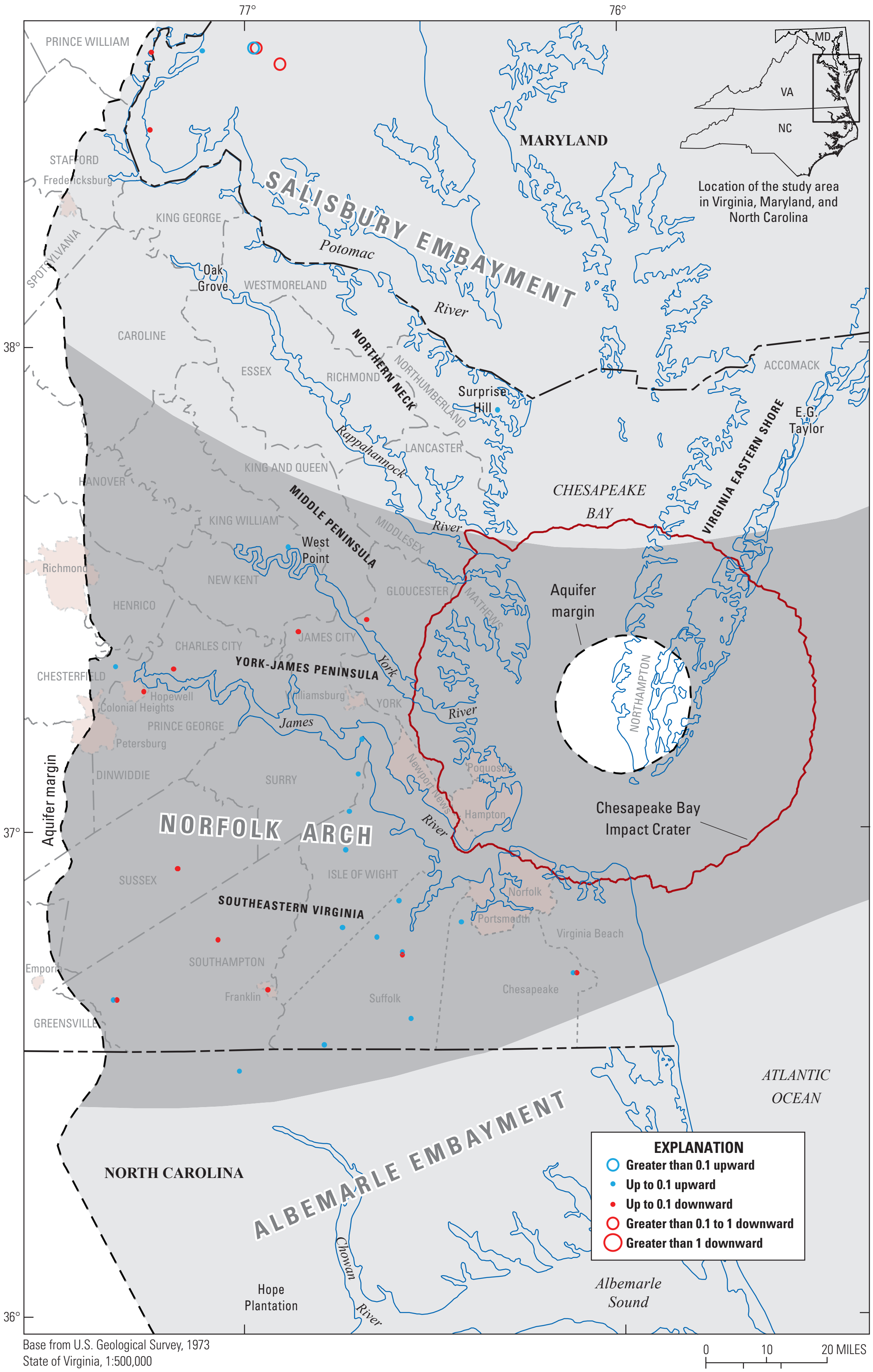


Figure 33. Historical mean vertical hydraulic gradients within the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

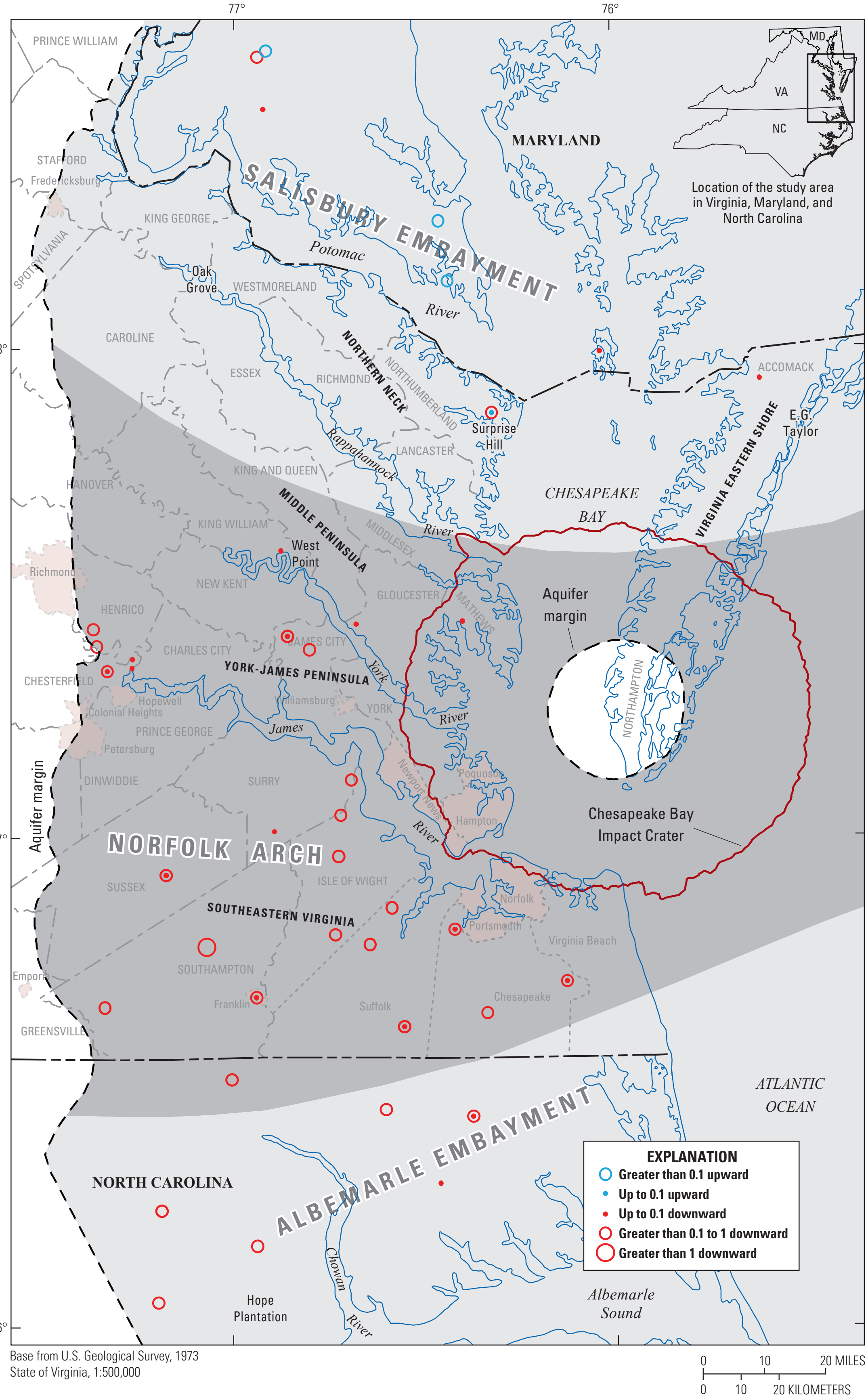


Figure 34. Historical mean vertical hydraulic gradients between the Potomac aquifer and overlying aquifers in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

Thus, withdrawals from the Aquia aquifer are inducing upward gradients from the Potomac aquifer at some well pairs.

Across most of the Albemarle embayment depositional subarea, vertical hydraulic gradients between the Potomac aquifer and overlying aquifers are large and downward (fig. 34). The upper Cenomanian confining unit hydraulically separates the Potomac aquifer from overlying upper Cretaceous sediments (see section “Hydrostratigraphy of Cretaceous Age Sediments in Southeastern Virginia and Northeastern North Carolina”).

Water-Resource Management Applications

Information on the Potomac aquifer presented here can be used to support water-resource management efforts in the Virginia Coastal Plain. Applications of data and concepts can aid characterization of the aquifer, provide a context for regulation of groundwater withdrawal, and guide future data collection.

Aquifer Characterization

Water-supply planning and development can be aided by reducing uncertainty associated with the design and siting of production wells in the heterogeneous fluvial sediments of the Potomac aquifer. Design and construction of high yielding wells can be facilitated by using the local scale information presented here on water-bearing beds in existing boreholes. Specifically, borehole sediment-interval and related data can be applied toward site-specific targeting of productive beds composed of coarse-grained sand and gravel and avoidance of low yielding fine-grained beds. Illustrations and tabulated data provide sediment textures and interval thicknesses (see section “Borehole Sediment Intervals;” Attachment 1) and hydraulic properties (see section “Sediment Hydraulic Properties;” Attachment 2).

More broadly, optimal locations for groundwater development can be identified on the basis of the development potential among planning areas. Data, illustrations, and descriptions presented here distinguish parts of the Potomac aquifer dominated by relatively dense concentrations of coarse-grained beds from concentrations of fine-grained beds (see section “Regional Lithologic Trends”). Development-project designs can thereby designate production-well locations and estimate completion depths to optimize drilling operations and associated costs.

In addition to specific information that supports water-supply planning and development, a broadened perspective on the Potomac aquifer provides accurate conceptualization of its hydrologic function that is fundamental to effective management as a water resource. Characterizations of Potomac aquifer sediments presented here largely resolve inconsistencies between previously used designations of aquifers and confining units, and explain the observed lack of stratigraphic continuity among the heterogeneous fluvial sediments. Moreover, clear relations are demonstrated between the spatial distribution of the sediments and their hydrologic function, including the hydraulic properties of the sediments and vertical hydraulic connectivity within the Potomac aquifer and with other aquifers.

Regulatory Implications

The three structurally based depositional subareas of the Potomac aquifer designated here provide a possible context for resource management (see section “Depositional Subareas”). Contrasting hydrologic characteristics among different parts of the Potomac aquifer are organized and geologically accounted for by the depositional subareas (see section “Conceptual Depositional Model”). Effects of current and future groundwater withdrawals also likely differ among the subareas, and regulatory approaches could be applied accordingly. Designation of the sediments as a single aquifer in the Norfolk arch and Albemarle embayment subareas—and as a series of vertically spaced subaquifers and intervening confining units in the Salisbury embayment subarea—best reflects understanding of the Potomac aquifer. By contrast, the VA DEQ currently (2013) limits water-level declines to no more than 80 percent from pre-development levels to the top surfaces of the subdivided upper, middle, and lower Potomac aquifers as delineated by the USGS RASA investigation across the entire Virginia Coastal Plain. This criterion has the potential to exceed the same limit relative to a single undivided Potomac aquifer.

The three Potomac subaquifers are known to extend from Maryland into Virginia at least as far as the boreholes on the northernmost Northern Neck and Virginia Eastern Shore in which the intervening confining units are identified (figs. 17–21). The confining units are theorized to extend farther south across most of the Salisbury embayment subarea, but data are lacking from boreholes deep enough to intercept them. Consequently, subaquifer boundaries cannot currently be explicitly demarcated. Resource-management options for designating areas to be regulated as an undivided Potomac aquifer versus multiple subaquifers include recognition of the subaquifers (1) only as far south as the Northern Neck and Virginia Eastern Shore boreholes, (2) as theorized across most of the Salisbury embayment subarea, or (3) beyond the Northern Neck and Virginia Eastern shore boreholes but across only part of the Salisbury embayment subarea. Practical needs of the regulatory program could be met by approximating the extents of the subaquifers along county boundaries or other jurisdictional lines.

On the basis of the above information, simulation modeling performed by the VA DEQ to evaluate effects of groundwater withdrawals could potentially base vertical discretization of the Potomac aquifer on subaquifers present across the Salisbury embayment subarea but undivided farther south. In addition, zonation of simulated hydraulic properties of the Potomac aquifer could be based on the geographic distribution of the subareas. Alternatively, a more complex and detailed geostatistical distribution of sediment hydraulic properties could be derived from borehole sediment-interval data. Vertical hydraulic gradients presented here also provide a possible basis for model calibration.

Information Needs

Results presented here provide guidance for future data-collection efforts needed to support management of the Potomac aquifer as a sustainable water supply. Few existing boreholes penetrate the total thickness of the Potomac aquifer as it deepens and thickens eastward (fig. 35). Consequently, knowledge of the spatial distribution of sediments composing the Potomac aquifer lessens eastward. Across much of southeastern Virginia and northeastern North Carolina, conditions within the deepest part of Potomac aquifer are unknown. Moreover, only the shallowest part of the Potomac aquifer is known across much of the Northern Neck and Middle Peninsula where borehole and observation-well data are generally sparse. As a result, the extent of subaquifers and intervening confining units in the southernmost part of the Salisbury embayment subarea cannot currently be accurately characterized.

Historically, information to support the needs of water-resource management efforts in the Virginia Coastal Plain has been derived from groundwater characterizations made in tandem with and reliant upon groundwater development. Consequently, conditions in the middle to upper part of the Potomac aquifer are generally best known because it has been the most heavily developed. Future broadening and deepening of groundwater withdrawals are likely to increase information needs for further development. Controls on groundwater levels and flow within the developed part of the Potomac aquifer, however, are likely already being imposed by deeper parts of the aquifer for which data are largely unavailable. Characterization of the Potomac aquifer requires inclusion of its deepest parts, even if groundwater is heavily developed only in shallower parts.

Several aspects of the structural configuration of the Potomac aquifer remain relatively unknown. Many more faults probably exist throughout the Virginia Coastal Plain that have not been identified, particularly in and around the Chesapeake Bay impact crater. A more complete determination is needed of the distribution of faults as well as their hydrologic effects. In stratified sediments, faults can function as either conduits or barriers to groundwater flow depending on specific structural details (Caine and others, 1996). Basement bedrock underlies the entire Potomac aquifer, yet its composition, structure, and hydrologic function remain largely unknown. In addition to pervasive faults and fracture zones in crystalline bedrock, permeable sediments associated with buried Mesozoic-age basins could affect groundwater flow and quality substantially.

Lastly, better understanding is needed of the Chesapeake Bay impact crater. Specifically regarding the Potomac aquifer, a more fully developed conceptualization of the megablocks could help assess their current designation as part of the Potomac aquifer or alternatively as a separate hydrogeologic unit.

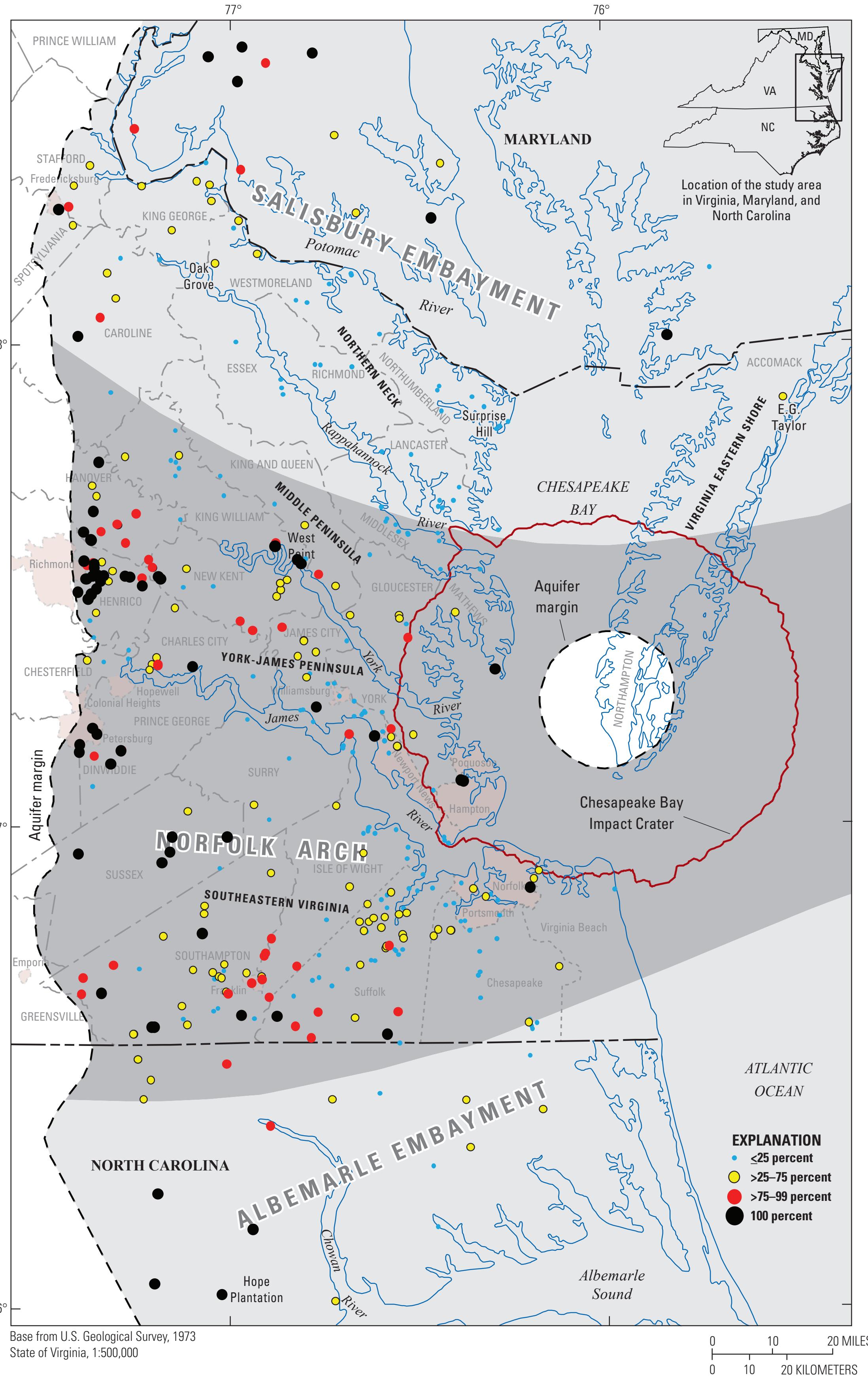


Figure 35. Percent of thickness penetrated by boreholes in the Potomac aquifer in Virginia and parts of Maryland and North Carolina. Location of Chesapeake Bay impact crater from Powars and Bruce (1999).

Summary and Conclusions

The widespread and several-thousand-foot thick Potomac aquifer is the largest and most heavily used source of groundwater in the Atlantic Coastal Plain Physiographic Province in eastern Virginia. It accounts for approximately 90 Mgal/d or three-fourths of the groundwater withdrawn to supply major industries, many towns and cities, and low density residential developments in rural areas. Resulting water-level declines as great as 200 ft near large withdrawal centers have reversed flow gradients to create the potential for saltwater intrusion. Conventional stratigraphic correlation does not accurately characterize the complex spatial distribution of highly interbedded and sharply contrasting fluvial sediments that compose the Potomac aquifer. Without a full understanding of the aquifer's internal hydraulic connectivity and overall hydrologic function, water-supply planning and development efforts are hampered, and interpretations of regulatory criteria for allowable water-level declines are ambiguous.

An investigation by the USGS in cooperation with the VA DEQ during 2010–11 provides a comprehensive regional description of the Potomac aquifer in the Virginia Coastal Plain. Hydrogeologic data characterize the spatial distribution of Potomac aquifer sediments and their relation to hydrologic conditions. The Potomac aquifer is considered to consist of all lower Cretaceous to lowermost upper Cretaceous fluvial sediments of the Potomac Formation, including undisrupted sediments outside of the Chesapeake Bay impact crater and megablock beds of the Potomac Formation that formed within the crater during the late Eocene Epoch.

The spatial distribution of Potomac aquifer sediments in the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina is represented by altitudes and thicknesses of 2,725 vertical sediment intervals, designated as dominantly coarse or fine grained. Sediment intervals were determined by interpretation of geophysical logs and descriptions of sediment cuttings and core from a network of 456 boreholes. Coarse-grained sediment intervals represent channel and bar sands and gravels, which commonly are targeted for completion of water-supply wells. Fine-grained sediment intervals represent floodplain paleosols, weathered interstitial clays, and freshwater swamp and abandoned-channel fill deposits, which generally are avoided for completion of water-supply wells.

A visually apparent trend among sediment intervals along with borehole summary statistical data indicate that thicknesses and relative dominance of coarse- and fine-grained sediments broadly contrast across major structural features of the Virginia Coastal Plain and adjacent parts of Maryland and North Carolina. Three corresponding sediment depositional subareas are designated on the basis of regional trends in sediment lithology and stratigraphic continuity.

1. The Norfolk arch depositional subarea spans the central and southern parts of the Virginia Coastal Plain and encompasses the thickest and most widespread coarse-grained sediment intervals. Closely spaced intervals exhibit widely varying thicknesses and large vertical offsets, and lack alignment to any consistent regional structural trend. Thus, the entire sediment thickness functions hydraulically as a single interconnected aquifer.

2. The Salisbury embayment depositional subarea spans the northern part of the Virginia Coastal Plain and extends into southern Maryland. The Salisbury embayment subarea encompasses thinner and less widespread coarse-grained sediment intervals than the Norfolk arch subarea. It also includes fine-grained sediment intervals that are increasingly thick and widespread northward. Two continuous confining units are delineated that include fine-grained intervals collectively as thick as several hundred feet. The confining units are consistently aligned to a regional structural trend and stratigraphically correlate from southern Maryland into Virginia to the northernmost Northern Neck and Virginia Eastern Shore. Although their southern margins are uncertain because of inadequate boreholes depths, the confining units are inferred to extend across most of the Salisbury embayment subarea. The confining units hydraulically separate three vertically spaced subaquifers between which vertical flow is impeded. The subaquifers are continuous northward with aquifers in southern Maryland. Southward into the Norfolk arch subarea, the subaquifers merge into a single undivided Potomac aquifer. The distinction between divided and undivided parts of the Potomac aquifer in Virginia provides a new hydrogeologic understanding of the sediments in the area.

3. The Albemarle embayment depositional subarea spans southeastern Virginia into northeastern North Carolina and encompasses thinner and less widespread coarse-grained sediment intervals than the Norfolk arch subarea. Fine-grained intervals are of only moderate thicknesses. Closely spaced intervals exhibit widely varying thicknesses and large vertical offsets, and lack alignment to any consistent regional structural trend. Thus, the entire sediment thickness functions hydraulically as a single interconnected aquifer. The relatively open structural configuration of the Albemarle embayment differs from the more closed configuration of the Salisbury embayment, and possibly was not as conducive to accumulation of thick fine-grained sediments.

Published sediment pollen-age data indicate regionally uniform deposition of Potomac aquifer sediments across most of the area over time. Delineated pollen-zone age-boundary surfaces broadly represent the sediment-age distribution internally within the Potomac aquifer. The spatial distribution of Potomac aquifer sediments transgresses the ages of the sediments, although the two confining units within the

Salisbury embayment subarea are approximately aligned with the age-boundary surfaces.

Fine-grained marine sediments of the upper Cenomanian confining unit are a major hydrologic upper boundary on the Potomac aquifer. The upper Cenomanian confining unit was previously recognized only in southeastern Virginia and is newly delineated as extending into northeastern North Carolina, based on distinctive borehole geophysical-log signatures and a recently documented geologic map and corehole. A substantial hydraulic separation is imposed by the upper Cenomanian confining unit between the Potomac aquifer and overlying sediments across southeastern Virginia and northeastern North Carolina. Discrepancies in previously drawn hydrostratigraphic relations among Cretaceous age sediments between southeastern Virginia and northeastern North Carolina are partly resolved with recognition that the Potomac aquifer deepens and thins southward before being truncated to the southwest against a fault. Large parts of overlying late Cretaceous age sediments previously designated in northeastern North Carolina as the upper and lower Cape Fear aquifers are not continuous with the Potomac aquifer in southeastern Virginia, but possibly are partly continuous with the Virginia Beach aquifer.

A fluvial depositional complex spanning the Virginia Coastal Plain produced the spatial distribution of Potomac aquifer sediments between approximately 100 and 145 Ma. The depositional complex is a counterpart to an earlier theorized complex in Maryland and probably was among a series of depositional complexes arrayed along the Atlantic Coastal Plain. Within the Virginia depositional complex, coarse-grained sand and gravel from an uplifted source area to the west was deposited across the Norfolk arch subarea by immature, high-gradient braided streams as longitudinal bars and channel fills. From the Norfolk arch subarea, braided streams transitioned across the Salisbury embayment and Albemarle embayment subareas to mature, medium- to low-gradient meandering streams. Medium- to coarse-grained sand was deposited as channel fills and point bars, and fine-grained sediments as overbank deposits. The broad pattern of deposition across the Norfolk arch and Albemarle embayment subareas remained relatively fixed over time by persistently uplifted granite and gneiss source rocks that sustained the supply of coarse-grained sediments. Across the Salisbury embayment subarea, the Virginia depositional complex likely merged northward with the Maryland depositional complex. Sediments originating from two different source areas were received at different times. Deposition changed dynamically as schist source rocks underwent three cycles. Initial uplift and rapid erosion generated coarse-grained sediments. With crustal stability and erosional leveling, thick fine-grained sediments were deposited by mature meandering streams spanning the structurally closed concave basement bedrock surface.

The spatial distribution of Potomac aquifer sediments controls variations among its hydraulic properties and groundwater flow. Documented pumping tests of the Potomac aquifer at 197 locations produced 336 values of transmissivity. Across the Norfolk arch depositional subarea, transmissivity is generally large and broadly correlates with the predominance of coarse-grained sediments. Toward the Salisbury embayment subarea, transmissivity is generally small and correlates with increasingly fine-grained sediments. Similarly, 296 values of sediment hydraulic conductivity, calculated from transmissivity values and tested well open-interval length, consistently align with relative proportions of coarse-grained sediments among the depositional subareas. Hydraulic conductivity in turn correlates with and controls regional velocities of lateral flow through the Potomac aquifer, based on published estimates of groundwater ages relative to the time of recharge. A velocity of approximately 10 ft/yr across the Norfolk arch subarea correlates with large hydraulic conductivity values and predominance of coarse-grained sediments. Velocities northward into the Salisbury embayment slow progressively from approximately 4 ft/yr to 0.1 ft/yr and correlate with small hydraulic conductivity values and increasingly fine-grained sediments. Storativity of the Potomac aquifer does not exhibit a regional trend. Specific storage calculated from storativity values and effective aquifer thicknesses, however, broadly reflects the degree of sediment compaction resulting from depth of burial.

Effects of contrasting sediment texture are inferred on vertical hydraulic connectivity within the Potomac aquifer and with overlying aquifers. Values of vertical hydraulic gradient were calculated from 9,479 pairs of water levels measured between November 17, 1953, and October 4, 2011, in 129 closely spaced pairs of wells. Mostly large downward gradients between the Potomac aquifer and overlying aquifers indicate that hydraulic separation is imposed by intervening confining units, including in northeastern North Carolina by the upper Cenomanian confining unit. Conversely, generally small vertical gradients within the Potomac aquifer indicate that most of the sediments in Virginia function hydraulically as a single interconnected aquifer. Most fine-grained sediments are too thin and discontinuous to hydraulically separate overlying and underlying coarse-grained sediments. Large vertical gradients in Maryland along with results of earlier studies indicate that the three vertically spaced subaquifers are hydraulically separated by intervening confining units at least as far as the northernmost Northern Neck and Virginia Eastern Shore.

Information on the Potomac aquifer can be used to support water-resource management in the Virginia Coastal Plain. Uncertainty associated with effective siting, design, and construction of high yielding production wells can be reduced by using borehole sediment-interval and related data to target productive coarse-grained beds and avoid low yielding fine-grained beds. Optimal locations for groundwater development can also be identified on the basis of advance knowledge of the development potential of different parts of the Potomac aquifer among planning areas. Characterizations of the Potomac aquifer presented here also largely resolve inconsistencies between previously used designations of aquifers and confining units, and demonstrate clear relations between the spatial distribution of aquifer sediments and their hydrologic function.

The single undivided Potomac aquifer recognized in the Norfolk arch and Albemarle embayment depositional subareas—and a series of vertically spaced subaquifers and intervening confining units in the Salisbury embayment subarea—provide a possible context for resource management. As currently (2013) delimited by the VA DEQ, water-level declines relative to previously subdivided aquifers have the potential to be exceeded relative to the single undivided Potomac aquifer. Given that subaquifer boundaries cannot currently be explicitly demarcated, resource-management options for designating areas to be regulated as an undivided Potomac aquifer versus multiple subaquifers include recognition of the subaquifers (1) only as far as identified in boreholes on the northernmost Northern Neck and Virginia Eastern Shore, (2) as theorized across most of the Salisbury embayment subarea, or (3) beyond the Northern Neck and Virginia Eastern Shore boreholes but across only part of the Salisbury embayment subarea. Simulation modeling performed by the VA DEQ to evaluate effects of groundwater withdrawals could be similarly based, including vertical discretization and (or) zonation of Potomac aquifer, or a geostatistical distribution of aquifer properties derived from borehole sediment-interval data.

Hydrogeologic conditions of the Potomac aquifer are less known eastward where less of the aquifer is penetrated by existing boreholes. Particularly, only the shallowest part of the Potomac aquifer is known across much of the Northern Neck and Middle Peninsula. Consequently, southward margins of confining units that hydraulically separate vertically spaced subaquifers are not accurately determined. Information needs for water-resource management extend beyond the developed part of the Potomac aquifer to include its deepest parts, along with hydrologic effects of structural aspects such as faults, basement bedrock, and the Chesapeake Bay impact crater.

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References Cited

Andreasen, D.C., 1999, The geohydrology and water-supply potential of the lower Patapsco aquifer and Patuxent aquifers in the Indian Head-Bryans Road area, Charles County, Maryland: Maryland Geological Survey Report of Investigations No. 69, 119 p.

Andreasen, D.C., 2004, Optimization of ground-water withdrawals from the lower Patapsco and Patuxent aquifers in the Bryans Road service area, Charles County, Maryland: Maryland Geological Survey Administrative Report, 21 p.

Benson, R.N., 2006, Internal stratigraphic correlation of the subsurface Potomac Formation, New Castle County, Delaware, and adjacent areas in Maryland and New Jersey: Delaware Geological Survey Report of Investigations No. 71, 15 p.

Bradley, R.S., 1999, Paleoclimatology: Burlington, Mass., Harcourt/Academic Press, 613 p.

Brown, G.A., and Cosner, O.J., 1974, Ground-water conditions in the Franklin area, southeastern Virginia: U.S. Geological Survey Hydrologic Investigations Atlas HA–538, 3 sheets, scale 1:125,000.

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, v. 24, no. 11, p. 1025–1028.

Calis, Nadine, and Drummond, D.D., 2008, Hydrogeologic data from six test wells in the upper Patapsco and lower Patapsco aquifers in southern Maryland: Maryland Geological Survey Basic Data Report No. 22, 73 p.

Cederstrom, D.J., 1939, Geology and artesian-water resources of a part of the southern Virginia Coastal Plain: Virginia Geological Survey Bulletin 51–E, p. 123–136.

Cederstrom, D.J., 1941, Ground-water resources of the southeastern Virginia Coastal Plain: Virginia Geological Survey Circular 1, 11 p.

Cederstrom, D.J., 1943, Chloride in ground water in the Coastal Plain of Virginia: Virginia Geological Survey Bulletin 58, 36 p.

Cederstrom, D.J., 1945a, Geology and ground-water resources of the Coastal Plain in southeastern Virginia: Virginia Geological Survey Bulletin 63, 384 p.

Cederstrom, D.J., 1945b, Selected well logs in the Virginia Coastal Plain north of James River: Virginia Geological Survey Circular 3, 82 p.

Cederstrom, D.J., 1946a, Chemical character of ground water in the Coastal Plain of Virginia: Virginia Geological Survey Bulletin 68, 62 p.

Cederstrom, D.J., 1946b, Genesis of ground waters in the Coastal Plain of Virginia: Economic Geology, v. 41, no. 1, p. 218–245.

Cederstrom, D.J., 1957, Geology and ground-water resources of the York-James Peninsula, Virginia: U.S. Geological Survey Water-Supply Paper 1361, 237 p.

Cederstrom, D.J., 1968, Geology and ground-water resources of the Middle Peninsula, Virginia: U.S. Geological Survey Open-File Report (unnumbered), 231 p.

CH2M Hill, 1990a, Injection and recovery testing cycles for the aquifer storage and recovery (ASR) well no. 4-1 pilot project, Appendix B, Analysis of aquifer test data, 4 p.

CH2M Hill, 1990b, Aquifer simulation modeling of potential expanded aquifer storage and recovery (ASR) systems at the Western Branch well field, 38 p.

CH2M Hill, 1997, Chesapeake deep well project report, Appendix B, Aquifer testing data, 6 p.

Clark, W.B., and Miller, R.L., 1912, The physiography and geology of the Coastal Plain Province of Virginia: Virginia Geological Survey Bulletin 4, p. 13–322.

Commonwealth of Virginia, 1973, Ground water of the York-James Peninsula, Virginia: Virginia State Water Control Board Basic Data Bulletin 39, 74 p.

Commonwealth of Virginia, 1974, Groundwater of southeastern Virginia: Virginia State Water Control Board Planning Bulletin 261–A, 33 p.

Consolvo, C.A., 2008, Aquifer test report, courthouse water system, New Kent County, New Kent, Virginia: GeoResources, Inc., 10 p.

Cosner, O.J., 1975, A predictive computer model of the Lower Cretaceous aquifer, Franklin area, southeastern Virginia: U.S. Geological Survey Water-Resources Investigations Report 51–74, 72 p.

Cosner, O.J., 1976, Measured and simulated ground-water levels in the Franklin area, southeastern Virginia 1973–74: U.S. Geological Survey Water-Resources Investigations Report 76–83, 5 sheets, scale 1:250,000.

Curtin, S.E., Andreasen, D.C., and Staley, A.W., 2010a, Potentiometric surface of the Aquia aquifer in southern Maryland, September 2009: U.S. Geological Survey Open-File Report 2010–1201, 1 p.

Curtin, S.E., Andreasen, D.C., and Staley, A.W., 2010b, Potentiometric surface of the upper Patapsco aquifer in southern Maryland, September 2009: U.S. Geological Survey Open-File Report 2010–1205, 1 p.

Curtin, S.E., Andreasen, D.C., and Staley, A.W., 2010c, Potentiometric surface of the lower Patapsco aquifer in southern Maryland, September 2009: U.S. Geological Survey Open-File Report 2010–1207, 1 p.

Curtin, S.E., Andreasen, D.C., and Staley, A.W., 2010d, Potentiometric surface of the Patuxent aquifer in southern Maryland, September 2009: U.S. Geological Survey Open-File Report 2010–1209, 1 p.

Doyle, J.A., and Robbins, E.A., 1977, Angiosperm pollen zonation of the continental Cretaceous of the Atlantic Coastal Plain and its application to deep wells in the Salisbury embayment: Palynology, v. I, American Association of Stratigraphic Palynologists, Proceedings of the Eighth Annual Meeting, Houston, Texas, October 1975, p. 43–78.

Drummond, D.D., 2007, Water-supply potential of the Coastal Plain aquifers in Calvert, Charles, and St. Mary's Counties, Maryland, with emphasis on the upper Patapsco and lower Patapsco aquifers: Maryland Geological Survey Report of Investigations No. 76, 48 p.

Edwards, L.E., Powars, D.S., Horton, J.W., Gohn, G.S., Self-Trail, J.M., and Litwin, R.J., 2010, Inside the crater, outside the crater: Stratigraphic details of the margin of the Chesapeake Bay impact structure, Virginia, U.S.A., *in* Gibson, R.L., and Reimold, W.U., eds., Large Meteorite Impacts and Planetary Evolution IV, Vredefort Dome, South Africa, August 17–21, 2008: Geological Society of America Special Paper 465, p. 319–394.

Ellison, R.P., III, and Masiello, R.A., 1979, Groundwater resources of Hanover County, Virginia: Virginia State Water Control Board Planning Bulletin 314, 130 p.

Fleck, W.B., and Vroblesky, D.A., 1996, Simulation of ground-water flow of the Coastal Plain aquifers in parts of Maryland, Delaware, and the District of Columbia: U.S. Geological Survey Professional Paper 1404–J, 40 p., 9 pls.

Fleck, W.B., and Wilson, J.M., 1990, Geology and hydrologic assessment of Coastal Plain aquifers in the Waldorf area, Charles County, Maryland—Water-supply potential of the aquifers: Maryland Geological Survey Report of Investigations No. 53, p. 39–96.

Fredericksen, N.O., Edwards, L.E., Self-Trail, J.M., Bybell, L.M., and Cronin, T.M., 2005, Paleontology of the impact-modified and impact-generated sediments in the USGS-NASA Langley core, Hampton, Virginia, *in* Horton, J.W., Jr., Powars, D.S., and Gohn, G.S., eds., Studies of the Chesapeake Bay impact structure—The USGS-NASA Langely corehole, Hampton, Virginia, and related coreholes and geophysical surveys: U.S. Geological Survey Professional Paper 1688, chap. D, 37 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice Hall, 604 p.

Gellici, J.A., and Lautier, J.C., 2010, Hydrogeologic framework of the Atlantic Coastal Plain, North and South Carolina, *in* Campbell, B.G., and Coes, A.L., eds., Groundwater availability in the Atlantic Plain of North and South Carolina: U.S. Geological Survey Professional Paper 1773, chap. B, p. 49–162.

Giese, G.L., Eimers, J.L., and Coble, R.W., 1997, Simulation of ground-water flow in the Coastal Plain aquifer system of North Carolina: U.S. Geological Survey Professional Paper 1404–M, 142 p.

Glaser, J.D., 1969, Petrology and origin of Potomac and Magothy (Cretaceous) sediments, middle Atlantic Coastal Plain: Maryland Geological Survey Report of Investigations No. 11, 101 p.

Hamilton, P.A., and Larson, J.D., 1988, Hydrogeology and analysis of the ground-water flow system in the Coastal Plain of southeastern Virginia: U.S. Geological Survey Water-Resources Investigations Report 87–4240, 175 p.

Hammond, E.C., McFarland, E.R., and Focazio, M.J., 1994a, Potentiometric surface of the Brightseat-upper Potomac aquifer in Virginia, 1993: U.S. Geological Survey Open-File Report 94–370, 1 p.

Hammond, E.C., McFarland, E.R., and Focazio, M.J., 1994b, Potentiometric surface of the middle Potomac aquifer in Virginia, 1993: U.S. Geological Survey Open-File Report 94–372, 1 p.

Hammond, E.C., McFarland, E.R., and Focazio, M.J., 1994c, Potentiometric surface of the lower Potomac aquifer in Virginia, 1993: U.S. Geological Survey Open-File Report 94–373, 1 p.

Hansen, H.J., 1969, Depositional environments of subsurface Potomac Group in southern Maryland: American Association of Petroleum Geologists Bulletin, v. 53, no. 9, p. 1923–1937.

Hansen, H.J., 1971, Transmissivity tracts in the Coastal Plain aquifers of Maryland: Southeastern Geology, v. 13, no. 3, p. 127–149.

Hansen, H.J., 1978, Upper Cretaceous (Senonian) and Paleocene (Danian) pinchouts on the south flank of the Salisbury embayment, Maryland, and their relationship to antecedent basement structures: Maryland Geological Survey Report of Investigations No. 29, 34 p.

Hansen, H.J., 1982, Waste Gate Formation Part One—Hydrogeologic framework and potential utilization of the brine aquifers of the Waste Gate Formation, a new unit of the Potomac Group underlying the Delmarva Peninsula: Maryland Geological Survey Open File Report, p. 1–50.

Hansen, H.J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.

Hansen, H.J., and Wilson, J.M., 1990, Hydrogeology and stratigraphy of a 1,515-foot test well drilled near Princess Anne, Somerset County, Maryland: Maryland Geological Survey Open File Report No. 91–02–5, 59 p.

Harsh, J.F., 1980, Ground-water hydrology of James City County, Virginia: U.S. Geological Survey Open-File Report 80–961, 73 p.

Harsh, J.F., and Laczniak, R.J., 1990, Conceptualization and analysis of ground-water flow system in the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina: U.S. Geological Survey Professional Paper 1404-–F, 100 p.

Heywood, C.E., and Pope, J.P., 2009, Simulation of groundwater flow in the Coastal Plain aquifer system of Virginia: U.S. Geological Survey Scientific Investigations Report 2009–5039, 115 p.

Hopkins, H.T., Bower, R.F., Abe, J.M., and Harsh, J.F., 1981, Potentiometric surface map for the Cretaceous aquifer, Virginia Coastal Plain: U.S. Geological Survey Open-File Report 80–965, 1 sheet, scale 1:500,000.

Johnson, G.H., and Ramsey, K.W., 1987, Geology and geomorphology of the York-James Peninsula, Virginia, in Proceedings of the Atlantic Coastal Plain Geological Association: Williamsburg, Va., College of William and Mary, 45 p.

Klohe, C.A., and Kay, R.T., 2007, Hydrogeology of the Piney Point-Nanjemoy, Aquia, and upper Patapsco aquifers, Naval Air Station Patuxent River and Webster Outlying Field, St. Marys County, Maryland, 2000–06: U.S. Geological Survey Scientific Investigations Report 2006–5266, 26 p.

Laczniak, R.J., and Meng, A.A., III, 1988, Ground-water resources of the York-James Peninsula of Virginia: U.S. Geological Survey Water-Resources Investigations Report 88–4059, 178 p.

Larson, J.D., 1981, Distribution of saltwater in the Coastal Plain aquifers of Virginia: U.S. Geological Survey Open-File Report 81–1013, 25 p.

Lautier, J.C., 1998, Hydrogeologic framework and ground water resources of the north Albemarle region, North Carolina: North Carolina Department of Environment, Health and Natural Resources, Division of Water Resources, 42 p.

Leahy, P.P., and Martin, Mary, 1993, Geohydrology and simulation of ground-water flow in the northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Professional Paper 1404–K, 81 p., 22 pls.

Lichtler, W.F., 1974, Report on the development of a ground-water supply at George Washington Birthplace National Monument: National Park Service Administrative Report, 12 p.

Lichtler, W.F., and Wait, R.L., 1974, Summary of the ground-water resources of the James River basin, Virginia: U.S. Geological Survey Open-File Report 74–139, 54 p.

Mack, F.K., 1966, Ground water in Prince George's County: Maryland Geological Survey Bulletin 29, 101 p.

McFarland, E.R., 1997, Hydrogeologic framework, analysis of ground-water flow, and relations to regional flow in the Fall Zone near Richmond, Virginia: U.S. Geological Survey Water-Resources Investigations Report 97–4021, 56 p.

McFarland, E.R., 1998, Design, revisions, and considerations for continued use of a ground-water-flow model of the Coastal Plain aquifer system in Virginia: U.S. Geological Survey Water-Resources Investigations Report 98–4085, 49 p.

McFarland, E.R., 1999, Hydrogeologic framework and ground-water flow in the Fall Zone of Virginia: U.S. Geological Survey Water-Resources Investigations Report 99–4093, 83 p.

McFarland, E.R., 2010, Groundwater-quality data and regional trends in the Virginia Coastal Plain, 1906–2007: U.S. Geological Survey Professional Paper 1772, 86 p.

McFarland, E.R., and Bruce, T.S., 2005, Distribution, origin, and resource-management implications of ground-water salinity along the western margin of the Chesapeake Bay impact structure in eastern Virginia, *in* Horton, J.W., Jr., Powars, D.S., and Gohn, G.S., eds., Studies of the Chesapeake Bay impact structure—The USGS-NASA Langely corehole, Hampton, Virginia, and related coreholes and geophysical surveys: U.S. Geological Survey Professional Paper 1688, chap. K, 32 p.

McFarland, E.R., and Bruce, T.S., 2006, The Virginia Coastal Plain hydrogeologic framework: U.S. Geological Survey Professional Paper 1731, 118 p.

McGee, W.J., 1886, Geologic formations of Washington, D.C., and vicinity: American Journal of Science, 3d series, v. 31, p. 473–474.

Meng, A.A., III, and Harsh, J.F., 1988, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1404–C, 82 p.

Mixon, R.B., Berquist, C.R., Jr., Newell, W.L., Johnson, G.H., Powars, D.S., Schindler, J.S., and Rader, E.K., 1989, Geologic map and generalized cross sections of the Coastal Plain and adjacent parts of the Piedmont, Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I–2033, scale 1:250,000.

Naeser, C.W., Naeser, N.D., Newell, W.L., Southworth, C.S., Weems, R.E., and Edwards, L.E., 2004, Provenance studies in the Atlantic Coastal Plain: What fission-track ages of detrital zircons can tell us about the source of sediments: Geological Society of America Northeastern and Southeastern Section Joint Meeting, Tysons Corner, Va., March 2004, 1 p.

Naeser, C.W., Naeser, N.D., Newell, W.L., Southworth, C.S., Weems, R.E., and Edwards, L.E., 2006, Provenance studies in the Atlantic Coastal Plain: What fission-track ages of detrital zircons can tell us about the erosion history of the Appalachians: Geological Society of America Annual Meeting, Philadelphia, Pa., October 2006, 1 p.

Naeser, N.D., Naeser, C.W., Southworth, C.S., Morgan, B.A., and Schultz, A.P., 2004, Paleozoic to Recent tectonic and denudation history of rocks in the Blue Ridge Province, central and southern Appalachians—Evidence from fission-track thermochronology: Geological Society of America Northeastern and Southeastern Section Joint Meeting, Tysons Corner, Va., March 2004, 1 p.

National Weather Service, 1996, Climatological data, Virginia, December 1996: National Oceanic and Atmospheric Administration, v. 106, no. 12, 26 p.

Nelms, D.L., Harlow, G.E., Plummer, L.N., and Busenberg, Eurybiades, 2003, Aquifer susceptibility in Virginia, 1998–2000: U.S. Geological Survey Water-Resources Investigations Report 03–4278, 58 p.

Newton, V.P., and Siudyla, E.A., 1979, Groundwater of the Northern Neck Peninsula, Virginia: Virginia State Water Control Board Planning Bulletin 307, 48 p.

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

Peltier, W.R., 1994, Ice age paleotopography: Science, v. 265, no. 5169, p. 195–201.

Plummer, L.N., Eggleston, J.R., Andreasen, D.C., Raffensperger, J.P., Hunt, A.G., and Casile, G.C., 2012, Old groundwater in parts of the upper Patapsco aquifer, Atlantic Coastal Plain, Maryland, U.S.A.: Evidence from radiocarbon, chlorine-36, and helium-4: Hydrogeology Journal, 26 p.

Pope, J.P., and Burby, T.J., 2004, Multiple-aquifer characterization from single borehole extensometer records: Groundwater, v. 42, no. 1, p. 45–58.

Pope, J.P., McFarland, E.R., and Banks, R.B., 2008, Private domestic-well characteristics and the distribution of domestic withdrawals among aquifers in the Virginia Coastal Plain: U.S. Geological Survey Scientific Investigations Report 2007–5250, 47 p.

Powars, D.S., 2000, The effects of the Chesapeake Bay impact crater on the geological framework and correlation of hydrogeologic units of southeastern Virginia, south of the James River: U.S. Geological Survey Professional Paper 1622, 53 p., 1 pl.

Powars, D.S., and Bruce, T.S., 1999, The effects of the Chesapeake Bay impact crater on the geological framework and correlation of hydrogeologic units of the lower York-James Peninsula, Virginia: U.S. Geological Survey Professional Paper 1612, 82 p., 9 pls.

Reinhardt, Juergen, Newell, W.L., and Mixon, R.B., 1980, Geology of the Oak Grove core, Part 1, Tertiary lithostratigraphy of the core: Charlottesville, Virginia Division of Mineral Resources Publication 20, p. 1–13.

Russnow-Kane and Associates, 1995, Report on the hydrogeologic framework and well construction activities, Lee Hall water treatment plant test site, section 4, aquifer testing program, 30 p.

Russnow-Kane and Associates, 1996a, Report on the hydrogeologic framework and well construction activities at the Kristiansand production well site, upper and middle Potomac aquifers well lot W-38, 24 p.

Russnow-Kane and Associates, 1996b, Report on the hydrogeologic framework and well construction activities at the Toano/Owens-Illinois production well site, upper and middle Potomac aquifers well lot W-1, 20 p.

Russnow-Kane and Associates, 1997, Report on the hydrogeologic framework and well construction activities, Harwood Drive (LH-1) and Lee Hall (LH-2) well sites, section 4, aquifer testing program, 39 p.

Russnow-Kane and Associates, 2000, Report on the hydrogeologic framework and well construction activities, Gloucester County water treatment plant test/monitor well, 5 p.

Russnow-Kane and Associates, 2002, Report on the hydrogeologic framework and well construction activities, Gloucester County brackish groundwater supply project production well no. 2, 6 p.

Russnow-Kane and Associates, 2004, Report on the hydrogeologic framework and well construction activities at the groundwater treatment facility—Five Forks site, middle and lower Potomac aquifers, 32 p.

Sanford, Samuel, 1913, The underground water resources of the Coastal Plain Province of Virginia: Virginia Geological Survey Bulletin 5, 361 p.

Sanford, W.E., Voytek, M.A., Powars, D.S., Jones, B.F., Cozzarelli, I.M., Cockell, C.S., and Eganhouse, R.P., 2009, Pore-water chemistry from the ICDP-USGS corehole in the Chesapeake Bay impact structure—Implications for paleohydrology, microbial habitat, and water resources: Geological Society of America Special Paper 458, p. 867–890.

Sinnott, Allen, 1969a, Results of aquifers tests in sands of the Potomac Group in the Franklin area, southeastern Virginia (1949–50): U.S. Geological Survey Open-File Report 69–260, 80 p.

Sinnott, Allen, 1969b, Ground-water resources of the Northern Neck Peninsula, Virginia: U.S. Geological Survey Open-File Report 69–259, 269 p.

Siudyla, E.A., Berglund, T.D., and Newton, V.P., 1977, Ground water of the Middle Peninsula, Virginia: Virginia State Water Control Board Planning Bulletin 305, 90 p.

Siudyla, E.A., May, A.E., and Hawthorn, D.W., 1981, Ground water resources of the four cities area, Virginia: Virginia State Water Control Board Planning Bulletin 331, 90 p.

Sohl, N.F., and Owens, J.P., 1991, Cretaceous stratigraphy of the Carolina coastal plalin, *in* Horton, J.W., Jr., and Zullo, V.A., eds., The geology of the Carolinas: Carolina Geological Society, 50th anniversary volume, p. 191–220.

Teifke, R.H., 1973, Geologic studies, Coastal Plain of Virginia: Virginia Division of Mineral Resources Bulletin 83, pts. 1 and 2, 101 p.

Trapp, Henry, Jr., 1992, Hydrogeologic framework of the northern Atlantic Coastal Plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York: U.S. Geological Survey Professional Paper 1404–G, 59 p., 13 pls.

Virginia State Water Control Board, 1973, Ground water of the York-James Peninsula, Virginia: Virginia State Water Control Board, Bureau of Water Control Management, Basic Data Bulletin 39, 74 p.

Vroblesky, D.A., and Fleck, W.B., 1991, Hydrogeologic framework of the Coastal Plain of Maryland, Delaware, and the District of Columbia: U.S. Geological Survey Professional Paper 1404–E, 45 p., 2 pls.

Weems, R.E., Lewis, W.C., and Aleman-Gonzalez, W.B., 2009, Surficial geologic map of the Roanoke Rapids 30' x 60' quadrangle, North Carolina: U.S. Geological Survey Open-File Report 2009–1149, 1 sheet, 1:100,000 scale map.

Weems, R.E., Seefelt, E.L., Wrege, B.M., Self-Trail, J.M., Prowell, D.C., Durand, Colleen, Cobbs, E.F., III, and McKinney, K.C., 2007, Preliminary physical stratigraphy and geophysical data of the USGS Hope Plantation core (BE-110), Bertie County, North Carolina: U.S. Geological Survey Open-File Report 2007–1251, 16 p.

Werkheiser, W.H., 1990, Hydrogeology and ground-water resources of Somerset County, Maryland: Maryland Geological Survey Bulletin 35, 156 p.

Wigglesworth, H.A., Perry, T.W., and Ellison, R.P., III, 1984, Groundwater resources of Henrico County, Virginia: Virginia State Water Control Board Planning Bulletin 328, 118 p.

Wilson, J.M., 1986, Stratigraphy, hydrogeology, and water chemistry of the Cretaceous aquifers of the Waldorf/La Plata area, Charles County, Maryland: Maryland Geological Survey Open File Report No. 86–02–2, 66 p.

Wilson, J.M., and Fleck, W.B., 1990, Geology and hydrologic assessment of Coastal Plain aquifers in the Waldorf area, Charles County, Maryland—Geology, hydrogeologic framework, and water quality: Maryland Geological Survey Report of Investigations No. 53, p. 1–38.

Winner, M.D., Jr., and Coble, R.W., 1996, Hydrogeologic framework of the North Carolina Coastal Plain: U.S. Geological Survey Professional Paper 1404–I, 106 p.

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