The Effects of the Chesapeake Bay Impact Crater on the Geologic Framework and the Correlation of Hydrogeologic Units of Southeastern Virginia, South of the James River

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THE EFFECTS OF THE CHESAPEAKE BAY IMPACT CRATER ON THE GEOLOGIC FRAMEWORK AND THE CORRELATION OF HYDROGEOLOGIC UNITS OF SOUTHEASTERN VIRGINIA, SOUTH OF THE JAMES RIVER

By David S. Powars

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1622

Prepared in cooperation with the
HAMPTON ROADS PLANNING DISTRICT COMMISSION

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 2000

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

Library of Congress Cataloging in Publications Data:

0-607-93693-2

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
inch (in.)	2.54	centimeters
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
cubic inch (in^3)	16.387	cubic centimeter (cm^3)
pound per square inch (lb/in^2)	6.895	kilopascal

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level (bsl).

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

Age designations: The time of a geological event and the age of an epoch boundary are expressed as Ma (mega-annum), which means 1,000,000 years, or years $\times 10^6$.

The Effects of the Chesapeake Bay Impact Crater on the Geologic Framework and the Correlation of Hydrogeologic Units of Southeastern Virginia, South of the James River

By D.S. Powars

Abstract

About 35 million years ago, a large comet or meteor slammed into the shallow shelf on the western margin of the Atlantic Ocean, creating the Chesapeake Bay impact crater (CBIC). Virginia Coastal Plain sediments, the southern part of the Chesapeake Bay, and a small part of the Atlantic Ocean now cover the crater. The impact apparently affected pre-impact structures near the CBIC. Subsequent structural adjustments of these structures likely were influenced by the crater and by the regional post-rift stress regime typical of the passive margin scenario described for the Atlantic Coastal Plain. Structural adjustments disrupted pre-impact sediments and basement rocks in the southern Chesapeake Bay region and influenced subsequent deposition, erosion, and preservation of sediments. Correlations of litho- and biostratigraphic data from borehole cores and cuttings and geophysical logs were used to identify the location and geometry of the CBIC and possible pre-impact structures. This report focuses on the Virginia Coastal Plain south of the James River and complements a recent study of the CBIC's effects on the geologic framework beneath the lower York-James Peninsula.

Pollen data indicate that only Lower Cretaceous deposits are present in the subsurface north of the James River, whereas on the south side of the river, both Lower Cretaceous (pollen zones I and II) and Upper Cretaceous (pollen zones III, IV, and V) deposits are present in the subsurface. Extreme variations in thickness of these deposits across the river, combined with an angular unconformity that separates these deposits from overlying, pre-impact lower Tertiary deposits, provide evidence for a pre-impact James River structural zone. The distribution of sediment suggests that the region north of the river was relatively depressed during pollen zone I, and relatively elevated for the remainder of Cretaceous time. By contrast, the region south of the James River was relatively depressed during pollen zones II, III, IV, and V.

South of the James River, Upper Cretaceous deposits younger than pollen zone III form a southeastward-thickening wedge across the south-eastern half of the study area, but are thin and irregularly distributed across the northwestern half. The pre-impact lower Tertiary deposits dip eastward to northward and are structurally higher and thinner along the southern side of the study area, near the Virginia-North Carolina border, than along the northern side.

The complex distribution of post-impact units across the James River provides evidence for post-impact adjustments of this James River structural zone initiated by the emplacement of the impact crater, and subsequent burial. The truncation of many earlier post-impact (upper Eocene to middle Miocene) deposits indicates that the area south of the James River structural zone was relatively elevated during that time or at least prior to deposition of the upper Miocene St. Marys Formation. The presence of thicker post-middle Miocene deposits south of the James River, compared to those north of the river, indicates downwarping of the area south of the river during this period and a complex structural history of adjustments to the CBIC.

The structural and stratigraphic features created by the impact, and the consequent structural adjustments of the James River structural zone, have influenced the hydrogeology, ground-water flow system, and water quality of a large part of the Virginia Coastal Plain. Regional flow paths apparently were altered by emplacement of the possibly low permeability, lithologically heterogeneous Exmore tsunami-breccia deposits, as well as by subsequent deposition of primarily very fine grained deposits in the CBIC's structural low. The buried CBIC created a large region where differential flushing of seawater from the

Coastal Plain sediments in and around the crater possibly resulted in Virginia's "inland salt-water wedge." The outer rim of the crater appears to act as a boundary and/or mixing zone separating ground water of high salinity inside the outer rim from lower salinity water outside the outer rim. The James River structural zone apparently abruptly offsets stratigraphic units that have been preserved differently north and south of the James River.

INTRODUCTION

The discovery of a large impact crater beneath Chesapeake Bay has prompted a revision of the structural, stratigraphic, and hydrogeologic framework of a large part of the Virginia Coastal Plain. The 56-mile-wide Chesapeake Bay impact crater (CBIC) is located beneath the lower Chesapeake Bay, its surrounding peninsulas, and a small part of the Atlantic Ocean east of the lower part of the Delmarva Peninsula (fig. 1); the approximate center of the crater is beneath the town of Cape Charles, Va. The CBIC was formed when a large comet or meteorite crashed into shallow-shelf waters of the western Atlantic Ocean approximately 35 million years ago (Ma). The impact produced an inverted, sombrero-shaped, complex crater that was immediately filled with chaotically mixed sediments and rim-collapse material and eventually buried by younger sedimentary deposits. A disruption boundary separates the impact rubble from primarily undisturbed sediments and rocks (fig. 2). Walled terraces, central peaks, and flat floors characterize complex craters (Melosh, 1989), and the CBIC has all these features.

The CBIC impactor slammed into part of an apparent structural zone, herein referred to as the James River structural zone, that traversed the Coastal Plain east to west beneath the eastern part of the present-day James River Basin. Deformational processes such as faulting, folding, and igneous intrusion created the unique structural features of this area. The emplacement of the crater appears to have caused adjustments to this James River structural zone, dramatically disrupted the pre-impact sediments and rocks in the southern Chesapeake Bay region, and influenced subsequent sediment deposition and distribution patterns. Powars and Bruce (1999) described how the impact resulted in several regional anomalies: (1) a large crater, partly filled by impact and collapse debris; (2) an impact tsunami-breccia consisting of a mixture of sea water and sediments of Lower Cretaceous, Upper Cretaceous, Paleocene, and lower and upper Eocene age; (3) a large area of anomalous water quality (Virginia's "inland salt-water wedge"); (4) transformation of the depositional environment from inner neritic (shallow-shelf) to bathyal (deep-water) depths within the crater, in which fine-grained, low permeability sediments accumulated; and (5) a regional depression that persisted because of post-impact loading and differential compaction. The existence of the CBIC, combined with structural adjustments of a pre-impact structural zone, helps explain the distribution of saline water in the Virginia Coastal Plain aquifers. This information needs to be considered in revisions of the hydrogeologic framework and ground-water-flow models of the aquifer system.

In July 1997, the U.S. Geological Survey (USGS), in cooperation with the Hampton Roads Planning District Commission (HRPDC), initiated a multi-phase study to refine the geologic and hydrogeologic frameworks of the Coastal Plain sediments in and near the CBIC. This information will be the basis for revisions of the ground-water flow models that are used to guide water-supply management decisions. The York-James Peninsula was the focus of Phase I (Powars and Bruce, 1999; fig. 1). This report presents the results of Phase II of the study, which focused on an area in southeastern Virginia, south of the James River. Additionally, this report integrates Phase II results with the Phase I evaluation of the York-James Peninsula.

The discovery of the buried CBIC, and its apparent effect on a pre-impact structural zone, revealed the inadequacy of the multi-aquifer conceptual model currently being used to represent the ground-water systems of the Virginia Coastal Plain. The existing hydrogeologic framework and ground-water models were built upon a geologic framework that described the Virginia Coastal Plain as an eastward dipping and thickening wedge of unconsolidated sediments, readily subdivided into aquifers and confining units. Knowledge of the formation of the crater and of the structural adjustments of a pre-impact structural zone has disrupted this model, however, leading to the need for a re-appraisal of the hydraulic properties, ground-water flow, and geochemistry of the aquifer system. First, the physical features created and affected by the impact crater must be defined and described–in other words, the geologic framework must be established–in order to understand and refine the hydrogeologic framework in this region.

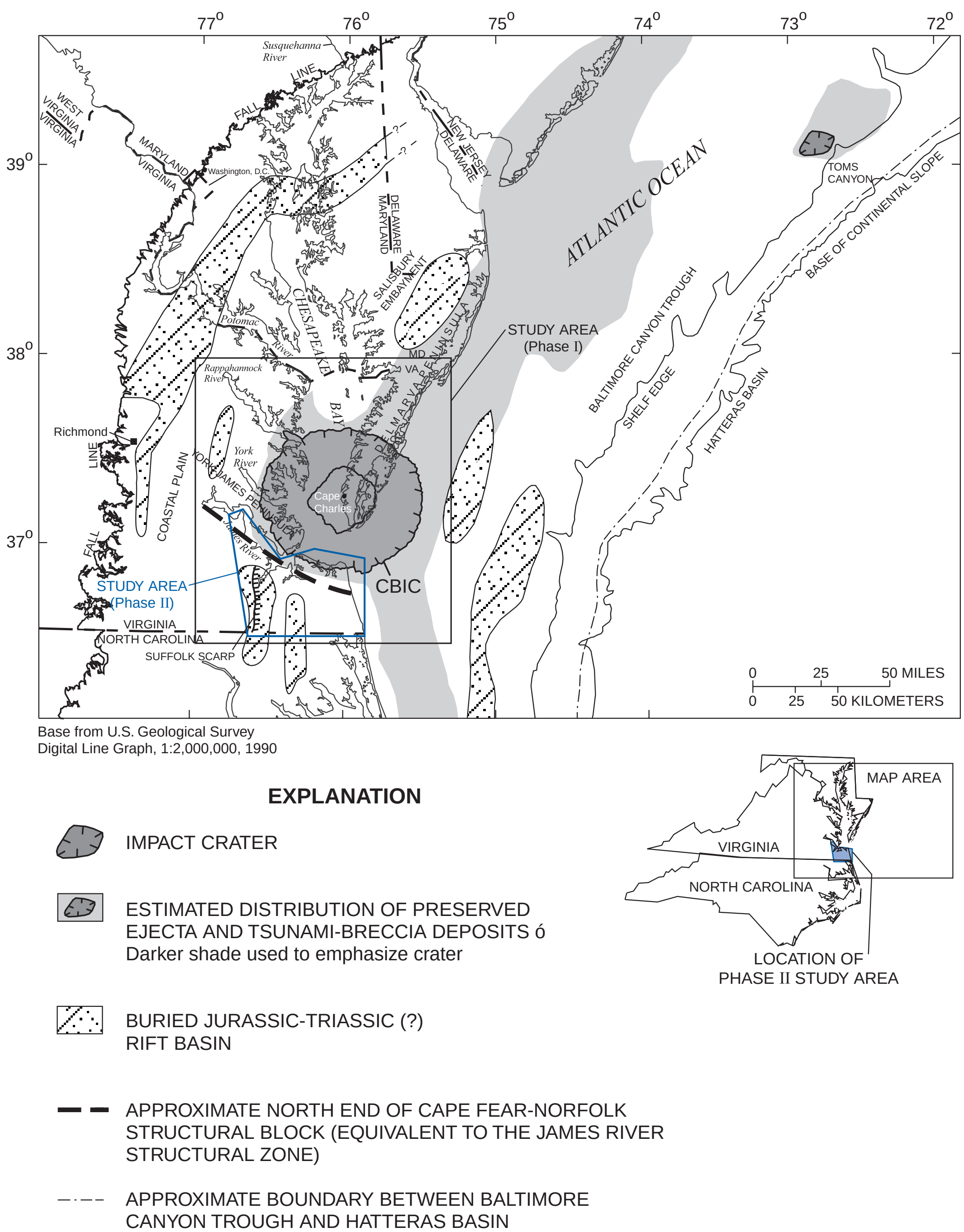


Figure 1. Location of study areas (Phase I and Phase II), the Chesapeake Bay impact crater (CBIC), and significant regional physiographic and geologic features.

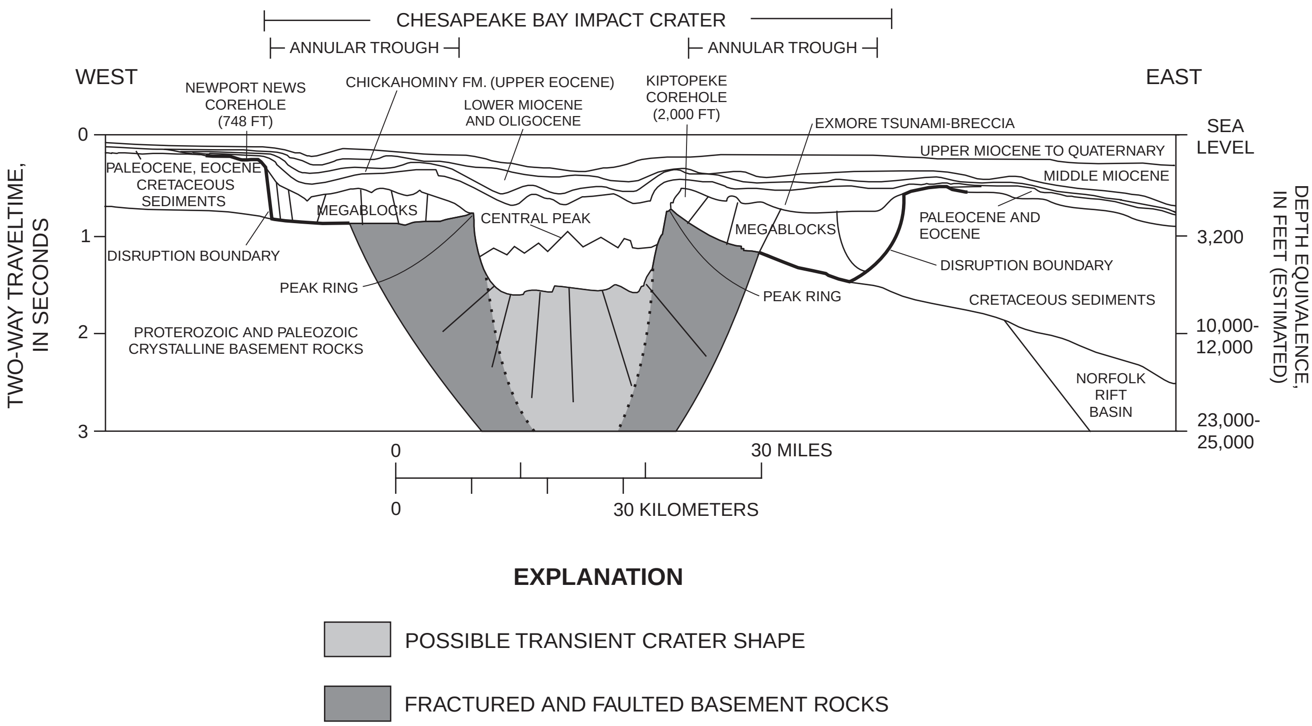


Figure 2. Generalized geologic section of Chesapeake Bay impact crater. (From Powars and Bruce, 1999.)

Purpose and Scope

This report refines the geologic framework of southeastern Virginia, south of the James River, in and near the CBIC, and presents evidence for the existence of a pre-impact James River structural zone that was reactivated by the impact. Lithologies of cores from exploratory holes are correlated with borehole geophysical logs to characterize the physical properties of the stratigraphic units and their geophysical signatures. The correlation of cores, cuttings from wells, and borehole geophysical logs provides the building blocks for compilation of stratigraphic cross sections. To further develop our understanding of this structurally complex area, these cross sections are tied into the geologic framework of the lower York-James Peninsula as refined by Powars and Bruce (1999). The correlation of geologic units to hydrogeologic units is an important step towards the refinement of the hydrogeologic framework.

Description of Study Area

The study area encompasses the southeastern part of the Virginia Coastal Plain south of the Chesapeake Bay and the James River and extends to just west of the Suffolk scarp (fig. 1). Most of this area from the Atlantic Ocean to the Suffolk scarp has low relief, generally less than 30 ft. The scarp marks where the relief jumps up to 100 ft and is one of a succession of step-like terraces and intervening scarps that trend either parallel to the coast or to the major streams and were created by Pleistocene sea-level oscillations. These terraces become progressively lower in altitude and younger in age toward the coast and rivers; the younger the terrace surface, the less dissected it is. The buried outer rim of the crater is geomorphically expressed by its alignment and concentric parallelism with various Pleistocene wave-cut scarps.

The study area covers part of the north flank of the Cape Fear-Norfolk block (a structural basement high). Figure 1 shows that part of the area is underlain by buried rift basins that have been regionally dated as Jurassic and/or Triassic. Other major regional structural features of the basement include the Salisbury Embayment, the Baltimore Canyon Trough (a major structural low), the Hatteras Basin, and buried Jurassic-Triassic rift basins outside the study area.

Previous Investigations

In the late 1930's and early 1940's, the need to develop ground-water resources in the southeastern Virginia region was heightened by water demands for the military bases and by shortages caused by a severe drought. These pressures led to Cederstrom's (1945a, c) hydrogeologic studies of the southeastern Virginia region. Cederstrom's studies provide lithologic logs from water-well cuttings, including those he logged himself. His reports contain biostratigraphic data analyzed by J.A. Cushman (USGS), and water-quality data, including the initial delineation of Virginia's inland salt-water wedge and its associated Eocene basin north of the James River. Cederstrom first postulated the existence of a James River fault zone to explain his interpretation of the erratic distribution and abrupt thickening of various strata north and south of the James River. Until the late 1980's, the subsurface geology of this region was interpreted primarily on the basis of water-well cuttings and geophysical logs (Brown and others, 1972; Meng and Harsh, 1988; Hamilton and Larson, 1988). Coch (Coch, 1968, 1971), Oaks (Oaks and Coch, 1973), and Johnson (Johnson, 1969, 1976; Johnson and Peebles, 1985; Johnson and others, 1985, 1987) provided detailed surficial mapping of southeastern Virginia south of the James River. A regional compilation of the surficial units at 1:250,000 scale was prepared by Mixon and others (1989).

The combined efforts of the USGS, the HRPDC, and the Virginia Department of Environmental Quality (VDEQ) over the last 14 years have greatly changed our understanding of the geologic framework of southeastern Virginia (Powars and others, 1987, 1990, 1991, 1992; Poag and others, 1992; Powars and Bruce, 1999). These investigations document the existence of the Chesapeake Bay impact crater (Powars and others, 1993; Poag, Powars, and Mixon, 1994; Poag, Powars, Poppe, and Mixon, 1994); the crater's association with the inland salt-water wedge (Powars and others, 1994, 1998; Bruce and Powars, 1995); and the crater's structural and stratigraphic effects on post-impact sediment distribution and on the development of the present-day landscape (Powars and others, 1993, 1998; Poag, Powars, and Mixon, 1994; Poag, Powars, Poppe, and Mixon, 1994; Poag, 1996, 1997c; Johnson and Powars, 1996; Riddle and others, 1996; Johnson, Kruse, and others, 1998; Johnson, Powars, and others, 1998). Most recently, Powars and Bruce (1999) refined the geologic framework of the Lower York-James Peninsula and described the effects that the CBIC structure has had on the southeastern Virginia Coastal Plain.

Acknowledgments

The stratigraphic and lithologic interpretations presented in this report benefited from several years of research by the author and his colleagues. Special thanks are extended to USGS colleagues for the biostratigraphic data on dinoflagellates (Lucy E. Edwards), Foraminifera (C. Wylie Poag; Thomas G. Gibson, now with the Smithsonian Institution; and Scott E. Ishman), Tertiary mollusks (L.W. Ward, now with the Natural History Museum of Virginia), Cretaceous mollusks (Norman F. Sohl, deceased), ostracodes (Thomas M. Cronin), calcareous nannofossils (Laurel M. Bybell), and pollen (Ronald J. Litwin and Norman O. Frederiksen).

Thanks to the Hampton Roads Planning District Commission (HRPDC) and its Directors of Utilities Committee, which made this study possible. The HRPDC represents the Cities of Chesapeake, Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Suffolk, Virginia Beach, and Williamsburg, Va., and the Counties of Gloucester, Isle of Wight, James City, Southampton, Surry, and York.

Much appreciation also to Gregory S. Gohn (USGS), T. Scott Bruce (VDEQ), Gerald H. Johnson (College of William and Mary), and Scott R. Emry (HRPDC) for their helpful scientific reviews, and to Martha Erwin for editorial review of this report. Special thanks to Theodore B. Samsel III and Brent Banks for their help in the digitization of many figures, and to Wendy Danchuck for cartographic assistance. The assistance of George E. Harlow, Jr., in the location and proper labeling of many wells is greatly appreciated.

Finally, special appreciation is extended to USGS drillers Donald Queen, Dennis Duty, Gene Cobbs, and Gene Cobbs III, and VDEQ drillers John Creason and Jay Owens for their determination in obtaining continuous core samples that provide the ground truth needed for this kind of investigation, discovery, and report. Appreciation is given to Sydnor Hydrodynamics, Inc., for providing geophysical logs for this study.

METHODS OF INVESTIGATION

The geologic framework of southeastern Virginia, south of the James River, was refined by analyzing stratigraphic and lithologic data from cores, well cuttings, and borehole geophysical logs. Selected core intervals were sampled for mineralogic and biostratigraphic analysis. The more recent data were combined with re-evaluations of previously published data to provide new interpretations that account for the effects of the CBIC, including its apparent effects on the pre-impact James River structural zone.

Compilation of Lithologic Data from Cores and Well Cuttings

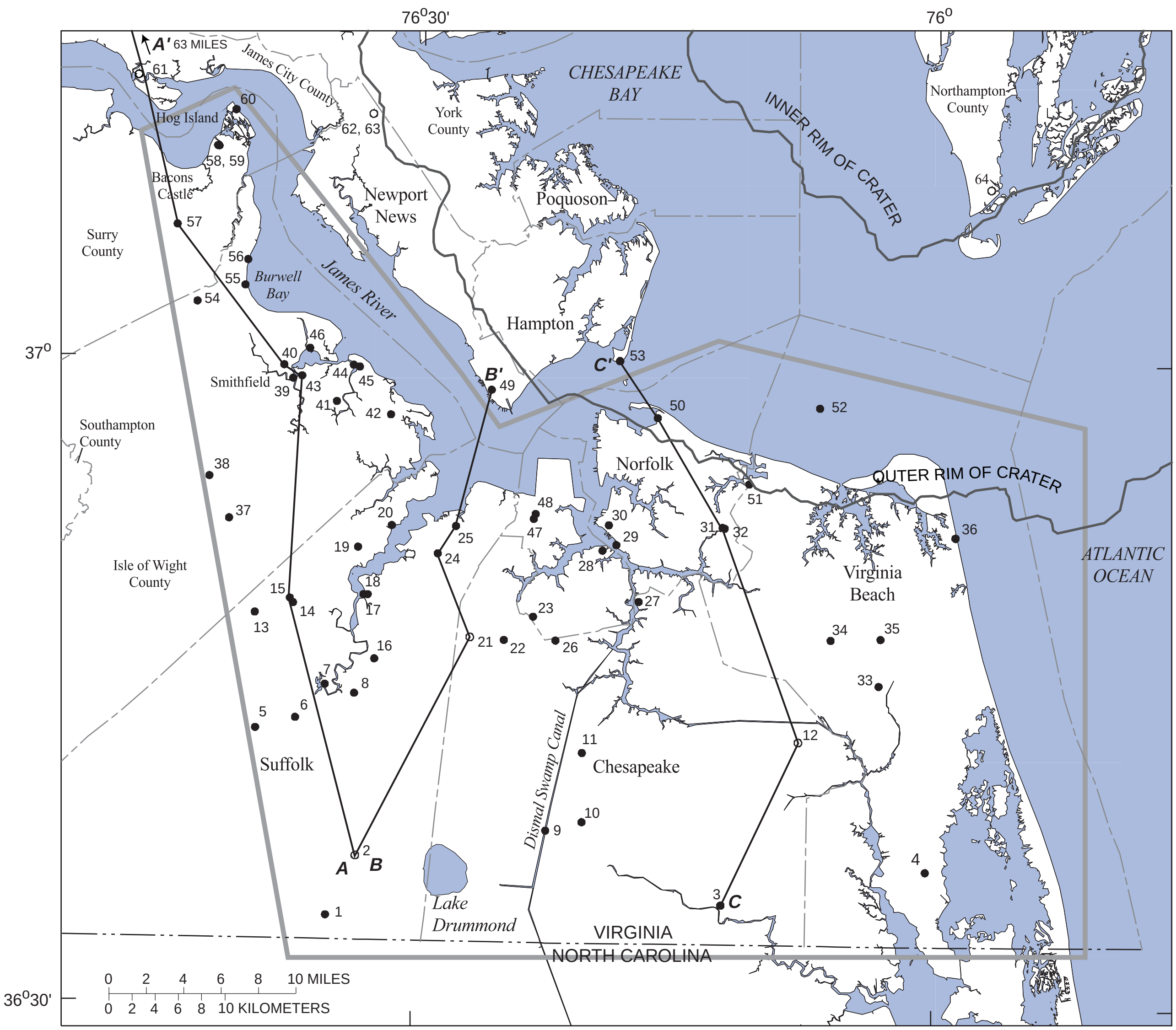
The borehole-numbering system used in this study refers to a location number on figure 3—printed in bold in the text, for example, (**12**)—and in appendixes 1 and 2. To maintain continuity with Powars and Bruce (1999), appendix 1 includes the local reference number, such as the USGS Ground-Water Site Inventory (GWSI) number or the well number assigned in other reports (Cederstrom, 1945a, b; Brown and others, 1972). The GWSI is based on a system in which Virginia's 7-1/2-min quadrangles are numbered 1 through 69 from west to east, and lettered A through Z (omitting I and O) from south to north; wells are identified and numbered serially within each 7-1/2-min quadrangle. As an example, well 58A76 is in quadrangle 58A and is the 76th well in that quadrangle for which the location and other data were recorded by the USGS. Appendix 2 lists the altitudes of the tops of stratigraphic units used in this report.

Litho- and biostratigraphic data derived from continuous coreholes with high recovery rates (fig. 3) provided the stratigraphic control for this investigation. Nine cores were obtained between 1986 and 1995 by the USGS and the VDEQ as part of their cooperative research efforts (Powars and others, 1992; Powars and Bruce, 1999). These cores are stored at the USGS core-storage areas in Reston and Herndon, Va., or at the VDEQ in Richmond, Va. Corehole names are derived from nearby geographic features and include (listed in the order drilled) Exmore, Dismal Swamp (**2**), Jenkins Bridge, Fentress (**12**), Kiptopeke (**64**), Newport News Park 2 (**63**), Windmill Point, Airfield Pond, and Jamestown (**61**). (Only those coreholes assigned a borehole number are discussed in this report.) The Dismal Swamp (**2**) and Fentress (**12**) coreholes are located in the southern part of the study area, and the Newport News Park 2 (**63**) and Kiptopeke (**64**) coreholes, which lie just outside the northern boundary of the study area, were used for control across the northern part. An additional corehole was drilled for the City of Chesapeake as part of its Western Branch Aquifer Storage and Recovery Project and is labeled **21** on figure 3. This corehole is referred to as MW4-1 (the original field designation) in Powars and Bruce's 1999 report, but is herein given the name Chesapeake-Portsmouth Airport corehole. This core also is stored at the USGS core-storage area in Herndon, Va. In this study, the Dismal Swamp (**2**), Fentress (**12**), and Chesapeake-Portsmouth Airport (**21**) coreholes provided the key lithostratigraphic and biostratigraphic data for borehole log correlation.

Lithologic and biostratigraphic data from selected cored intervals in test holes drilled in the 1970's by the VDEQ and by the U.S. Department of Energy and the Virginia Polytechnic Institute and State University (VPI) provided additional stratigraphic control. Subsurface data consisting primarily of lithologic data from cuttings, borehole geophysical logs, and selected cored intervals became available from a Brackish Groundwater Development Project recently conducted by the City of Chesapeake at the Northwest River Water Treatment Plant. The deepest borehole drilled at this site is herein referred to as the Chesapeake Northwest River Water Treatment Plant (WTP) borehole (**3**).

Descriptions of borehole cuttings were interpreted by correlation to the coreholes, resulting in many reinterpretations of stratigraphic units described by Cederstrom (1945a, b) and by Brown and others (1972). The biostratigraphic data in these earlier reports were emphasized, while noting the potential for down-hole contamination. The detailed Virginia Division of Mineral Resources (VDMR) lithologic descriptions of washed samples are from mud-rotary drilled wells and clearly reflect down-hole contamination. Therefore, the descriptions were carefully scrutinized for the first occurrences of stratigraphically significant lithologic components, for example, shells and glauconite for marine deposits; and feldspar, gravel, lignitized wood, and oxidized, multicolored clays for deltaic and fluvial deposits. Where available, decreasing or increasing percentages of the various lithic components were also used to help define stratigraphic horizons.

When conflicting data were encountered, either within a single borehole (for example, when lithologic descriptions did not agree with the geophysical log) or between wells, priority was given to cuttings descriptions that were made by an on-site geologist (primarily D.J. Ceder-



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EXPLANATION

A——A' CROSS SECTION

CHESAPEAKE BAY IMPACT CRATER RIM

STUDY AREA

• 1 BOREHOLE AND NUMBER

○ 12 CONTINUOUS COREHOLE AND NUMBER

Figure 3. Location of boreholes, continuous coreholes, and stratigraphic cross sections. See Appendixes 1 and 2 for data on boreholes.

strom, and T.S. Bruce, VDEQ). In some cases, emphasis was placed on the interpretation of geophysical logs from boreholes that were similar to and located near one of the three key coreholes. Emphasis was also placed on any biostratigraphic data that were included. Data from wells that were drilled by the cable tool method also were given priority over rotary-drilled wells because rotary methods tend to produce greater mixing than cable methods.

Analysis of Borehole Geophysical Logs

Borehole geophysical logs were interpreted by establishing geophysical signatures for the various units defined in several continuous coreholes. These geophysical signatures were then correlated to those of other logs gathered for this investigation. Interpretation for each borehole was an iterative process because the detail of the lithic descriptions ranged from generalized drillers' logs to microscopic descriptions of samples. Correlations also were made to other nearby borehole lithologic logs published by Cederstrom (1945a, b), and by Brown and others (1972), and to unpublished VDMR, VDEQ, and USGS data. Powars and Bruce (1999) found that conflicting data were encountered most often around the outer rim of the CBIC, especially for the uncored boreholes located far from one of the continuous coreholes.

The number and type of geophysical logs varied greatly from borehole to borehole. Single-point resistance and natural gamma logs were the most numerous and therefore were used for establishing the geophysical signatures. Correlation also was made with multipoint resistivity, 6-foot lateral resistivity, and spontaneous potential logs. The cross sections in this report are based on interpretation of the lithic descriptions and geophysical logs.

STRUCTURAL SETTING OF SOUTHEASTERN VIRGINIA

In contrast to the regional post-rift thermal- and load-driven subsidence typical of the "passive margin" scenario described for the Atlantic Coastal Plain (Grow and Sheridan, 1988), the basement rocks and sediments of the Coastal Plain of Virginia record a complex geological history, including the effects of the catastrophic upper Eocene comet or meteorite impact. This impact produced the CBIC, the largest impact crater found so far in the United States. The southwestern portion of the outer rim of the crater extends from the Newport News and Hampton area to the northern Norfolk and Virginia Beach area (fig. 3).

This section subdivides the structural history into pre-impact, syn-impact, and post-impact sections and presents evidence for the existence of a pre-impact James River structural zone and the CBIC's effects on this zone. Table 1 shows the geologic units described in this report and their correlation with geologic units of key previous investigations, as well as Cretaceous pollen data. This table provides the stratigraphic nomenclature and position of the geologic units discussed in this section. A more detailed description of the geologic units is given in the Geologic Framework section.

Pre-impact Structural History

The basement rocks beneath the Coastal Plain of Virginia have been interpreted to be an assembly of various tectonostratigraphic terranes that were accreted to the North American continent during Paleozoic continental collisions (Horton and others, 1991). Most of the central to outer Coastal Plain of Virginia is underlain by the Chesapeake Block, which has been interpreted as African Archean to Lower Proterozoic rocks that were left accreted on to the North American continent during the Mesozoic opening of the present Atlantic Ocean (Lefort and Max, 1991). Recently, Sheridan and others (1999) presented a rubidium/strontium date from rocks beneath the southeastern New Jersey Coastal Plain that suggests a Middle Proterozoic age for the Chesapeake Block. Late Paleozoic granitic plutons also are present. It appears that some major structural zones are present in the crystalline basement rocks, some of which likely were zones of weakness (faults) that became involved with Mesozoic rift basin formation.

The last breakup of North America, Eurasia, and Africa began with Triassic rifting and was associated with an extensional stress regime that pulls apart and thins the crust. This rifting continued into the Early Jurassic and produced crustal instability and asymmetrical, down-dropped, sediment-filled basins (grabens) with wrench and transform faults, tilting, folding, igneous intrusion, and widespread volcanism (see fig.1 for location of rift basins beneath the Coastal Plain). Part of the study area is underlain by two of these rift basins, both having northern boundaries south of the CBIC and extending southward 10 to 20 miles into North Carolina

Table 1. Correlation of stratigraphic units, including Cretaceous pollen zones of the Mid-Atlantic states. Modified from Powars and Bruce, 1999

[Upper, upper; M, middle; L, lower; Fm, formation]

SYSTEM	SERIES		Geologic units this report	Cederstrom (1957)	Brown and others (1972)	Mixon, Berquist, and others (1989)		Pollen Zonation[1]
QUATERNARY	Holocene		Alluvium, swamp, beach	Recent beach sand	Rocks of post Miocene age	Coastal barriers, lagoons alluvial, swamp, eolian	(East of the Chesapeake Bay)	Not studied
	Pleistocene	U	Tabb Formation	Columbia Group (Quaternary)		Tabb Formation	U: Kent Island Formation; Wachapreague Formation; Nassawadox Formation	
		M	Shirley Formation			Shirley Formation	M: Omar Formation	
		M	Chuckatuck Formation			Chuckatuck Formation		
		L	Charles City Formation			Charles City Formation		
		L	Windsor Formation			Windsor Formation		
						Moorings unit		
TERTIARY	Pliocene	U	Bacons Castle Formation			Bacons Castle Formation		
		U	2	Yorktown Formation (Miocene)		Pliocene sand + gravel; CHESAPEAKE GROUP: Chowan River Formation		
		U	CHESAPEAKE GROUP: Yorktown Formation: Moore House Member			Yorktown Formation		
		U	Mogarts Beach Member					
		U	Rushmere Member					
		L	Sunken Meadow Member		?------?			
	Miocene	U	Eastover Formation: Unnamed beds[3]		?------?	Miocene sand + gravel; Eastover Formation		
		U	? Cobham Bay Member		Rocks of late Miocene age			
		U	Claremont Manor Member	St. Marys Formation (Miocene)				
		U	St. Marys Formation			St. Marys Formation		
		M	Choptank Formation (not present in study area)	Calvert Formation (Miocene)	Rocks of middle Miocene age	Choptank Formation	Choptank Formation not present east and south of Chesapeake Bay	
		M	Calvert Formation[4]: Calvert Beach Member			Calvert Formation		
		M	Plum Point Member					
		M	Fairhaven Member					
		L	Newport News unit	?------?				
	Oligocene	U	Old Church Formation	?------?	?------?	Old Church Formation		

[1]Follows Brenner (1963) and Owens and Gohn (1985).

[2]Chowan River Formation.

[3]Powars, D.S. and Cronin, T., U.S. Geological Survey, unpub. data, 1995.

[4]Not present south of James River.

Table 1. Correlation of stratigraphic units, including Cretaceous pollen zones of the Mid-Atlantic states. Modified from Powars and Bruce, 1999—Continued

[Upper, upper; M, middle; L, lower; Fm, formation]

SYSTEM	SERIES		Geologic units this report	Cederstrom (1957)	Brown and others (1972)	Mixon, Berquist, and others (1989)		Pollen Zonation[1]
TERTIARY	Miocene	L	Newport News unit of Calvert Fm	Calvert Formation (Miocene) ? ?	Rocks of Middle Miocene age (?)	Calvert Formation		Not studied
	Oligocene	U	Old Church Formation	? ?		Old Church Formation		
		L	Delmarva beds		? ?	Delmarva beds[5]		
	Eocene	U	Chickahominy Formation	Chickahominy Formation (upper Eocene)	Rocks of Jackson age	Chickahominy Formation		
			Exmore tsunami-breccia	?	? ?	Exmore beds[5]		
			Exmore megablock beds	?	? ?			
		M	Piney Point Formation[4]	Nanjemoy Formation (Eocene) — Pamunkey Group	Rocks of Claiborne age	Piney Point Formation		
		L	Nanjemoy Formation		Rocks of Sabine age	Nanjemoy Formation	Woodstock Member[5] / Potapaco Member[5]	
			Marlboro Clay			Marlboro Clay		
	Paleocene	U	Aquia Formation	Aquia Formation (Eocene)		Aquia Formation	Pasapotansa Member[5] / Piscataway Member[5]	
		L	Brightseat Formation	Mattaponi Formation (Paleocene + Upper Cretaceous) ?	Rocks of Midway age	Brightseat Formation		
CRETACEOUS	Upper		Unnamed[6]		Rocks of unit A / Rocks of unit B / Rocks of unit C			
			Red beds[6] — Glauconitic sand unit[6]		Rocks of unit D	Red beds[5]	Glauconitic sand unit[5]	V — [7]
			Upper Cenomanian beds[6]	? Potomac Group (Upper Cretaceous)	Rocks of unit E	Upper Cenomanian beds[5]		IV
	Lower		Potomac Formation	Potomac Group (Lower Cretaceous)	Rocks of unit F	Potomac Formation		III
					Rocks of unit G			II —?— —?—
					Rocks of unit H			I
JURASSIC-TRIASSIC			Lower Mesozoic rift-basin deposits					
PALEOZOIC AND PROTEROZOIC			Basement rocks					

[1]Follows Brenner (1963) and Owens and Gohn (1985).

[2]Chowan River Formation.

[3]Powars, D.S. and Cronin, T., U.S. Geological Survey, unpub. data, 1995.

[4]Not present south of James River.

[5]From Powars and others (1992).

[6]Not present north of James River.

[7]Glauconitic sand unit not studied.

(fig. 1). The major border faults of these rift basins generally are parallel to old Appalachian lineaments.

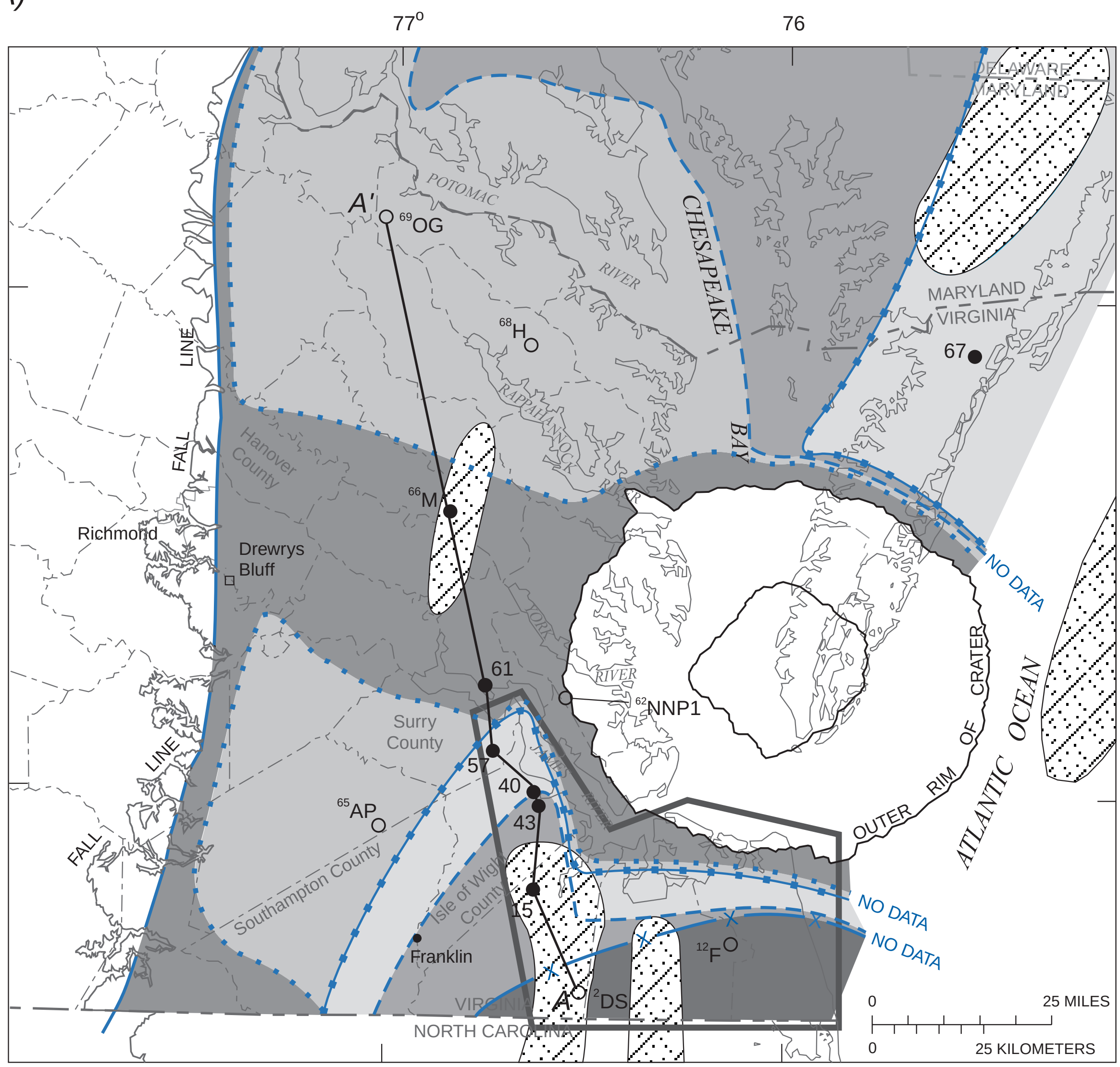
Deposition of the Coastal Plain sediments began in the Late Jurassic with the opening of the Atlantic Ocean and the beginning of sea floor spreading. The initial stages of accumulation of post-rift sediments in southeastern Virginia occurred in the Early Cretaceous with deposition of fluvial and deltaic deposits by streams and rivers. As the Atlantic Ocean widened, the environment of deposition was influenced by regional-scale tectonism that involved gentle subsidence of the entire Atlantic continental margin and major alternating marine transgressive and regressive phases (the passive margin scenario), as well as local independent structural movement that created a transverse arch-basin structural configuration. The axes of these arches and basins trend in an easterly or southeasterly direction transverse to the northeast- southwest strike of the Atlantic continental margin. This arch-basin configuration has been explained, using tectonic models, as block-like structures bounded by zones of weakness in the crystalline basement rocks or resulting from the possible movement of the landward parts of oceanic transform faults. The structural blocks would have moved up or down relative to each other in response to non-uniform loading or basement rock tectonics. Brown and others (1972) suggested that structural blocks were bounded by basement faults that created recurrently reversing vertical movement along wrench faults during deposition to explain the stratigraphic thinning and thickening of Cretaceous- and Tertiary-age formations associated with these arches and basins.

The Norfolk arch trends eastward across southeastern Virginia just south of the James River and appears to represent a basement and stratigraphic structural high that is part of the north end of the Cape Fear-Norfolk block (see fig. 1). North of the arch is a major tectonic downwarped basin referred to as the Salisbury Embayment; south of the arch, in the outer Coastal Plain of North Carolina within the Cape Fear-Norfolk block, is a minor basin known as the Albemarle Embayment. The Albemarle Embayment is located on the northern side of Albemarle Sound, just south of the study area. The Norfolk arch appears to coincide with (1) the north end of shallow rift basin deposits (indurated red beds) that overlie granite and (2) the north end of the Cape Fear-Norfolk block, which also aligns with the onshore extension of the Norfolk Fracture zone. These factors point to the existence of a structural zone in the vicinity of the James River Basin. Cederstrom (1945a) originally suggested that a basin controlled by basement faulting occupied the area immediately north of the present James River from Hampton Roads northwestward to at least Hog Island, in Surry County. Powars and Bruce (1999) interpreted much of this postulated James River fault zone as part of the outer rim of the crater, but also suggested some pre-impact structural involvement. The distribution of Cretaceous pollen zones, which extends outside of the crater and its preserved ejecta, also supports the existence of a pre-impact James River structural zone (fig. 4). This James River structural zone coincides with the north side of the Norfolk arch. A series of isopach maps by Hamilton and Larson (1988) show several confining units that dramatically thin or pinch out northward across or in proximity to the postulated James River structural zone.

Structure contour maps of the top of the Upper Cretaceous and the top of the pre-impact lower Tertiary deposits show east to southeast deflections of the contours, possibly reflecting faulted zones (figs. 5 and 6); the main deflection coincides with a previously postulated fracture zone (Johnson and others, 1998). Figure 5 also shows the truncated distribution of the red beds, which may be fault controlled, and that in the Norfolk to Virginia Beach area adjacent to the crater, Upper Cretaceous deposits are truncated and overlain by the Exmore tsunami-breccia. An isopach map of the Upper Cretaceous, younger than pollen zone III deposits (upper Cenomanian beds, glauconitic sand unit, red beds, and Upper Cretaceous and/or Paleocene) combined shows a southeastward-thickening wedge that thickens from 30 to 500 ft across the study area (fig. 7). Some of this thickening occurs because more Upper Cretaceous units are preserved on the southeast side of the Norfolk arch. An isopach map of the pre-impact lower Tertiary deposits indicates that these deposits thicken north of the James River and west of their truncation by the CBIC (fig. 8). These deposits thicken and thin across the rest of the study area with their erratic distribution apparently caused primarily by syn- and post-impact erosional and structural influences of the CBIC on the pre-impact James River structural zone. Part of the pattern also appears to reflect radial fault systems that were created by the CBIC.

Three north-south stratigraphic cross sections show the complex stratigraphy encountered across this region (figs. 4, 9, and 10). Figure 9A shows the entire section of Coastal Plain sediments and the top of the basement rocks in a cross section that extends from near the Dismal Swamp corehole (**2**) to the City of Newport News City Hall Complex borehole (**49**). This section is within the disruption boundary that separates pre-impact units from impact debris or syn-impact units. Figure 9B shows the

(A)



Base from U.S. Geological Survey
Geologic Map, 1:250,000, Mixon, Berquist, and others, 1989

EXPLANATION

A——A' STRATIGRAPHIC CROSS SECTION

APPROXIMATE EXTENT OF POLLEN ZONE

Zone V	Coniacian to Santonian	Upper Cretaceous
Zone IV	Cenomanian	Upper Cretaceous
Zone III	Cenomanian	Upper Cretaceous
Zone II	middle to late Albian	Lower Cretaceous
Zone I	Barremian to early Albian	Lower Cretaceous

BURIED JURASSIC-TRIASSIC (?) RIFT BASIN

STUDY AREA

F ○ CONTINUOUS COREHOLE (AND NUMBER) WITH POLLEN ANALYSIS

- 2DS - Dismal Swamp
- 12F - Fentress
- 65AP - Airfield Pond
- 68H - Haynesville
- 69OG - Oak Grove
- 62NNP1 - Newport News Park 1
- 66M - Mann Tract Monitor well #1

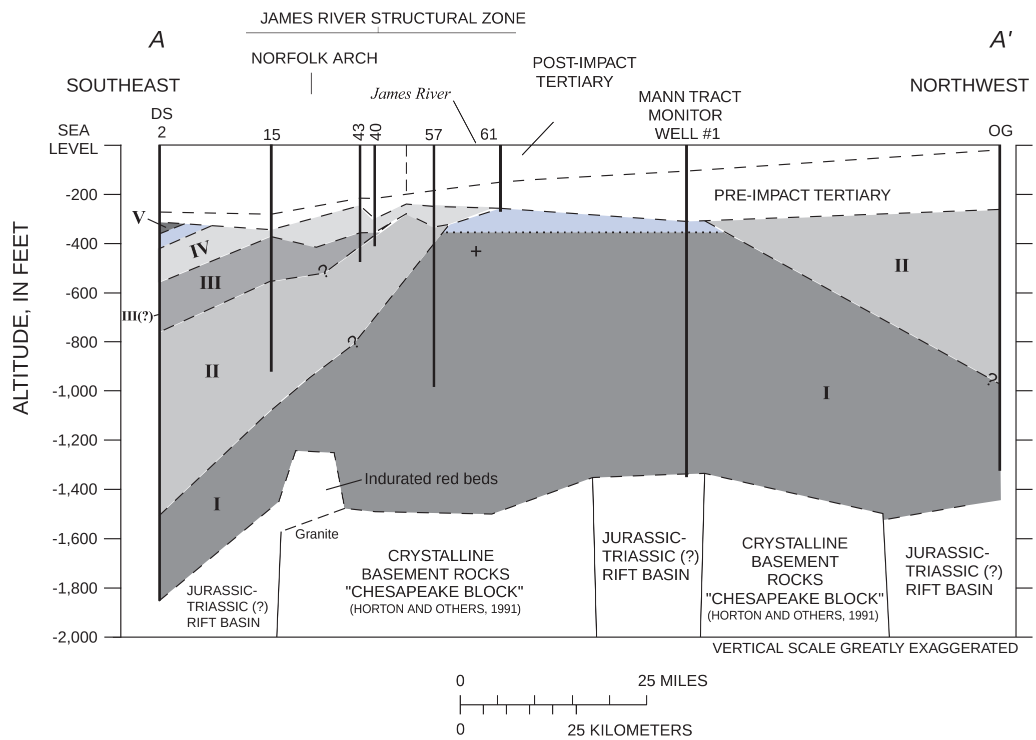
43 ● BOREHOLE AND NUMBER

67 - Taylor #1, oil test well (includes Cretaceous deposits younger than pollen zone V)

□ OUTCROP AT DREWRYS BLUFF (Owens and Gohn, 1985)

Figure 4. Distribution of Cretaceous pollen zones—these deposits were removed or disturbed inside the crater—across the Virginia Coastal Plain (modified from Owens and Gohn, 1985) *(A)*, and generalized stratigraphic cross section of Virginia Coastal Plain *(B)*. See Appendix 2 for data on boreholes outside study area.

(B)



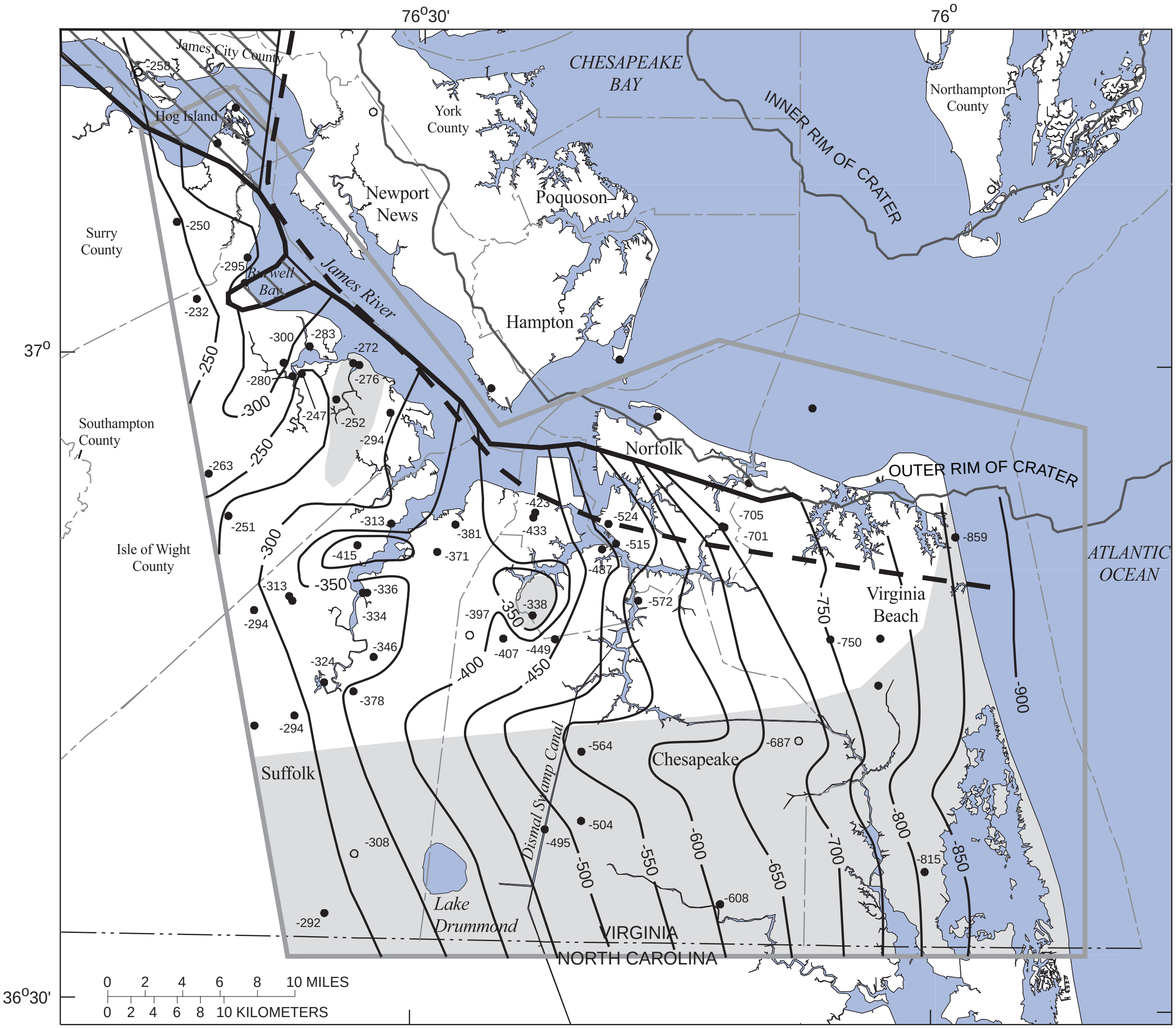
EXPLANATION

Inconclusive or no pollen data

? Position of contact uncertain

\+ Newport News Park 1 pollen data (**I**) projected into line of section

Figure 4. Distribution of Cretaceous pollen zones—these deposits were removed or disturbed inside the crater—across the Virginia Coastal Plain (modified from Owens and Gohn, 1985) *(A)*, and generalized stratigraphic cross section of Virginia Coastal Plain *(B)*. See Appendix 2 for data on boreholes outside study area. —Continued.



EXPLANATION

DISTRIBUTION OF RED BEDS

AREA WHERE UPPER CRETACEOUS DEPOSITS ARE ABSENT (OUTSIDE LIMIT OF PRESERVED EXMORE TSUNAMI-BRECCIA)

-100- STRUCTURE CONTOUR—Contour interval 50 feet. Datum is sea level

-294 BOREHOLE—Number is altitude of top of unit, in feet below sea level

-397 CONTINUOUS COREHOLE—Number is altitude of top of unit, in feet below sea level

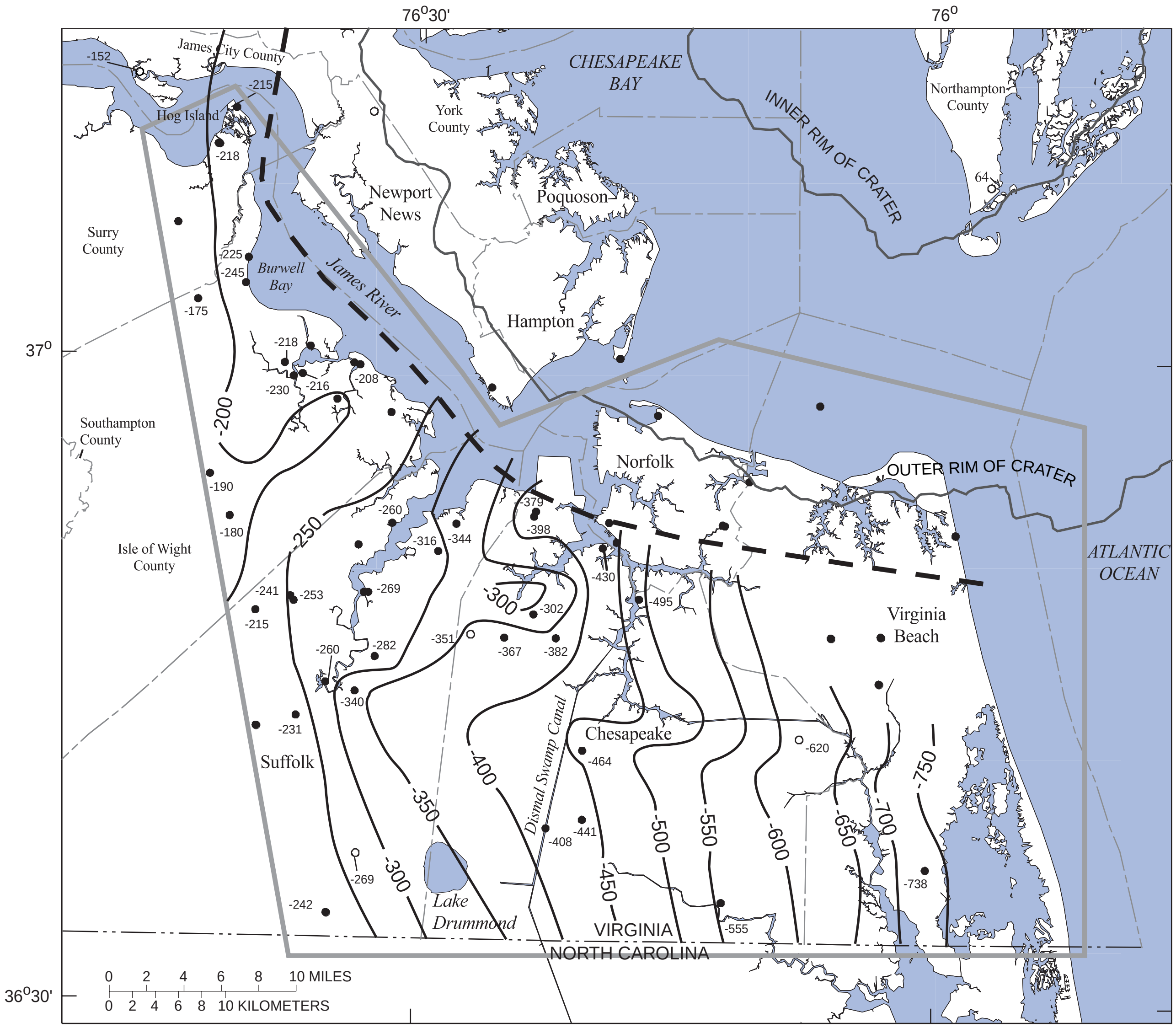
STUDY AREA

APPROXIMATE SOUTHERN LIMIT OF PRESERVED EXMORE TSUNAMI-BRECCIA

CHESAPEAKE BAY IMPACT CRATER RIM

APPROXIMATE LIMIT OF UPPER CRETACEOUS DEPOSITS

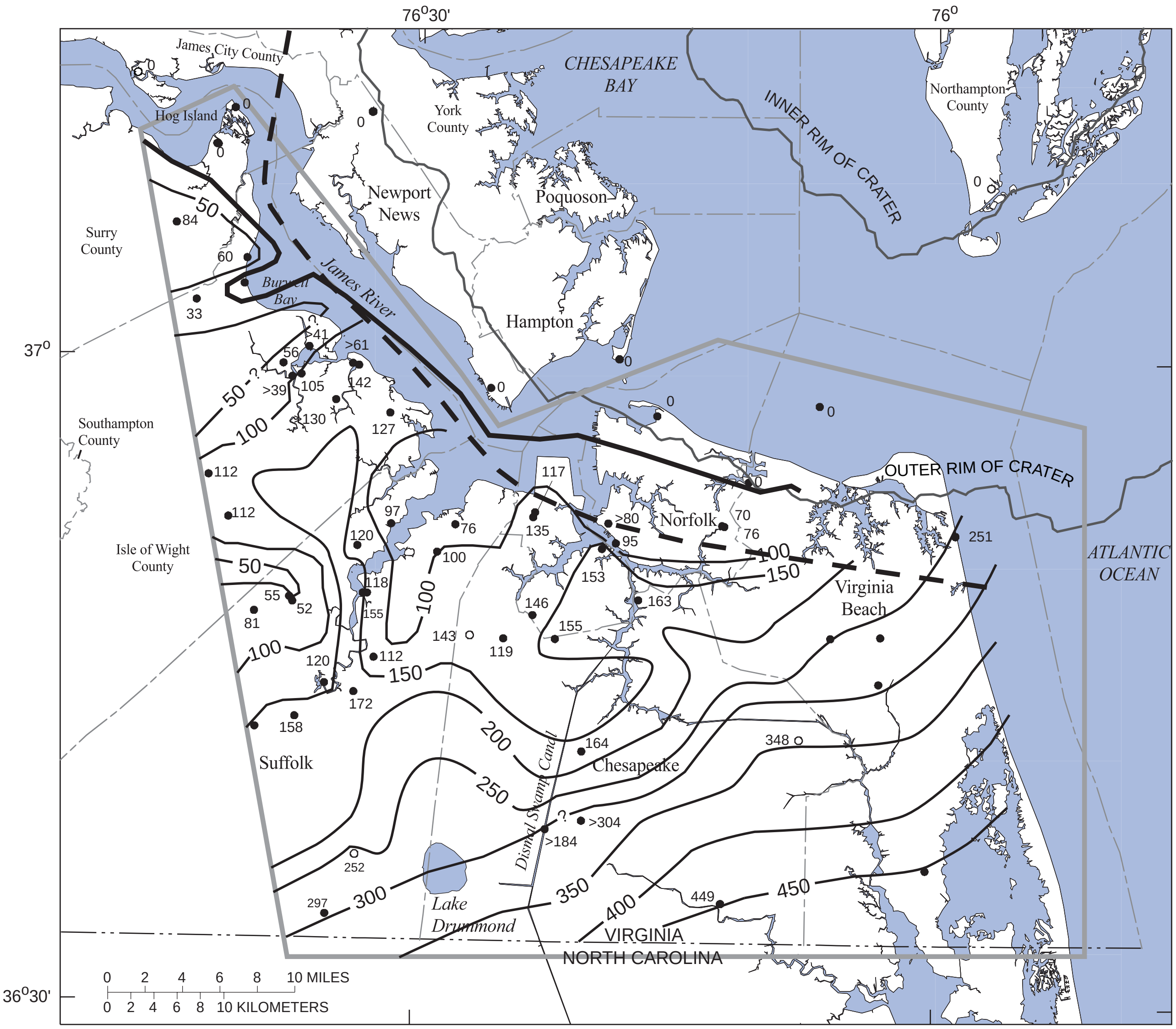
Figure 5. Structure contour map of the top of the Upper Cretaceous deposits. East to southeast deflections of the contours and the truncated distribution of the red beds suggest possible faulting.



EXPLANATION

- -300- STRUCTURE CONTOUR—Contour interval 50 feet. Datum is sea level
- -441 ● BOREHOLE—Number is altitude of top of unit, in feet below sea level
- -269 ○ CONTINUOUS COREHOLE—Number is altitude of top of unit, in feet below sea level
- CHESAPEAKE BAY IMPACT CRATER RIM
- MARKS TRUNCATION BY CBIC (EQUIVALENT TO APPROXIMATE LIMIT OF PRESERVED EXMORE TSUNAMI-BRECCIA)
- STUDY AREA

Figure 6. Structure contour map of the top of the pre-impact Lower Tertiary deposits (equals top of Nanjemoy Formation except for northwest corner where equals top of the Piney Point Formation).



EXPLANATION

–250– LINE OF EQUAL THICKNESS OF UNIT—Interval 50 feet. Queried where inferred

297 ● BOREHOLE—Number is thickness of unit, in feet (>, greater than)

252 ○ CONTINUOUS COREHOLE—Number is thickness of unit, in feet

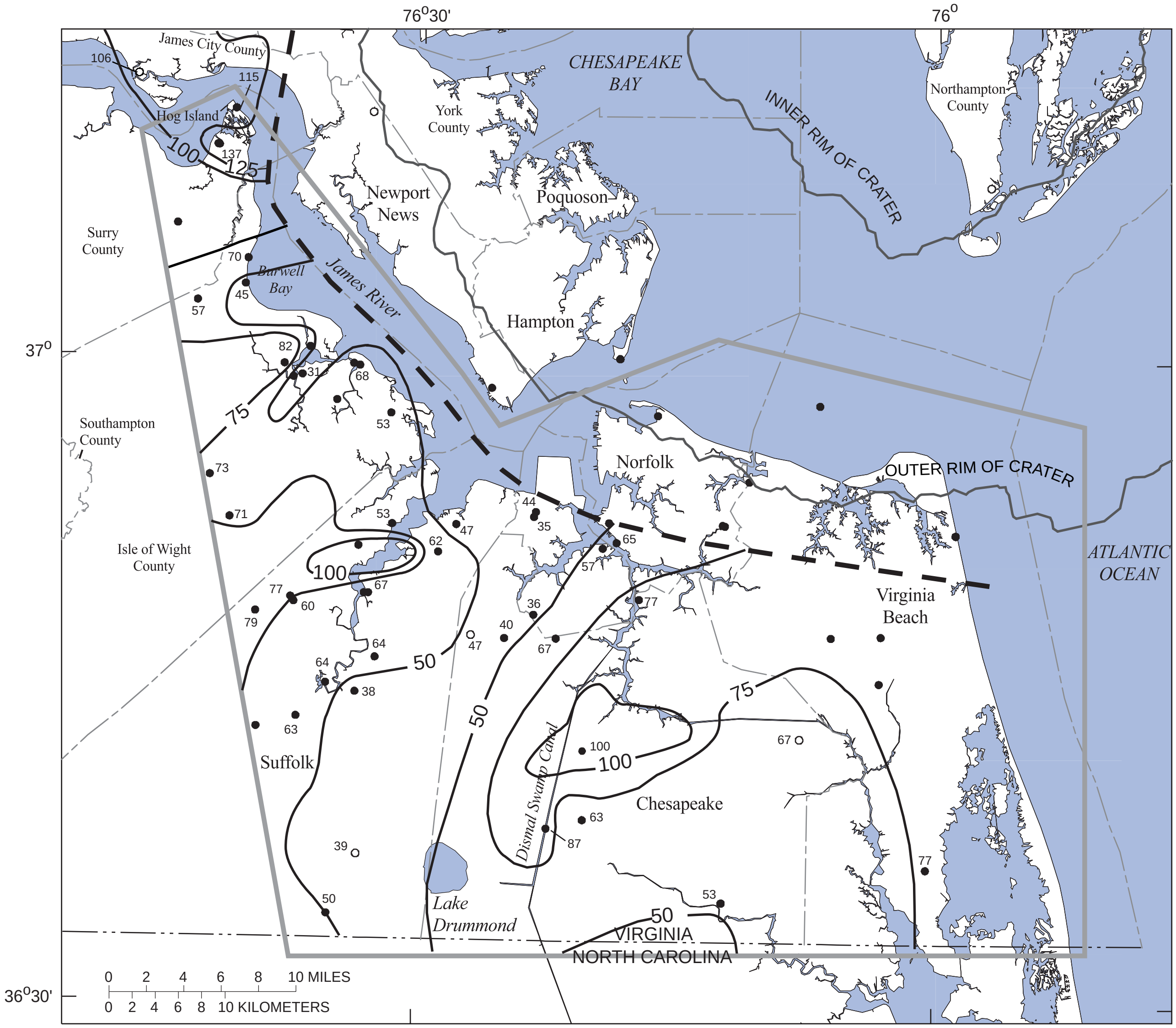
CHESAPEAKE BAY IMPACT CRATER RIM

APPROXIMATE LIMIT OF UPPER CRETACEOUS DEPOSITS

STUDY AREA

APPROXIMATE SOUTHERN LIMIT OF PRESERVED EXMORE TSUNAMI-BRECCIA

Figure 7. Isopach map of the Upper Cretaceous deposits younger than pollen zone III showing abrupt truncation along the northern part of the study area, irregular thickening and thinning in the northwestern part, and a southeast-thickening wedge. The 449-feet thickness in the Chesapeake Northwest River WTP borehole **(3)** includes 107 feet of Cretaceous and/or Palocene (?) deposits.



EXPLANATION

—50— LINE OF EQUAL THICKNESS OF UNIT—Interval 25 feet

50 ● BOREHOLE—Number is thickness of unit, in feet

39 ○ CONTINUOUS COREHOLE—Number is thickness of unit, in feet

CHESAPEAKE BAY IMPACT CRATER RIM

MARKS TRUNCATION BY CBIC

STUDY AREA

Figure 8. Isopach map of the pre-impact Lower Tertiary deposits showing a pattern of thickening and thinning. This pattern is apparently related to the effects of the Chesapeake Bay impact crater on the James River structural zone.

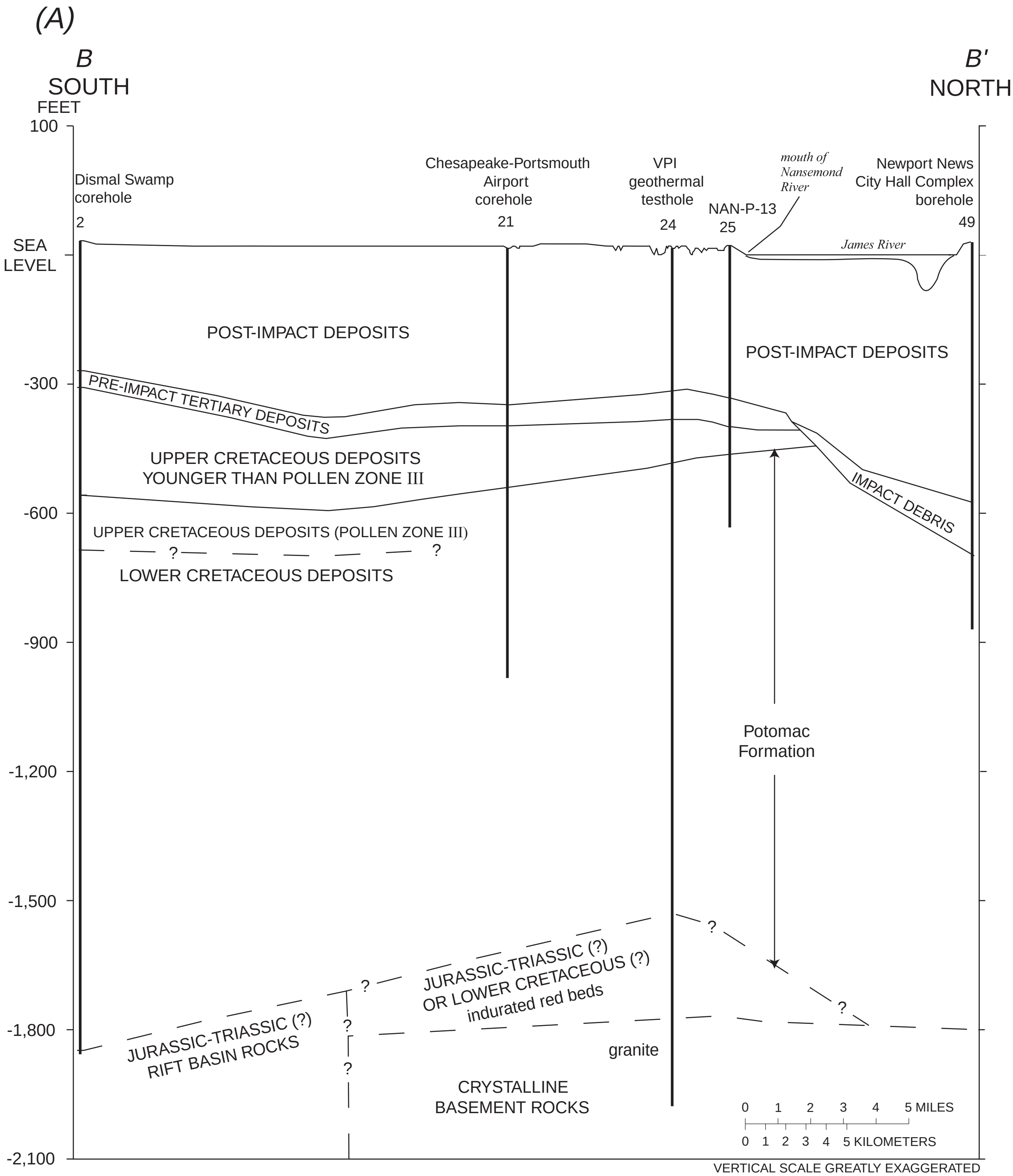
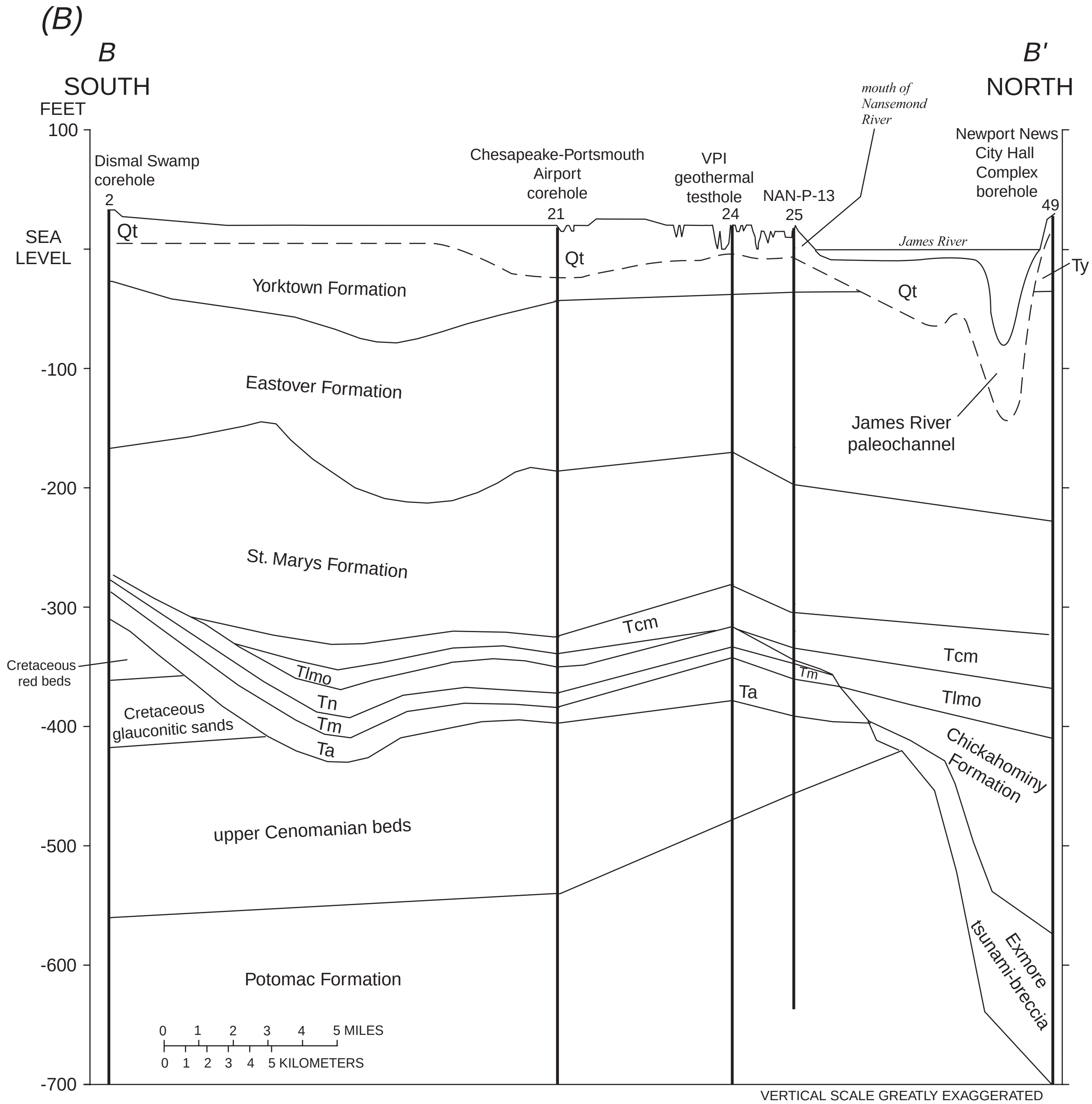


Figure 9. Stratigraphic cross section *B-B'*, Dismal Swamp to Newport News, showing the entire thickness of the Virginia Coastal Plain deposits and the top of the basement rocks *(A)*, and details of the upper section of Coastal Plain deposits *(B)*. Cross section location shown in figure 3.



EXPLANATION

Qt	Quaternary deposits	Tn	Nanjemoy Formation (lower Eocene)
Ty	Yorktown Formation (upper and lower Pliocene)	Tm	Marlboro Clay (Eocene and Paleocene?)
Tcm	Calvert Formation (middle Miocene)	Ta	Aquia Formation (upper Paleocene)
Tlmo	Newport News unit of Calvert Formation (lower Miocene), Old Church Formation (upper Oligocene), and Delmarva beds (lower Oligocene), undivided		

Figure 9. Stratigraphic cross section *B-B*′, Dismal Swamp to Newport News, showing the entire thickness of the Virginia Coastal Plain deposits and the top of the basement rocks *(A)*, and details of the upper section of Coastal Plain deposits *(B)*. Cross section location shown in figure 3—Continued.

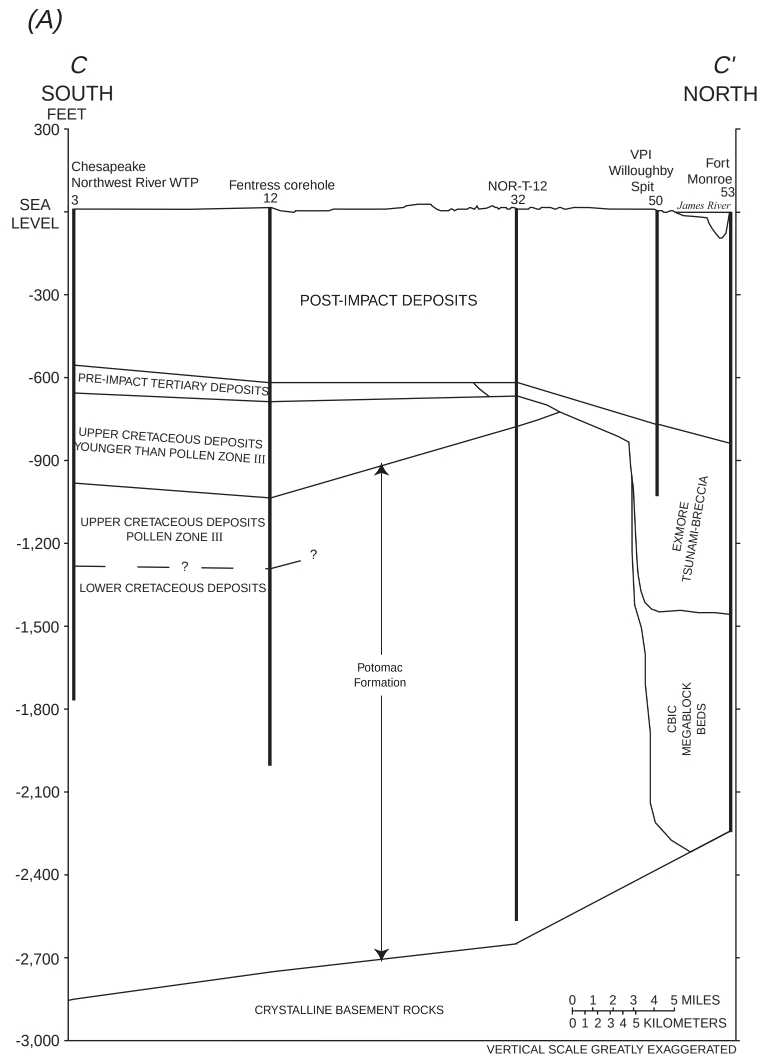
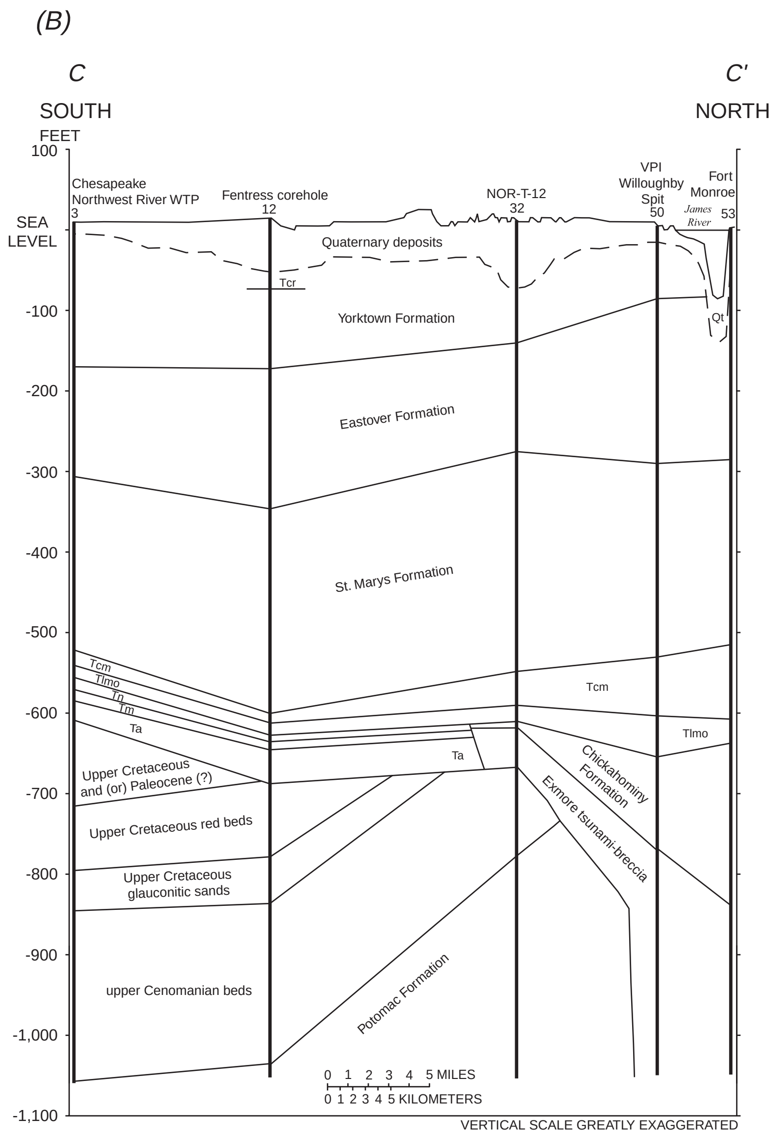


Figure 10. Stratigraphic cross section *C-C*′, Chesapeake Northwest River WTP to Fort Monroe, showing the entire thickness of the Coastal Plain deposits and the top of the basement rocks *(A)*, and details of the upper section of Coastal Plain deposits *(B)*. Cross section location shown in figure 3.



EXPLANATION

Qt	Quaternary deposits	Tn	Nanjemoy Formation (lower Eocene)
Tcr	Chowan River Formation (upper Pliocene)	Tm	Marlboro Clay (Eocene and Paleocene?)
Tcm	Calvert Formation (middle Miocene)		
Tlmo	Newport News unit of Calvert Formation (lower Miocene), Old Church Formation (upper Oligocene), and Delmarva beds (lower Oligocene), undivided	Ta	Aquia Formation (upper Paleocene)

Figure 10. Stratigraphic cross section *C-C*′, Chesapeake Northwest River WTP to Fort Monroe, showing the entire thickness of the Coastal Plain deposits and the top of the basement rocks *(A)*, and details of the upper section of Coastal Plain deposits *(B).* Cross section location shown in figure 3—Continued.

upper part of this line of section and shows the angular unconformity between the Upper Cretaceous deposits younger than pollen zone III and pre-impact Tertiary deposits and some possible upwarping of pre-impact deposits that are close to the outer rim of the impact crater. Figure 10 is similar to figure 9, except that the line of section shown is farther to the east and the northwestern end steps into the crater across the outer rim escarpment.

As suggested by Powars and Bruce (1999) and shown graphically in figure 4, only Lower Cretaceous deposits are present in the subsurface of the Virginia Coastal Plain north of the James River. In contrast, both Lower Cretaceous and Upper Cretaceous deposits are present on the south side of the James River. The available pollen data indicate that a very thick section of Lower Cretaceous deposits assigned to pollen zone I is present in the subsurface north of the James River, west of the impact crater, and south of the northern part of Hanover County to the mouth of the Rappahannock River. In contrast, on the south side of the river, both Lower Cretaceous deposits (pollen zones I and II) and Upper Cretaceous deposits (pollen zones III, IV and V) are present in the subsurface. The Upper Cretaceous deposits younger than pollen zone III are absent in the Hog Island area and locally in the Burwell Bay area (figs. 4 and 5). These deposits do not appear to thin or feather out, but end abruptly, supporting the existence of a pre-impact James River structural zone. These Upper Cretaceous deposits are truncated to the north of the James River and west of the preserved limit of impact debris by an apparent structural upwarping prior to the impact; farther east, they are truncated by the impact crater across the lower Chesapeake Bay region (figs. 4 and 5).

The extreme variations in thickness in the various Cretaceous units across the James River, combined with the angular unconformity with the overlying pre-impact lower Tertiary deposits and coincidence with a highly probable basement structural zone, provide evidence for the existence of a pre-impact James River structural zone.

In figure 11, an alternative interpretation to that shown in figure 9, faults are shown cutting across the basement and Coastal Plain sediments. The interpretations depicted in both figures 9 and 11 indicate that this region has experienced a combination of structural events involving pre-impact movements of the James River structural zone, syn-impact faulting and fracturing of the region, and post-impact adjustments to the recovery phase of the CBIC.

Given that sediment deposition and preservation are greater on the down-dropped side of a structural zone, it would appear that the region north of the James River was relatively depressed in pollen zone I time and relatively elevated for the remainder of Cretaceous time. By contrast, the region south of the James River was relatively depressed during pollen zones II, III, IV, and V time. Part of this distribution has been attributed to a southward shift in the depositional basin during Late Cretaceous time along with a reduction in the rate of subsidence across the region (Johnson, 1976).

During Late Cretaceous and Early Tertiary time, oscillations of sea level up to 400 ft produced major transgressions and regressions across the study area. North and south of the James River, the Paleocene to middle Eocene pre-impact deposits vary in their distribution and thickness. The middle Eocene Piney Point Formation is found outside the disruption boundary, primarily north of the James River, where it is underlain by sections of the upper Paleocene Aquia and lower Eocene Nanjemoy Formations that are thicker here than south of the James River. The limited extent of Piney Point strata south of the James River is probably caused by a combination of syn-impact erosional processes and post-impact uplift and removal by post-impact transgressions (Powars and Bruce, 1999). The distribution of the basement rocks and the pre-impact Cretaceous and Tertiary deposits indicates the existence of a generally east-to-west-trending pre-impact James River structural zone beneath the lower James River Basin and appears to correspond to the north side of the Cape Fear-Norfolk block.

Syn-impact Structural History

The CBIC impactor sliced through the water column, penetrated the full thickness of the existing Coastal Plain sediments, slammed into the basement rock, and vaporized, creating a catastrophic explosion that generated a series of gigantic tsunamis and sent tremendous amounts of steam and ejecta into the atmosphere. The debris was spread over most of the U.S. Atlantic shelf and coastal areas (the coastline was then west of the present-day Fall Line; Poag, Powars, Poppe, and Mixon, 1994, Powars and Bruce, 1999). The high-velocity impact left an immense crater that is almost 1.2 mi deep and is partly filled with debris and tsunami deposits. The Coastal Plain sediments and basement rocks lining the crater cavity were melted, and the basement rocks in a region beneath and around the crater were faulted and fractured (fig. 2).

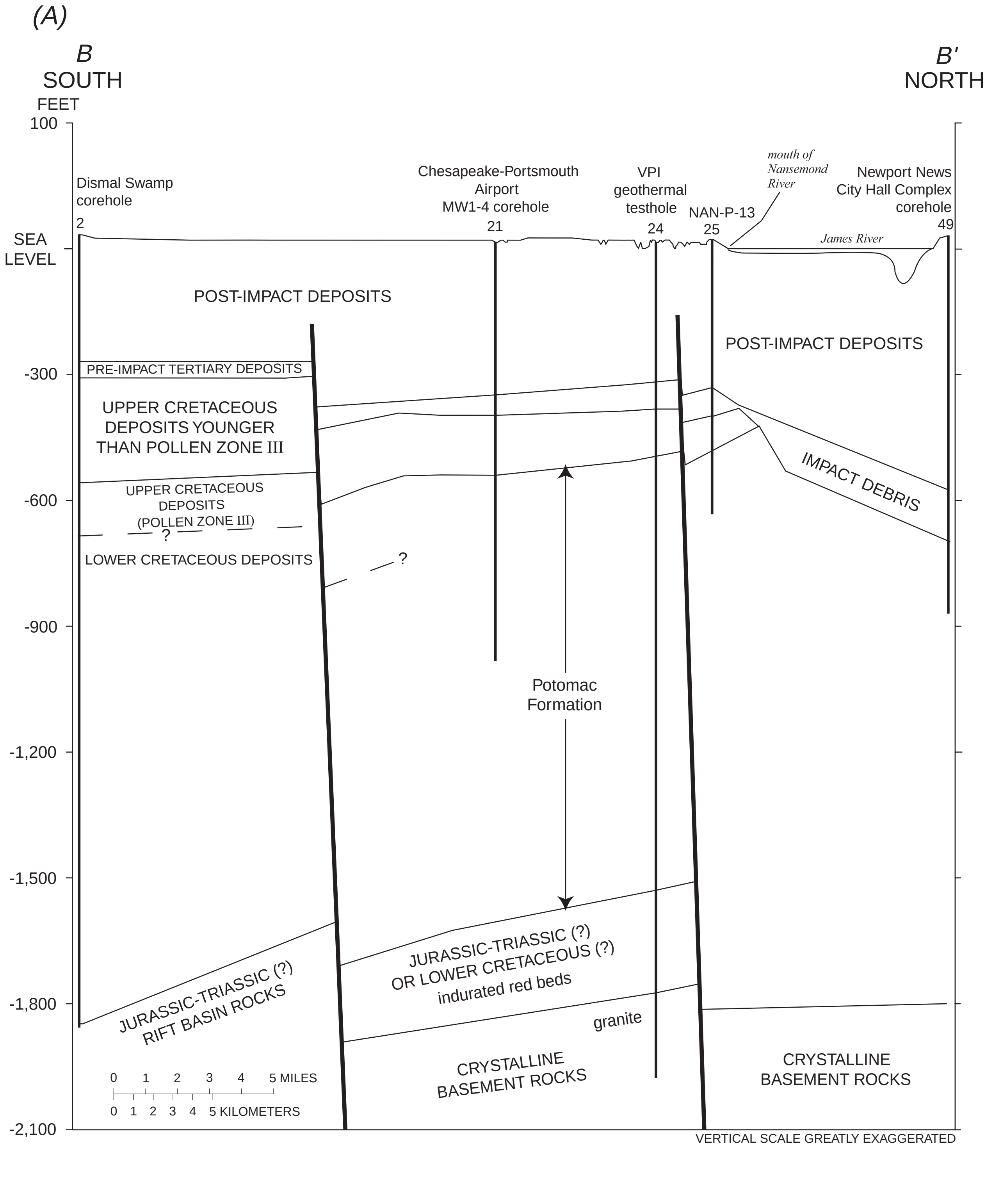
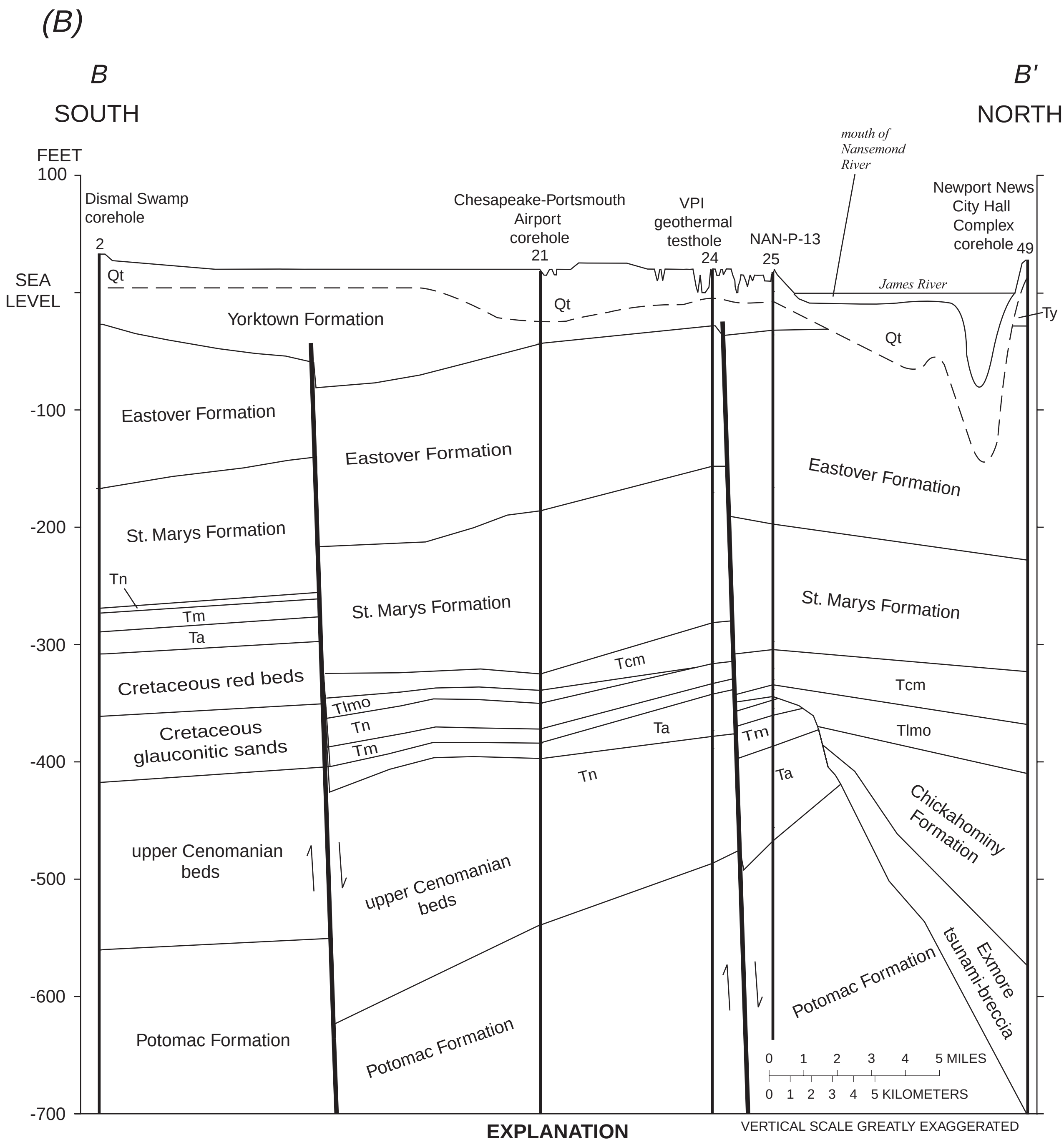


Figure 11. Fault interpretation of stratigraphic cross section *B-B'*, Dismal Swamp to Newport News, same section as figure 9A *(A)*, and fault interpretation of same section as figure 9B *(B)*. Cross section location shown in figure 3.



EXPLANATION

Qt	Quaternary deposits	Tn	Nanjemoy Formation (lower Eocene)
Ty	Yorktown Formation (upper and lower Pliocene)	Tm	Marlboro Clay (Eocene and Paleocene?)
Tcm	Calvert Formation (middle Miocene)	Ta	Aquia Formation (upper Paleocene)
Tlmo	Newport News unit of Calvert Formation (lower Miocene), Old Church Formation (upper Oligocene), and Delmarva beds (lower Oligocene), undivided		

Figure 11. Fault interpretation of stratigraphic cross section *B-B′*, Dismal Swamp to Newport News, same section as figure 9A *(A)*, and fault interpretation of same section as figure 9B *(B)*. Cross section location shown in figure 3—Continued.

The formation of the CBIC truncated and excavated large quantities of Eocene to Cretaceous Coastal Plain sediments and the underlying Proterozoic, Paleozoic crystalline, and possibly Jurassic- Triassic rift-basin basement rocks, creating the CBIC megablock beds and the Exmore tsunami-breccia deposits. The CBIC is a complex peak-ring crater with an inner and outer rim, a slumped terrace zone, and a relatively flat-floored annular trough that encircles a deep central depression into the basement (fig. 2). The central depression is also referred to as the inner basin and contains a series of concentric valleys and ridges that surround a central uplift (Powars and Bruce, 1999).

The seismically defined syn-impact CBIC megablock beds are a product of large-scale slumping into the crater that occurs during an early stage of crater filling; these deposits covered the basement surface of the annular trough (Poag, 1996, 1997; Powars and Bruce, 1999).

A narrow band of preserved Exmore tsunami-breccia deposits surrounds the crater's outer rim; these deposits also are probably offset by the bounding outer rim fault zone and other faults apparently produced or adjusted by the impact. The location of the preserved limit of the Exmore tsunami-breccia beneath the river, however, is uncertain.

A zone of normal-faulted slump blocks characterizes the highly irregular outer rim of the CBIC (fig. 2). These features encircle and are downthrown into the annular trough, forming a buried escarpment. On seismic reflection data, this escarpment is easily distinguished from the nearly flat-lying Coastal Plain deposits outside the disruption boundary. The relief of the escarpment ranges from 1,000 to nearly 4,000 ft and its width varies from about 0.5 to 2 mi (Poag, 1996; Powars and Bruce, 1999). Its geometry is characterized as a steep wall in places; elsewhere, the escarpment stair-steps down into the annular trough. This variation is expected because the escarpment was produced by a combination of complex catastrophic events, including the collapse of the crater's outer wall interacting with subsequent gigantic tsunamis. This variation also is related to the unconsolidated nature of the sediments involved. Section C-C' shows the tremendous relief at the escarpment of the outer rim and how the post-impact deposits drape over the outer rim and thicken into the crater (fig. 10).

Post-impact Structural History

Post-impact deposits from numerous marine transgressions across the lower mid-Atlantic Coastal Plain have now buried the crater with about 1,300 to 1,600 ft of sediment. In the study area, south of the crater, the post-impact deposits form an eastward-dipping wedge of sediments 225 to 750 ft thick. Seismic data show that most of these deposits dip concentrically into the crater, especially across the outer and inner rims (Powars and Bruce, 1999).

The post-impact upper Tertiary deposits outside the crater and south of the James River are thicker than comparable units north of the river. The area south of the river apparently was downwarped during this period. This downwarping appears to be related to structural adjustments of the James River structural zone. Two features indicate that structural instabilities persisted in the areas adjacent to the crater's outer rim, at least through late Tertiary time: (1) the stratigraphic anomalies found in upper Tertiary deposits outside the disruption boundary, and (2) faults that displace basement rocks and Cretaceous through upper Tertiary sediments observed in the seismic data north of the crater where the faults extend outside the disruption boundary (Powars and Bruce, 1999). These structural instabilities likely are produced by several factors: (1) faulting caused by the initial impact and structural adjustments to older faults; (2) post-impact structural readjustment of the basement; (3) post-impact differential compaction; and (4) post-impact differential movement of fault blocks.

The Oligocene to middle Miocene post-impact deposits exhibit a patchy distribution pattern south of the James River. These deposits appear to be preserved adjacent to the outer rim and inside the crater along the northern boundary of the study area, as well as downdip along the Atlantic coastline. The thinness and local absence of the Oligocene and lower Miocene strata in the boreholes make it very difficult to correlate these deposits without data from a corehole. The absence of the Calvert Formation south of the river suggests that large-scale structural readjustments to the impact, such as movement along faults in the James River structural zone, were still occurring in the middle Miocene.

The very clayey, upper Miocene, post-impact St. Marys Formation was the first unit distributed and preserved across the entire region and therefore serves as an easily recognized marker unit.

The juxtaposition of the pre-impact deposits with the syn-impact deposits marks the disruption boundary and, except for the narrow, relatively thin band of ejecta, coincides with the outer rim of the crater. Relatively thin post-impact deposits outside the crater abruptly thicken across the outer rim of the crater and are up to ten times thicker inside the crater. The absence of many early post-impact deposits (upper Eocene to middle Miocene) south of the James River and the presence of relatively thick upper Miocene and Pliocene shallow-marine deposits suggest that the impact crater is responsible for structural adjustments to the pre-impact James River structural zone. The distribution of strata suggests that these structural adjustments have caused the area south of the river to be uplifted or downwarped at various times. In this transgressive-regressive depositional setting, the uplift causes erosion of strata or little deposition whereas the downwarp allows deposition and preservation if sediment is available.

Borehole data indicate that most of these post-impact deposits are overall coarser grained (including Miocene and Pliocene marine bioclastic sands) along the outer rim and become finer grained toward the interior of the crater and farther outside and away from the outer rim (Powars and Bruce, 1999).

Pliocene to Quaternary deposits show complex lithofacies distribution and thickness patterns that include thin to thick and fine to coarse beds within 12.5 miles of the crater's outer rim (Johnson, Powars, and others, 1998; Powars and others, 1998). Pliocene deposits, which dip radially away from the center of the impact structure over areas several miles in width, exhibit dips that are discordant from the typical eastward regional dip of Tertiary strata. These dip reversals are generally less than one degree and commonly include fan-like inter- and intraformational angular unconformities, indicating that deformation and deposition were synchronous and a product of post-impact deformation related to slump-block motion near the outer rim of the crater (Johnson, Kruse, and others, 1998; Johnson, Powars, and others, 1998; Powars and others, 1998; Powars and Bruce, 1999).

The CBIC has also had a major effect on the development of the regional drainage to the sea of the mid-Atlantic rivers (from the Susquehanna River to the James River) that converge on the crater. The location of the outer rim of the crater and its relation to the course of the lower James River is apparent, as the river turns sharply northeastward as it crosses the outer rim and into the crater.

The Holocene transgression, along with higher subsidence rates over the crater, has produced generally the highest measured rates of subsidence in the mid-Atlantic region (Nerem and others, 1998), which possibly account for the abundant swamps that border the lower Chesapeake Bay.

GEOLOGIC FRAMEWORK OF SOUTHEASTERN VIRGINIA, SOUTH OF THE JAMES RIVER

The following sections describe the lithology, distribution, and borehole geophysical signatures for each Coastal Plain stratigraphic unit. The basement rocks are also discussed briefly.

Basement Rocks

Within the study area, Coastal Plain deposits are underlain by igneous and metamorphic Paleozoic and Upper Proterozoic crystalline basement rocks and by Jurassic-Triassic rift basin sedimentary rocks. The crystalline basement rocks beneath much of the mid-Atlantic Coastal Plain, including the study area, have been mapped by Horton and others (1991) as part of the Chesapeake Block (a tectonostratigraphic unit) and were defined as rocks of undetermined affinity east of the Alleghanian "Chesapeake Bay suture" of Lefort and Max (1991). Lefort and Max (1991) suggested that the Chesapeake Block includes African rocks left behind in the Mesozoic breakup of Africa and North America. Late Paleozoic granitic plutons are included in this block (for details, see Horton and others, 1991).

Four boreholes penetrated basement rocks within the study area. Two geothermal test holes, #26 Isle of Wight (**38**) (top of granite at –1308 ft) and #25 Suffolk (**24**) (top of granite at –1772 ft), encountered 210 to 250 ft of mostly indurated sediments overlying granite and greenstone basement rocks. The cuttings from these indurated sediments consist of a mixture of reddish siltstone, shale and feldspathic and quartz sand and represent either Jurassic-Triassic rift basin deposits or Lower Cretaceous deposits. Jurassic-Triassic rift basin rocks were also encountered in the Dismal Swamp corehole (**2**) (top of rock at –1817 ft) and at the VDEQ borehole (**1**) (top of rock at –1822 ft).

Structure contours of the top of the basement surface show an overall eastward dip and stepping beneath Virginia Beach (Brown and others, 1972; Meng and Harsh, 1988; Powars and others, 1992). A basement high (an arch or ridge) trends east to west from Norfolk to the northeastern corner of Southampton County and appears to be coincident with the north end of the two Jurassic-Triassic rift basins within the study area (figs. 1 and 4). The #26 Isle of Wight (**38**) and #25 Suffolk (**24**) boreholes provide the main evidence for this arching. The arching is reflected even if the indurated sediments are interpreted as Lower Cretaceous. It is likely that the basement high is a product of faulting, possibly a part of Jurassic-Triassic rift basin faulting, which is connected to Paleozoic fault systems.

Two boreholes north of the study area on the lower York-James Peninsula, just inside the outer rim of the impact crater, penetrated a few feet of white granite. These are the NASA-Langley Air Force Base borehole (top of rock at –2084 ft; for location and details see Powars and Bruce, 1999), and the Fort Monroe borehole (**53**) (top of rock at –2251 ft).

Cretaceous Deposits

Within the study area, the Cretaceous sediments consist of Lower and Upper Cretaceous deposits that range in age from about 120 to 85 Ma. An interval in the Chesapeake Northwest River WTP borehole (**3**), however, possibly represents some younger Upper Cretaceous sediments (85 to 65 Ma). Updip (westward), the Lower Cretaceous deposits (Potomac Formation) consist of a complex array of fluvial-deltaic deposits that intertongue downdip (eastward) with thin glauconitic sands typical of shallow-shelf deposits. The Lower Cretaceous deposits extend across the study area, except where disturbed by the impact, forming an east- to-southeast-dipping wedge that ranges from around 725 ft thick over an apparent basement high on the western side of the study area to around 2,400 ft thick along the coastline at Virginia Beach. If the indurated sediments are interpreted as Lower Cretaceous deposits, then the deposits are 935 ft thick on the western side of the study area.

Regionally, the Cretaceous section includes Upper Cretaceous deposits that are relatively thick south and southwest of the crater. The Upper Cretaceous deposits form a wedge that thickens from 377 ft in the Dismal Swamp corehole to 628 ft in the Fentress corehole. The Upper Cretaceous deposits younger than pollen zone III thicken from 252 ft thick in the Dismal Swamp corehole (**2**) (pl. 1) to 350 ft thick in the Fentress corehole (**12**) (pl. 1) to 449 ft thick in the Chesapeake Northwest River WTP borehole (**3**) (pl. 1). These deposits are absent north of the pre-impact James River structural zone. Lower Cretaceous core samples (at -455 ft and -648 ft) from the Newport News Park 1 borehole (**62**) documented that pollen zone I is present nearly to the top of the Cretaceous section (L.A. Sirkin, Adelphi University, written commun. to A. Meng, formerly with the USGS, 1983). This implies that the entire Cretaceous section at the Newport News Park 1 borehole (**62**) is represented by a 1300-ft-thick interval of pollen zone I; however, Lower Cretaceous deposits that are older than zone I were found in the downdip Taylor #1 oil testhole, located on the Delmarva Peninsula (Robbins and others, 1975), and equivalent deposits may be present in the lower part of the Newport News Park 1 borehole (**62**). Brenner (1963) reported that an outcrop of the Potomac Formation at Drewrys Bluff on the James River southeast of Richmond contained pollen indicative of zone I. The author has found no documentation of Upper Cretaceous deposits containing pollen zones III, IV, or V in Virginia west of the Chesapeake Bay, north of the James River, and south of the Potomac River. The apparent absence of Lower Cretaceous pollen zone II deposits west of the Chesapeake Bay, north of the James, and south of the northern part of Hanover County to the mouth of the Rappahannock River (fig. 4), suggests the need to re-evaluate Meng and Harsh's (1988) hydrogeologic subdivision and regional correlation of Lower Cretaceous deposits across the entire Coastal Plain, outside the outer rim of the crater. Correlation of the geologic to hydrogeologic units outside the study area, however, is beyond the scope of this report. The reader is referred to Meng and Harsh (1988) for a detailed and comprehensive discussion of log correlations and identification of depositional patterns and settings that guided the delineation of the regional hydrogeologic units of the Potomac Formation.

Powars and Bruce (1999) concluded that the unit mapped in the southeastern Virginia Coastal Plain by Cederstrom (1945b) as the Mattaponi Formation actually represents Lower Cretaceous to lower Miocene deposits outside the preserved limit of Exmore tsunami-breccia deposits. Furthermore, inside this preserved limit and inside the outer rim of the crater, the Mattaponi Formation is equivalent to the Exmore tsunami-breccia deposits.

Potomac Formation - Lower and Upper Cretaceous Deposits

Within the study area, the Potomac Formation consists of fluvial-deltaic deposits of Early Cretaceous (Barremian (?) to Albian) and Late Cretaceous (early Cenomanian) age. These deposits extend across the study area, forming an eastward-thickening wedge that ranges from about 1,000 ft thick beneath the Hog Island to Bacons Castle area to about 1,700 ft thick at Fentress to 2,400 ft at Virginia Beach. The Potomac Formation variously overlies metamorphic and igneous rocks of the crystalline basement and red siltstones, shales, and sandstones of Jurassic-Triassic rift basins.

These deltaic deposits are highly variable in their lithology and thickness and probably represent stacked deposits of meandering streams, braided streams, and river- and wave-dominated delta-plain and delta-front facies (Glaser, 1969; Reinhardt and others, 1980; Owens and Gohn, 1985; Meng and Harsh, 1988). These deposits are difficult to correlate and subdivide because of their lateral and vertical heterogeneity, lithic similarities, and the paucity of biostratigraphic data; pollen is the only biostratigraphic indicator that is found consistently in these deposits. Recent development and refinement of a pollen zonation for these deposits (Brenner, 1963; Robbins and others, 1975) has provided a basis for subdividing the sequences into units of temporal and possibly genetic significance (Reinhardt and others, 1980; Meng and Harsh, 1988; Powars and others, 1992). Some investigators (Glaser, 1969; Hansen, 1969; Brown and others, 1972) suggest that a correlation exists among the lithologic and depositional patterns, the five major pollen zones (labeled I, II, III, IV, V), and their corresponding "formations" (table 1). Meng and Harsh (1988) based their hydrogeologic subdivision of the Potomac Formation primarily on geophysical log interpretations of lithologic characteristics, mode of deposition, available palynostratigraphic zonation data, and hydrologic data.

The fining-upward fluvial-deltaic deposits consist primarily of light-gray to pinkish to greenish-gray to green, in part mottled red, brown, and yellow, poorly sorted, fine to coarse, quartzose and feldspathic sand and gravel, which grade up into silt and clay. The sands vary from being thick-bedded and trough crossbedded to interbedded with thin- to thick-bedded clay-silts to thick-bedded clays. Locally, the sands also contain clay-clast conglomerates and lignitic material (finely disseminated to wood chunks to logs). The finer grained beds range from gray to dark-gray, finely laminated, carbonaceous clays interbedded with thin, sandy clay beds to highly oxidized, multicolored (reds, browns, purples, and yellow), laminated to thick-bedded clays. The highly oxidized clays include intervals that represent stacked paleosols typical of channel-overbank deposits that have characteristic pedotubules (cracks and fractures) and abundant iron-rich glaebules (nodules and concretions).

Within the crater, all deposits traditionally mapped as Lower Cretaceous (Potomac Formation) are now interpreted as sediments disturbed by the impact and were informally named by Powars and Bruce (1999) as the "Chesapeake Bay impact crater megablock beds" (CBIC megablock beds). These deposits are considered an Eocene stratigraphic unit because the slump blocks were transported and rapidly emplaced by impact cratering processes that most likely mixed them with Exmore tsunami-breccia and possible basement fragments and melted rocks from the initial blast.

South of the James River and the Chesapeake Bay, relatively thick Upper Cretaceous marine and fluvial-deltaic deposits overlie fluvial-deltaic deposits of the Potomac Formation. The Upper Cretaceous fluvial-deltaic facies exhibit a sporadic, patchy distribution and intertongue with the marine facies, which have a more consistent distribution.

The resistivity and gamma logs reflect the litho-stratigraphic differences of the thin-bedded, glauconitic, shelly, marine Upper Cretaceous deposits that overlie the thicker bedded, fluvial-deltaic Potomac Formation. Where Upper Cretaceous deltaic deposits overlie Potomac fluvial-deltaic sediments, however, the logs do not reflect these differences; therefore, lithic log and data from nearby wells must be analyzed. Generally, the marine lower Tertiary (Aquia Formation) and Upper Cretaceous deposits have consistently higher gamma values (deflection to the right) and are thinner bedded than the Potomac fluvial-deltaic deposits. The fact that both of these units underlie the consistently clayey Chickahominy and Nanjemoy-Marlboro units throughout the area is also helpful. Overall, the deposits of the Potomac Formation have a blockier, thicker stratified resistivity and gamma log signature. Within this overall blocky pattern, the resistivity and gamma logs of the Potomac deposits also show numerous gradational fining-upward sequences (about 5- to 100-ft-thick) that typically have sharp contacts between the tops of the clays and the basal sands of the overlying sequence. These logs reflect large-scale, fining-upward cycles (about 100- to 200-ft-thick) that are typical for the Potomac deposits. The saw-toothed appearance of the resistivity and gamma logs of the Potomac deposits reflects their highly stratified, commonly relatively thin-bedded nature. The quartzo-feldspathic sands and tough, multicolored clays of the Potomac deposits contrast lithologically with the glauconitic, shelly Aquia Formation and Exmore tsunami-breccia deposits.

Because of the paucity of borehole and geophysical log data from inside the crater and because of the lithic similarities between undisturbed Potomac deposits and the CBIC megablock beds, these units were differentiated primarily on the basis of seismic reflection data by Powars and Bruce (1999). A subtle dampening of the resistivity and gamma-log signatures for the deposits interpreted as CBIC megablock beds distinguish them from undisturbed Potomac deposits.

Upper Cretaceous Deposits Younger Than Pollen Zone III

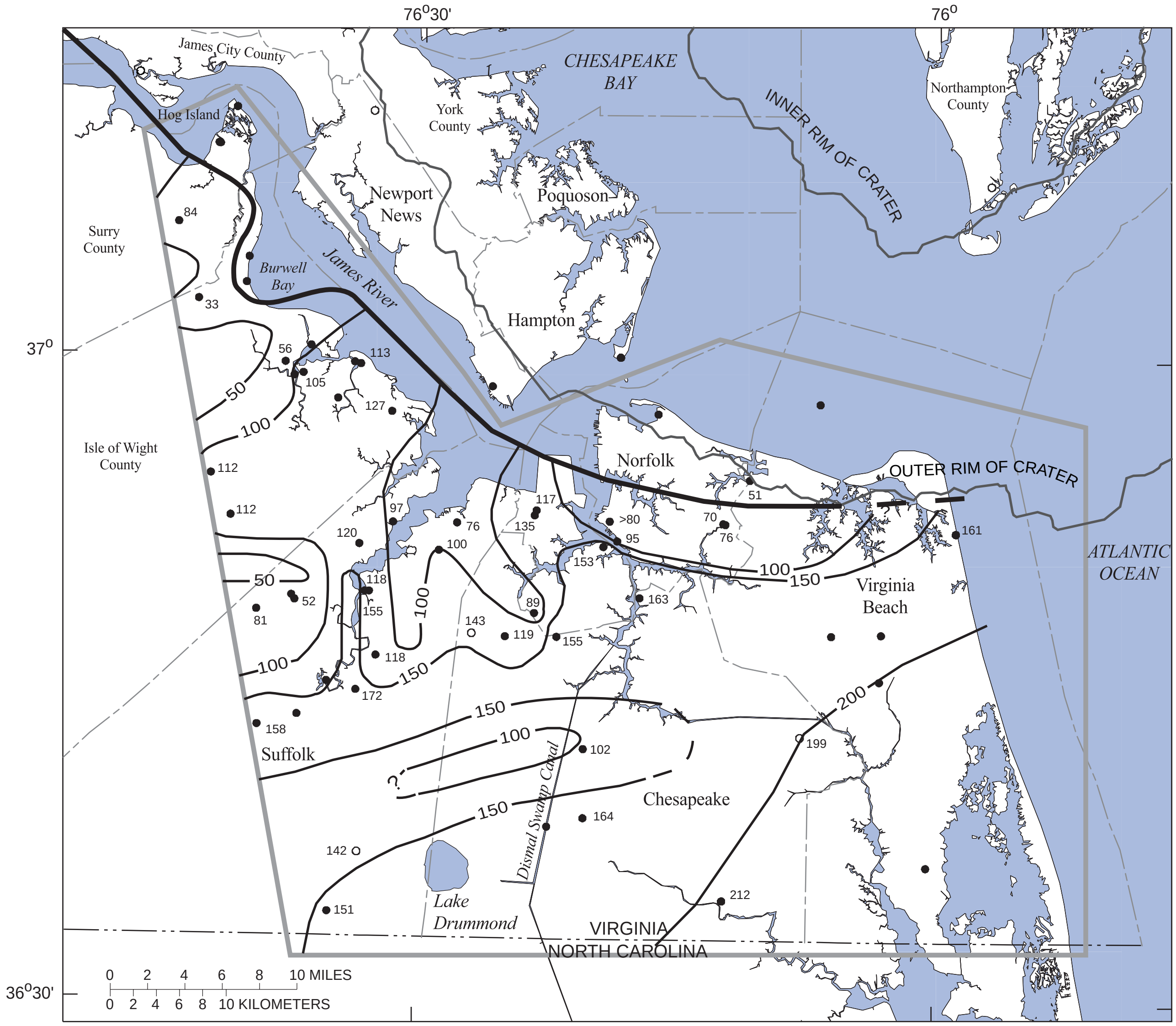
Upper Cretaceous deposits (upper Cenomanian to Santonian) south of the James River younger than pollen zone III are present in the subsurface south and southwest of the outer rim of the crater (Powars and others, 1992; Powars and Bruce, 1999). As shown in figure 4A, these deposits extend eastward from central Southampton County and eastern Surry County to Virginia Beach; they form a wedge that thickens from 200 to 500 ft across the southeastern half of the study area but are thinner, from 30 to 150 ft, have a irregular distribution across the northwestern half, and are abruptly truncated on the northernmost part of the study area.

Powars and others (1992) subdivided the Upper Cretaceous deposits into three lithic units on the basis of data from the Dismal Swamp (**2**), Fentress (**12**), and Chesapeake-Portsmouth Airport (**21**) coreholes. In ascending order, they are (1) upper Cenomanian beds consisting of marine and deltaic deposits, (2) a glauconitic sand unit, and (3) oxidized red-bed fluvial-deltaic deposits that include multiple paleosols. Evidence for the presence of Upper Cretaceous pollen zone III was only recently obtained from the Fentress corehole (**12**) (N. Frederiksen, USGS, written commun., 1999) and was therefore not included in Powars and others' (1992) subdivision. Lithic and geophysical log data obtained from the Chesapeake Northwest River WTP borehole (**3**) (pl. 1) indicate the presence of 107 ft of Upper Cretaceous and(or) lower Paleocene deltaic sands and clays overlying the red-bed unit. These deposits are interpreted to be overlain by the upper Paleocene Aquia Formation and underlain by the red bed unit, which is Coniacian-Santonian in age (pollen zone V) in the Fentress corehole (**12**) (N. Frederiksen, USGS, written commun., 1999). These deposits may be partially or completely equivalent to the Black Creek Formation or Peedee Formation of North Carolina, and they also may be partially equivalent to the lower Paleocene Brightseat Formation that was documented in the Dismal Swamp corehole (**2**) (Powars and others, 1992). Throughout the study area, relatively thin (less than 75 ft thick) pre-impact Paleocene and lower Eocene marine strata locally overlie these various Upper Cretaceous deposits south of the James River.

Upper Cenomanian Beds (Pollen Zone IV)

The upper Cenomanian beds form a southeastward-dipping wedge that ranges from 33 ft (**54**) to 212 ft (**3**) in thickness. An isopach map of this unit shows zones of thinning and thickening that are interpreted to be a product of pre-impact faulting (fig. 12). These beds are found throughout the study area where they form the oldest lithic unit of the Upper Cretaceous units younger than pollen zone III. In the Chesapeake-Portsmouth Airport corehole (**21**), only the upper Cenomanian part of these younger Upper Cretaceous units is preserved. The upper Cenomanian beds in the Dismal Swamp (**2**) and Fentress (**12**) coreholes contain a pollen assemblage indicative of pollen zone IV (R.J. Litwin, USGS, written commun., 1988; N. Frederiksen, USGS, written commun., 1999). The upper Cenomanian deposits also contain index macro- and microfossils that allow local and regional correlation of this unit. For example, the presence of the mollusks *Inoceramus arvanus* and *Exogyra woolmani* indicates a late Cenomanian age (N.F. Sohl, oral commun., 1988) and suggests correlation with unit E of Brown and others (1972) and sequence 2 of Gohn (1988).

In the Fentress corehole (**12**) (pl. 1), the basal 50 ft of the upper Cenomanian beds consists of two fining-upward sequences. Abundant wood fragments suggest a nearshore-shelf to deltaic depositional environment. The base of the upper Cenomanian deposits here is marked by a sharp lithic contact at -1,035 ft elevation where an olive-gray to light-gray, micaceous, lignitic, loose, medium to very coarse, glauconitic quartz sand overlies the Potomac Formation. The Potomac Formation consists of greenish-gray, silty and sandy clay that grades downward into medium to coarse, crossbedded sand. At Fentress (**12**) these nearshore and deltaic deposits are overlain by 115 ft of laminated to thick-bedded, olive-gray to dark-gray silt, clay, and fine to coarse sand containing variable amounts of glauconite, mica, pyrite,



EXPLANATION

—50— LINE OF EQUAL THICKNESS OF UNIT–Dashed where approximately located. Interval 50 feet. Queried where inferred

151 BOREHOLE—Number is thickness of unit, in feet

142 CONTINUOUS COREHOLE—Number is thickness of unit, in feet

CHESAPEAKE BAY IMPACT CRATER RIM

APPROXIMATE LIMIT OF UPPER CENOMANIAN BEDS

STUDY AREA

Figure 12. Isopach map of upper Cenomian beds (pollen zone IV) showing thickening, thinning, and truncation apparently related to the pre-impact James River structural zone and the Chesapeake Bay impact crater.

shells, microfossils, wood, and burrows that indicate a marine origin. This section contains numerous fining-upward sequences. The sandier, coarser grained beds at the bases of sequences are generally more glauconitic and shelly than the overlying sediments. Many of the sandier shell beds and shell hashes (representing storm deposits) are cemented by calcium carbonate. These indurated beds are generally reflected on resistivity logs by thin, sharp, high-resistivity spikes.

In the Dismal Swamp (**2**) corehole (pl. 1), the lowest upper Cenomanian beds consist of glauconitic sands, which grade upward into shelly, glauconitic silt, clay, and sand of marine origin. The base of the upper Cenomanian is an erosional unconformity; dark-gray to black, clayey, glauconitic, phosphatic, pyritic, carbonaceous, pebbly quartz sand overlies and is burrowed down into the Potomac Formation, consisting of white to light-gray clay showing some yellow mottling. Within a few feet, these Lower Cretaceous beds grade downward into multicolored sands and clays, which are oxidized red, purple, brown, and yellow. At Dismal Swamp, 128 ft of cyclic Cenomanian marine beds were penetrated. Abundant finely disseminated lignitic material indicates nearshore deposition. This marine unit is overlain by a section of dark gray, very fine grained, thinly laminated, very micaceous clayey silt to muddy sand containing abundant wood fragments that indicate a deltaic-lagoonal depositional environment. This section is 21.5 ft thick in the Dismal Swamp corehole (**2**) and 33.9 ft thick in the Fentress corehole (**12**). The very abundant mica imparts a greasy feel to the sediments and enhances recognition of the unit in well cuttings.

The resistivity and gamma logs generally reflect numerous fining-upwards sequences, which are represented in the cores as glauconitic shelly sands that grade upwards into clayey silts to silty clays. Differentiation of these sequences from overlying similar marine Paleocene or Eocene deposits is very difficult. By contrast, it is relatively easy to distinguish the Upper Cretaceous marine sequences from the underlying thicker bedded, fluvial-deltaic Potomac deposits using resistivity and gamma-log responses. In general, the resistivity logs of the upper Cenomanian beds indicate an overall thick, fine-grained section with numerous thin, indurated or slightly sandier layers. The upper Cenomanian log signature contrasts well with the blocky, more distinct sand and clay logs of the Potomac fluvial-deltaic deposits. The gamma logs also show consistently higher values (deflection more to the right) for the upper Cenomanian beds as compared to the Potomac deposits.

Glauconitic Sand Unit

The Upper Cretaceous glauconitic sand unit is loose sand that is found only across the southern part of the study area. The Dismal Swamp and Fentress coreholes penetrated 54.5 ft and 59 ft of this unit respectively, with almost no recovery. The lack of clay or silt and the apparent well-sorted nature of the sands appear to be responsible for the poor core recovery. The small amount of recovered core, the drill cuttings, and the geophysical logs indicate that most of the unit is fine to very coarse glauconitic quartz, marine sand. In the Dismal Swamp corehole, the basal 0.7 ft of this unit was recovered along with contact with the underlying deltaic-lagoonal upper Cenomanian unit. This contact is an erosional unconformity where light-green to olive-gray, poorly sorted, pebbly, muddy sand sharply overlies dark-gray, finely laminated, very micaceous, lignitic clayey silt. The basal bed of the glauconitic sand unit contains rip-up clasts from the underlying micaceous silt.

Upper Cretaceous Red Beds (Pollen Zone V)

The distribution of the Upper Cretaceous red beds is similar to that of the glauconitic sand unit and is shown in figure 5. The red beds are found throughout the southern half of the study area but have a patchy distribution across the northern half. The red beds were not encountered in the Chesapeake-Portsmouth Airport corehole (**21**). The thickness of the red beds is 53.4 ft in the Dismal Swamp corehole, 91.3 ft in the Fentress corehole (**12**), and 80 ft in the Chesapeake Northwest River WTP borehole (**3**). The unit has a heterogeneous lithology including uniform gray and green and bright red, mottled purple, yellow, orange, and brown sequences of interbedded oxidized clay, silty clay, silty fine sand, and pebbly coarse sand. Some beds contain scattered mica, carbonaceous material, wood chunks, mud cracks, and rootlets. Several paleosols occur at the top of fining-upward sequences. The bases of the fining-upward sequences typically consist of muddy pebbly sand that overlies the clay to silty clay or sandy clay of an underlying paleosol. At the base of the red beds in the Dismal Swamp corehole (**2**) is a gray to multicolored, interbedded, micaceous clayey sand to sandy clay, which sharply overlies the glauconitic sand unit. This lower unit consists of dark-green to gray-green, fairly well sorted, fine to coarse quartz sand containing small amounts of glauconite and phosphate. The extensive development of these red beds indicates a fluvial to upper-delta-plain depositional environment.

Recent pollen analysis (N. Frederiksen, USGS, written commun., 1999) of samples from the red bed unit in the Fentress corehole (**12**) indicates assignment to Coniacian-Santonian pollen zone V, which is equivalent to the Amboy Stoneware Clay Member of the Magothy Formation in New Jersey and the Black Creek or Peedee Formations in North Carolina. This analysis provides, for the first time, a definitive age for the red-bed unit, and for the first time, deposits of this age have been documented in Virginia. The glauconitic sand unit is still not definitively dated; however, it is positioned between the Coniacian-Santonian age red-bed unit above and late Cenomanian strata below, and therefore may be Cenomanian to Santonian in age. This investigation found that both the glauconitic sand unit and red beds correlate with unit D of Brown and others (1972) and sequence 3 of Gohn (1988).

Upper Cretaceous and/or Paleocene Beds

In the southeastern corner of the study area, the Chesapeake Northwest River WTP borehole (**3**) (pl. 1) encountered a 107-ft-thick section of deltaic sands and clays that are interpreted to be underlain by the Coniacian-Santonian age red-bed unit and overlain by the upper Paleocene Aquia Formation. These deposits can be subdivided into three units: 51-ft-thick lower glauconitic sand overlain by 15-ft-thick organic-rich clay that is capped by 41-ft-thick clayey-silty quartz sand. Their position between the red bed unit and the Aquia Formation indicates that the deposits are either Upper Cretaceous (pollen zone V or younger) and/or Paleocene deposits.

Tertiary Deposits

Interpretations of Tertiary deposits are based on correlations between corehole and borehole data, with emphasis placed on correlations between the Dismal Swamp (**2**), Chesapeake-Portsmouth Airport (**21**), and Fentress (**12**) coreholes. Powars and Bruce (1999) provided the geologic framework adjacent to and including the northwestern to central part of the present study area (figs. 1 and 2). The Jamestown (**61**) and Newport News Park 2 (**63**) coreholes provide lithostratigraphic interpretations for the northwestern part of the study area; on the northeastern side of the study area, the Kiptopeke corehole (**64**) gives stratigraphic control inside the crater. Chronostratigraphic control is based on fauna and flora analyses of core samples. Biostratigraphic information is included on the Dismal Swamp (**2**) and Fentress (**12**) corehole stratigraphic columns (pl. 1).

Following Powars and Bruce (1999), the Tertiary deposits beneath southeastern Virginia are grouped into pre-impact, syn-impact, and post-impact deposits. The pre-impact deposits consist of shallow-shelf to marginal-marine facies that are characteristically thinly stratified, partly shelly, glauconitic, clayey sands and silts. These deposits include the Brightseat Formation (lower Paleocene), Aquia Formation (upper Paleocene), Marlboro Clay (which straddles the Paleocene-Eocene boundary), Nanjemoy Formation (lower Eocene), and Piney Point Formation (middle Eocene). The syn-impact deposits are represented by the instantaneously deposited Exmore tsunami-breccia that has a highly variable mixture of autochthonous sedimentary intraclasts (from Early Cretaceous to late Eocene age) and by the CBIC megablock beds, defined by Powars and Bruce (1999) on seismic data. The upper Eocene to Middle Miocene post-impact deposits consist of bathyal, shallow shelf and marginal-marine sediments that have progressively filled much of the upper part of the crater. The upper Miocene to Pliocene shallow shelf, and marginal-marine deposits filled the upper part of the crater and blanketed the entire region, thereby burying the crater. Post-impact deposits include, in ascending order: the very clayey Chickahominy Formation (upper Eocene); the glauconitic, phosphatic, and partly shelly Delmarva beds (lower Oligocene) and Old Church Formation (upper Oligocene); the shelly and sandy beds of the Calvert Formation (lower Miocene); the primarily siliciclastic, fine-grained, Calvert (middle Miocene), St. Marys (upper Miocene), and lower Eastover (upper Miocene) Formations; the siliciclastic, locally glauconitic, fine- to coarse-grained fossiliferous upper Eastover (upper Miocene), Yorktown (lower and upper Pliocene), and Chowan River (upper Pliocene) Formations; and fluvial to estuarine Quaternary units.

Pre-impact Tertiary Deposits (Paleocene and lower and middle Eocene)

Within the study area, the pre-impact Tertiary deposits consist of shallow-shelf to marginal-marine facies that are characteristically thinly stratified, shelly, glauconitic, clayey sands and silts, and include the Brightseat, Aquia, Nanjemoy, and Piney Point Formations and the Marlboro Clay. The pre-impact lower Tertiary deposits dip eastward to northward and are higher and thinner near the Virginia-North Carolina border.

The Brightseat Formation is a muddy, glauconitic sand only a few feet thick (Powars and others, 1992). It is biostratigraphically documented only in the Dismal Swamp corehole (**2**) (pl. 1) on the basis of Foraminifera (T.G. Gibson, formerly USGS, written commun., 1988), calcareous nannofossils (L.N. Bybell, USGS, oral commun., 1988), and dinoflagellates (L.E. Edwards, USGS, written commun., 1988).

The Aquia Formation (upper Paleocene) consists of massive to thinly stratified, black to greenish-black to light-greenish-gray clayey and silty, fine to coarse glauconitic quartz sands, with variable amounts of shells, microfossils, mica, pyrite, lignitic material, and calcium-carbonate cemented layers and concretions. The glauconitic sand typically is found floating in a clay-silt matrix, and some intervals have abundant burrows. Quartz and phosphatic pebbles and very coarse glauconitic quartz sand mark the base of the unit. South of the James River, a few hard streaks of shells or thin "rock" layers are fairly abundant and show up as sharp peaks on the resistivity logs. Drillers' logs use a variety of lithic descriptions for this unit such as a "black sand" or "black pepper sand" or "marl" or "clay and shell" or "shell rock."

South of the James River, the Aquia Formation ranges in thickness from 30 to 60 ft at Hog Island (**60, 58**) to 21 ft in the town of Rescue (**45**), 13 ft in the Chesapeake-Portsmouth Airport corehole (**21**), 19 ft in the Dismal Swamp corehole (**2**), 42 ft in the Fentress corehole (**12**), and 24 ft in the Chesapeake Northwest River WTP borehole (**3**). The regional distribution of the Aquia Formation is similar to that of the overlying Marlboro Clay and Nanjemoy Formations (Powars and Bruce, 1999).

A distinctive suite of micro- and macrofossils (for example, the brachiopod *Oleneothyris harlani*) found in the lower part of the Aquia in the Fentress corehole indicates a late Paleocene age and equivalence to the Piscataway Member (Powars and others, 1992). Dinocyst data (analyzed by L.E. Edwards) also establish that the entire unit in the Dismal Swamp corehole and the upper part of the Aquia in the Fentress corehole (**12**) are equivalent to the updip outcrop Paspotansa Member of the Aquia (Powars and others, 1992). A summary of the chronostratigraphic data is included on the stratigraphic columns of the Dismal Swamp (**2**) and Fentress (**12**) coreholes (pl. 1) and on the stratigraphic column of the Chesapeake-Portsmouth Airport corehole (**21**) (Powars and Bruce, 1999, MW4-1 corehole, pl. 5). These Aquia micro- and macrofossil assemblages are also found as intraclasts in the Exmore tsunami-breccia deposits.

The resistivity log signatures from the three key coreholes (**2**, **12,** and **21**) within the study area are typical for the Aquia Formation and reflect the sandy nature of the section. Thin calcium-carbonate-cemented layers are reflected on the resistivity log by sharp peaks. The gamma readings reflect the variable amount (20-75 percent) of glauconite (and some phosphate) found in the Aquia strata, which generally causes deflections to the right, indicating increasing radiation.

It is difficult to differentiate the Aquia strata from the underlying Upper Cretaceous marine deposits south of the James River. Differentiating the Aquia from the Exmore tsunami-breccia outside the outer rim also is difficult because these units are thin and have similar lithologic and borehole signatures. Powars and Bruce (1999) suggested that differentiation might be aided by noting the vertical stacking order of the units. They pointed out that the Marlboro Clay and Nanjemoy Formation are most likely underlain by the Aquia Formation whereas the Chickahominy Formation is most likely underlain by the Exmore tsunami-breccia. The distinctive, nearly flat resistivity signature of the homogeneous, clayey Chickahominy Formation has thus far only been found overlying the Exmore tsunami-breccia. This signature contrasts well with the more irregular, curvy resistivity signature of the Nanjemoy and Marlboro Clay logs above the Aquia Formation; this irregular, curvy signature is caused by variations in the sand content and the sand-filled burrows in the Marlboro Clay.

The Marlboro Clay (upper Paleocene and lowermost Eocene) ranges in thickness from 8 ft in the Chesapeake-Portsmouth Airport corehole (**21**), to 16 ft in the Dismal Swamp corehole (**2**), 10 ft in the Fentress corehole (**12**), and 14 ft in the Chesapeake Northwest River WTP borehole (**3**). It consists of light-gray to pinkish-gray and reddish-brown kaolinitic clay and is found consistently outside the crater between the glauconitic Aquia and Nanjemoy Formations. The clays are massive to thinly laminated with silt and very fine, micaceous-rich sands. The contact between the Marlboro Clay and underlying Aquia is gradational, whereas a sharp, burrowed contact exists between the Marlboro Clay and the overlying Nanjemoy beds. The contrast in lithology and color between the Marlboro Clay and the underlying and overlying glauconitic units facilitates identification. Resistivity logs reflect the very clayey nature of the Marlboro; however, the lowest Nanjemoy beds are often described as gray clay, making differentiation between these two units difficult.

The Nanjemoy Formation (lower Eocene) ranges in thickness from about 3 to 40 ft south of the James River. Powars and Bruce (1999) described its regional distribution pattern as similar to those of the Aquia and Marlboro Clay Formations. The Nanjemoy Formation consists of massive to thin-bedded, dark-olive-gray, greenish-gray, and olive-black, variably clayey, silty, fine to coarse glauconitic-quartz sand, with varying amounts of shells, microfossils, mica, lignitic material, pyrite, and goethite. The unit is characteristically intensely burrowed (including clay-filled, clay-lined, and sand-filled types) and contains several fining-upwards sequences that are usually capped with a sandy clay-silt. South of the James River, the Nanjemoy section contains thin deposits of both the Woodstock and Potapaco members (Powars and others, 1992). The Nanjemoy has a sharp, burrowed contact with the underlying Marlboro Clay.

The Nanjemoy Formation contains a distinctive suite of early Eocene micro- and macrofossils (Powars and others, 1992). Dinocyst data (analyzed by L.E. Edwards, USGS) from the Dismal Swamp corehole (**2**) indicate that the Nanjemoy Formation includes Beds A and B of the Potapaco Member (Powars and others, 1992). Dinocyst data (also analyzed by L.E. Edwards) from the Fentress corehole (**12**) indicate that the Nanjemoy Formation consists of 8 ft of the Woodstock Member, which consists of poorly sorted, black, fine to coarse, rounded, glauconitic sand in a muddy matrix.

At Hog Island in the northwestern corner of the study area, the Nanjemoy Formation appears to be overlain by the shelly, glauconitic Piney Point Formation. A high-resistivity signature is characteristic of the Piney Point and distinguishes it from the underlying Nanjemoy. Along the northern side of the study area (adjacent to and stepping into the CBIC), the Nanjemoy is overlain by a patchy distribution of shelly, sandy, Oligocene and/or lower Miocene deposits that have distinctively high-resistivity and high gamma-log signatures.

In the Fentress corehole (**12**) (pl. 1), the Nanjemoy is overlain by 15 ft of coarser glauconitic sand containing middle or late Eocene or early Oligocene dinocysts (L.E. Edwards, written commun., 1989). The middle and late Eocene dinocysts are probably reworked into lower Oligocene deposits (Powars and others, 1992). The very clayey upper Miocene St. Marys Formation overlies the Nanjemoy farther west, in the Dismal Swamp corehole (**2**). The clayey nature of these upper Miocene deposits exhibits a fairly uniform low resistivity signature; therefore, they are readily distinguishable from the Nanjemoy. The thin sandy basal beds of the Calvert and St. Marys Formations often contain phosphate, which causes a high-radiation peak on the gamma log. The Nanjemoy's variable percentage of glauconite and phosphate (20 to 70 percent) creates high-radiation gamma-log signatures, similar to the Aquia Formation and the thin basal beds of the Oligocene to middle Miocene deposits.

The Piney Point Formation (middle Eocene) is a richly fossiliferous, olive-gray to grayish-olive-green, poorly sorted, medium to coarse, glauconitic quartz sand that commonly contains interbedded calcium-carbonate-cemented sand to shelly sand and moldic limestone (hard "shell rock" with voids). The sand contains varying amounts of clay, silt, shells, microfossils and glauconite (25 to 50 percent). The Piney Point Formation is preserved mainly north of the James River, and its present distribution is due to the immense erosional power of the impact blast and subsequent train of tsunamis that largely shaped the upper surface of the Piney Point. The Piney Point is present only in the northwestern corner of the study area, beneath Hog Island. Its thickness varies from 7 to 17 ft in wells on Hog Island. On the north side of the James River, 6.6 ft of the Piney Point strata were documented in the Jamestown corehole, which represents the only biostratigraphically dated section of this unit close to the study area (Powars and Bruce, 1999).

High resistivity-log signatures are characteristic of the interbedded sand and limestone of the Piney Point Formation (Powars and Bruce, 1999). Piney Point strata at Hog Island appear to be overlain by Oligocene glauconitic sands and shelly sands and are underlain by lower Eocene glauconitic clayey sands of the Nanjemoy Formation. These interpretations are based largely on correlation with the Jamestown corehole.

Syn-impact Deposits (upper Eocene)

The syn-impact deposits are divisible into two principal depositional units: the Exmore tsunami-breccia (the upper deposit) and the CBIC megablock beds (the lower deposit). The Exmore tsunami-breccia overlies either the CBIC megablock beds or the relatively undisturbed or little disturbed Upper and Lower Cretaceous deposits (fig. 2). The Exmore tsunami-breccia has a highly variable lithology, which consists of an overall fining-upwards sequence of pebble- to boulder-size intraclasts in a gray, shelly, clayey and silty, fine to granular, glauconitic sand matrix (partially sublithified). The abundant intraclasts contain fauna and flora from Lower Cretaceous (Albian), Upper Cretaceous (Cenomanian, Santonian, Campanian, and Maestrichtian), Paleocene, and lower, lower middle, and upper Eocene deposits (Powars and others, 1992; Powars and Bruce, 1999). The clasts consist of a wide variety of lithologies and sizes and are rounded to angular, mostly deformed fragments up to 6.5 ft in diameter. They occur isolated to amalgamated, and are composed of soft, friable, marine to fluvial-deltaic sands and clays, hard silty clays, and indurated sands and bioclastic limestones. As expected, these clasts display a wide variety of colors, from black to various grays and greens to oxidation colors (red, purple, yellow, and brown).

Core samples of the Exmore tsunami-breccia contain trace amounts of shocked quartz, a high-pressure mineral produced only by the high pressures created by impact events (Powars and Bruce, 1999). Koeberl and others (1996) also found abundant, centimeter-sized fragments of melt rock and scattered clasts of crystalline basement that contain many quartz and feldspar deformation features in core samples.

The syn-impact Exmore tsunami-breccia ranges in thickness from 30 to 110 ft outside the outer rim of the crater to about 125 to 664 ft a short distance inside the outer rim (**50**, **51, 53**). Farther into the crater, seismic data (recorded in two-way traveltime) indicate that the unit is 1,200 to 1,300 ft thick and up to approximately 2,300 ft thick inside the crater's inner basin (Powars and Bruce, 1999). It abruptly thickens across the faulted outer rim of the crater and across the faulted peak ring of the inner basin but generally thins above the variably uplifted peak ring (fig. 2)

The Exmore tsunami-breccia is overlain by the clayey post-impact Chickahominy Formation, which also is found only inside the disruption boundary that separates pre-impact units from syn-impact units. Core data indicate that this stratigraphic contact is gradational and that the Exmore tsunami-breccia deposits are capped by a thin (2 to 20 ft), olive-gray to brownish-purple, very clayey unit that contains abundant, coarse-grained to fine pebble-size intraclasts and mixed fauna similar in lithology to the Chickahominy Formation. Except for this thin clay cap, the characteristic flat resistivity signature of the Chickahominy strata is easily differentiated from the irregular resistivity signature typical of the rest of the Exmore tsunami-breccia (Powars and Bruce, 1999).

Within the study area, the Exmore tsunami-breccia deposits are underlain by pre-impact Upper and Lower Cretaceous deposits outside the outer rim of the crater and by the CBIC megablock beds inside the outer rim. The location of the disruption boundary beneath the irregular, near-surface outer rim is uncertain, and undisturbed Lower Cretaceous deposits may extend far into the annular trough. Powars and Bruce (1999) pointed out that differentiating the Exmore tsunami-breccia from the Lower Cretaceous fluvial-deltaic deposits is difficult, but, in general, the Lower Cretaceous deposits have blockier, thicker stratified, resistivity and gamma log signatures than the more subdued signatures of the thinner stratified Exmore tsunami-breccia deposits.

Powars and Bruce (1999) defined the CBIC megablock beds as a seismic-stratigraphic unit found inside the disruption boundary. This unit represents all the deposits (700 to 2,500 ft thick) found in the annular trough beneath the Exmore tsunami-breccia and above the basement rocks. The syn-impact CBIC megablock beds are interpreted to consist primarily of Lower Cretaceous fluvial-deltaic deposits that slumped into the crater during an early stage of crater filling and covered the floor (basement surface) of the annular trough (Poag, 1996, 1997; Powars, and Bruce, 1999).

Post-impact Deposits

The post-impact deposits consist of approximately 1,300 to 1,600 ft of upper Eocene to Holocene deposits that buried the crater and the syn-impact deposits (fig. 2; Powars and Bruce, 1999, pl. 7a). Except for some Quaternary fluvial-estuarine deposits, most of the post-impact deposits are marine clays, silts, and very fine to very coarse sands that may include diatomaceous, glauconitic, shelly, and thin calcium carbonate indurated intervals. Microfauna and macrofauna indicate a marine to restricted marine origin.

Post-impact deposits include, in ascending order: the very clayey Chickahominy Formation (upper Eocene); the glauconitic, phosphatic, and partly shelly Delmarva beds (lower Oligocene) and Old Church Formation (upper Oligocene); the shelly and sandy beds of the Calvert Formation (lower Miocene); the primarily siliciclastic, fine-grained Calvert (middle Miocene), the St. Marys (upper Miocene) and lower Eastover (upper Miocene) Formations; the siliciclastic, locally glauconitic, fine- to coarse-grained fossiliferous upper Eastover (upper Miocene), Yorktown (lower and upper Pliocene), and Chowan River (upper Pliocene) Formations; and various fluvial to estuarine Quaternary and Holocene units.

Upper Eocene, Oligocene, and lower Miocene Post-impact Deposits

The upper Eocene Chickahominy Formation is the first post-impact deposit and conformably overlies the Exmore tsunami-breccia. Within the study area, this unit ranges in thickness from 55 ft (**32**) to 227 ft (**51**). The Chickahominy Formation consists of massive to thin-bedded, olive-gray, very compact, dry, micaceous, clayey silt to silty clay (Powars and Bruce, 1999). It contains variable amounts of fine-sand to silt-sized, primarily black to dark green glauconite, shells including solitary corals, abundant iron sulfides, and pyrite. The abundant microfauna impart a white-speckled appearance to some intervals. The entire unit contains a wide variety of locally scattered to extensive burrows. The lower part of the section coarsens downward to very fine-to-fine sand and contains pebbles and reworked microfauna from Upper Cretaceous through middle Eocene deposits (Powars and others, 1992).

The Oligocene to middle Miocene post-impact deposits exhibit a patchy, very thin distribution pattern south of the James River. These deposits appear to be preserved adjacent to the outer rim and to thicken inside the crater along the northern boundary of the study area (Powars and Bruce, 1999). In the Fentress corehole (**12**) (pl. 1), dinocyst data (L.E. Edwards, USGS, written commun., 1989) indicate the presence of 15 ft of lower Oligocene Delmarva beds consisting of black, very fine, glauconitic and phosphatic sand in an olive-brown clay-silt matrix (Powars and others, 1992). Therefore, the unit is most likely locally present along the Virginia Beach coastal area.

The upper Oligocene deposits are found in the Jamestown corehole (**61**) and probably are also present in the northwest corner of the study area. However, they were not encountered in the Dismal Swamp (**2**) or Fentress coreholes (**12**) and, therefore, probably are absent over most of the study area outside the crater.

Powars and Bruce (1999) presented biostratigraphic and strontium-isotope data that document the presence of lower Miocene marine bioclastic sand deposits in the Virginia Coastal Plain, which they informally named the Newport News unit of the Calvert Formation. Strontium-isotope analysis of shells from these deposits indicates that they range in age from about 20.1 to 17.1 Ma.

Within the study area, the thinness and local absence of the Oligocene and lower Miocene strata, combined with their general lithologic similarity, make it difficult to correlate these deposits between cores. Therefore, in this report the thin lower Oligocene Delmarva beds are combined with the overlying upper Oligocene Old Church Formation and lower Miocene Newport News unit of the Calvert Formation into a single stratigraphic unit. The shelly, sandy, Oligocene and/or lower Miocene deposits characteristically have high-resistivity and high gamma-log signatures, which contrast with the characteristic low-resistivity signatures (deflection to the left) of the underlying fine-grained Nanjemoy or Chickahominy Formations and overlying finer grained Calvert or St. Marys Formations.

Middle and upper Miocene, Pliocene, and Quaternary Post-impact Deposits

Post-impact deposits from numerous marine transgressions and regressions across the lower mid-Atlantic Coastal Plain have covered the study area with a generally eastward-dipping wedge of sediments that ranges from 225 to 750-ft-thick outside the crater. These deposits thicken and dip into the crater, becoming up to 1,300 to 1,600 ft thick. Miocene and Pliocene shallow-shelf to nearshore marine deposits account for most of the section and are overlain by relatively thin Quaternary fluvial-estuarine deposits.

Most of the post-impact middle and upper Miocene deposits cored in Virginia’s central to outer Coastal Plain have been found to consist of fining-upward sequences that have thin basal sands overlain by thick, very fine grained clays, silts, and sands with scattered shell material. These deposits consistently display a low-resistivity signature except along and adjacent to the outer rim of the crater, where the deposits become coarser grained, which results in higher resistivity signatures. In general, the uppermost part of the upper Miocene Eastover Formation and parts of the Pliocene Yorktown Formation have shelly sands that produce high-resistivity signatures throughout the study area.

The middle Miocene Calvert Formation is absent from the Dismal Swamp corehole (**2**) and consists of 12 ft of shelly sand in the Fentress corehole (**12**); northeast of the study area (within the crater) it thickens to 458 ft of primarily very fine grained sediments in the Kiptopeke corehole (**64**). A thin section of Calvert Formation is, therefore, locally present along the eastern side of the study area. The thicker beds in the crater contain sparse to abundant diagnostic diatoms that are easily visible using a 10X hand lens, and were not visible in the Fentress core. Similar to the other thin pre-impact and post-impact units, differentiation of thin units is very difficult between cores.

The St. Marys Formation is the oldest post-impact unit that extends across the entire study area and progressively onlaps and truncates older units west to southwest of the crater. The St. Marys appears to be thickest in the southern part of the crater and south of the crater in the Norfolk to Virginia Beach area (Powars and Bruce, 1999). In the Dismal Swamp corehole (**2**), Foraminifera (T. Gibson, written commun., 1987) from a thin, benthic-foraminifera-rich, brownish gray, sandy clay indicates that the upper Miocene St. Marys Formation overlies the Nanjemoy Formation. The St. Marys consists of up to 330 ft (**51**) of mostly muddy, very fine sand and sandy clay and silt containing scattered shells, abundant iron sulfide, and finely disseminated organic material.

Ostracode (T. Cronin, USGS, written commun., 1995) and Foraminifera (S. Ishman, formerly with the USGS, written commun., 1995) data from the upper part of the Eastover Formation in the Dismal Swamp (**2**) and Fentress (**12**) coreholes indicate the presence of a thick younger section that has no correlative units in outcrop (Powars and Bruce, 1999). Powars and Bruce (1999) reported strontium-isotope ages for the St. Marys strata that range from about 6.7 to 5.5 Ma, which extrapolates to foraminiferal zone N17.

The Eastover Formation (upper Miocene) also extends across the entire study area and ranges in thickness from 140 ft in the Dismal Swamp corehole (**2**) to 174 ft in the Fentress corehole (**12**). The Eastover consists of dark-gray to bluish-gray to greenish-gray, muddy fine sand interbedded with finer and coarser grained beds. The Eastover is sparsely to abundantly shelly, contains shell hashes and indurated beds, and is locally glauconitic and micaceous. Macrofauna and microfauna indicate a shallow-water, marine to restricted-marine depositional environment. The pearly luster, tabular mollusk *Isognomon maxillata* is a common species in the upper part of the Eastover Formation, but not present in the overlying Yorktown Formation. Throughout the study area, the lower part of the Eastover Formation consists of a clayey, fine-grained facies and the upper part is a shelly, coarser grained, sandy facies. Powars and Bruce (1999) pointed out that regionally the lower, finer grained facies has characteristically low resistivity-log signatures (deflection to the left) that show an upward-coarsening trend into the upper shelly, coarse-grained facies that has characteristically high resistivity-log signatures (deflection to the right).

The Yorktown Formation (lower and lower upper Pliocene) extends across the entire study area except where it has been cut out by Quaternary James River paleochannels (see Powars and Bruce, 1999). The Yorktown deposits overlie the Eastover strata throughout the study area and locally are overlain by shallow-marine deposits of the Chowan River Formation (late Pliocene). The Yorktown consists of bluish-gray, greenish-gray, and dark greenish-gray, very fine to coarse sand, in part glauconitic and phosphatic, commonly very shelly and interbedded with gray and blue-gray sandy and silty clay. The Yorktown also contains abundant microfauna and locally includes cross-bedded biofragmental lenticular sand bodies.

Subdivision of the Yorktown Formation into its four members (from oldest to youngest: Sunken Meadow, Rushmere, Mogarts Beach, and Moore House) is beyond the scope of this report. Within the study area, however, outcrops of the Yorktown Formation found along much of the James River shoreline in Isle of Wight County expose the upper part of the Rushmere Member and the Mogarts Beach and Moore House Members. The Yorktown has been documented to range in thickness from 42 ft in the Dismal Swamp corehole (**2**) to 107 ft in the Fentress corehole (**12**). Ostracode data (T. Cronin, written commun., 1995) from these two coreholes indicate that the Yorktown consists of the Sunken Meadows, Rushmere, and Mogarts Beach Members. The youngest Moore House Member may be present at the Fentress corehole (**12**) site but was not resolved because of poor core recovery from the upper section of the Yorktown.

The Chowan River Formation (upper Pliocene) has a very limited, irregular distribution across the southeastern part of the study area. It consists of interbedded, silty, fine sand, clayey silt, and bioclastic sand. The Chowan River Formation (upper Pliocene) was reported (Gibson, 1983) in the Moores Bridge well (**31**) at depths from 90 to 115 ft and consists of blue-green fossiliferous clayey fine sand. It is also reported (Johnson and others, 1987) 1ocally only in a few borrow pits (the Gomez and Yadkin pits) and in the subsurface of southeastern Virginia. Exposure of the Chowan River Formation in relatively shallow borrow pits less than 5 miles south of the NOR-T-12 well (**32**) suggests that either a steep gradient exists between these sites (possibly caused by structural effects) or that identification was incorrect. A bioclastic, silty, fine to medium sand found in the Fentress corehole from -51 to -65 ft elevation is assigned to the Chowan River Formation. Where present, this unit unconformably overlies the Yorktown Formation and is truncated by

Quaternary fluvial to estuarine and marginal-marine deposits. The lithology of the Chowan River is so similar to the underlying Yorktown Formation that biostratigraphic differentiation is required. No attempt was made to differentiate the Chowan River from the Yorktown, however, because of the lack of biostratigraphic data, the Chowan River's patchy distribution, and their similar hydrogeologic characteristics.

Quaternary strata in the study area include fluvial, estuarine, marginal-marine, and nearshore-shelf sediments deposited during the Pleistocene epoch. The early, middle, and late Pleistocene deposits form a step-like succession of terraces and intervening scarps that parallel the coast (or the buried outer rim of the crater) and major streams, thereby dominating the topography of the Coastal Plain (Johnson and Ramsey, 1987). These terraces decrease in elevation and age towards the coast and major streams. The Pleistocene and Holocene deposits consist of light- to dark-gray, blue-gray, to oxidized variegated (brown, yellow, orange, red), interbedded sand, gravel, silt, clay, and locally include shells and peat. The estuarine and coast- facing deposits east of the Suffolk scarp commonly include scattered to dense shell accumulations. The Holocene deposits include estuarine, marsh, swamp, dune, alluvial and colluvial sediments.

Across the study area, Pleistocene scarps and paleochannels cut into the older units (Johnson, 1969; Johnson and Ramsey, 1987; Powars and Bruce, 1999). Near the mouth of the James River, a paleochannel cuts down to nearly -160 ft beneath the modern James River (fig. 9B). Paleochannel fills of the Atlantic Coastal Plain generally are transgressive sequences consisting, from bottom to top, of coarse fluvial gravel and sand, estuarine muds, and fossiliferous lower estuarine to open-bay sand and sandy mud. The channel fills are overlain by nearshore shelf and barrier-spit deposits representing deposition during interglacial highstands (when the sea level is high due to melting of continental glaciers and partial melting of the polar ice caps).

The Pleistocene scarps were formed by fluvial and estuarine erosion (valley-facing scarps) and shoreline erosion (coast-facing scarps) caused by changes in sea level that occurred during the glacial-interglacial period. The proximity and parallelism of the coast-facing scarps to the outer rim of the crater, and the stacked nature of some of the scarps near the outer rim, indicate an influence by episodic differential movement around the buried outer rim and continued higher subsidence rates inside the crater. In addition, late Pleistocene and Holocene deposits appear to be the only surficial units found inside the buried outer rim of the crater (Powars and Bruce, 1999).

Subdivision of the Quaternary deposits is beyond the scope of this report. For more information about individual Quaternary units, the reader is referred to the geologic map of the Virginia Coastal Plain (Mixon, Berquist, and others, 1989), which shows the surficial distribution and briefly describes the lithology of the Quaternary units.

CORRELATION OF GEOLOGIC UNITS TO HYDROGEOLOGIC UNITS

On the basis of lithology, biostratigraphy, and borehole geophysical logs, the geologic units described in this report are correlated with the hydrogeologic units of the Virginia Coastal Plain described by Meng and Harsh (1988) as part of the Regional Aquifer-System Analysis (RASA) program (table 2). The 56-mi-wide CBIC truncated the aquifers and confining units (Lower Potomac through the lower part of the Chickahominy-Piney Point) that were identified by Meng and Harsh (1988). The St. Marys-Choptank aquifer, an important aquifer in the Maryland Coastal Plain, is not present in this area (Laczniak and Meng, 1988), and the Virginia Beach aquifer is present only south of the James River and Chesapeake Bay (Hamilton and Larson, 1988).

The variability of correlation of the geologic and hydrogeologic units across the study area is shown in figure 13. For example, the Virginia Beach aquifer is correlated to (1) the top of the upper Cenomanian beds, (2) the glauconitic sands unit, (3) the red beds unit, and (4) the lower part of the Upper Cretaceous and/or Paleocene (?) unit. In some places, very clayey or fine-grained strata correlate with intervals assigned to aquifers instead of confining units. These correlations call for the revision of the hydrogeologic units of Meng and Harsh (1988) and Hamilton and Larson (1988).

Various structural and stratigraphic complexities related to the CBIC and its burial have altered the hydraulic characteristics of the aquifers and confining units inside and adjacent to the crater. Regional ground-water flow paths apparently were altered by emplacement of the lithically heterogeneous, seawater-saturated Exmore tsunami-breccia and its burial by fine-grained post-impact deposits in the structural low. The combined effect apparently resulted in differential flushing of freshwater over and around the primarily fine-grained deposits inside the crater. The distribution of Virginia's inland

Table 2. Correlation of geologic units to hydrogeologic units. Modified from Powars and Bruce, 1999

[U, upper; M, middle; L, lower; RASA, Regional Aquifer-System Analysis; Fm, formation; AQ, aquifer; CU, confining unit]

SYSTEM	SERIES		Group	Formation	Geologic units this report	Hydrogeologic units: Meng and Harsh (1988)	Hydrogeologic units: Virginia RASA model unit[1]	Hydrogeologic units: Hamilton and Larson (1988)
QUATERNARY	Holocene				Alluvium, swamp, + beach	Columbia aquifer	AQ10	Columbia aquifer
	Pleistocene	U			Tabb Formation			
		M			Shirley Formation			
		M			Chuckatuck Formation			
		L			Charles City Formation			
		L			Windsor Formation			
TERTIARY	Pliocene	U			Bacons Castle Formation	Yorktown confining unit	CU9	Yorktown confining unit
		U	CHESAPEAKE GROUP	Yorktown Formation	Moore House Member	Yorktown-Eastover aquifer	AQ9	
		U			Mogarts Beach Member			
		U			Rushmere Member			Yorktown-Eastover aquifer
		L			Sunken Meadow Member			
	Miocene	U		Eastover Formation	Unnamed beds[2] ?			
		U			Cobham Bay Member			
		U			Claremont Manor Member	St. Marys confining unit	CU8	St. Marys confining unit
		U			St. Marys Formation			
		M			Choptank Formation (not present in study area)	St. Marys-Choptank aquifer	AQ8	Calvert confining unit
		M		Calvert Formation	Calvert Beach Member	Calvert confining unit	CU7	
		M			Plum Point Member			
		M			Fairhaven Member			
		L			Newport News unit	Chickahominy-Piney Point aquifer	AQ7	Chickahominy-Piney Point aquifer
	Oligocene	U			Old Church Formation			
		L			Delmarva beds			

[1]Meng and Harsh (1988).

[2]Powars, D.S. and Cronin, T., U.S. Geological Survey, unpub. data, 1995.

Table 2. Correlation of geologic units to hydrogeologic units. Modified from Powars and Bruce, 1999—Continued

SYSTEM	SERIES		Geologic units this report	Hydrogeologic units: Meng and Harsh (1988)	Virginia RASA model unit[1]	Hamilton and Larson (1988)
TERTIARY	Miocene	M	Plum Point Member of the Calvert Fm	Calvert confining unit	CU7	Calvert confining unit
		M	Fairhaven Member of the Calvert Fm			
		L	Newport News unit of the Calvert Fm	Chickahominy-Piney Point aquifer	AQ7	Chickahominy-Piney Point aquifer
	Oligocene	U	Old Church Formation			
		L	Delmarva beds			
	Eocene	U	Chickahominy Formation			
		U	Exmore tsunami-breccia			
		U	Exmore megablock beds			
		M	Piney Point Formation			
		L	Nanjemoy Formation	Nanjemoy-Marlboro Clay confining unit	CU6	Nanjemoy-Marlboro Clay confining unit
		L	Marlboro Clay			
	Paleocene	U	Aquia Formation	Aquia aquifer	AQ6	Aquia aquifer
		L	Brightseat Formation	Brightseat confining unit	CU3	Not present in study area
				Brightseat aquifer	AQ3	
CRETACEOUS	Upper		Unnamed	Upper Potomac confining unit	CU3	Virginia Beach confining unit CU4
			Red beds			Virginia Beach aquifer AQ4
			Glauconitic sand unit			
			upper Cenomanian beds	Upper Potomac aquifer	AQ3	Upper Potomac confining unit
						Upper Potomac aquifer
	Lower		Potomac Formation	Mid-Potomac confining unit	CU2	Mid-Potomac confining unit
				Mid-Potomac aquifer	AQ2	Mid-Potomac aquifer
				Lower Potomac confining unit	CU1	Lower Potomac confining unit
				Lower Potomac aquifer	AQ1	Lower Potomac aquifer
JURASSIC-TRIASSIC			Rift-basin deposits			
PALEOZOIC AND PROTEROZOIC			Basement rocks			

[1]Meng and Harsh (1988).
[2]Powars, D.S. and Cronin, T., U.S. Geological Survey, unpub. data, 1995.

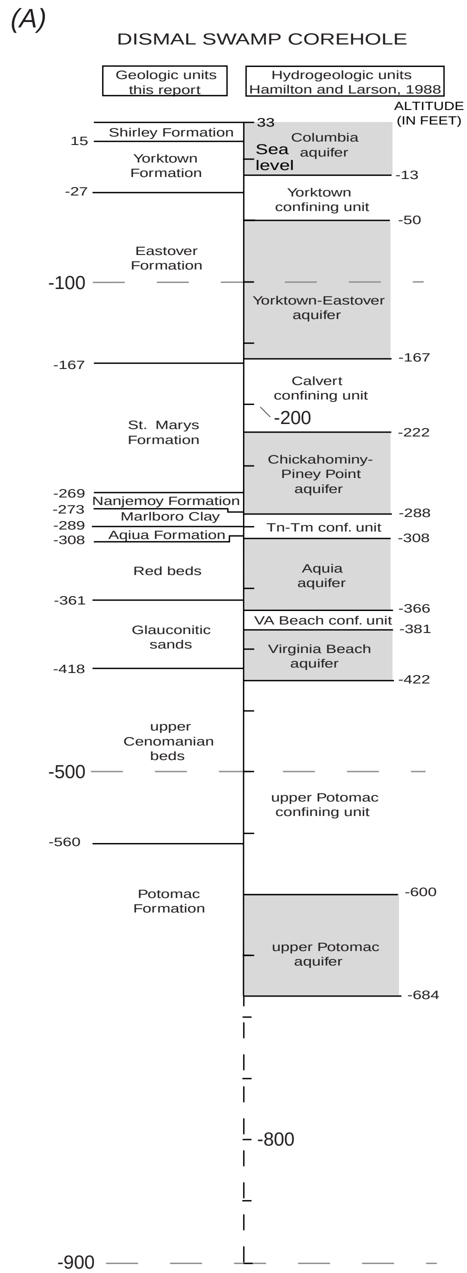


Figure 13. Correlation of geologic and hydrogeologic units in three key boreholes—the Dismal Swamp corehole (A), the Fentress corehole (B), and the Chesapeake Northwest River WTP borehole (C)—showing the variability in unit correlation across the study area. Hydrogeologic unit contacts include estimates from structure contour and isopach maps of units by Hamilton and Larson (1988).

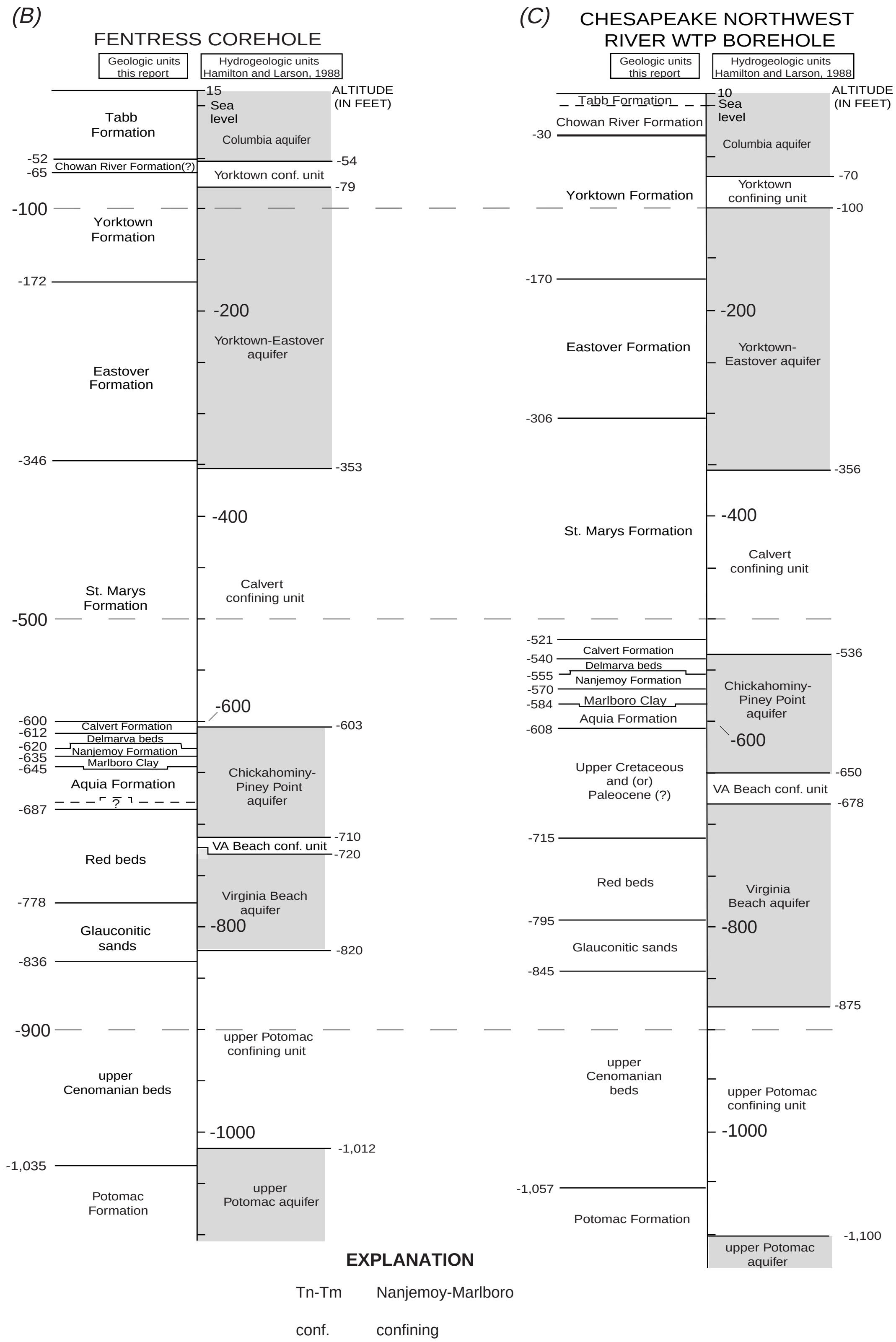


Figure 13. Correlation of geologic and hydrogeologic units in three key boreholes—the Dismal Swamp corehole (A), the Fentress corehole (B), and the Chesapeake Northwest River WTP borehole (C)—showing the variability in unit correlation across the study area. Hydrogeologic unit contacts include estimates from structure contour and isopach maps of units by Hamilton and Larson (1988)—Continued.

salt-water wedge coincides with the location of the CBIC. Prior to the discovery of the CBIC, Focazio and others (1993) compiled contour maps depicting the quality of ground water across the Virginia Coastal Plain. Figure 14 shows that an increase in the concentration of total dissolved solids in the middle Potomac aquifer coincides with the outer rim of the crater. The Brightseat-upper Potomac and Chickahominy-Piney Point aquifers have similar contour patterns (Focazio and others, 1993).

The location of the CBIC with respect to the transverse arch-basin configuration apparently provides a relatively easy downslope flow pathway around the northeastward side of the crater toward the axis of the Salisbury Embayment. In contrast, the Norfolk arch, which is close to the crater on the south side, possibly inhibits flow southeastward around the crater. The abrupt juxtaposition of dissimilar stratigraphic sections north and south of the river produced by the James River structural zone, and the indurated red beds associated with the Norfolk arch, probably also inhibits flow southeastward around the crater by adding barriers to flow paths or by creating more vertical flow paths. In addition, if the CBIC partially truncated a portion of the pre-existing structural zone, as Powars and Bruce (1999) have suggested, then the area along and adjacent to that truncation would be more faulted and fractured than other areas and therefore would possibly provide more barriers or vertical flow paths.

Increasing our knowledge of the complex geologic framework in this area is important for water-resource management. Alternate water supplies are lacking, and water utilities in this region have begun to develop projects that withdraw brackish ground water from just outside the outer rim of the crater. The results of this study indicate that the area south of the lower James River is structurally more complex than other areas adjacent to the crater because of the CBIC's effects on the James River structural zone. These structural complexities apparently have disrupted the pre-impact aquifers and confining units; as a result, the physical properties of the ground-water flow system have been altered significantly.

SUMMARY AND CONCLUSIONS

The influence of the Chesapeake Bay impact crater (CBIC) on the structural, stratigraphic, and hydrogeologic framework of southeastern Virginia's Coastal Plain is complicated by the presence of a pre-impact James River structural zone. The emplacement of the CBIC and subsequent structural adjustments to this James River structural zone help explain the complex distribution patterns of post-impact deposits found across the region.

Litho- and biostratigraphic data from cores and well cuttings and borehole geophysical log data were compiled and analyzed to refine the geologic framework of southeastern Virginia south of the James River. Cross sections were constructed to show the stratigraphic and structural configuration west of the crater and the configuration of the south to southwest side of the crater. The western cross section, which traverses a region that apparently was little affected by the impact crater, was constructed to show the existence of the pre-impact James River structural zone. The other two cross sections connect the geologic framework south of the James River to that of the lower York-James Peninsula; these sections illustrate the structural and stratigraphic relations of geologic units inside and adjacent to the outer rim of the impact crater.

The abrupt truncation and variations in thickness of the various fluvial, deltaic, and marginal marine Cretaceous units across the James River, combined with the angular unconformity with the overlying pre-impact lower Tertiary marine deposits, provide evidence of a pre-impact James River structural zone. Given that sediment deposition and preservation are greater on the down-dropped side of structural zones, it would appear that the region north of the James River was relatively depressed during pollen zone I and relatively elevated for the remainder of Cretaceous time. In contrast, the region south of the James River was relatively elevated during pollen zone I and relatively depressed during the time periods represented by pollen zones II, III, IV, and V.

The Upper Cretaceous deposits consisting of pollen zones III, IV, and V form a wedge that thickens from 377 ft in the Dismal Swamp corehole to 628 ft in the Fentress corehole. The Upper Cretaceous deposits younger than pollen zone III thicken from 200 to 500 ft across the southeastern part of the study area. The deposits are thinner, 30 to 150 ft, and have an irregular distribution across much of the northwestern part of the study area. The Upper Cretaceous deposits are abruptly truncated along the northernmost part of the study area. On the western side of the study area, the truncation appears to be a product of pre-impact movements of the James River structural zone; on the eastern side of the study area, the CBIC was responsible for the truncation. An isopach map of the pre-impact lower Tertiary deposits shows that these deposits thicken north of the James River and west of their abrupt truncation by the CBIC. The variable thickness of these deposits across the rest of the study area apparently is a

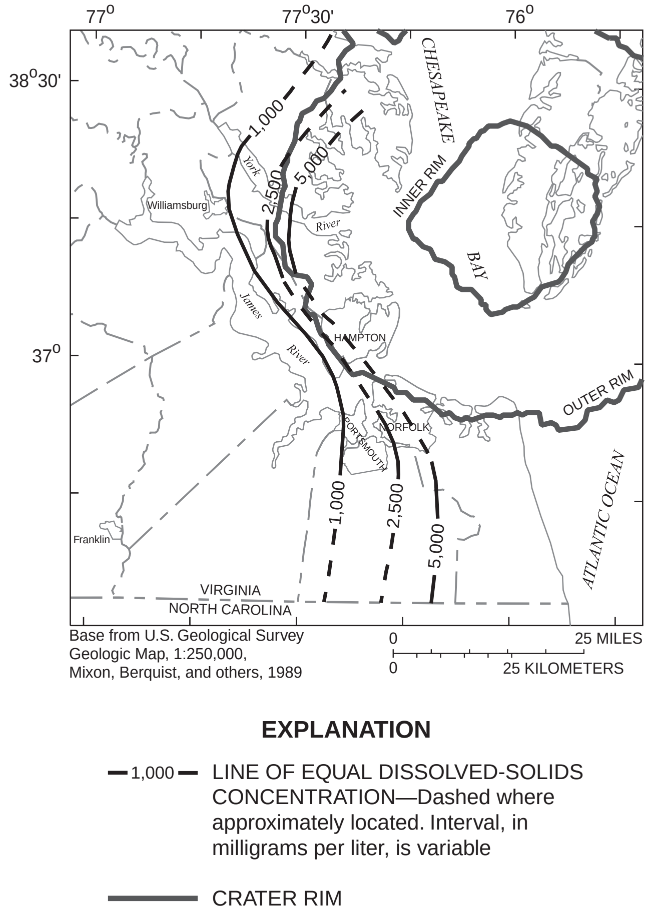


Figure 14. Relation of dissolved-solids concentrations in the middle Potomac aquifer to the location of the Chesapeake Bay impact crater. (Modified from Smith, 1999.)

result of syn- and post-impact structural influences of the CBIC that caused erosion of uplifted areas. Part of the pattern also appears to reflect radial fault systems that were created by the Chesapeake Bay impact crater. Within the study area, the pre-impact lower Tertiary deposits dip eastward to northward and are higher and thinner near the Virginia-North Carolina border. East to southeast deflections of structure contours on top of the Upper Cretaceous and pre-impact Tertiary deposits show possible structural effects; the southernmost deflections coincide with a previously postulated fracture zone.

Complex distributions and truncations of post-impact units across the James River suggest post-impact structural influences of the CBIC on the James River structural zone. The truncation of many of the earlier post-impact units, such as the upper Eocene to middle Miocene deposits, indicates that the area south of the James River structural zone was relatively up during that time or at least prior to deposition of the upper Miocene St. Marys Formation.

The pre-impact Tertiary deposits south of the James River consist of shallow-shelf to marginal-marine deposits, including the Brightseat Formation (lower Paleocene), Aquia Formation (upper Paleocene), Marlboro Clay (straddles the Paleocene-Eocene boundary), Nanjemoy Formation (lower Eocene), and Piney Point Formation (middle Eocene). These pre-impact units are characteristically thin, partly shelly, glauconitic, clayey sands and silts that are bounded by unconformities.

The syn-impact deposits consist of the upper Eocene Exmore tsunami-breccia and the seismically defined CBIC megablock beds. The Exmore tsunami-breccia fills much of the relatively flat-floored annular trough and central basin. The CBIC megablock beds appear to form a concentric wedge that thins toward the center of the crater and covers nearly all the rest of the flat-floored annular trough.

Post-impact upper Eocene to Holocene deposition buried the crater and the syn-impact deposits with approximately 1,300 to 1,600 ft of sediment, which explains the abrupt thickening of these stratigraphic units into the crater across the northeastern part of the study area.

The Pliocene and Quaternary deposits have a complex distribution of lithofacies within 12.5 miles of the crater's outer rim, indicating synchronous deposition and deformation. This deformation is attributed to episodic differential movement of the bounding faults associated with the buried outer rim of the crater and the rotation of slump blocks near the crater's perimeter.

The structural and stratigraphic features created by the impact and adjustments to the James River structural zone also have influenced our understanding of the hydrogeologic framework, ground-water flow system, and regional water quality of the Virginia Coastal Plain. Pre-impact aquifers and confining units were truncated and disrupted in and adjacent to the crater.

Regional flow paths possibly were altered by emplacement of the lithically heterogeneous, seawater-saturated Exmore tsunami-breccia and its burial by fine-grained post-impact deposits in the structural low. The result was differential flushing of fresh water over and around the primarily fine-grained deposits inside the crater. The location of the CBIC with respect to the pre-existing transverse arch-basin configuration also apparently has provided a relatively easy downslope flow pathway around the northeastward side of the crater toward the axis of the Salisbury Embayment. The proximity of the Norfolk arch to the south side of the crater possibly inhibits flow southeastward around the crater. The distribution of Virginia's anomalous inland salt-water wedge coincides with the CBIC's location. An increase in concentrations of total dissolved-solids in the middle Potomac, Brightseat-upper Potomac, and Chickahominy-Piney Point aquifers coincides with the outer rim of the crater. In the absence of alternate water supplies, water utilities in this region have begun to develop projects that withdraw brackish ground water along the edge of the CBIC.

The location and geometry of the outer rim of the CBIC beneath the lower York-James Peninsula and the Norfolk to Virginia Beach area are poorly understood, and additional data are needed to enhance that understanding. The outer rim coincides with an increase in concentrations of total dissolved solids and chloride; therefore, the outer rim separates ground water of high salinity inside the outer rim from fresher water outside the outer rim. To locate this boundary accurately, we need additional land-based seismic reflection profiles, cores, and borehole geophysical logs, especially a sonic velocity log that would allow for accurate depth correlation between borehole and seismic data. Hydrologic data for the western side of the crater, such as flow direction, water quality, and permeability, are non-existent, and information about the depositional processes associated with such a large impactor into water-saturated, unconsolidated sediments is sparse. Obtaining cores and installing observation wells in and around the crater would help us understand how this impact crater has affected the regional ground-water resources. This information also is needed to more accurately model and evaluate the ground-water flow and the potential for saltwater intrusion in the vicinity of the impact crater. As ground-water use increases in the Hampton Roads region and as public water utilities increasingly rely on brackish-water aquifers as sources of drinking water, additional information about the CBIC will be needed for future management of these ground-water resources.

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APPENDIXES

Appendix 1. List of boreholes used in this report

[Altitudes are in feet; latitude and longitude are in degrees, minutes, and seconds; VDEQ, Virginia Department of Environmental Quality; VPI, Virginia Polytechnic Institute; VEPCO, Virginia Electric Power Company; --, local number not assigned]

Bore-hole location number on figure 3	Local number	Identifying name, owner, or organization, and some references	Latitude	Longitude	Surface altitude	Bottom altitude
1	58A2	VDEQ	36 34 08	76 35 00	58	–1,959
2	58A76	Dismal Swamp corehole (Powars and others,1992; unpub. data, D.S. Powars, USGS, and T.S. Bruce, VDEQ)	36 36 55	76 33 20	33	–1,827
3	61A15	City of Chesapeake-Northwest River Water Treatment Plant	36 34 50	76 12 10	10	–1,769
4	62A4	VPI geothermal well # C32	36 36 25	76 00 26	7	–1,014
5	57B6	City of Suffolk	36 42 48	76 39 13	55	–662
6	58B270	VDEQ, Kilby	36 43 20	76 36 55	26	–674
7	58B115	City of Suffolk, City farm 1	36 44 52	76 35 14	30	–986
8	58B11	NAN-P-8 (Brown and others, 1972)	36 44 28	76 33 32	20	–654
9	60B1	Clay Bank Motorlodge (Cederstrom, 1945a)	36 38 11	76 22 22	17	–679
10	60B3	VDEQ	36 38 40	76 20 20	16	–984
11	60B2	CHE-P-5 (Brown and others, 1972)	36 41 49	76 20 19	14	–806
12	61B11	Fentress corehole (Powars and others, 1992; unpub. data, D.S. Powars, USGS and T.S. Bruce, VDEQ)	36 42 27	76 07 47	15	–2,005
13	57C17	City of Norfolk, Lake Prince 4 (Cederstrom)	36 48 10	76 39 21	30	–882
14	58C7	City of Norolk, Lake Prince 1 (Cederstrom)	36 48 38	76 37 09	43	–906
15	58C48	City of Norfolk, Well #80 (Cederstrom, 1945a)	36 48 52	76 37 30	54	–926
16	58C10	City of Suffolk, Well #1	36 46 05	76 32 24	24	–611
17	58C5	Well #37 (Cederstrom, 1945a) Drivers-Monogram Farm	36 49 04	76 32 50	20	–520
18	58C51	City of Norfolk, DR Well #1	36 49 00	76 33 10	20	–1,040
19	58C6	Well #8 (Cederstrom, 1945a) Chuckatuck-Cedarbrook Farm	36 51 16	76 33 26	15	–535
20	58C8	Nimmo Well, Chuckatuck, Va.	36 52 18	76 31 30	22	–563
21	59C39	MW4-1 corehole (Powars and others, 1992); Chesapeake-Portsmouth Airport (this report)	36 47 10	76 26 52	17	–983
22	59C28	City of Chesapeake-Bowers Hill-production well #1	36 47 02	76 24 55	21	–979
23	59C2	Virginia Division of Forestry	36 48 08	76 23 15	20	–633
24	59C40	VPI geothermal well #25	36 51 01	76 28 49	22	–1,978
25	59C13	Tidewater Water Co., NAN-P-13 (Brown and others, 1972)	36 52 18	76 27 47	16	–639
26	60C40	City of Chesapeake IW1	36 47 00	76 22 00	20	–950
27	60C6	Lone Star Cement Corp.	36 48 53	76 17 09	5	–790
28	60C7	City of Portsmouth	36 51 15	76 19 17	10	–1,144
29	60C25	Campbell Soup Co., Well #1	36 51 30	76 18 30	5	–900
30	--	Well #9 (Cederstrom, 1945a) Lamberts Point-Norfolk & Western Railway Co.	36 52 26	76 18 56	10	–606
31	--	Well #20 (Cederstrom, 1945a) Moores Bridge	36 52 21	76 12 13	10	–1,730
32	61C1	NOR-T-12 (Brown and others, 1972)	36 52 23	76 12 21	15	–2,563
33	62C5	VDEQ	36 47 15	76 03 15	14	–386
34	62C4	VDEQ	36 47 11	76 06 01	13	–387
35	62C2	VDEQ	36 47 15	76 03 08	14	–386
36	63C1	VB-P-3 (Brown and others, 1972)	36 52 00	75 58 51	5	–1,583

Appendix 1. List of boreholes used in this report—Continued

[Altitudes are in feet; latitude and longitude are in degrees, minutes, and seconds; VDEQ, Virginia Department of Environmental Quality; VPI, Virginia Polytechnic Institute; VEPCO, Virginia Electric Power Company; --, local number not assigned]

Borehole location number on figure 3	Local number	Identifying name, owner, or organization, and some references	Latitude	Longitude	Surface altitude	Bottom altitude
37	57D20	City of Virginia Beach, Isle of Wight 2	36 52 32	76 40 56	50	–970
38	57D28	VPI geothermal well #26,Town of Isle of Wight	36 54 29	76 42 07	75	–1,310
39	57D2	Well #81 (Cederstrom, 1945a) Smithfield Ice Plant	36 59 05	76 37 21	10	–311
40	57D1	IW-P-13 (Brown and others, 1972)	36 59 42	76 37 53	40	–414
41	58D3	Well #108 (Cederstrom, 1945a) Carrolton	36 58 02	76 34 48	8	–382
42	58D9	Tidewater Virginia Properties-Graymor Estates	36 57 27	76 31 39	15	–541
43	58D7	Town of Smithfield-Red Point Heights	36 59 12	76 36 50	35	–477
44	58D2	Well #54 (Cederstrom, 1945a) Battery Park Water Co.	36 59 32	76 29 44	13	–333
45	58D6	Rescue Water Company	36 59 39	76 33 30	22	–528
46	--	Well #25 (Cederstrom, 1945a) Lone Star Cement Co., near Mogarts Beach	37 00 29	76 36 24	12	–324
47	59D6	CHE-P-11 (Brown and others, 1972)	36 52 41	76 23 17	3	–597
48	59D1	Tidewater Water Co.	36 52 55	76 23 11	15	–573
49	59D20	City of Newport News-City Hall Complex	36 58 40	76 25 50	30	–870
50	60D7	VPI geothermal well #c24 -Willoughby Bay	36 57 27	76 29 19	5	1,030
51	61D5	City of Virginia Beach, ferry slip	36 54 25	76 10 50	11	–1,589
52	62D2	VB-T-4 (Brown and others, 1972)	36 57 59	76 06 47	–35	–1,500
53	60E1	Well #8 (Cederstrom, 1945b, 1957)-Fort Monroe	37 00 05	76 18 25	3	–2,251
54	57E10	VDEQ, Moonlight, Isle of Wight Co.	37 02 36	76 42 59	85	–615
55	--	Well #7 (Cederstrom, 1945a) Burwells Bay	37 03 23	76 40 13	15	–306
56	--	Well #3a (Cederstrom, 1945a) Rushmere	37 04 34	76 40 05	5	–381
57	--	Well #42a (Cederstrom, 1945a) Bacons Castle test well	37 06 10	76 44 13	70	–985
58	57F5	Hog Island Nuclear Power Plant	37 09 50	76 41 52	34	–386
59	57F26	VEPCO	37 09 51	76 41 57	35	–385
60	57F16	Hog Island (unpub. data, T.S. Bruce, VDEQ, and D.S. Powars, USGS)	37 11 33	76 40 53	5	–1,235
61	--	Jamestown corehole (unpub. data, D.S. Powars, USGS)	37 13 05	76 46 37	1	–272
62	58F50	Newport News Park 1 corehole (Meng and Harsh, 1988; unpub. data, T.S. Bruce, VDEQ, and D.S. Powars, USGS)	37 12 08	76 34 11	55	–1,423
63	58F67	Newport News Park 2 corehole (unpub. data, T.S. Bruce, VDEQ, and D.S. Powars, USGS)	37 12 08	76 34 11	52	–570
64	63F50	Kiptopeke corehole (Powars and others, 1992; unpub. data, D.S. Powars, USGS, and T.S. Bruce, VDEQ)	37 08 07	75 57 08	7	–1,993
65[1]	--	Airfield Pond corehole (unpub. data, J.S. Schindler, R. Weems, and D.S. Powars, USGS)	36 54 48	77 01 28	91	–130
66[1]	--	Mann Tract Monitor well #1 (unpub. data, D.S. Powars, USGS, and T.S. Bruce, VDEQ)	37 26 21	76 40 42	90	–1,225
67[1]	66M1	Taylor #1, Oil test well	37 53 03	75 31 01	42	–6,237
68[1]	--	Haynesville corehole (Mixon, Berquist, and others, 1989)	37 57 14	76 40 10	87	–469
69[1]	--	Oak Grove corehole (Reinhardt and others, 1980)	38 10 10	77 02 19	180	–1,180

[1]Borehole lies outside the study area and is not shown on figure 3.

Appendix 2. Altitudes of the tops of stratigraphic units

[Altitudes are in feet; ?, unit present, contact uncertain; --, unit not present; nd, no data available; ??, insufficient data; *, contact extrapolated from compilation of cross section *B–B'* ; Fm., Formation]

Borehole location number on figure 3	Potomac Fm.	Upper Cenomanian beds	Glauconitic sand unit	Red beds	Aquia Fm.	Marlboro Clay	Nanjemoy Fm.	Piney Point Fm.	Exmore tsunami-breccia deposit	Chickahominy Fm.	Delmarva beds	Old Church Fm.	Calvert Fm. Newport News unit	Calvert Fm.	St. Marys Fm.	Eastover Fm.	Yorktown Fm.	Pleistocene beds
1	–589	–438	–339	–292	–262	–252	–242	--	--	--	--	--	--	--	–122	–22	8	60
2	–560	–418	–361	–308	–289	–273	–269	--	--	--	--	--	--	--	–167	–27	15	33
3	–1,057	–845	?–795	?–715	?–584	?–570	?–555	--	--	--	?–540	??	??	?–521	?–306	–170	–30	10
4	nd	–985	–922	–815	?–771	?–754	?–738	--	--	--	?–721	??	??	??	?–318	?–183	?–60	7
5																		
6	–452	–294	--	--	?–279	?–268	?–231	--	--	--	--	??	??	--	?–118	?–24	6	26
7	–448	–324	--	--	–306	–290	–260	--	--	--	--	--	?–233	--	?–127	?–20	8	30
8	–550	?–378	--	--	?–365	?–352	?–340	--	--	--	--	--	??	??	?–202	?–50	–2	20
9	nd	?–599	–543	–495	–432	–420	–408	--	--	--	--	--	??	?–346	–205	?	?–39	17
10	–808	–644	–602	–504	–471	–452	–441	--	--	--	??	--	??	?–390	–222	?	?–44	16
11	–728	–626	--	–564	–508	–500	–464	--	--	--	??	--	??	?–416	–198	?	?–43	14
12	–1,035	–836	–778	–687	–645	–635	–620	--	--	--	–612	--	--	–600	–346	–172	–65	15
13	–375	–294	--	--	–254	–242	?–215	--	--	--	--	--	--	--	?–110	?–8	18	30
14	?–365	?–313	--	--	?–287	?–267	?–253	--	--	--	--	--	--	--	?–143	?–21	?21	43
15	–373	?–318	--	--	?–286	–269	–241	--	--	--	--	--	--	??	?–140	?–10	?–28	54
16	–458	?–346	--	--	?–326	?–300	?–282	--	--	--	--	--	??	??	?–156	?–57	?–6	24
17	–489	–334	--	--	??	?–295	?–285	--	--	--	?	?	–271	--	?	?	?–25	8
18	–454	–336	--	--	–320	?–297	?–269	--	--	--	--	--	??	??	?–120	?	?–30	20
19	–535	–415	--	--	?–365	?	?	--	--	--	nd	nd	nd	nd	nd	nd	nd	15
20	?–410	?–313	--	--	?–278	?–268	?–260	--	??	??	??	??	??	??	?–152	?–60	?2	22
21	–540	–397	--	--	–384	–372	–350	--	--	--	--	??	–339	–325	–186	–43	–24	17
22	–526	–407			–386	–378	–367	--	--	--	?	?	–349	–330	–186	–45	6	21
23	–534	?–446	?–423	?–388	–366	?–352	??	--	--	--	??	??	??	??	?–227	?–77	?	20
24	*–486	–378	--	--	–342	–333	–316	--	--	--	??	??	??	?–281	?–166	?–28	*–5	22
25	–467	?–391	--	--	?–360	?–347	?–344	--	??	??	??	??	?–334	?–304	?–194	?	–7	16
26	–604	–449	--	--	–433	–415	–382	--	--	--	??	??	??	??	?–242	?	?	20
27	?–735	?–572	--	--	?–525	?–511	?–495	--	27	17	??	??	??	?–459	–275	?–143	?–30	5
28	?–640	–487	--	--	–453	–448	–430	--	??	??	??	??	?–418	?–403	?–254	?–96	?–25	10
29	?–610	–515	--	--	–475	–462	–450	--	??	??	??	??	?–439	?–409	?–255	?–103	?	–15
30	nd	?–524	--	--	??	??	??	--	?–397	?–387	??	??	??	??	?–254	?	–7	10
31	?–775	–705	--	--	--	--	--	--	?–655	?–625	?–615	??	?	?	?–250	?	?–75	10
32	?–777	?–701	--	--	--	--	--	--	?–650	?–610	?–606	??	?–595	?–540	?–275	?–140	?–72	15
33	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	?–171	?–39	14
34	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	?–172	?–27	13
35	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	?–174	?–45	14
36	–1,110	?–949	--	?–859	--	--	--	--	??	??	??	??	??	?–700	–435	?–190	?	5

Appendix 2. Altitudes of the tops of stratigraphic units—Continued

[Altitudes are in feet; ?, unit present, contact uncertain; --, unit not present; nd, no data available; ??, insufficient data; *, contact extrapolated from compilation of cross section *B–B'* ; Fm., Formation]

Bore-hole loca-tion number on figure 3	Potomac Fm.	Upper Cenom-anian beds	Glauc-onitic sand unit	Red beds	Aquia Fm.	Marlboro Clay	Nan-jemoy Fm.	Piney Point Fm.	Exmore tsunami-breccia deposit	Chicka-hominy Fm.	Del-marva beds	Old Church Fm.	Calvert Fm. Newport News unit	Calvert Fm.	St. Marys Fm.	East-over Fm.	York-town Fm.	Pleisto-cene beds
37	?–363	?–251	--	--	–226	–212	?–180	--	--	--	--	--	--	--	–100	?	?40	50
38	–375	–263	--	--	–231	–220	–190	--	--	--	--	--	??	?–172	?–97	?–27	?45	75
39	??	–280	--	--	?	?	?–230	--	--	--	nd	nd	nd	nd	nd	nd	nd	nd
40	–356	?–300	--	--	?–258	?–238	?–218	??	??	??	??	??	??	?–210	?–124	?–36	?18	?40
41	??	?–325	--	?–252	?	?	?	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
42	?–425	?–298	--	--	–280	–262	–245	--	??	??	??	?–241	?–235	?	–182	–43	15	--
43	?–352	?–247	--	--	–227	–219	?–216	--	??	??	??	??	??	?	–144	–40	–4	35
44	??	?–297	--	–272	–247	?	?	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
45	?–418	?–305	--	–276	–255	–246	–208	--	--	--	nd	?	?–191	?	–149	–34	22	--
46	??	?–283	--	--	–253	?	?	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
47	?–568	?–433	--	--	?–413	?–405	?–398	--	??	??	??	??	??	?–373	–227	?	?	3
48	?–540	?–423	--	--	?–390	?–385	?–379	--	??	??	??	??	?–367	?–344	–210	?	?	15
49	–700	--	--	--	--	--	--	--	–574	–410	–392	–378	–368	–323	–228	–35	12	30
50	nd	--	--	--	--	--	--	--	–769	–654	–623	–613	–603	–540	–240	–85	–15	5
51	--	--	--	--	--	--	--	--	–925	–739	?	?–709	?–698	–647	?–317	?–177	?–51	11
52	--	--	--	--	--	--	--	--	?–910	–830	?	?	–810	?–508	? –290	? –160	?	–35
53	??	--	--	--	--	--	--	--	–837	–637	?–628	?–618	–607	?–400	–292	–95	–47	?3
54	?–265	?–232	--	--	?–215	?–204	?–175	--	--	--	--	--	--	--	–172	?–3	?27	85
55	–290	--	--	--	?	?	–245	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
56	?–355	?–295	--	--	?	?	–225	--	--	--	?	?	?–214	nd	nd	nd	nd	nd
57	–334	–250	--	--	–231	?	?	?	--	--	?	–169	–167	--	–105	?–18	49	70
58	–333	--	--	--	–270	–254	–212	–205	--	--	–196	–187	–168	? –162	–92	–66	--	34
59	?–355	--	--	--	?–293	?–277	–223	?–218	--	--	??	??	??	??	?–106	?	?	35
60	–330	--	--	--	–300	–286	–232	–215	--	--	?	–200	–185	–166	–125	??	--	–15
61	–258	--	--	--	–217	–203	–159	–152	--	--	--	–139	–120	?–115	–55	–24	--	–14
63	–411	--	--	--	--	--	--	--	–357	–323	–308	–293	–279	–216	–127	–19	25	52
64	--	--	--	--	--	--	--	--	–1,279	–1.077	–1,063	--	?–1,028	–613	–455	–189	–74	7

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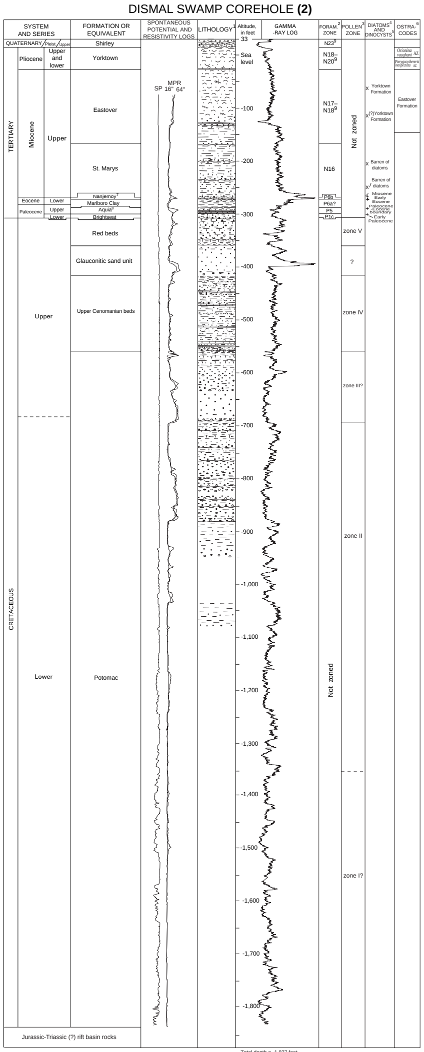
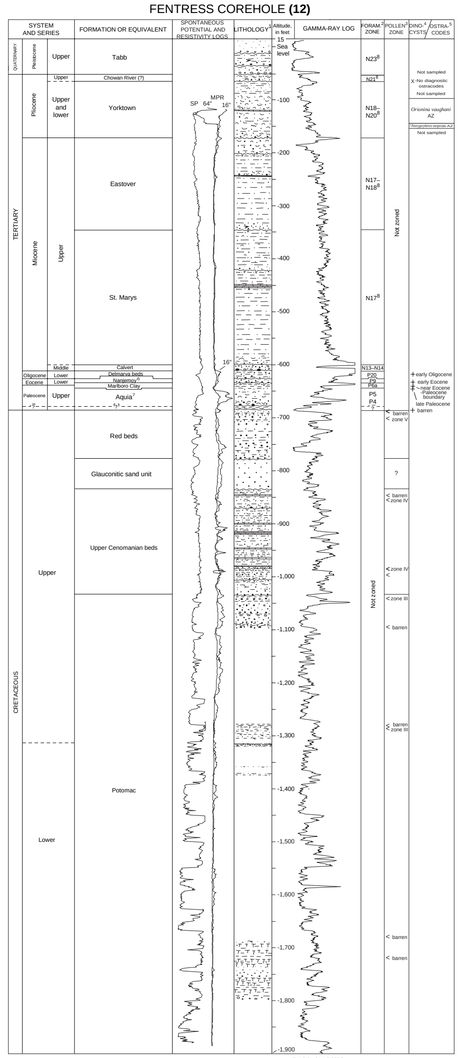
PROFESSIONAL PAPER 1622
Stratigraphic columns of three key boreholes—PLATE 1
Powars, D.S., 2000, The effects of the Chesapeake Bay impact crater on the geologic framework and the correlation of hydrogeologic units of southeastern Virginia, south of the James River

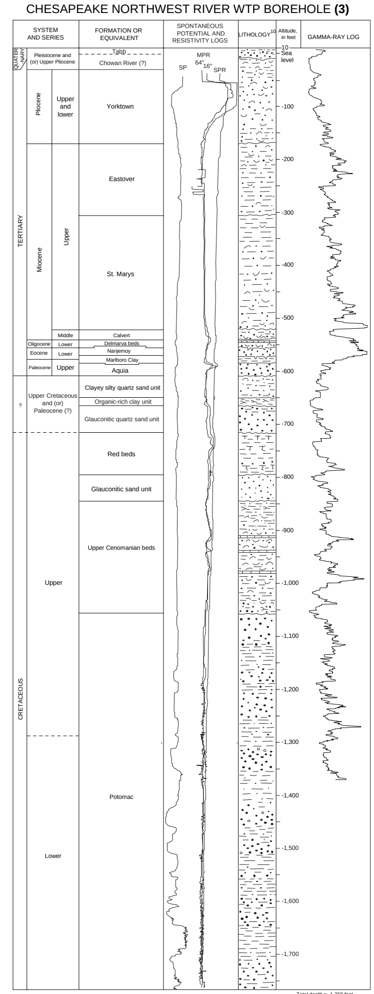
DISMAL SWAMP COREHOLE (2)

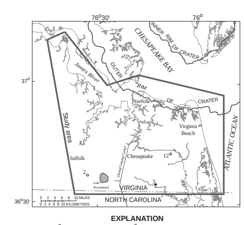


FENTRESS COREHOLE (12)



CHESAPEAKE NORTHWEST RIVER WTP BOREHOLE (3)





Location map of coreholes and borehole

EXPLANATION

LITHOLOGY

- CLAY
- CLAYEY SILT
- SANDY SILTY CLAY TO SANDY CLAYEY SILT
- CLAYEY SILTY SAND
- SAND: VERY FINE, FINE, MEDIUM, COARSE, VERY COARSE, GRANULES
- PEBBLES
- PALEOSOLS
- SHELLS
- *TURRITELLA*
- LIGNITIC MATERIAL
- INDURATED LAYER (GENERALLY CALCITE CEMENTED)
- BURROWED CONTACT
- SHARK TOOTH

SP	SPONTANEOUS POTENTIAL LOG—Negative to the left, positive to the right
SPR	SINGLE-POINT RESISTANCE LOG—Resistance increases to the right
MPR	MULTIPOINT RESISTIVITY LOG—16- and 64-inch multipoint resistivity log
N	FORAMINIFERA NEOGENE ZONE
P	FORAMINIFERA PALEOGENE ZONE
AZ	ASSEMBLAGE ZONE
x	DIATOM SAMPLE
+	DINOCYST SAMPLE
<	POLLEN SAMPLE

[1] Lithology shown is a generalized summary based on cored intervals. Dismal Swamp continuously cored down to -950 ft, and cored from -1,040 to -1,080 ft. Fentress continuously cored down to -1,109 ft, and cored from -1,275 to -1,375 ft and from -1,682 to -1,852 ft.

[2] Gibson, T., formerly USGS, now with Smithsonian Institution, written commun., 1990

[3] Frederiksen, N., USGS, written commun., 1999

[4] Andrews, G., USGS, written commun., 1989

[5] Edwards, L., USGS, written commun., 1989

[6] Cronin, T., USGS, written commun., 1995

[7] Potopaco Member

[8] Paspotansa Member

[9] Extrapolated from regional correlation including strontium isotope data.

[10] Lithology shown is a generalized summary based on a combination of lithic and geophysical data from several boreholes at the Northwest River Water Treatment Plant (WTP) site. Multipoint (16- and 64-inch) and spontaneous potential (SP) logs come from borehole **3** (61A15). The gamma log comes from borehole 61A18. Cuttings descriptions from borehole 61A15 and 61A18 were used from the surface down to - 990 ft. Core descriptions from borehole 61A16 were used from -990 to -1,524 ft. Drillers logs from borehole 61A2 were also used, especially for the interpretation shown for the base of the Tertiary. The geophysical logs guided a very generalized interpretation from -1,524 to -1,769 ft.

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STRATIGRAPHIC COLUMNS OF THREE KEY BOREHOLES

By
David S. Powars
2000