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The Effects of the Chesapeake Bay Impact Crater on the Geological Framework and Correlation of Hydrogeologic Units of the Lower York-James Peninsula, Virginia

By DAVID S. POWARS *and* T. SCOTT BRUCE

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

Multiply	*By*	*To obtain*
inch	25.4	millimeters
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), and intervals of time are expressed as m.y. (million years). Both terms mean 1,000,000 years or years $\times 10^6$. For example, sediments were deposited at 85 Ma (85×10^6 years before 1950 A.D.), and the deposition continued for the next 2 m.y.

THE EFFECTS OF THE CHESAPEAKE BAY IMPACT CRATER ON THE GEOLOGICAL FRAMEWORK AND CORRELATION OF HYDROGEOLOGIC UNITS OF THE LOWER YORK-JAMES PENINSULA, VIRGINIA

By D.S. Powars *and* T.S. Bruce

ABSTRACT

About 35 million years ago, a large comet or meteorite slammed into the western Atlantic Ocean on a shallow shelf, creating the Chesapeake Bay impact crater. The crater is now covered by Virginia's central to outer Coastal Plain sediments and the lower Chesapeake Bay. Descriptions of the location and geometry of the Chesapeake Bay impact crater are based on correlation of lithostratigraphic and biostratigraphic data from cores and well cuttings, borehole geophysical logs, and seismic-reflection data. The Chesapeake Bay impact crater is a 56-mile wide, complex peak-ring crater with an inner and outer rim, a relatively flat-floored annular trough, and an inner basin that penetrates the basement to a depth of at least 1.2 miles. The inner basin includes a central uplift surrounded by a series of concentric valleys and ridges. A line tracing of seismic-reflection data, including basement data down to 6.0 seconds two-way travel time, shows the seismic "fingerprint" of a bowl-shaped zone of intensely shocked basement rocks down to about 3.5 seconds two-way travel time (about 33,000 to 37,000 feet; 6.2 to 7 miles). The outer rim of the crater traverses the lower York-James Peninsula, which is the focus area of this report.

The structural and stratigraphic features created by the impact have influenced the hydrogeology, ground-water flow system, and water quality of a large part of the Virginia Coastal Plain. Regional flow paths have apparently been altered by emplacement of the possibly low permeability, lithologically heterogeneous Exmore tsunami-breccia deposits that are mixed with seawater, as well as by subsequent deposition of primarily very fine-grained deposits in the structural low. Differential flushing of seawater from the Coastal Plain sediments has 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 fresher, lower salinity water outside the outer rim.

The outer rim of the crater, characterized by a zone dominated by normal-faulted slump blocks, forms a buried, 1,000- to 4,000-foot escarpment. The geometry and slope of the escarpment vary around the perimeter of the Chesapeake Bay impact crater, from a steep wall to inward-stepping stairs, ranging in width from 0.5 to 1.9 miles. Lateral contacts between undisturbed stratigraphic units and syn-impact (at the time of the impact) units are complex. A narrow band (2.5 to 8 miles, generally less than 5 miles) of Exmore tsunami-breccia deposits is preserved around the outside of the crater's outer rim and is affected by the bounding fault zone and other faults that were apparently produced or reactivated by the impact. Pre-impact sediments of Early Cretaceous to middle Eocene age laterally abut syn-impact Exmore tsunami-breccia and the slumped terrace deposits (referred to herein as the Chesapeake Bay megablock beds) along the faulted escarpment of the outer rim of the Chesapeake Bay impact crater and the outer edge of the disruption boundary.

The crater's structural depression and subsequent structural adjustments since burial have controlled post-impact environmental depositional settings and stratigraphic relations within and among formations and are responsible for the higher subsidence rates in and adjacent to the crater. Post-impact units deposited across the disruption boundary thicken into the annular trough. The post-impact upper Eocene Chickahominy Formation caps the Exmore tsunami-breccia within the disruption boundary, and the upper Oligocene Old Church Formation is the first post-impact unit preserved across the disruption boundary west of the crater. Oligocene to lower Miocene deposits are coarse-grained across the western outer rim and outer part of the annular trough but become finer grained farther into the annular trough. More homogeneous, overall fine-grained middle to upper Miocene deposits prograde and thicken into the crater, reflecting a primary sediment source from the northwest to north.

Pliocene to Quaternary deposits show complex lithofacies distribution and thickness patterns that include thinner to coarser beds within 12.4 miles of the crater's outer rim. Pliocene deposits dip radially away from the center of the impact structure over regions several miles in width, resulting in dips that differ from the typical eastward regional dip of Cenozoic strata. The parallelism of Quaternary coast-facing scarps and their proximity to the outer rim, the stacked nature of some scarps near the outer rim, and the late Pleistocene and Holocene age of the surficial deposits inside the outer rim suggest the strong influence of episodic differential movement along and adjacent to the buried outer rim of the crater.

INTRODUCTION

The recent discovery of a large impact crater beneath the Chesapeake Bay has prompted a revision of the structural, stratigraphic, and hydrogeologic framework of a large part of the Virginia Coastal Plain. The Chesapeake Bay impact crater (CBIC) was formed when a large comet or meteorite crashed into shallow shelf-depth waters of the western Atlantic Ocean approximately 35 million years ago (Ma). The 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 set off trains of gigantic tsunamis and sent tremendous amounts of steam and ejecta into the atmosphere. The basement rocks lining the crater cavity were melted, and the basement rocks in a region beneath and around the crater were faulted and fractured. The impact produced an inverted, sombrero-shaped, 56-mi-wide complex crater that was immediately filled with chaotically mixed sediments and rim collapse material and eventually buried by younger sedimentary deposits. A complex crater is characterized by wall terraces, central peaks, and flat floors (Melosh, 1989), and the CBIC has all these features.

The Chesapeake Bay impact dramatically disrupted the Eocene and pre-Eocene sediments and rocks in the lower Chesapeake Bay region and influenced subsequent sediment deposition. The impact resulted in several regional anomalies: (1) a large crater, partly filled by impact and collapse debris; (2) mixing of Lower Cretaceous, Upper Cretaceous, Paleocene, and lower and upper Eocene sediments with seawater to form an impact tsunami-breccia; (3) a large area of anomalous water quality; (4) transformation of the depositional environment from inner neritic (shallow shelf) to bathyal (deep water) depths, in which fine-grained, low permeability sediments accumulated; and (5) a regional depression that persisted due to post-impact loading and differential compaction. These anomalies help explain the distribution of saline water in the Virginia Coastal Plain aquifers and need to be fully considered in any revisions of the conceptual hydrogeologic framework and existing ground-water-flow models of the aquifer system.

In 1997, the U.S. Geological Survey (USGS), in cooperation with the Hampton Roads Planning District Commission, began a study to obtain information that could be used to refine the geological and hydrogeologic frameworks of the Coastal Plain sediments in and near the impact crater. This information is critical to revisions of the existing ground-water flow models that have been used to guide water-supply management decisions.

The discovery of the buried, 56-mi-diameter CBIC revealed the inadequacy of the layer-cake, multi-aquifer model currently being used to represent the ground-water system of the Virginia Coastal Plain. The existing hydrogeologic framework and ground-water models were built upon a geological framework that described the Virginia Coastal Plain as an eastward dipping and thickening wedge of unconsolidated sediments, readily subdivided into uniform, homogeneous aquifers and confining units. The discovery of the crater disrupted this scenario and raises many questions concerning the crater's possible effects on eastern Virginia's ground-water system, such as effects on the aquifer system's flow system, hydraulic properties, and geochemistry. To understand these effects, the physical features created and affected by the impact crater must be defined and described. The geological framework must be refined in order to produce a new hydrogeological framework.

Purpose and Scope

This report documents the highly variable structure, stratigraphy, and buried topography of the outer rim of the Chesapeake Bay impact crater created by its impact and burial. Lithologies of cores are correlated with borehole geophysical logs to characterize the physical properties of the stratigraphic units and their geophysical signatures. The correlation between cores, well cuttings, and borehole geophysical logs is augmented with seismic-reflection data, and these data are compiled into a lithostratigraphic cross section that illustrates the geological framework of the lower York-James Peninsula and immediate surrounding areas.

Description of Study Area

The study area encompasses the central to eastern part of the Virginia Coastal Plain (fig. 1). The Chesapeake Bay and its tributaries subdivide this region into three large areas: the area west of the bay that has moderate relief (generally less than 250 ft); the lower portion of the Delmarva Peninsula (the landmass separating the Chesapeake Bay from the Atlantic Ocean) east of the bay that has low relief (up to 50 ft); and the area south of the bay and the James River that has low relief (generally less than 100 ft). The study area covers part of the south flank of the Salisbury embayment (a structural basement downwarp) and part of the north flank of the Cape Fear-Norfolk block (a structural basement high). The distribution of Lower and Upper Cretaceous and lower Paleogene deposits documents the existence of a pre-impact, east-west structural zone, approximately located along the James River, which represents the north flank of the Cape Fear-Norfolk block. Other major structural features of the basement include the Baltimore Canyon Trough (a major structural low), the Hatteras Basin, buried Triassic rift basins, a possible Paleozoic suture zone, and a few possible granitic plutons. The CBIC, nearly in the center of the study area, appears to be geomorphically expressed by concentric stacking of Pleistocene wave-cut scarps

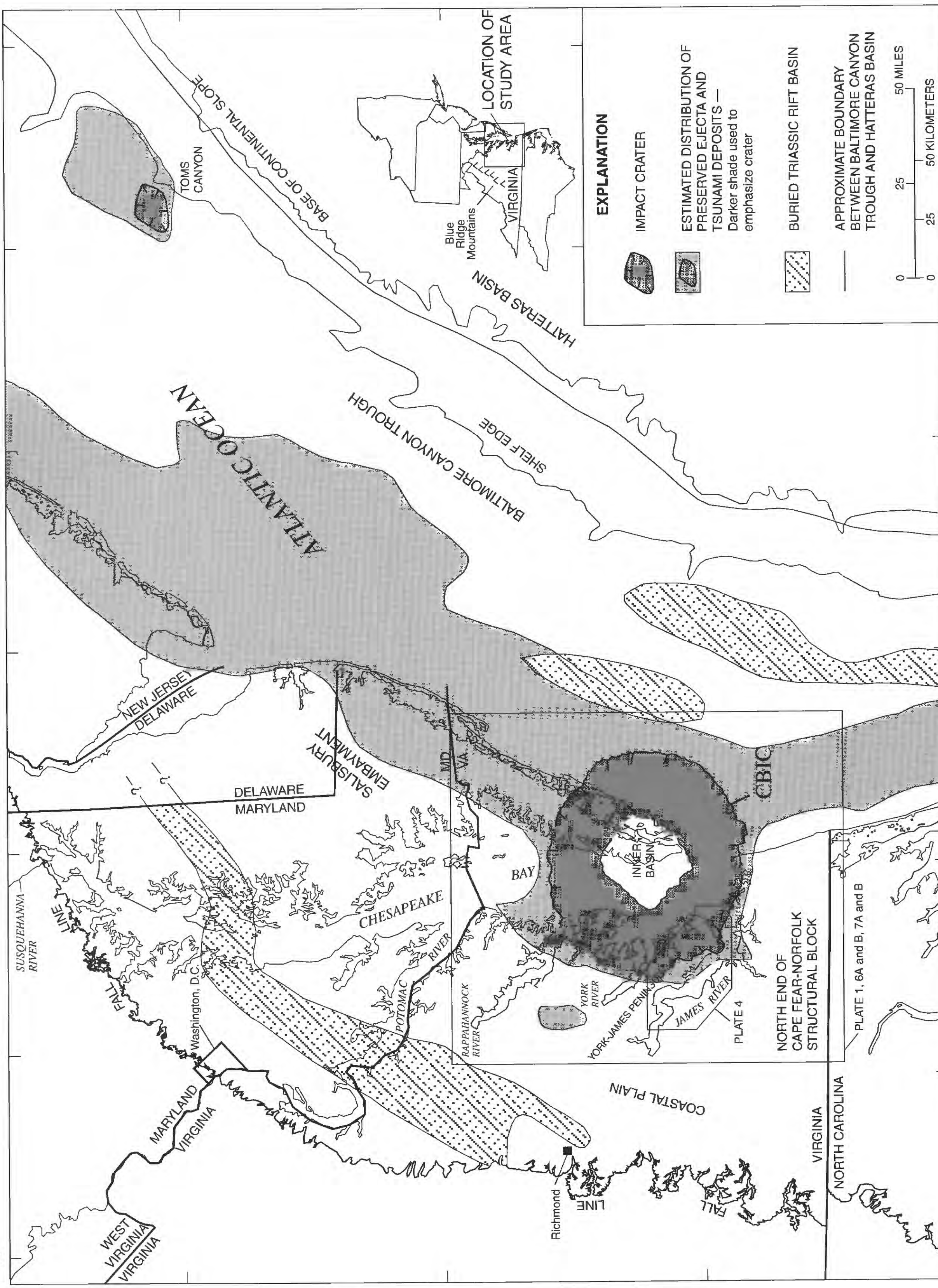

Figure 1. Location of the York-James Peninsula, the Chesapeake Bay impact crater (CBIC), and significant regional physiographic and geological features.

scattered around its outer rim. The CBIC also has had a major effect on the development of the mid-Atlantic rivers (from the Susquehanna River to the James River), which act as the regional drainage way to the sea that converges on the crater.

This report focuses on the lower York-James Peninsula and the immediate surrounding areas. The York-James Peninsula is bounded by the James River on the south, the York River on the north, and the Chesapeake Bay on the east (fig. 1). Pliocene and Pleistocene sea-level oscillations created a coast-parallel and river-parallel series of terraces and scarps across the peninsula. The 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 Holocene transgression, along with higher subsidence rates over the crater, has generally produced 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.

Previous Investigations

Many investigators have attempted to define regional- to county-scale geological and hydrogeologic settings in the Coastal Plain of Virginia, including the York-James Peninsula. Cederstrom's (1945b, 1957) work was the first comprehensive hydrogeologic investigation of the subsurface of the lower York-James Peninsula, and along with his other studies of southeastern Virginia (Cederstrom, 1945a, c), provides lithological logs from water well cuttings, including those he logged himself. His reports contain biostratigraphic data, including analysis of Foraminfera by J. A. Cushman (USGS), and water-quality data, including the initial delineation of Virginia's "inland salt-water wedge" and its associated Eocene-filled basin north of the James River. Until the late 1980's, knowledge of this region's subsurface geology was derived primarily from studies of water well cuttings and geophysical logs (Sinnott and Tibbitts, 1968; Brown and others, 1972; Meng and Harsh, 1988; Laczniak and Meng, 1988). Recent investigations have focused on refinement of the shallow geohydrologic framework (Brockman and Richardson, 1992; Brockman and others, 1997). Detailed mapping of the surficial units of the York-James Peninsula has been led by G.H. Johnson (Johnson, 1969, 1972, 1976; Johnson and others, 1980, 1982, 1987; Johnson and Ramsey, 1987).

From 1986 to 1992, analysis of a series of coreholes drilled by the USGS and the Virginia Department of Environmental Quality (VDEQ) has greatly changed our understanding of the geological framework of southeastern Virginia (Powars and others, 1987, 1990, 1991, 1992; Poag and others, 1992). Over the last 12 years, subsurface investigations of the Virginia Coastal Plain have been conducted by Federal, State, and local governments (including water well installation projects), oil companies, and local colleges and universities. These investigations culminated in the discovery 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).

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METHODS OF INVESTIGATION

The geological framework of the lower York-James Peninsula was redefined by analyzing stratigraphic and lithologic data from cores and well cuttings, borehole geophysical logs, and seismic-reflection profiles. Selected core intervals were sampled for mineralogic, biostratigraphic, and isotopic 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.

Compilation of Lithologic Data From Cores and Well Cuttings

Lithostratigraphic, biostratigraphic, and isotopic data derived from several continuously cored test holes with high recovery rates provide the stratigraphic control for this investigation (pl. 1). 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, unpub. data). 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, Jenkins Bridge, Fentress, Kiptopeke, Newport News Park 2, Windmill Point, Airfield Pond, and Jamestown. An additional continuously cored test hole was drilled for the City of Chesapeake as part of its Western Branch Aquifer Storage and Recovery (ASR) Project and is labeled MW4-1 on plate 1. This core also is stored at the USGS core-storage area in Herndon, Va. Three additional USGS coreholes listed on plate 1 are Haynesville (Mixon, Powars, and others, 1989), Clarks Mill Pond, and Essex Mill Pond (Powars and Newell, unpub. data, 1983–1986).

The borehole-numbering system in this report refers to a location number on plate 1 (printed in bold in the text, for example, **65**) and a local reference number, such as the USGS ground-water storage inventory (GWSI) number or the well number assigned in other reports (Cederstrom, 1945a, b, 1957). The GWSI is based on a system in which Virginia's 7-1/2-minute 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-minute quadrangle. As an example, well 58F50 is in quadrangle 58F and is the 50^{th} well in that quadrangle for which the location and other data were recorded by the USGS. Appendix 1A lists identifying information about the boreholes used in this report and includes both plate 1 location numbers and local numbers. Appendix 1B lists the altitudes of the tops of the stratigraphic units used in this report.

Lithologic and biostratigraphic data from selected cored intervals in three wells (**65**, **120**, and **116**) drilled by the VDEQ and three test holes (**31**, **43**, and **44**) drilled as part of a regional geothermal study done by the U.S. Department of Energy and Virginia Polytechnic Institute and State University provided additional stratigraphic control. Subsurface data consisting primarily of lithologic data from cuttings, borehole geophysical logs, and selected spot cores became available from a Brackish Groundwater Development (BGD) Project conducted by the City of Newport News. Between 1995 and 1997, 17 wells (58F81–58F97) were drilled for the BGD project. Sixteen of the wells (including **68**, a 1,350-ft-deep borehole) were installed at three well fields just outside the projected outer rim of the crater, and one well (**69**, a 1,300-ft-deep borehole) was installed just inside the projected outer rim of the crater. These wells are located within 3 mi of the Newport News Park 2 corehole, which along with seismic data, provided the control for stratigraphic interpretation of these wells.

Descriptions of borehole cuttings were interpreted by correlation to the coreholes and resulted in many reinterpretations of stratigraphic units published by Cederstrom (1943, 1945a, b, 1957) and Brown and others (1972) and of units listed in unpublished records of the Virginia Division of Mineral Resources (VDMR). The biostratigraphic data in these earlier reports were emphasized, while noting the potential for down-hole contamination. The detailed VDMR lithologic descriptions of washed samples are from mud-rotary drilled wells and clearly reflect down-hole contamination. Therefore, care was taken to look 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 also were 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(s)] or between wells, priority was given to cuttings descriptions that were made by an onsite geologist (primarily D.J. Cederstrom and T.S. Bruce, co-author of this paper). Emphasis also was 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 continuously cored test holes. 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 quality 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, 1957) and Brown and others (1972) and to unpublished VDMR, VDEQ, and USGS data. Conflicting data were encountered most often around the outer edge of the CBIC, especially for the boreholes located far from one of the continuously cored test holes. Interpretation of these lithic descriptions and geophysical logs provides the basis for the lithostratigraphic cross section presented in this report.

The number and type of geophysical logs varied greatly from borehole to borehole. Single-point resistance and natural gamma logs were the most abundant and, therefore, were used for establishing the geophysical signatures. Correlation also was made with multipoint resistivity, 6-ft lateral resistivity, and spontaneous potential logs.

Analysis of Seismic-Reflection Data

Seven multichannel seismic-reflection profiles released by Texaco, Inc., and Exxon Exploration Co. in 1993 and 1994 provide clear images of the position, morphology, and structure of the CBIC (pl. 1). These profiles were collected in 1986 by Teledyne Exploration and were all processed the same way for the oil companies (see Appendix 3). These profiles are based on 96-channel, 48-fold, common depth point (CDP), digital seismic data that are recorded in two-way travel time (twt). Six air guns providing 984 in^3 at 2,000 psi (pounds per square inch) were used as the energy source and hydrophone groups were 41 ft apart. Data from the top 0.1 second (twt) were not processed. Two additional multichannel seismic profiles that help define the CBIC were collected and processed by the USGS in 1982. These two profiles are based on 12-channel, 6-fold, digital seismic data that were collected by a 15-in^3 airgun and a 393.6-ft long hydrophone streamer. The profiles provide good images of the shallow depths and the top of the basement's surface in some places, but they are generally "noisy" below the shallow depths. The profile collected in the mouth of the James River, however, resolves the outer rim of the crater quite well, and this profile, along with those released from the oil companies, were used for synthesizing the geological framework presented in this report. In 1996, the USGS and the National Geographic Society collected more than 497 mi of seismic-reflection profiles in and around the CBIC; however, the authors of this report did not have access to those data.

The seismic-reflection data from the oil companies were correlated and calibrated to coreholes and boreholes and to synthetic seismograms published by Dysart (1981), Dysart and others (1983), Hansen (1978, 1988), and Hansen and Wilson (1990). It should be noted that until a sonic velocity log is obtained from a borehole inside the crater, there is uncertainty about correlation between the seismic data and the corehole and borehole data. The Windmill Point and Kiptopeke coreholes are located within 3.1 mi of a seismic line profile (pl. 1) and thus provide the best correlation possible at this time and the most probable range of depth equivalence for the seismic data.

For the area covered by these seismic lines, generally the top 0.1 second of twt is equivalent to 246 ft. Depth equivalence for the deeper, unconsolidated Coastal Plain sediments from 0.2 second twt to 0.9 second twt is about 262–328 ft. Depth equivalence for the crystalline basement down to 6.0 seconds twt is based on average stacking velocities for bedrock in this region ranging from about 10,000 to 20,000 ft/s (Parish

Erwin, Texaco, Inc., oral commun., 1994). According to Erwin, however, approximately the top 0.9 second twt represents Coastal Plain deposits; therefore, 1.5 seconds twt is most likely equivalent to between 6,000- to 8,000-ft-depth, and 2.0 seconds twt is equivalent to 10,000- to 12,000-ft-depth. It should be noted, however, that these depth conversion estimates are based on a regional average and are probably incorrect inside the crater. This caveat is based on Gorter and others' (1989) interpretation of the Tookoonooka Complex in southwest Queensland, Australia, which is a buried, 34.2-mi-wide impact crater; they found that the average seismic velocity within breccia infilling and peripheral slump blocks is significantly less than the internal velocities outside the crater.

The seismic data provide a view of the geometry of sedimentary strata, including the lateral continuity (or the lack of continuity) of strata and the structural aspects of the impact crater; for example, the crater's outer edge and inner edge escarpments and faults. The seismic data helped guide compilation of the stratigraphic cross section and the structure contour and isopach maps, especially from the outer edge of the crater inward. Wherever there are no seismic profiles that traverse the outer rim, the location of the outer rim is only approximate. In these areas, the location of the outer rim was guided by borehole data and by interpretations by Poag, Powars, Poppe, and Mixon (1994) and Poag (1996, 1997a, b).

CHESAPEAKE BAY IMPACT CRATER

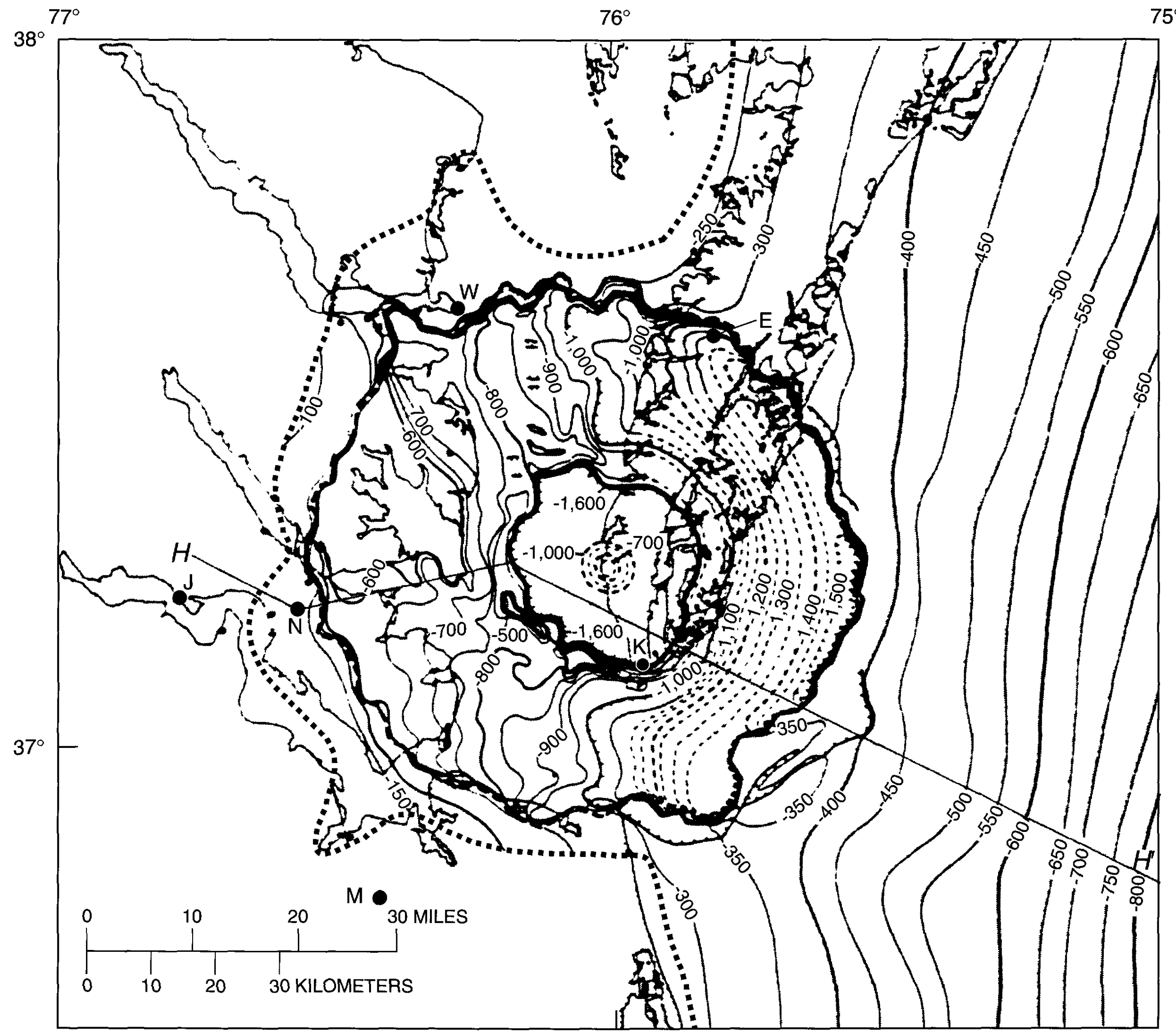
The 56-mi-wide CBIC is located beneath the lower Chesapeake Bay, its surrounding peninsulas, and the continental shelf east of the Virginia part of the Delmarva Peninsula (figs. 1 and 2*A*); the center of the crater is beneath the town of Cape Charles, Va. The recent discovery of the crater (Powars and others, 1993; Poag, Powars, and Mixon, 1994; Poag, Powars, Poppe, and Mixon, 1994) has led to a change in our understanding of the geological framework of the middle and outer Virginia Coastal Plain. The existence and location of the crater help explain structural, stratigraphic, and ground-water quality anomalies that had been previously described. These anomalies range from the distribution and abrupt thickening of stratigraphic units north of the lower James River and the mouth of the Chesapeake Bay (Cederstrom, 1945a, b, 1957; Powars and others, 1992); to complex facies relations of upper Tertiary units near the crater's buried outer rim (Johnson, 1972); to Virginia's inland salt-water wedge (Cederstrom, 1943); to the configuration and location of the Chesapeake Bay (Powars and others, 1993; Poag, Powars, Poppe, and Mixon, 1994). The correlations between the location, size, and structure of the CBIC and these features are excellent.

The first evidence of this impact crater came from the identification of shocked quartz in cores (G. Izett and L. Poppe, USGS, written commun., 1993) and structure contour and isopach mapping of the upper Eocene "Exmore beds" (herein named the Exmore tsunami-breccia) and the overlying upper Eocene Chickahominy Formation (D.S. Powars, unpub. data, 1990–92). In 1993 and 1994, Texaco, Inc., and Exxon Exploration Co. released to the senior author seismic-reflection profiles that traverse the bay and some of its major tributaries; these profiles provided the structural data to support an impact origin for the Exmore tsunami-breccia. Final confirmation came from the identification in cores of partially melted basement rocks and multiple deformation features in minerals from basement clasts (Koeberl and others, 1996).

The CBIC was created approximately 35 Ma, when a comet or meteorite struck the inner continental shelf producing a complex impact crater, ejecting a large amount of debris, and generating a series of gigantic tsunamis that spread the debris over most of the U.S. Atlantic shelf (the coastline was then west of the present-day Fall Line; Poag, Powars, Poppe, and Mixon, 1994). It is likely that the tsunamis reached and possibly overran the Blue Ridge Mountains. The high-velocity impact left an immense crater that is almost 1.3 mi deep and is partly filled with debris and tsunami deposits. The crater is underlain and surrounded by fractured and faulted basement rock (fig. 2*B*).

The impactor cut through Eocene to Cretaceous Coastal Plain sediments and into the underlying Proterozoic and Paleozoic crystalline 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 (Poag, Powars, and Bruce, 1994). This central depression also is referred to as the inner basin, which contains a series of concentric valleys and ridges that surround a central uplift (D.S. Powars, unpub. data, 1995). The slumped terrace zone is a product of the collapse of the crater's outer rim and the ensuing tsunami backwash, which spread large amounts of debris from the outer rim into the interior of the crater. The creation of a terrace zone occurs before the impact melt solidifies (Melosh, 1989). Research has shown that the terrace-like features of this zone are typical of the head-scarps of landslides that form in plastic materials

A



EXPLANATION

H——*H'* LINE OF SECTION

—-800— BASEMENT CONTOUR INTERVAL—Shows approximate altitude of Proterozoic and Paleozoic crystalline basement. Dashed where approximately located. Contour interval 50 meters (164 feet). Datum is sea level

▪▪▪▪▪▪▪▪ LIMIT OF THE PRESERVED EJECTA

J ● CONTINUOUS COREHOLE
J – Jamestown
K – Kiptopeke
W – Windmill Point
N – Newport News Park 2
E – Exmore
M – MW4-1 (Chesapeake)

Figure 2. Structure map showing Chesapeake Bay impact crater (modified from Poag, 1997b) (*A*) and generalized geological cross section (*B*).

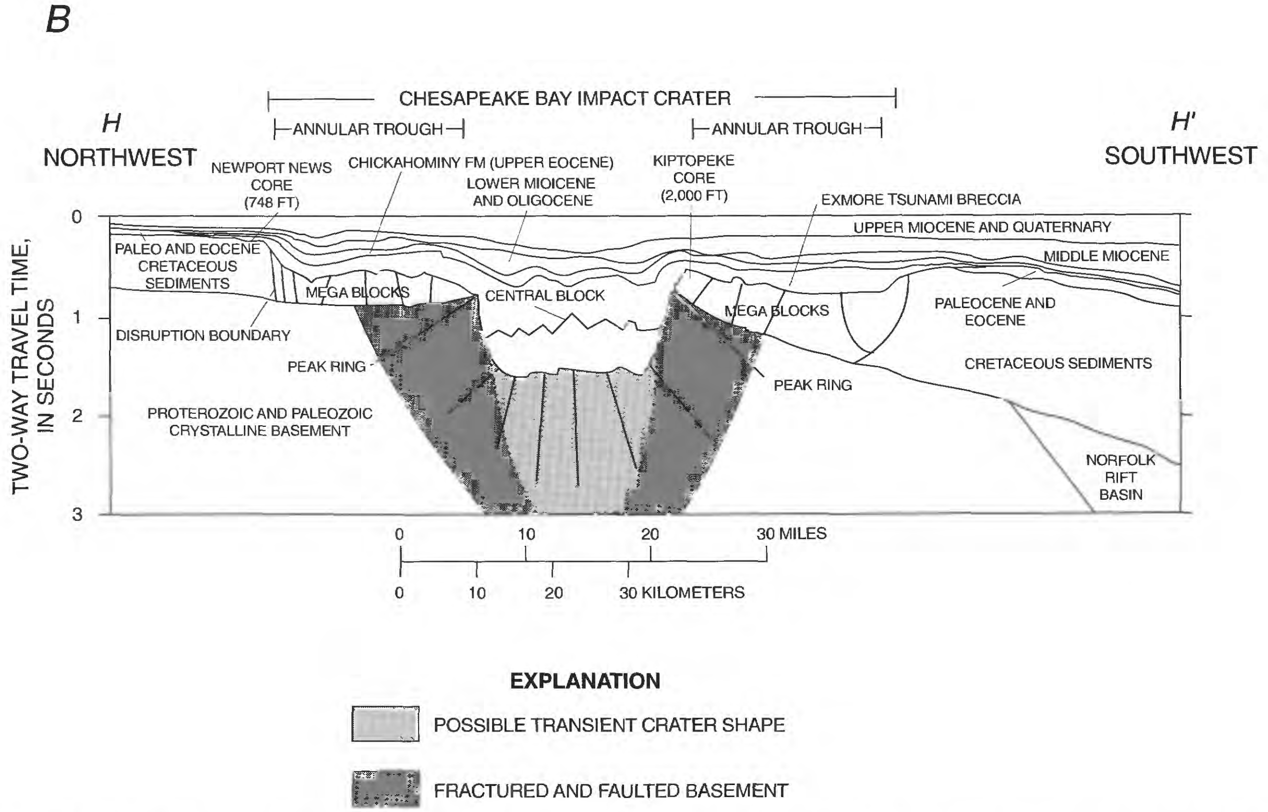


Figure 2. Structure map showing Chesapeake Bay impact crater (modified from Poag, 1997b) (*A*) and generalized geological cross section (*B*)—Continued.

such as water-saturated clays; this occurs even on the moon, where there is no water (Melosh, 1989).

The Exmore tsunami-breccia fills most of the inner basin and annular trough. Post-impact deposits from numerous marine transgressions across the lower mid-Atlantic Coastal Plain have buried the crater with about 1,300 to 1,600 ft of sediment. The seismic data show that most of these post-impact deposits dip concentrically into the crater, especially across the outer and inner rims. The post-impact deposits are commonly offset by numerous compaction faults (Poag, Powars, Poppe, and Mixon, 1994). For a more detailed description of the mechanics and stages of crater formation and breccia deposition, the reader is referred to Melosh (1989).

Plate 2 includes a line tracing of some of the basement seismic data down to 6.0 seconds twt and shows a bowl-shaped zone that most likely represents the transient crater and that extends down to about 3.5 seconds twt (about 33,000 to 37,000 ft; 6.2 to 7 mi). The transient crater is defined as the crater's maximum radial shape before gravitational collapse and includes material that is ejected (approximately one-third of the crater volume based on crater mechanics studies) and displaced basement rock (approximately two-thirds of the crater volume; Melosh, 1989). A zone of intensely shocked basement rock appears to extend down to nearly 5.0 seconds twt. The broad-sweeping, bowl-shaped reflections from 4.0 to 6.0 seconds twt also are found outside the area below the inner basin and, therefore, are not considered a product of the impact. Instead, these so-called "smiles" are apparently an artifact created by seismic-data processing.

A zone of concentric rings of ridges and valleys is typical for complex craters and represents the inner basin's floor for the Exmore tsunami-breccia. A melt zone may exist along this surface, which appears as broken, single to double, high-amplitude reflections. Poag (1997a) offers an alternative interpretation of this "fuzzy" seismic boundary as the contact between sediment-clast breccia overlying a crystalline-clast breccia. The inner basin is surrounded by a peak ring (raised rim) that varies in shape and relief. The south side of this ring shows the maximum known relief of about

575 ft and may represent overturned basement rock. The peak ring is faulted with possible underplating, which results when a segment of the basement is shoved into and under another basement segment. The high relief of the peak ring on the south side of the crater and the apparent underplating of the peak ring on the north side indicates an angled impact trajectory from the northeast (D.S. Powars, unpub. data, 1995). This trajectory is in line with the Toms Canyon impact crater offshore from New Jersey (fig. 1); this crater was formed at approximately the same time as the CBIC (Poag and others, 1993). On the basis of more than 497 mi of seismic-reflection profiles, Poag (1997b) delineated bulges in the outer rim and peak ring of the CBIC toward the northwest and southeast which according to Schultz and Anderson (1996), also suggests an impactor trajectory from the northeast (perpendicular to the bulge axis).

Geological Framework

The Coastal Plain deposits found in and around the CBIC can be grouped into pre-impact, syn-impact (at the time of the impact), and post-impact deposits. The pre-impact deposits include the Potomac (Lower and Upper Cretaceous), Aquia (upper Paleocene), Marlboro Clay (upper Paleocene and lower Eocene boundary), Nanjemoy (lower Eocene), and Piney Point (middle Eocene) Formations and informally named or unnamed Upper Cretaceous deposits. The syn-impact deposits are represented by the instantaneously deposited Exmore tsunami-breccia (upper Eocene) and the seismically defined CBIC megablock beds. The post-impact deposits include, in ascending order: the Chickahominy Formation (upper Eocene); the Delmarva beds (lower Oligocene); the Old Church Formation (upper Oligocene); the Calvert Formation (lower and middle Miocene); St. Marys (upper Miocene), Eastover (upper Miocene), Yorktown (lower and upper Pliocene), Chowan River and Bacons Castle (upper Pliocene), Windsor (upper Pliocene or lower Pleistocene), Charles City (lower Pleistocene), Chuckatuck (middle Pleistocene), Shirley (middle Pleistocene), and Tabb (upper Pleistocene) Formations; and unnamed Holocene strata. A correlation of stratigraphic units is given in table 1.

Figures 3, 4, and 5 show examples of the geophysical signatures characteristic of the stratigraphic units described in this report and the vertical stacking order of these units. Across the region, some of the marine units have very consistent lithologies and, therefore, consistent geophysical signatures, making them excellent regional marker beds. For example, the curvy nature of the single-point resistance line typical of the variably clayey Nanjemoy Formation and the clayey Marlboro Clay (figs. 3*A* and *B*) is typical across the region and contrasts with the flat multipoint resistivity and single-point resistance lines shown for the uniformly very clayey Chickahominy Formation (figs. 4*A* and *B*, and 5*B*). Another example is the overall fine-grained nature of the Calvert, St. Marys, and lower Eastover Formations, as reflected by low single-point resistance and multipoint resistivity-log responses (deflection to the left; figs. 3*A*, 4*B*, 5*B*). These fine-grained deposits grade upward into the sandy upper Eastover and lower Yorktown Formations, which have high resistivity-log responses (deflection to the right). Within these stacked marine sequences, strong gamma-log deflections (kicks) to the right commonly indicate a stratigraphic boundary overlain by a lag deposit that contains phosphate, sharks' teeth and bone, and sometimes glauconite.

Some consistent geophysical signatures are found in a group of stratigraphic units, as shown by the generally high single-point resistance, multipoint resistivity, and gamma signatures (all with strong deflections to the right). This is typical for the shelly glauconitic and/or phosphatic sands of the Piney Point and Old Church Formations, the Delmarva beds, and the lower Miocene beds of the Calvert Formation. These deposits are found consistently within and outside the western side of the crater and separate the clayey, siliciclastic middle to upper Miocene deposits (Calvert and St. Marys Formations) from the clayey, variably glauconitic Eocene deposits (Chickahominy and Nanjemoy Formations; figs. 4 and 5*B*).

Generally, the resistivity- and gamma-log signatures for the Exmore tsunami-breccia are quite variable and are not easily differentiated from the Aquia Formation or the Lower Cretaceous deposits. For example, in the southwest corner of the lower York-James Peninsula, Cederstrom (1957) had interpreted the sediments between –558 to –1,070 ft below sea level (bsl) of the Newport News Virginia Public Service Co. (Gas Works) well (**29**) as the Mattaponi Formation (Upper Cretaceous and Paleocene) based on lithic and Foraminifera data. Cederstrom logged this well from –360 to –1,070 ft bsl, and the Foraminifera were determined by J.A. Cushman. More recently, the borehole geophysical signature of the equivalent section (–475 to –870 ft bsl) in the nearby (approximately 1,000 ft to the north) Newport News City Hall well (**26**) has been interpreted as undisturbed Lower Cretaceous deposits (Meng and Harsh, 1988). Re-interpretation of the lithic and Foraminifera data from the 59D4 well identifies the section from –592 to –694 ft bsl as Exmore tsunami-breccia and, therefore, the section from –574 to –700 ft bsl in the nearby well (**26**) is interpreted as Exmore tsunami-breccia.

Locally, however, the resistivity log in well 58F82 (**69**) shows a subdued signature compared to the underlying, apparently undisturbed Lower Cretaceous deposits. In general, the Lower Cretaceous fluvial-deltaic deposits have a much more blocky appearance on their resistivity and gamma logs, reflecting in part the sharp nature of their sand-to-clay contacts.

Structural Complexities of the Outer Rim of the Crater

On the basis of nine seismic-reflection profiles (primarily five of the oil company lines) that traverse the outer rim of the CBIC, Poag (1996) described the highly variable nature of the outer rim. The outer rim is characterized by a zone of normal-faulted slump blocks (pl. 3). These encircle and are down-thrown into the annular trough, forming a buried escarpment that is easily differentiated from the nearly flat-lying seismic signature of the Coastal Plain deposits outside this disruption boundary (Poag, 1996, 1997a; D.S. Powars, unpub. data, 1995). The relief of the buried escarpment ranges from 1,000 to nearly 4,000 ft, and its width varies from about 0.5 to 2 mi (Poag, 1996). The geometry and slope of the escarpment in some places can be characterized as a steep wall; other parts of the escarpment resemble stairs stepping down into the annular trough. These variations are expected because the escarpment is most likely a product of the hydraulic erosion created by the oceanic water collapse and subsequent gigantic tsunamis. The competency of various sediments also may have influenced, to a smaller degree, the shape of the escarpment and of the disruption boundary that continues outside the outer rim of the crater.

Plate 3 shows an east-west stratigraphic cross section that extends from within the inner basin to beyond the disruption boundary (the boundary between pre-impact and syn-impact deposits). The section is based on corehole and borehole data correlated to two oil company seismic profiles (*C–C'* and *D–D'* on pl. 1). The York River profile portrays the geometry and structure of the crater's outer rim; the Chesapeake Bay profile shows an east-west cross section of the peak ring and inner basin. Because these profiles were processed for resolution of the deeper depths and show no data for about the top 0.1 second twt, the upper Miocene deposits are lumped with the relatively shallow and thin Pliocene and Quaternary deposits. As shown on the York River profile, post-impact deposits drape over the crater's outer rim and thicken in the crater; these deposits also sag and thicken into the inner basin, indicating ongoing crater subsidence during late Tertiary time.

A narrow band of preserved Exmore tsunami-breccia deposits surrounds the crater's outer rim; these deposits also are offset by the bounding fault zone and other faults apparently produced or reactivated by the impact. Two features indicating that structural instabilities persisted in this zone at least through late Tertiary time include stratigraphic anomalies found in upper Tertiary deposits outside the disruption boundary and faults that displace basement rocks and Cretaceous through upper Tertiary sediments observed in the seismic data north of the crater, where they reach outside the disruption boundary. The structural instabilities of the areas adjacent to the crater's outer rim are most likely a product of several factors: (1) the initial impact's faulting or reactivation of older faults; (2) post-impact basement structural readjustment; (3) post-impact differential compaction; and (4) post-impact differential movement of fault blocks. On the basis of seismic data gathered by the USGS, Poag (1997a) suggests that compaction faults penetrate the upper Eocene to Pleistocene post-impact deposits and nearly reach the Chesapeake Bay floor. For more details about the interpretations of the seismic profiles that traverse the crater's outer rim, the reader is referred to Poag (1996).

Table 1. Correlation of stratigraphic units

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

SYSTEM	SERIES		Geological units this report	Cederstrom (1957)	Brown and others (1972)	Mixon, Berquist, and others (1989)	+ Powars and others (1992)[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)
	Pleistocene	U	Tabb Formation	Columbia Group (Quaternary)		Tabb Formation	U: Kent Island Formation
		M	Shirley Formation			Shirley Formation	U: Wachapreague Formation
		M	Chuckatuck Formation			Chuckatuck Formation	U: Nassawadox Formation
		L	Charles City Formation			Charles City Formation	M: Omar Formation
		L	Windsor Formation			Windsor Formation	
						Moorings unit	
TERTIARY	Pliocene	U	Bacons Castle Formation			Bacons Castle Formation	
		U	CHESAPEAKE GROUP – Yorktown Formation: Moore House Member[2]	Yorktown Formation (Miocene)		Pliocene sand + gravel; CHESAPEAKE GROUP: Chowan River Formation	
		U	Yorktown Formation: Mogarts Beach Member			Yorktown Formation	
		U	Yorktown Formation: Rushmere Member				
		L	Yorktown Formation: Sunken Meadow Member				
	Miocene	U	Eastover Formation: Unnamed beds[3]			Miocene sand + gravel; CHESAPEAKE GROUP: Eastover Formation	
		U	Eastover Formation: Cobham Bay Member		Rocks of late Miocene age		
		U	Eastover Formation: Claremont Manor Member	St. Marys Formation (Miocene)			
		U	St. Marys Formation			St. Marys Formation	
		M	Calvert Formation[4]: 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 ChesapeakeBay
		M	Calvert Formation: Calvert Beach Member			Calvert Formation	
		M	Calvert Formation: Plum Point Member				
		M	Calvert Formation: Fairhaven Member				
		L	Calvert Formation: Newport News unit				
	Oligocene	U	Old Church Formation	?	?	Old Church Formation	

[1] From Powars and others (1992).
[2] Chowan River Formation.
[3] Unpublished data from D.S. Powars and T. Cronin (1995).
[4] Not present south of James River.

Table 1. Correlation of stratigraphic units—Continued

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

SYSTEM	SERIES		Geological units this report	Cederstrom (1957)	Brown and others (1972)	Mixon, Berquist, and others (1989) + Powars and others (1992)[1]	
TERTIARY	Miocene	L	Newport News unit of Calvert Fm	Calvert Formation (Miocene)	Rocks of Middle Miocene age (?)	Calvert Formation	
	Oligocene	U	Old Church Formation	? ?		Old Church Formation	
		L	Delmarva beds		?	Delmarva beds	
	Eocene	U	Chickahominy Formation	Chickahominy Formation (upper Eocene)	Rocks of Jackson age	Chickahominy Formation	
			Exmore tsunami-breccia			Exmore beds[1]	
			Exmore megablock beds	?			
		M	Piney Point Formation[4]	Pamunkey Group: Nanjemoy Formation (Eocene)	Rocks of Claiborne age	Piney Point Formation	
		L	Nanjemoy Formation		Rocks of Sabine age	Nanjemoy Formation	Woodstock Member[1] Potapaco Member[1]
			Marlboro Clay			Marlboro Clay	
	Paleocene	U	Aquia Formation	Aquia Formation (Eocene)		Aquia Formation	Pasapotansa Member[1] Piscataway Member[1]
		L	Brightseat Formation	? Mattaponi Formation (Paleocene + Upper Cretaceous)	Rocks of Midway age	Brightseat Formation	
CRETACEOUS	Upper		Unnamed Upper Cretaceous beds[5]		Rocks of unit A Rocks of unit B Rocks of unit C Rocks of unit D		Red beds[1] Glauconitic sand unit[1]
			Upper Cenomanian beds[5]	? Potomac Group (Upper Cretaceous)	Rocks of unit E		Upper Cenomanian beds[1]
	Lower		Potomac Formation	Potomac Group (Lower Cretaceous)	Rocks of unit F Rocks of unit G Rocks of unit H	Potomac Formation	
MESOZOIC	Lower		Lower Mesozoic rift-basin deposits				
PALEOZOIC AND PROTEROZOIC			Crystalline basement rocks				

[1]From Powars and others (1992).
[2]Chowan River Formation.
[3]Unpublished data from D.S. Powars and T. Cronin (1995).
[4]Not present south of James River.
[5]Not present north of James River.

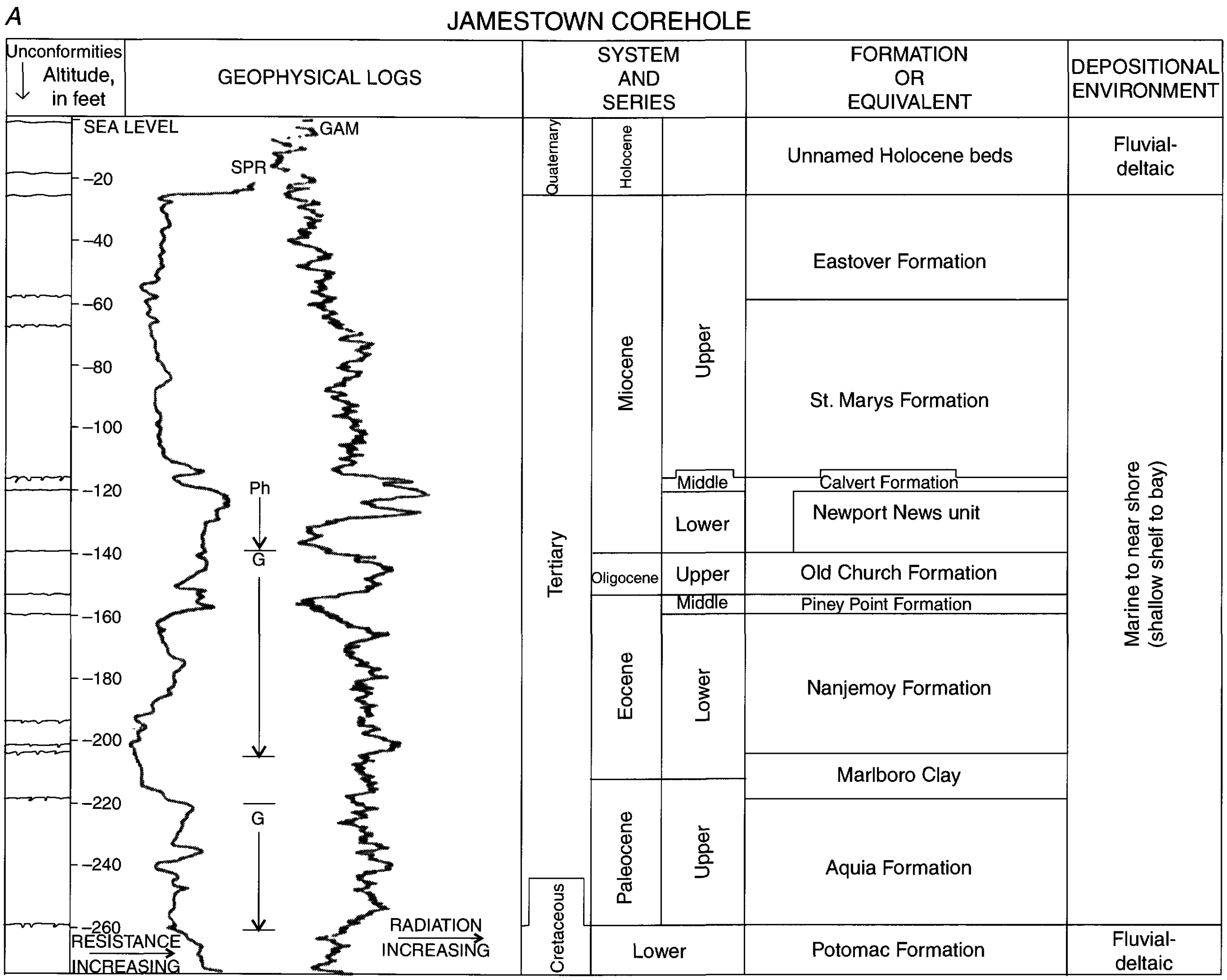


Figure 3. Borehole geophysical signature typical of undisturbed stratigraphic units outside the disruption boundary that separates pre-impact from syn-impact deposits; Jamestown (*A*) and MW4-1 (*B*) coreholes. See plate 1 for location of coreholes.

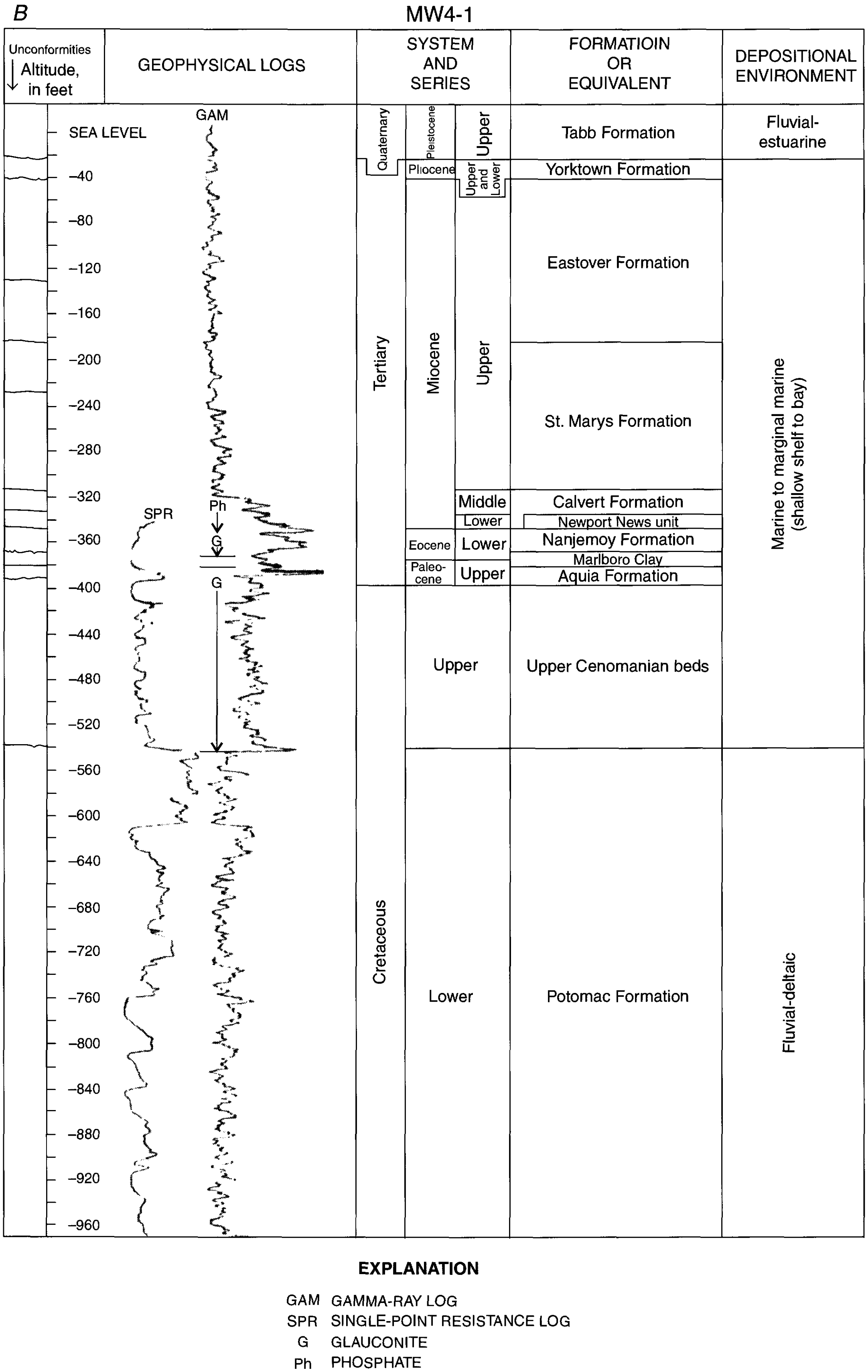


Figure 3. Borehole geophysical signature typical of undisturbed stratigraphic units outside the disruption boundary that separates pre-impact from syn-impact deposits; Jamestown (*A*) and MW4-1 (*B*) coreholes. See plate 1 for location of coreholes—Continued.

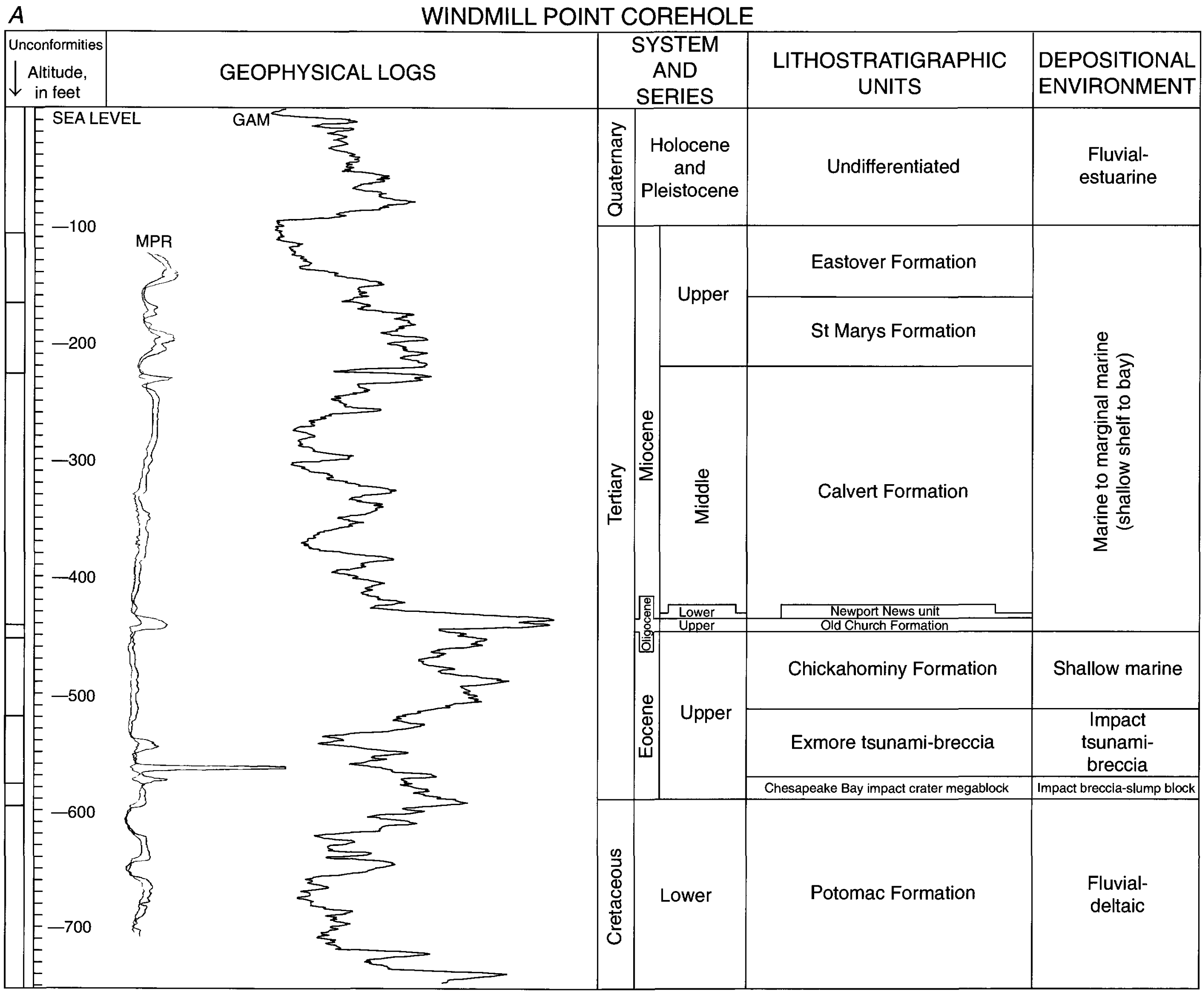


Figure 4. Borehole geophysical signature typical for stratigraphic units located outside the crater's outer rim but within or above the disruption boundary that separates pre-impact from syn-impact deposits: Windmill Point (*A*) and Newport News Park 2 (*B*) coreholes. See plate 1 for location of coreholes.

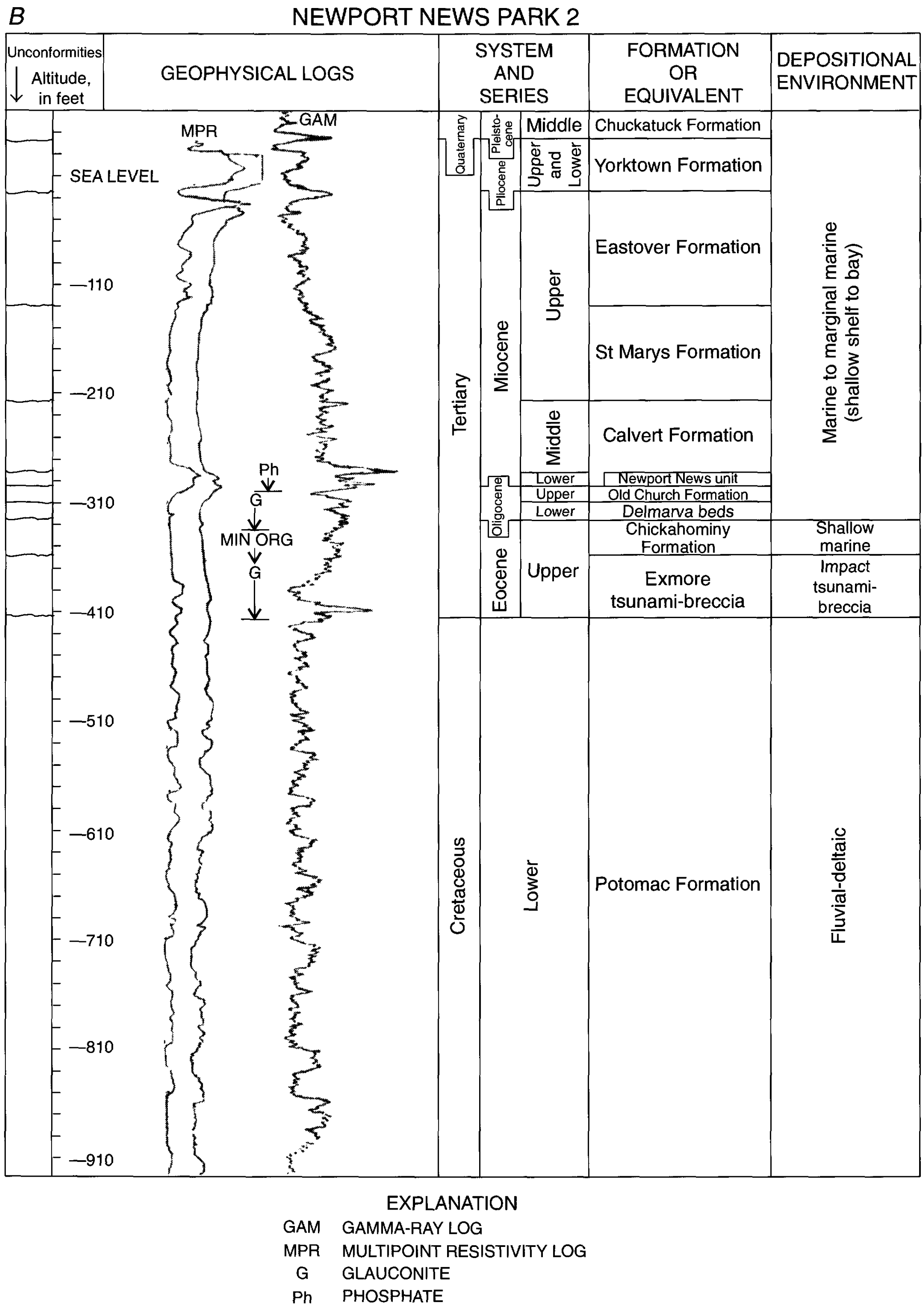


Figure 4. Borehole geophysical signature typical for stratigraphic units located outside the crater's outer rim but within or above the disruption boundary that separates pre-impact from syn-impact deposits: Windmill Point (*A*) and Newport News Park 2 (*B*) coreholes. See plate 1 for location of coreholes—Continued.

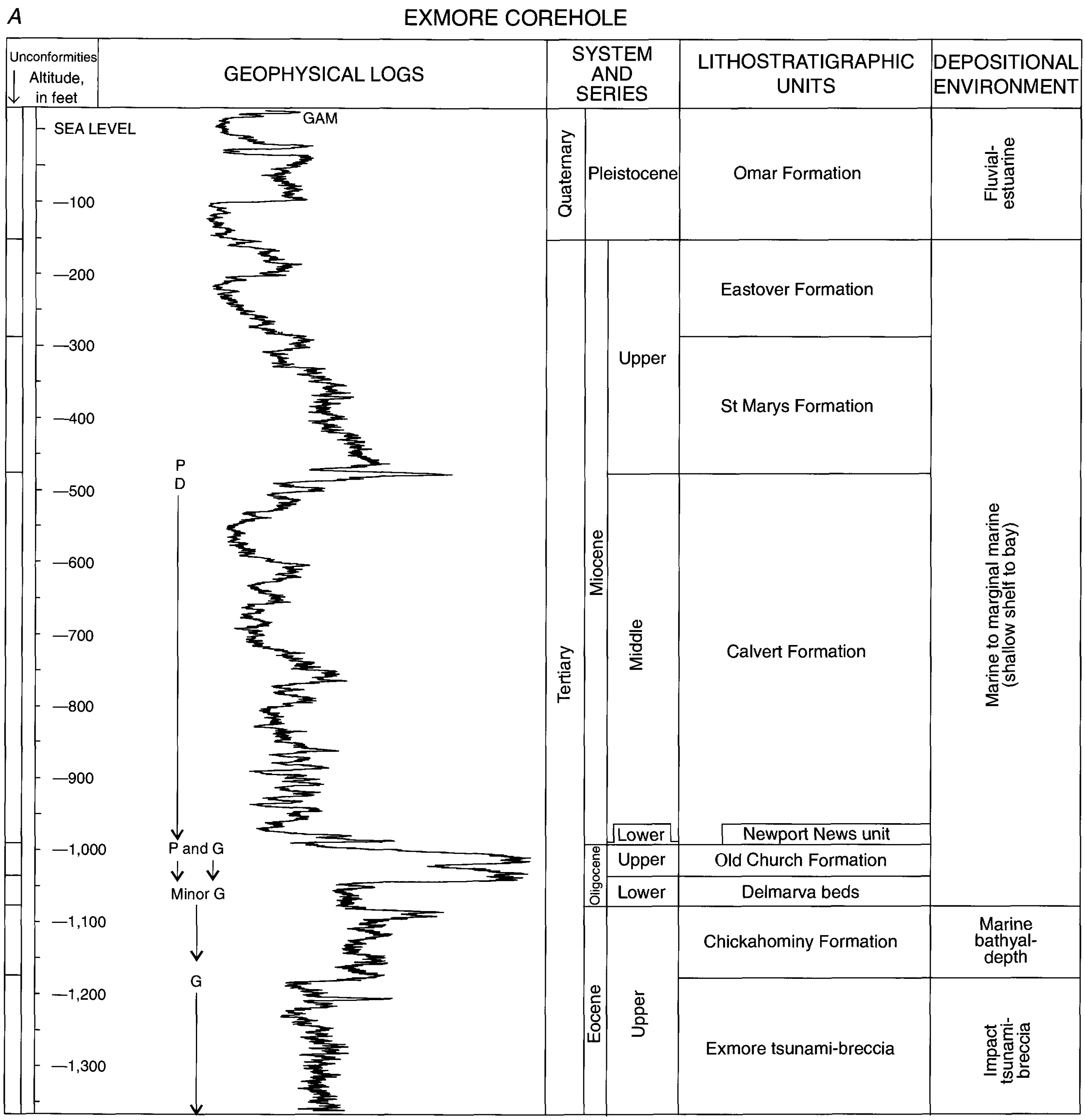
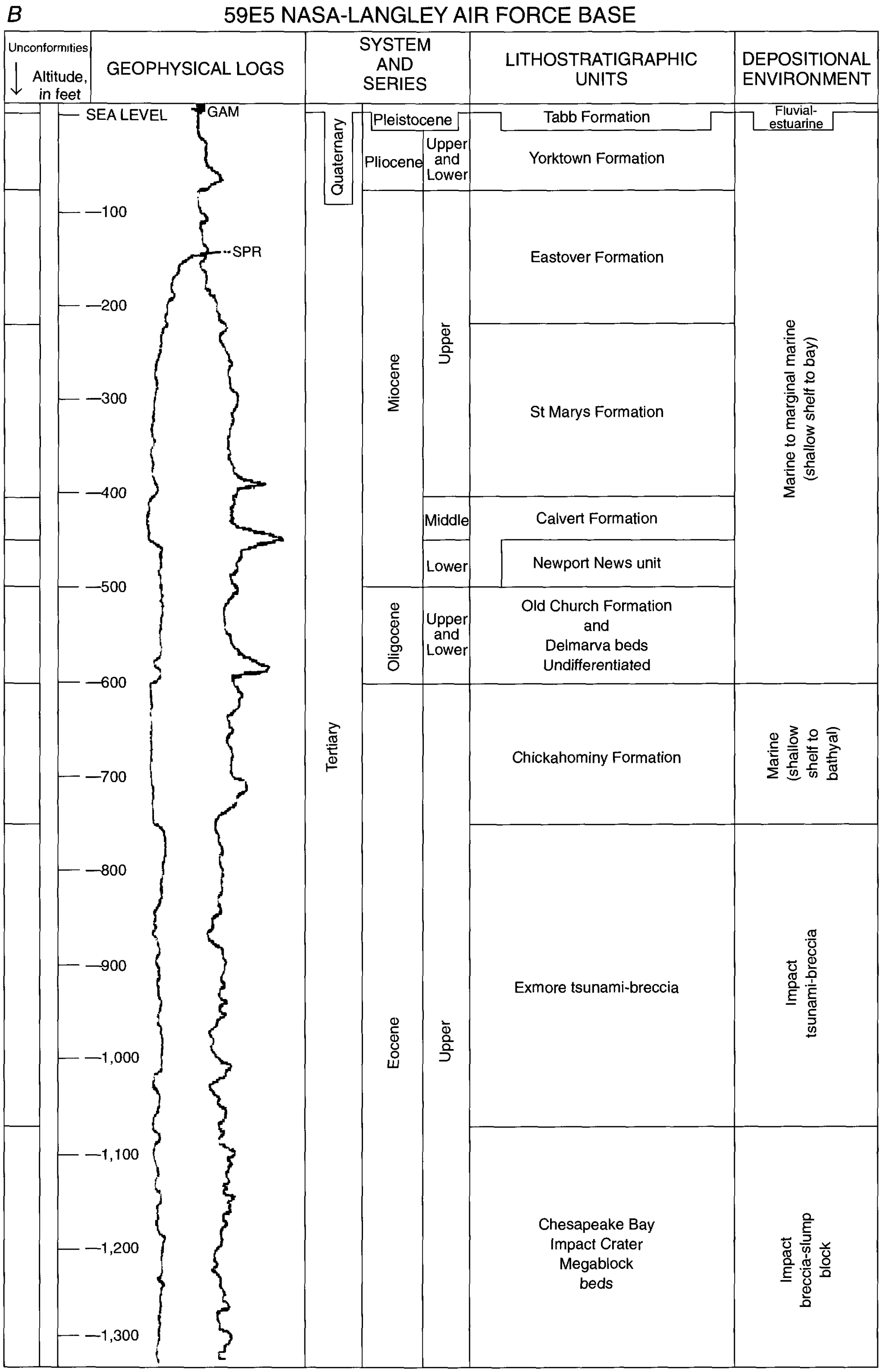


Figure 5. Borehole geophysical signature typical for stratigraphic units located just inside the crater's outer rim, Exmore corehole (*A*) and the 59E5 NASA-Langley Air Force Base (*B*). See plate 1 for location of coreholes and boreholes.



EXPLANATION

GAM GAMMA-RAY LOG
SPR SINGLE POINT RESISTANCE LOG
G GLAUCONITE
Ph PHOSPHATE
D DIATOMS

Figure 5. Borehole geophysical signature typical for stratigraphic units located just inside the crater's outer rim, Exmore corehole *(A)* and the 59E5 NASA-Langley Air Force Base *(B)*. See plate 1 for location of coreholes and boreholes—Continued.

GEOLOGICAL FRAMEWORK OF THE LOWER YORK-JAMES PENINSULA

The following sections describe the lithology and extent, borehole geophysical signatures, and seismic interpretations for each stratigraphic unit. The stratigraphic differences between the undisturbed zone outside the disruption boundary across the outer rim of the crater, and the zone inside the crater are briefly discussed.

Cretaceous Deposits

Only Lower Cretaceous deposits are distributed beneath the lower York-James Peninsula north of the James River, whereas on the south side of the river, both Lower and Upper Cretaceous deposits are distributed. 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 northward sharply as it crosses the outer rim and into the crater. The location, however, of the preserved limit of the Exmore tsunami-breccia somewhere beneath the river is uncertain. The concentration of borehole data extending from the Newport News Park reservoir to the Busch Gardens area (pl. 4) allows a fairly precise location of the preserved limit of the Exmore tsunami-breccia in this area.

The Cretaceous deposits are underlain by Paleozoic and Upper Proterozoic crystalline basement rocks. The Lower Cretaceous Potomac Formation consists of a complex updip array of fluvial-deltaic deposits that intertongue downdip (eastward) with thin glauconitic sands typical of shallow shelf deposits. In Virginia, downdip areas outside the CBIC include beds of earliest Late Cretaceous age. The Lower Cretaceous deposits extend across the region, except where disturbed by the impact, forming an east-northeast dipping wedge that ranges from a feather edge along the Fall Zone to more than 4,700 ft thick in the Taylor #1 oil test hole (**136**) located near the NASA Wallops Flight Facility on Virginia's Eastern Shore (Powars and others, 1992).

As is typically found in continental deltas, these deposits primarily consist of fining-upward sequences that are highly variable in their lithology and thickness. These deposits are interpreted as representing 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). As noted in most previous studies of the Chesapeake Bay region, it is difficult to correlate among and subdivide these deposits, even over a short distance. This is due in part to the similarities of the lithic facies and the paucity of biostratigraphic data. Pollen is the only biostratigraphic indicator found consistently in these continental fluvial-deltaic deposits. Development and refinement of a pollen zonation for these deposits (Brenner, 1963; Robbins and others, 1975) have given more recent investigations 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 K1, I, II, III, IV), and their corresponding "formations" (Brenner, 1963). 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.

Regionally, the Cretaceous section includes Upper Cretaceous deposits that are relatively thick south and southwest of the crater (up to 350 ft in the Fentress corehole); relatively thin (121 ft in the Jenkins Bridge corehole) north of the crater beneath the Delmarva Peninsula; and apparently absent west of the crater. Lower Cretaceous core samples (at −455 ft and −648 ft bsl) from the Newport News Park 1 borehole (**65**) documented that pollen zone I is present nearly to the top of the Cretaceous section (L.A. Sirkin, Adelphi University, written commun., 1983). This implies that the entire Cretaceous section there (about 1,300-ft-thick) is represented only by pollen zone I; however, the older pollen zone K1 may be present. The authors have found no documentation of Upper Cretaceous deposits in Virginia west of the Chesapeake Bay and north of the James River. The absence of pollen zones II, III, and IV in that area suggests a need to re-evaluate Meng and Harsh's (1988) hydrogeologic subdivision of Lower Cretaceous deposits outside the outer edge of the crater and their inter-regional correlations. Subdivision of these units, 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 correlation and recognition of depositional patterns and settings that guided the delineation of the hydrogeologic units of the Potomac Formation.

Cederstrom (1945a, 1957) suggested a Late Cretaceous to Paleocene age for his Mattaponi Formation; however, coreholes relatively close to the type wells (Reinhardt and others, 1980; D.S. Powars and R.B. Mixon, unpub. data, 1982–1986) indicate normal undisturbed sequences of stratigraphic units (in descending order: Aquia, Brightseat, and Potomac Formations). The "older Foraminifera" on which Cederstrom based his interpretations belong to the Aquia (upper Paleocene) and Brightseat (lower Paleocene) Formations. Beneath the lower York-James Peninsula, the unit Cederstrom (1945b, 1957) mapped as the Mattaponi Formation actually represents Potomac to lower Miocene deposits outside the preserved limit of Exmore tsunami-breccia deposits. Inside this preserved limit and inside the crater, the Mattaponi Formation is equivalent to the Exmore tsunami-breccia deposits.

Potomac Formation— Lower Cretaceous Deposits

The Cretaceous deposits beneath the lower York-James Peninsula outside the CBIC megablock beds of the slumped terrace zone consist of fluvial-deltaic deposits of Early Cretaceous age. These deposits extend across the region, forming an eastward-thickening wedge that ranges from about 1,250 ft beneath the Jamestown to Williamsburg area to about 1,900 ft at the crater's outer edge beneath the Newport News-Williamsburg International Airport to the Hampton area (pl. 4).

The fluvial-deltaic deposits are primarily made up of fining-upward sequences that consist 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, with accompanying 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 deposits are re-interpreted as sediments disturbed by the impact. Poag (1996, 1997c) refers to these materials as a "mega-block zone"; this report informally names these deposits the "Chesapeake Bay impact crater megablock beds" (CBIC megablock beds). These deposits are considered an Eocene stratigraphic unit because the slump blocks are transported and rapidly emplaced by impact cratering processes that most likely mixed them with some Exmore tsunami-breccia and melt.

Differentiation of the Lower Cretaceous fluvial-deltaic deposits from the overlying Aquia Formation or the Exmore tsunami-breccia deposits is difficult when using only geophysical logs. In general, the Lower Cretaceous deposits have more blocky, thicker stratified resistivity- and gamma-log signatures than the more subdued, thinner stratified log signatures of the Exmore tsunami-breccia deposits (pl. 4). Resistivity and gamma logs of the Lower Cretaceous deposits show numerous (about 5- to 100-ft-thick), gradational fining-upward sequences that typically have sharp contacts between the tops of the clays and the basal sands of the next sequence. These logs also reflect large-scale fining-upward cycles (about 100- to 200-ft-thick) that are typical for the Lower Cretaceous deposits but not apparent in the logs interpreted as Exmore tsunami-breccia deposits. The saw-toothed appearance of the resistivity and gamma logs of the Lower Cretaceous deposits reflects their highly stratified, commonly relatively thin-bedded nature and contrasts with the more subdued signature of the more heterogeneous Exmore tsunami-breccia. Outside the outer rim of the crater, the thinness of the Exmore tsunami-breccia and Aquia Formation makes differentiation very difficult, and emphasis is placed on lithostratigraphic correlations to the Jamestown and Newport News Park 2 coreholes. The quartzo-feldspathic sands and tough, multicolored clays of the Lower Cretaceous deposits lithically contrast well with the glauconitic, shelly Aquia Formation and Exmore tsunami-breccia deposits.

South of the James River and the Chesapeake Bay, relatively thick Upper Cretaceous marine and fluvial-deltaic deposits overlie Lower Cretaceous fluvial-deltaic deposits. The Upper Cretaceous fluvial-deltaic facies exhibit a sporadic, patchy distribution, and intertongue with the marine facies that have a more consistent distribution. Where the thin-bedded, glauconitic, shelly, marine Upper Cretaceous deposits overlie the thicker bedded, fluvial-deltaic Lower Cretaceous deposits, the resistivity and gamma logs reflect these lithostratigraphic differences. Where Upper Cretaceous deltaic deposits overlie Lower Cretaceous fluvial-deltaic sediments, differentiation is quite difficult, and one must rely on careful analysis of the lithic log and data from nearby wells. Generally, the marine Tertiary and Upper Cretaceous deposits have consistently higher gamma logs (deflection to the right) and are thinner bedded compared to the fluvial-deltaic Lower Cretaceous deposits. The fact that both of these units underlie the Chickahominy and Nanjemoy-Marlboro marker units throughout the area also is a helpful guide.

Because of limited borehole and geophysical log data from inside the crater and because of the lithic similarities between undisturbed Lower Cretaceous deposits and the CBIC megablock beds, these units are primarily differentiated on the basis of seismic-reflection data. A subtle dampening of the resistivity- and gamma-log signatures for the deposits interpreted as CBIC megablock beds distinguishes them from Lower Cretaceous deposits.

Seismic reflections of undisturbed Lower Cretaceous deposits are characterized by relatively high-amplitude, relatively discontinuous, coherent, horizontal to sub-horizontal reflections that generally contrast well against the chaotic reflections of the Exmore tsunami-breccia or the very continuous, unbroken, parallel, horizontal reflections of the overlying marine Cretaceous and Tertiary units. The highly variable escarpment of the outer rim of the crater separates disturbed from undisturbed deposits and is marked seismically by a disruption boundary characterized by faults on the York River profile (pl. 3). The authors of this study concur with Poag's (1996, 1997a) interpretation that scattered, high-amplitude, horizontal and diagonal reflections and refractions below the tsunami-breccia deposits represent slumped megablocks (primarily Lower Cretaceous deposits) that cover the floor (basement surface) of the annular trough. The top of the crystalline basement is marked by two, closely spaced, parallel, high-amplitude reflectors that are in sharp contrast with the seismic signatures of the overlying undisturbed Lower Cretaceous deposits, the disturbed CBIC megablock beds, or the Exmore tsunami-breccia deposits (pl. 2).

Unnamed Upper Cretaceous Deposits

Upper Cretaceous deposits south of the James River younger than pollen zone III (lower Cenomanian) are documented in the subsurface south and southwest and northeast of the outer rim of the crater extending westward to central Southampton County and eastern Surry County (Powars and others, 1992; fig. 6). These deposits form an eastward-thickening wedge ranging from about 10 ft thick updip to 348 ft thick at the Fentress corehole downdip (Powars and others, 1992). Based on data from three coreholes (Dismal Swamp, Fentress, and MW4-1), Powars and others (1992) subdivided these Upper Cretaceous deposits into three lithic units. In ascending order, they are (1) upper Cenomanian beds consisting of marine and deltaic deposits, (2) a glauconitic sand unit, and (3) red-bed fluvial-deltaic deposits that include multiple paleosols. The upper Cenomanian beds (100 to 200 ft thick) are found in all three coreholes and appear to have the most consistent distribution of the three units. Thin (less than 75 ft thick) Paleocene and lower Eocene marine strata locally overlie the Upper Cretaceous deposits south of the James River.

The upper Cenomanian beds (pollen zone IV) contain shallow-shelf to marginal-marine to deltaic-lagoonal deposits. The marine deposits contain index macro- and microfossils that allow local and regional correlation of this unit. The deposits consist of thinly laminated to thick-bedded, olive-gray to light- to dark-gray and black silt, clay, and very fine to coarse sand containing variable amounts of glauconite, mica, shells, microfossils, wood (lignitic material), burrows, and pyrite. Many of the sandier shell beds and shell hashes (storm deposits) are cemented by calcium carbonate. These indurated beds are generally reflected on resistivity logs by thin, sharp spikes to the right. The deltaic-lagoonal deposits are so micaceous that they impart a greasy feel to the core and cuttings and enhance recognition of the unit in well cuttings. In the MW4-1 corehole, only the upper Cenomanian beds were encountered (pl. 5).

The MW4-1 core and borehole geophysical logs provide the information needed to correlate stratigraphic units south of the James River. The MW4-1 data were used to interpret the lithostratigraphy of well 58D9 (**22**), at the southern end of cross section *E–E'* shown in plate 4. The resistivity and gamma logs generally reflect numerous fining-upward sequences, which are represented in the cores as glauconitic shelly sands that grade upward into clayey silts to silty clays. Differentiation of these sequences from overlying similar marine Paleocene or Eocene deposits is very difficult. Differentiation of the Upper Cretaceous marine sequences from the underlying thicker bedded, fluvial-deltaic Lower Cretaceous deposits is easier and is reflected in the resistivity- and gamma-log responses to these very different lithostratigraphic units. In general, the resistivity logs of the upper Cenomanian beds reflect an overall thick, fine-grained section punctuated with thin, indurated or slightly sandier layers. The Cenomanian logs contrast well with the blocky, more distinct sand and clay logs of the fluvial-deltaic deposits. The gamma logs also show a consistently higher (deflection more to the right) signature for the upper Cenomanian beds compared to the Lower Cretaceous deposits.

Definitive ages for the glauconitic sand and red-bed units have not been determined, but these units overlie strata of late Cenomanian age and underlie strata of Danian age. The glauconitic sand unit is generally 55 to 60 ft thick and the uppermost red-bed unit is 50 to 100 ft thick, but both units have a sporadic patchy distribution and were not penetrated in the MW4-1 corehole. The glauconitic sand unit is a loose, fine to very coarse glauconitic quartz sand and appears to be restricted to the more downdip eastern side of the area. The red-bed unit primarily consists of fine-grained material, but its lithology is variable, including gray and green to mottled bright red, purple, yellow, orange, and brown sections of interbedded clay, silty clay, silty fine sand, and pebbly coarse sand. The red-bed unit probably correlates with the erratic but widely distributed Upper Cretaceous "bright-red to chocolate-brown clay" deposits of Cederstrom (1945b). These deposits apparently extend inland to within 10 mi of the Fall Line in Southampton County.

None of the seismic lines released by the oil companies traverse these Upper Cretaceous deposits south of

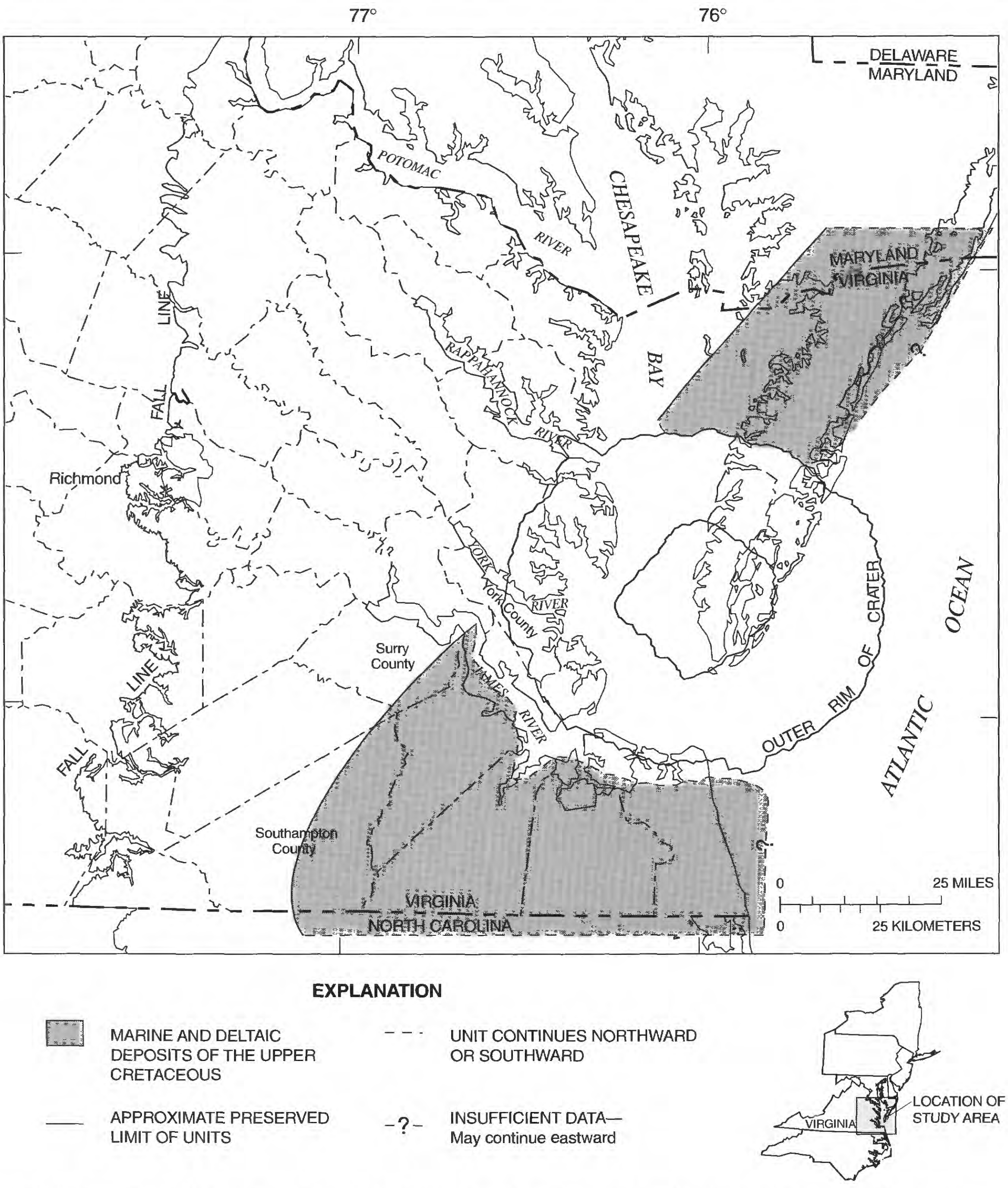


Figure 6. Distribution of the pre-impact Upper Cretaceous stratigraphic units and location of Chesapeake Bay impact crater.

the crater; the USGS line in the James River is "noisy" and has numerous multiples that make differentiation of individual units difficult. The interpretation of the presence or absence of Upper Cretaceous deposits in the James River seismic line depends on the borehole data used, north or south of the James River. Poag (1996) shows no Upper Cretaceous deposits in his interpretation of the James River seismic section and, therefore, follows Cederstrom's (1945b, 1957) interpretations and D.S. Powars' (unpub. data, 1990–94) reinterpretations of the boreholes on the north side of the river. Seismic lines from the north side of the crater show that marine Cretaceous deposits have long, unbroken, parallel, relatively high-amplitude reflections (D.S. Powars, unpub. data, 1993–95). A similar seismic signature is most likely for the marine Upper Cretaceous deposits distributed south of the crater.

Tertiary Deposits

Interpretations of Tertiary deposits are based on seismic- and borehole-data correlations with the Newport News Park 2 and Jamestown coreholes (pls. 3, 4, and 5). The MW4-1 corehole also was used as a guide for lithostratigraphic interpretations of the southeastern part of the study area, and the Kiptopeke and Exmore coreholes provide stratigraphic control inside the crater. Fauna and flora analyses of core samples and strontium-isotope analyses of shells provide chronostratigraphic control, and these data are included on the corehole stratigraphic columns.

The Tertiary deposits beneath the lower York-James Peninsula can be 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. The pre-impact deposits include the Aquia (late Paleocene), Marlboro Clay (straddles the Paleocene-Eocene boundary), Nanjemoy (early Eocene), and Piney Point (middle Eocene) Formations. The syn-impact deposits are represented by the instantaneously deposited Exmore tsunami-breccia with its highly variable mixture of autochthonous sedimentary intraclasts (from Early Cretaceous to late Eocene age) and the seismically defined CBIC megablock beds. The post-impact deposits consist of bathyal to shallow-shelf to marginal-marine facies. These deposits have progressively filled in the crater and blanket the entire region. 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 lower Miocene beds of the Calvert Formation; 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 upper Eastover (upper Miocene), Yorktown (lower and upper Pliocene), and Chowan River (upper Pliocene) Formations; and along the western edge of the study area, the fine-grained Bacons Castle (upper Pliocene) Formation.

North and south of the James River, the Paleocene to middle Eocene pre-impact deposits vary in their distribution and thickness. For instance, the Piney Point Formation is found outside the disruption boundary, primarily north of the James River, just opposite to the restricted distribution of the Upper Cretaceous deposits south of the river. The Piney Point Formation is underlain by relatively thick sections of the Aquia and Nanjemoy Formations, thicker than those sections south of the river. These stratigraphic variations, along with the truncation of Upper Cretaceous deposits north of the James River, indicates the existence of a pre-impact structural zone located beneath the river and represents the north flank of the Cape Fear-Norfolk block.

The Oligocene to middle Miocene post-impact deposits also exhibit complex patchy distribution patterns; again, especially across the James River. The absence of the Calvert Formation south of the river suggests that large-scale structural readjustments to the impact, such as reactivation of the north end of the Cape Fear-Norfolk block (Powars and others, 1992), were still occurring through the middle Miocene. The upper Miocene to upper Pliocene post-impact deposits blanket the region; the clayey St. Marys Formation was the first unit distributed and preserved across the entire region and, therefore, serves as an excellent marker unit.

The outer edge of the crater roughly separates the pre-impact deposits from the syn-impact deposits and separates thin post-impact deposits outside the crater from post-impact deposits that are up to ten times thicker inside the crater. The absence of the Calvert Formation from outside the crater's southwestern side suggests that these post-impact deposits may be several hundred times thicker inside the crater. Seismic reflections of the post-impact deposits show a south to southeast prograding depositional pattern for the northern and western parts of the crater and reflect the dominant sources of sediment. Borehole data indicate that most of these post-impact deposits are, overall, coarser grained (including Miocene and Pliocene marine bioclastic sands) along the outer edge of the crater and become finer grained toward the interior of the crater.

Aquia Formation

The Aquia Formation (upper Paleocene) consists of massive to thinly stratified, black to greenish-black to light-greenish-gray and "salt and pepper," 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/or very coarse glauconitic quartz sand mark the base of the unit. A few hard streaks of shells or thin "rock" layers are often reported but appear to be more abundant in the sections south of the James River. The Jamestown corehole encountered only one thin layer of semi-indurated shell hash in the Aquia strata. Drillers' logs use a variety of lithic descriptions for this unit, such as a "black sand," "black pepper sand," "marl," "clay and shell," or "shell rock." Generally, the lower one-half of the unit is more sandy and includes goethite grains and iron-stained quartz, all of which suggest correlation with the Piscataway Member of the Aquia Formation (Mixon, Powars, and others, 1989; D.S. Powars, unpub. data, 1988–95). The upper one-half of the unit is probably equivalent to the Paspotansa Member of the Aquia Formation based on the fact that this member was documented in both the Dismal Swamp and Fentress coreholes (Powars and others, 1992). The regional distribution of the Aquia Formation is similar to that of the Marlboro Clay and Nanjemoy Formation; therefore, these units are shown together in figure 7.

North of the James River, the Aquia strata dip generally eastward and range in thickness from about 36 ft (**102**) to about 60 ft (**56**) near the disruption boundary that separates pre-impact from syn-impact deposits. Just south of the James River, the Aquia Formation appears to have a fairly uniform thickness. This thickness ranges from 35 ft near the town of Claremont (Cederstrom, 1945a, well #4; **49**, pl. 1), to 21 ft in the town of Rescue (**19**), to 14 ft near the Rt. 17 James River Bridge (**22**). Farther east and south of the Chesapeake Bay, the Aquia Formation becomes 42 ft thick (**2**) in the Fentress corehole.

A distinctive suite of microfossils and macrofossils (for example, the brachiopod *Oleneothyris harlani*) found in the Aquia Formation indicates a late Paleocene age for the unit (Powars and others, 1992). Nannofossil data from the Jamestown corehole (**55**) also indicate a late Paleocene age and include the nannofossil zones NP 8–9 (see app. 4a). A summary of the chronostratigraphic data is included on the MW4-1 and Jamestown corehole stratigraphic columns (pl. 5). These Aquia microfossil and macrofossil assemblages also are found in the Exmore tsunami-breccia deposits.

The resistivity- and gamma-log signatures from the Jamestown corehole are typical for the Aquia Formation north of the James River (within the study area) and reflect the sandy nature of the lower one-half of the section and clayey nature of the upper one-half (pl. 5). Differentiation of the marine Aquia strata from the underlying fluvial-deltaic Lower Cretaceous deposits is relatively easy on the gamma logs. The Aquia gamma readings are consistently much higher due to the variable amount (20–75 percent) of glauconite (and some phosphate) found in the Aquia strata, which causes large deflections of the gamma log to the right, indicating increasing radiation. Blocky signatures on the resistivity and gamma logs also reflect the overall thicker bedded character of the Lower Cretaceous deposits compared to the thinner, more gradational curves representing the Aquia strata.

South of the James River, differentiation of the Aquia strata from the underlying Upper Cretaceous marine deposits is very difficult and requires careful correlation of the lithologic and biostratigraphic data available for this region. Differentiation between the Aquia and the Exmore tsunami-breccia also is difficult because of similarities in lithologic and borehole signatures. Differentiation is aided, however, by noting the vertical stacking order of the units. The Marlboro Clay and Nanjemoy Formation are most likely to be underlain by the Aquia Formation, whereas the Chickahominy Formation is most likely to be 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 Formation 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.

Available seismic data west and south of the crater are interpreted in this report as only extending as far as the preserved limit of the Exmore tsunami-breccia and, therefore, not encountering the Aquia strata. Seismic sections north and northwest of the crater show that the Aquia strata have long, unbroken, parallel, relatively high-amplitude reflectors typical for marine deposits.

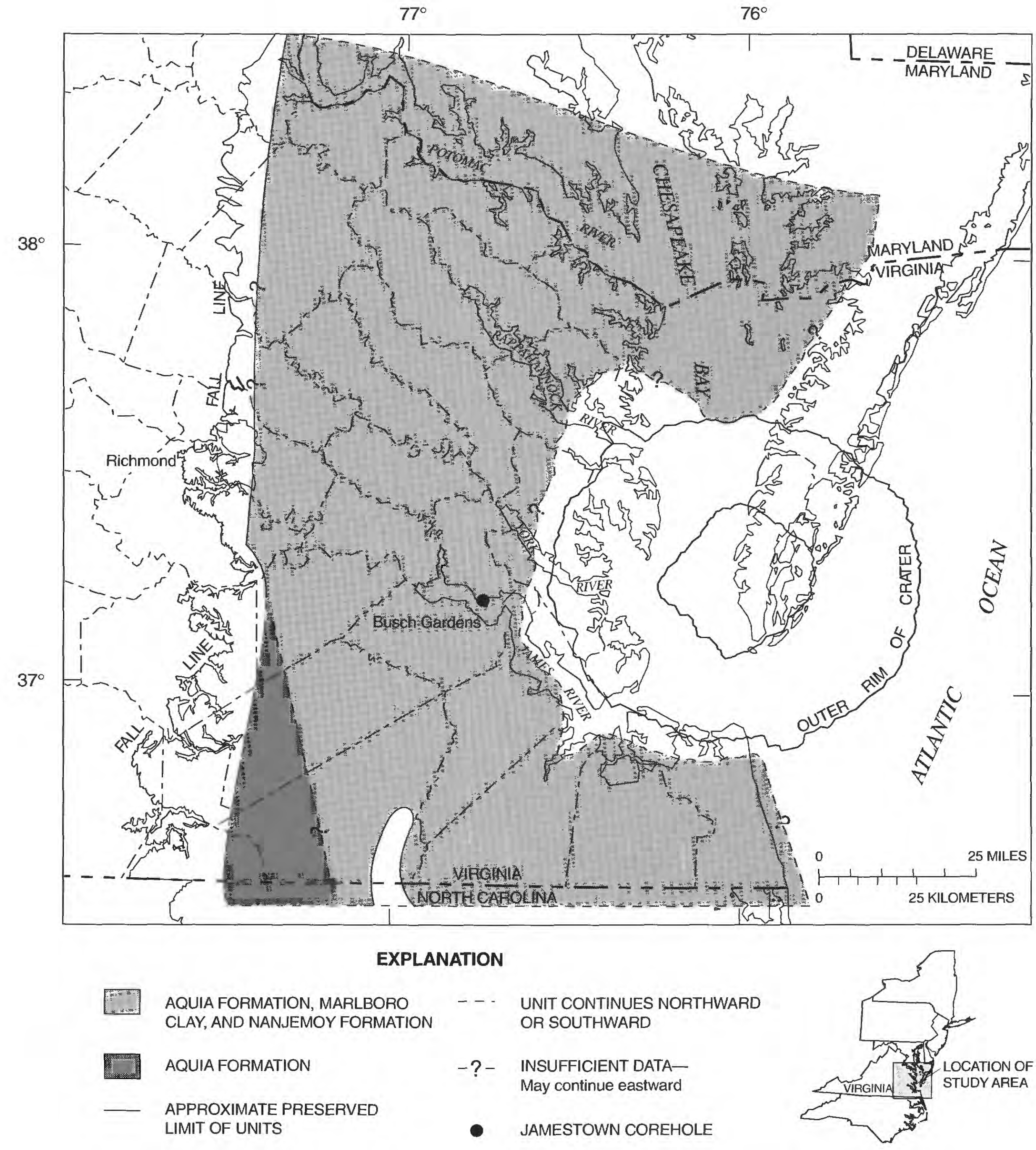


Figure 7. Distribution of the pre-impact Aquia Formation-Marlboro Clay-Nanjemoy Formation (upper Paleocene to lower Eocene).

Marlboro Clay

The Marlboro Clay (upper Paleocene and lowermost Eocene) consists of 8 to 18 ft of light-gray to pinkish-gray and reddish-brown kaolinitic clay and is found consistently outside of the crater between the glauconitic Aquia and Nanjemoy Formations (fig. 7). 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 a gray clay, making differentiation between these two units difficult. The Marlboro Clay is so thin that resolution on seismic lines may be difficult. Similar to the Aquia, the Marlboro Clay is present north and northwest of the crater but is too thin to resolve in the seismic sections.

Nanjemoy Formation

The Nanjemoy Formation (lower Eocene) ranges in thickness from about 45 to 60 ft north of the James River to about 3 to 40 ft south of the river, and its regional distribution pattern is similar to the Aquia Formation and Marlboro Clay. 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 a few to several fining-upward sequences that are generally capped with a sandy clay-silt.

In the Jamestown corehole (see fig. 3*A* and pl. 5), the upper 34 ft of the section is overall very micaceous, sandy and coarse-grained (including scattered granules) and possibly represents the Woodstock Member of the Nanjemoy Formation. The lower 10 ft of the section is much more clayey and probably belongs to the Potapaco Member. These sandy and clayey sections are reflected in the resistivity logs and, as pointed out previously, the curvy nature of these logs differentiates them from the Chickahominy Formation. South of the James River, the relatively thinner Nanjemoy section contains thin deposits of both the Woodstock and Potapaco Members (Powars and others, 1992).

A distinctive suite of microfossils and macrofossils is found in the Nanjemoy Formation, indicating an early Eocene age (Powars and others, 1992). The nannofossil data indicate an early Eocene age and include nannofossil zones NP 12–14 for the Woodstock Member and an NP 10 for the Potapaco Member (see app. 4a). A summary of chronostratigraphic data is included on the stratigraphic columns for the MW4-1 and Jamestown coreholes (pl. 5).

North of the James River, the Nanjemoy Formation is overlain by the shelly, glauconitic Piney Point Formation. A high resistivity signature is characteristic of the Piney Point and differentiates the formation from the underlying Nanjemoy. South of the James River, the Nanjemoy is overlain by either the shelly, sandy Newport News unit of the Calvert Formation or the clayey St. Marys Formation, making differentiation relatively easy. The Nanjemoy's variable percentage of glauconite and phosphate (20–70 percent) creates high-radiation gamma-log signatures that deflect to the right, similar to the Aquia Formation. Also, like the Aquia Formation and Marlboro Clay beds, the Nanjemoy strata were encountered only in the seismic sections north and northwest of the crater. These seismic sections show that the Nanjemoy Formation strata have long, unbroken, parallel, relatively high-amplitude reflections, typical of marine deposits.

Piney Point Formation

The Piney Point Formation (middle Eocene) consists of richly fossiliferous, olive-gray to grayish-olive-green, poorly sorted, medium to coarse glauconitic quartz sands that are commonly interbedded with calcium carbonate cemented sands to shelly sands and moldic limestone (hard "shell rock" with voids). The sands contain varying amounts of clay, silt, shells, microfossils and glauconite (25–50 percent). Available data indicate that the Piney Point Formation is present mainly north of the James River; however, as interpreted in this report, it also extends to just south of the river between Hog Island and the mouth of Powell Creek (fig. 8). The Piney Point ranges in thickness from about 25 ft on the western side of the study area, near Ewell, Va., to 15 to 20 ft in the Williamsburg, Va., area, and thins to about 10 ft near the disruption boundary. The Jamestown corehole encountered only 6.6 ft of the Piney Point strata and represents the only biostratigraphically dated section of this unit in the study area (L.M. Bybell, USGS, oral commun., 1998) (see pl. 5). The nannofossil data indicate an NP 16 nannofossil zone (see app. 4a). Thickness varies from 7 to 17 ft in wells on Hog Island. The thinning and variable thickness of the Piney Point strata to the east, closer to the disruption boundary, reflects the immense erosional power of the impact blast and subsequent train of tsunamis that largely shaped the upper surface of the Piney Point. The minimal extent of Piney Point strata south of the James River is probably caused by a combination of these syn-impact processes and post-impact uplift (reactivation of faults related to the north end of the Cape Fear-Norfolk structural block) and removal by post-impact transgressions.

High resistivity-log signatures (deflection to the right) are characteristic of the interbedded sand and limestone of the Piney Point Formation. Within the study area, the Piney Point strata are overlain by shelly glauconitic clayey sands of the Old Church Formation and the Delmarva beds (Oligocene) and under-

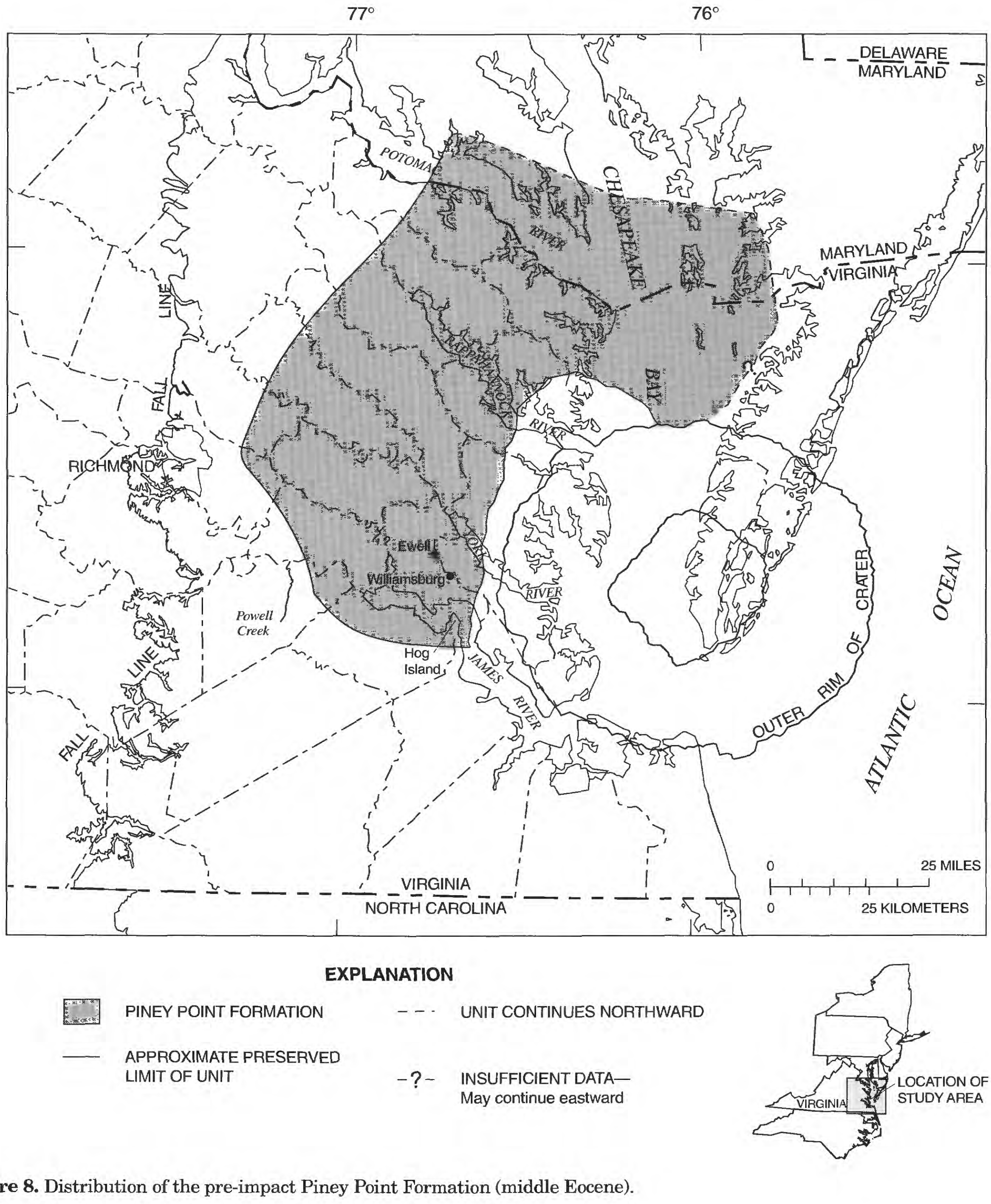


Figure 8. Distribution of the pre-impact Piney Point Formation (middle Eocene).

lain by glauconitic clayey sands of the Nanjemoy Formation. The highly variable vertical and lateral distribution of these glauconitic lithologies makes differentiation difficult, especially because there is no suite of geophysical logs for comparison. Differentiation often requires correlation of the stratigraphic stacking order found above and below the Piney Point strata. As in the Jamestown corehole, the Piney Point strata (outside the disruption boundary) are interpreted consistently to be the lowest part of the overall high-resistivity signature characteristic of the shelly sands of the lower Miocene, Old Church Formation, Delmarva beds, and Piney Point Formation. Again, similar to the Aquia, Marlboro Clay, and Nanjemoy strata, the Piney Point strata were encountered only in the seismic sections north and northwest of the crater where they exhibit typical marine seismic reflections of long, unbroken, parallel, relatively high-amplitude reflectors.

Exmore Tsunami-Breccia

The Exmore tsunami-breccia (upper Eocene) previously has been called the "Exmore beds" (Powars and others, 1992); the "Exmore boulder bed" (Poag and others, 1992); and the "Exmore breccia" (Powars and others, 1993; Poag, Powars, and Mixon, 1994; Poag, 1996, 1997a). For several reasons, combining "tsunami" with "breccia" is the most appropriate description for this unit. "Tsunami-breccia" connotes the unique "washed, tsunami look of the deposit" (Eugene Shoemaker, USGS, oral commun., 1994). "Tsunami" also best fits the process of deposition described in this report by Poag, Powars, and Bruce (1994); Poag, Powars, and Mixon (1994); Poag, Powars, Poppe, and Mixon (1994); and Poag (1996, 1997a). Even though the main infilling of debris was probably caused by gigantic tsunami backwash into the crater, "tsunami-breccia" describes the debris deposited in any direction a gigantic tsunami travels. In addition, oceanic impacts, such as the one that created the CBIC, differ substantially from terrestrial impacts; a major difference is tsunami-backwash modification of the initially emplaced breccia and ejecta blanket.

Within the crater, the seismic data suggest that the syn-impact deposits can roughly be divided into two principal depositional units (Poag, 1997a; D.S. Powars, unpub. data, 1995). The Exmore tsunami-breccia is the upper syn-impact deposit and overlies either the CBIC megablock beds (lower syn-impact deposit) or the crystalline basement (pls. 3 and 4). The Exmore tsunami-breccia was recognized in the cuttings descriptions of previous investigators, who describe alternating marine, deltaic, and fluvial deposits and often mention limestone fragments and/or rock; the best example is the oil test well at Mathews (**121**) (see app. 2 for lithic description). The Exmore tsunami-breccia also was recognized in boreholes where mixtures of these normally separate deposits were not considered to be an artifact of down-hole contamination.

This deposit has a highly variable lithology, which consists of an overall fining-upward sequence of gray, shelly, clayey and silty, fine to pebbly, glauconitic sand (partially sublithified). This material serves as a matrix for the abundant clasts and reworked fauna and flora from Lower Cretaceous (Albian), Upper Cretaceous (Cenomanian, Santonian, Campanian, and Maestrichtian), Paleocene, lower Eocene, and middle Eocene deposits (Powars and others, 1992). The clasts consist of a wide variety of lithologies and sizes. They include rounded to angular fragments up to 6.5 ft in diameter that are mostly deformed, singular to clumped and smashed together; soft, friable, marine to fluvial-deltaic sands and clays; hard silty clays; and indurated sands and bioclastic limestones. As expected, these clasts also display a wide variety of colors, from black to various grays and greens to oxidized colors (red, purple, yellow, and brown). The matrix contains trace amounts of shocked quartz (Poag and others, 1992; Poag, Powars, Poppe, and Mixon, 1994; Glen A. Izett, USGS, written commun., 1992), centimeter-size fragments of melt rock, and scattered clasts of crystalline basement that contain abundant quartz and feldspar deformation features (Koeberl and others, 1996).

Clay analysis of core samples from the top 54 ft of Exmore tsunami-breccia found in the Kiptopeke corehole indicate that the clayey matrix is dominated by montmorillonite (greater than 80 percent), with lesser amounts of illite and kaolinite (less than 10 percent each); one sample was nearly 100 percent montmorillonite. Trace amounts of salt (NaCl) were found in all these samples suggesting that compaction of these deposits, which had thoroughly mixed with the ocean water during tsunami-train deposition, concentrated the salt in the remaining water and clayey matrix (chlorinity values up to 25,700 mg/L from a well open to this strata at the Kiptopeke site). Cores from eight widely distributed boreholes (**128**, **88**, **66**, **127**, **120**, **43**, **44**, and **31**) provide stratigraphic evidence and guidance for seismic interpretations and for construction of the structure contour and isopach maps of the Exmore tsunami-breccia (pls. *6A* and *6B*).

The syn-impact Exmore tsunami-breccia is distributed within the disruption boundary and ranges in thickness from about 30 to 110 ft outside the outer rim of the crater to about 125 to 605 ft inside the outer rim

(**26** to **45**) beneath the lower York-James Peninsula (pl. 6*B*). Interpretation of the York River seismic line (pl. 3) indicates that the Exmore tsunami-breccia is about 825 ft thick where it lies on the crystalline basement near the outer rim of the crater. Farther into the crater, above the annular trough, the seismic data indicate that the Exmore tsunami-breccia is about 1,200 to 1,300 ft thick and up to about 2,300 ft thick inside the crater's inner basin (pl. 6*B*). It abruptly thickens across the faulted outer rim of the crater and across the faulted rim (peak ring) of the inner basin but generally thins above the highly variably uplifted peak ring (pls. 2, 3 and 4).

Throughout its extent, the Exmore tsunami-breccia is overlain by the clayey Chickahominy Formation, which also is found only inside the disruption boundary. 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 chocolate-purple, very clayey unit (a similar lithology to the Chickahominy Formation). Similar to the rest of the Exmore strata, this capping clay contains a mixture of fauna, flora, and scattered to fairly abundant, coarse-sand to pebble-sized lithic fragments (up to 0.4 in.). This clay cap has a resistivity signature that is similar to the Chickahominy strata (flat deflection to the left). Except for the 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.

Within the study area, the Exmore tsunami-breccia deposits are underlain by pre-impact Lower Cretaceous deposits outside the outer rim of the crater and by the seismically defined CBIC megablock beds inside the outer rim. The location of the disruption boundary beneath the highly variable outer rim is uncertain, and undisturbed Lower Cretaceous deposits may extend far into the annular trough. As previously mentioned, differentiation between the Exmore tsunami-breccia and 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, thinner stratified Exmore tsunami-breccia deposits.

The Exmore tsunami-breccia exhibits a characteristic chaotic, incoherent seismic signature that generally contrasts strongly with the very continuous, unbroken, parallel, horizontal reflections of the pre-impact marine Cretaceous and Tertiary strata and the relatively high-amplitude, relatively discontinuous, coherent horizontal to subhorizontal reflections of the pre-impact Lower Cretaceous strata (pl. 3). Differentiation of the Exmore signature from the underlying scattered, high-amplitude, horizontal and diagonal reflections and refractions characteristic of the syn-impact, slumped Chesapeake Bay megablock beds (primarily Lower Cretaceous deposits) is difficult. The top of the crystalline basement, marked by two closely spaced, parallel, high-amplitude reflectors, sharply contrasts with the overlying chaotic seismic signature of the Exmore tsunami-breccia deposits. The Exmore tsunami-breccia's chaotic seismic signature sharply contrasts with the long, continuous, parallel, high-amplitude reflectors of the overlying Chickahominy Formation strata and is easily recognized. All of the seismic sections show that the top of the Exmore tsunami-breccia and the overlying post-impact strata are cut by numerous normal faults. These faults are primarily the result of differential post-impact compaction and subsidence of the Exmore tsunami-breccia (Powars and others, 1993; Poag, Powars, Poppe, and Mixon, 1994; Poag, 1996, 1997a) and readjustments in the fractured and faulted basement.

Chesapeake Bay Impact Crater Megablock Beds

The CBIC megablock beds are defined as a seismic stratigraphic unit and have been extrapolated into the boreholes inside the disruption boundary beneath the lower York-James Peninsula. Following Poag's (1996, 1997a) explanation of the existence of a megablock zone, this unit is interpreted to represent all the deposits found in the annular trough beneath the Exmore tsunami-breccia and above the crystalline basement. Using this interpretation, the CBIC megablock beds range from about 700 to 2,500 ft in thickness. Borehole data from the lower York-James Peninsula indicate that the unit is generally less than 1,200 ft thick. As previously mentioned, there are many uncertainties about the location of the disruption boundary below the visible fault-bounded escarpment at the crater's outer rim.

Limited borehole data, including a thin interval cored at Kiptopeke (pl. 5), indicate that the CBIC megablock beds consist of typical fluvial-deltaic, Lower Cretaceous sediments. Mixed fauna, shells, and glauconite, typical of the overlying Exmore tsunami-breccia, were not encountered in the few tens of feet of CBIC megablock beds cored at Kiptopeke. 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, 1997a; D.S. Powars, unpub. data, 1995). Because of the lack of borehole geophysical data from inside the crater, and the lithologic similarities between undisturbed Lower Cretaceous deposits and the CBIC megablock beds, these units are differentiated primarily on the basis of seismic signatures. There does, however, appear to be a subtle dampening of both the resistivity- and gamma-log signatures for the deposits interpreted as CBIC megablock beds.

Scattered high-amplitude, horizontal and diagonal reflections and refractions characteristic of this unit sharply contrast with the underlying closely spaced, parallel, double, very high-amplitude seismic signature of the top of the basement and contrast somewhat with the overlying chaotic seismic signature of the Exmore tsunami-breccia.

Chickahominy Formation

The Chickahominy Formation (upper Eocene) consists predominantly of massive to thin-bedded, olive-gray, very compact, dry, micaceous, clayey silt to silty clay. These fine-grained sediments contain abundant microfauna, which give a white-speckled appearance to some intervals; abundant finely crystalline iron sulfide; and variable amounts of fine-sand to silt-sized glauconite, shells (including solitary corals), and pyrite. The entire unit contains a wide variety of scattered to extensive burrows, and the generally silt-sized glauconite is primarily black to dark green. Clay analysis of core samples from the 220-ft-thick section encountered in the Kiptopeke corehole indicates the clays consist primarily of a mixture of illite/smectite (50–75 percent), illite (10–20 percent), and kaolinite (0–30 percent; pl. 5). The lowest 20 to 30 ft of the section appears to be dominated by montmorillonite (90 percent), similar to the clayey matrix of the underlying Exmore tsunami-breccia. Above this basal interval, the kaolinite percentage increases upward to a maximum in the middle of the section and declines upward to the top. Calcite is present throughout the section. Salt (NaCl) similar to that found in the top of the Exmore tsunami-breccia was found in the lower two-thirds of the deposit.

The contact between the Chickahominy Formation and the underlying Exmore tsunami-breccia is gradational and is marked by the absence of very fine to fine sand, the presence of mixed fauna and flora, and scattered to fairly abundant, coarse-sand to pebble-sized lithic fragments (up to 0.4 in.). Lower Oligocene (Delmarva beds) or upper Oligocene (Old Church Formation) glauconitic, shelly, clayey sand deposits overlie the Chickahominy in all the coreholes and boreholes inside the disruption boundary and are interpreted in this report to have a more continuous distribution than interpreted by Poag (1997c). These Oligocene units may be fault bounded and appear to be consistently distributed within the disruption boundary, ranging in thickness from about 30 to 90 ft outside the outer rim of the crater to about 99 to 350 ft inside the outer rim (pl. 7). The much thinner Chickahominy strata found outside the crater's outer rim, like that found in the Newport News Park 2 corehole (pl. 5), represent shallow-shelf deposits and are overall more sandy and contain more shells than the much thicker, bathyal clays found inside the crater. Solitary coral is more abundant in these shallow-shelf deposits and sometimes are concentrated into thin layers that are often recorded as a thin rock or indurated layer in drillers' logs.

A distinctive suite of microfossils are found in the Chickahominy Formation, indicating a late Eocene age for this unit (Powars and others, 1992). A summary of chronostratigraphic data is included on the stratigraphic columns for the Kiptopeke and Newport News Park 2 coreholes (pl. 5).

The massive, clayey Chickahominy Formation exhibits a very distinct, flat resistivity signature (deflection to the left) that is easily differentiated from the thinly stratified, irregular resistivity signature typical of the underlying Exmore tsunami-breccia (except for the thin, capping clay discussed above). The stratified high resistivity signature (deflection to the right) of the overlying, more sandy, lower Oligocene (Delmarva beds) deposits also is relatively easy to differentiate from the resistivity signature of the Chickahominy. Gamma logs of the Chickahominy Formation are variable and, in some cases (as in the Kiptopeke corehole), reflect glauconite- and phosphate-filled burrows from the overlying Delmarva beds that reach down nearly 40 ft into the upper Chickahominy strata.

Long, continuous, parallel, high-amplitude reflectors are typical for the Chickahominy Formation's marine deposits and sharply contrast with the chaotic seismic signature of the underlying Exmore tsunami-breccia. Long-term differential compaction and subsidence of the syn- and post-impact deposits have produced extensive normal faulting that disrupts the post-impact Chickahominy Formation and the overlying post-impact strata (Powars and others, 1993; Poag, Powars, Poppe, and Mixon, 1994; Poag, 1997a). Many of these faults appear to nearly reach the floor of the Chesapeake Bay (Poag, 1997a). Seismic data indicate that the Chickahominy Formation thickens and sags just inside the inner basin on both the northwest and southeast sides of the crater (pl. 3). Differentiation of the marine Chickahominy strata from the overlying Delmarva beds, which have a similar seismic signature, was primarily based on correlation with the coreholes.

Delmarva Beds

The Delmarva beds (lower Oligocene), first described and informally named by Powars and others (1992), are characterized by variable lithology and thickness and include strata that span the planktonic Foraminifera zones P18 through P21a (C.W. Poag, USGS, oral commun., 1990, 1991). Inside the crater, the Delmarva beds are better sorted and much finer grained (clayey sands) than they are outside the crater, where they become a poorly sorted, intensely burrowed, clayey, fine to very coarse, glauconitic quartz sand. Outside the outer rim of the crater, the Delmarva beds appear to be preserved only north of the James River (Newport News Park 2 corehole) and along the Virginia Beach coastal area (Fentress corehole), where it is found within a short distance (10–15 mi) outside of the disruption boundary (fig. 9). The Delmarva beds appear to be the first post-impact unit preserved across the disruption boundary south of the crater. The thickness of the Delmarva beds ranges from 2 to 26 ft outside the outer rim of the crater and from 2 to 60 ft inside the crater.

The lithologic variability of the Delmarva beds is recorded in the five coreholes (Exmore, Kiptopeke, Windmill Point, Newport News Park 2, and Fentress) that encountered this unit. In the Exmore corehole, the Delmarva beds (zones P18–20) consist of 41 ft of olive-gray to grayish-olive, micaceous, clayey, silty, very fine glauconitic quartz sand, containing scattered patches of pyrite and marcasite (Powars and others, 1992). These beds coarsen upward to a very fine to fine sand. In contrast, in the Kiptopeke corehole, the Delmarva beds (P20) are only 6 ft thick and consist of black to greenish-black, very fine, glauconitic and phosphatic sand, with an olive-brown clay-silt matrix and interbedded, thin, indurated layers (pl. 5*C*). This is similar to the lithology assigned to the Old Church Formation (upper Oligocene) in the Exmore corehole (Powars and others, 1992) and suggests that the lower 17 ft of this section, as Poag's Foraminifera data had indicated, belong in the Delmarva beds (P21a).

Outside the outer rim of the crater, cores from the Newport News Park 2, Windmill Point, and Fentress coreholes contain Delmarva beds (P21a) that are intensely burrowed, poorly sorted, gray-olive to dark-green and black, shelly, microfossiliferous, fine to very coarse, glauconitic and phosphatic quartz sand generally in a clay-silt matrix. These beds include better sorted, finer grained, sandy clay-silts or thin, sandier, indurated layers. Granules of quartz, glauconite, and phosphate are scattered throughout, with minor amounts of pyrite, carbonaceous material (including wood), and very small sharks' teeth. The base of the unit becomes a very poorly sorted sand with scattered pebbles that sharply overlies and is burrowed down into the much finer grained Chickahominy strata.

Differentiation of this unit from the underlying clayey Chickahominy Formation is relatively easy and is discussed in the Chickahominy Formation section of this report. Differentiation of this unit from the overlying, somewhat lithically similar Old Church Formation is difficult. Outside the outer rim of the crater, the Delmarva beds are distinguished from the Old Church primarily through correlation of geophysical signatures with those of the Newport News Park 2 corehole (pls. 4, 5*D*). There, the Delmarva beds contain a higher percentage of glauconite and phosphate than the Old Church Formation, and this is reflected in gamma-log signatures (the Delmarva beds deflecting more to the right). Similarities in their overall clayey, sandy lithology limit the use of resistivity logs for differentiation of the Delmarva and Old Church strata. The Delmarva beds inside the crater are overlain by Old Church lithologies that are indistinguishable from the Delmarva beds. In the Kiptopeke corehole, diatomaceous, fine-grained deposits of the Calvert Formation [lower (?) to lowermost middle Miocene] truncate the Delmarva beds. These fine-grained deposits have very little, if any, glauconite and are much more clayey. These differences are reflected in the resistivity- and gamma-log signatures (both deflect to the left), which dramatically contrast with the high resistivity signatures typical of the more sandy Delmarva beds (pl. 5*C*).

The Kiptopeke corehole may be located over the crater's peak ring, which the seismic data shows as an area that has thinning and truncation of early post-impact deposits. Differentiation of the Delmarva beds from the Old Church is not always possible and, therefore, the two units are undifferentiated and labeled as Oligocene deposits in plates 3 and 4.

For this investigation, the thin Delmarva beds are grouped together with the overlying Old Church Formation and lower Miocene beds of the Calvert Formation into a single seismic stratigraphic unit and labeled as lower Miocene and Oligocene deposits on plates 2 and 3. The overall sandy nature of these units on the western side of the crater's annular trough may explain the thicker spacing of the seismic reflectors there. These beds prograde into the crater, forming a wedge that appears to thin eastward and southeastward across the annular trough; in the inner basin, these beds thicken but still show a thinning trend to the east-southeast. Beds that are farther into the crater have closer spaced, long, continuous, parallel, high-amplitude reflections typical of marine beds that have sand-over-clay contacts (often representing an unconformity). Inside the inner basin, the Delmarva beds are interpreted to thicken and sag along the northwestern and southeastern sides (similar to the Chickahominy). Seismic data from inside the inner basin suggest the undifferentiated Oligocene-Miocene deposits may be as much as 400 ft thick (pl. 3). Numerous compaction faults can be seen disrupting these beds inside the crater. Again, these seismic interpretations are primarily based on correlation with the coreholes.

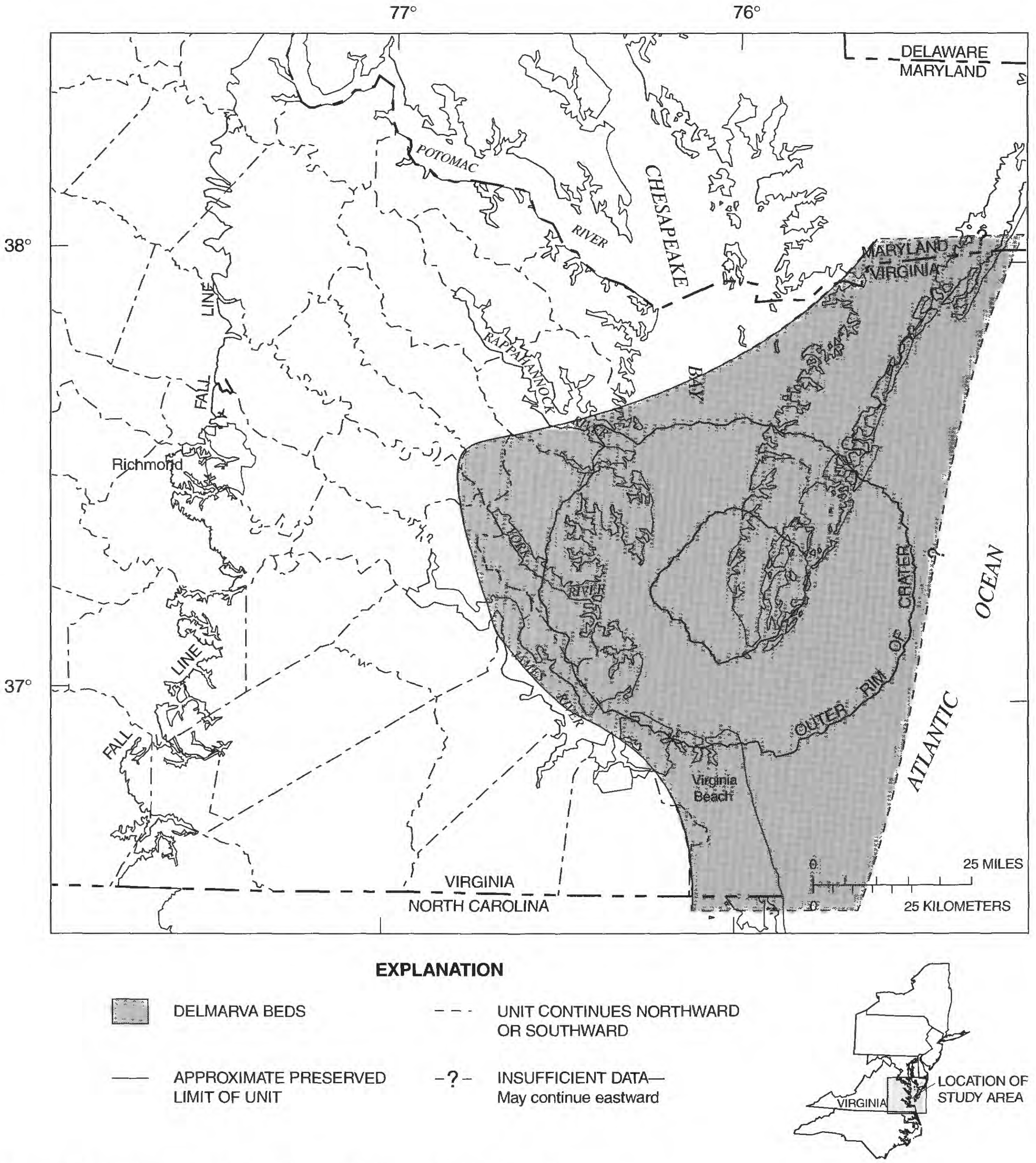


Figure 9. Distribution of the post-impact Delmarva beds (lower Oligocene).

Old Church Formation

The Old Church Formation (upper Oligocene) is similar to the Delmarva beds in that it contains shelly, sandy facies outside the outer rim of the crater that thicken and prograde into the crater, forming a wedge that thins and becomes finer grained toward the center of the crater. The Old Church Formation also has a distribution pattern similar to the Delmarva beds, except that the Old Church Formation extends farther west and northwest outside the disruption boundary (fig. 10). The Old Church deposits are the first post-impact unit preserved across the disruption boundary west of the crater and are another stratigraphic unit that is preserved only north of the James River. It ranges in thickness from a feather edge to about 30 ft outside the crater's outer rim, is absent in certain areas above the crater's peak ring, and is about 60 ft thick inside the crater.

The fine-grained facies of the Old Church is recorded by the 27-ft-thick section encountered in the Exmore corehole (fig. 5*A*) that consists of dark-olive-gray to greenish-black, glauconitic and phosphatic sand in an olive-brown to dark-brown clay-silt matrix. This section contains calcareous material in the top 10 ft. Biostratigraphic data from these beds indicate a late Oligocene to early Miocene age (Powars and others, 1992). The shelly sandy facies are lithically variable and range from relatively loose, massive, olive-gray, shelly, medium to coarse glauconitic phosphatic quartz sands to the same lithology but with a clay-silt matrix. They also include poorly sorted, dark-olive gray, Foraminifera-rich, massive to interbedded, sandy clay-silt to silty sand. These silts and sands contain scattered fine to very coarse glauconite phosphate and quartz grains (these beds may belong to the Delmarva beds). The occurrence of burrows varies from scarce to abundant in all of these facies.

Biostratigraphic studies of Pamunkey River outcrops and core samples (**66** and **128**) and the following coreholes located west and northwest of the study area [Putneys Mill (Bybell and Gibson, 1994), **133**, and **134**] indicate a late Oligocene to early Miocene age for the Old Church Formation (Ward, 1984; Edwards, 1989; Powars and others, 1992; L. de Verteuil, University of Toronto, written commun., 1994; A.P. Hoffmeister, Old Dominion University, written commun., 1995). These deposits include strata that span the P21 to N5–7 foram zones (Poag and Ward, 1993; Powars and others, 1992; C.W. Poag, USGS, written commun., 1989–1993). Nannofossil data from the Jamestown corehole (**55**) also indicate a late Oligocene to early Miocene age (see app. 4a). Analysis of dinocyst data in this corehole, however, indicates a late Oligocene age but includes some reworking of older taxa and burrowing downward of younger taxa from above and, therefore, may explain the mixed age reported by others (see app. 4b). A summary of chronostratigraphic data is included on the stratigraphic column for the Newport News Park 2 corehole (**66**; pl. 5), where the Old Church is interpreted to consist only of Oligocene beds. Overlying bioclastic to shelly sand deposits of early Miocene age are considered a separate stratigraphic unit in this report.

The Old Church Formation is overlain by lower Miocene beds of the Calvert Formation and by the middle Miocene beds of the Calvert Formation or St. Marys Formation in updip areas (pls. 3 and 4). Differentiation of the shelly sand facies from the overlying very shelly, sandy, lower Miocene beds is very difficult. The lower Miocene beds have more phosphate than the Old Church Formation, and gamma logs of the lower Miocene beds deflect to the right more than the Old Church Formation. The fine-grained St. Marys and Calvert strata with their characteristic low resistivity (deflection to the left) contrast strongly with the Old Church's shelly sandy facies and high resistivity signature (deflection to the right). Differentiation from the underlying Delmarva beds is discussed in the previous section.

Seismic resolution of the relatively thin Old Church Formation is very difficult; therefore, it is grouped together with the underlying Delmarva beds and the overlying lower Miocene beds into a single seismic stratigraphic unit (pl. 3).

Calvert Formation

Newport News Unit of the Calvert Formation

Biostratigraphic and strontium-isotope data from the Newport News Park 2, Windmill Point, and Exmore coreholes document the presence of lower Miocene deposits in the Virginia Coastal Plain. Interpretation of dinocyst and nannofossil data from the Jamestown corehole (**55**) (see app. 4a and 4b) indicates an early Miocene age that is most likely assigned to the NN 2 nannofossil zone. Strontium-isotope analysis of shells from these deposits indicate that their range in age is from about 20.1 Ma to 17.1 Ma; this range suggests these beds are equivalent to the Popes Creek Sand, the Fairhaven Member, and lower one-half of the Plum Point Member of the Calvert Formation. The older 20.1 Ma date came from the Newport News Park 2 corehole and may be older than the Popes Creek Sand, which has not been precisely dated. Until more definitive age resolutions for the Popes Creek Sand and

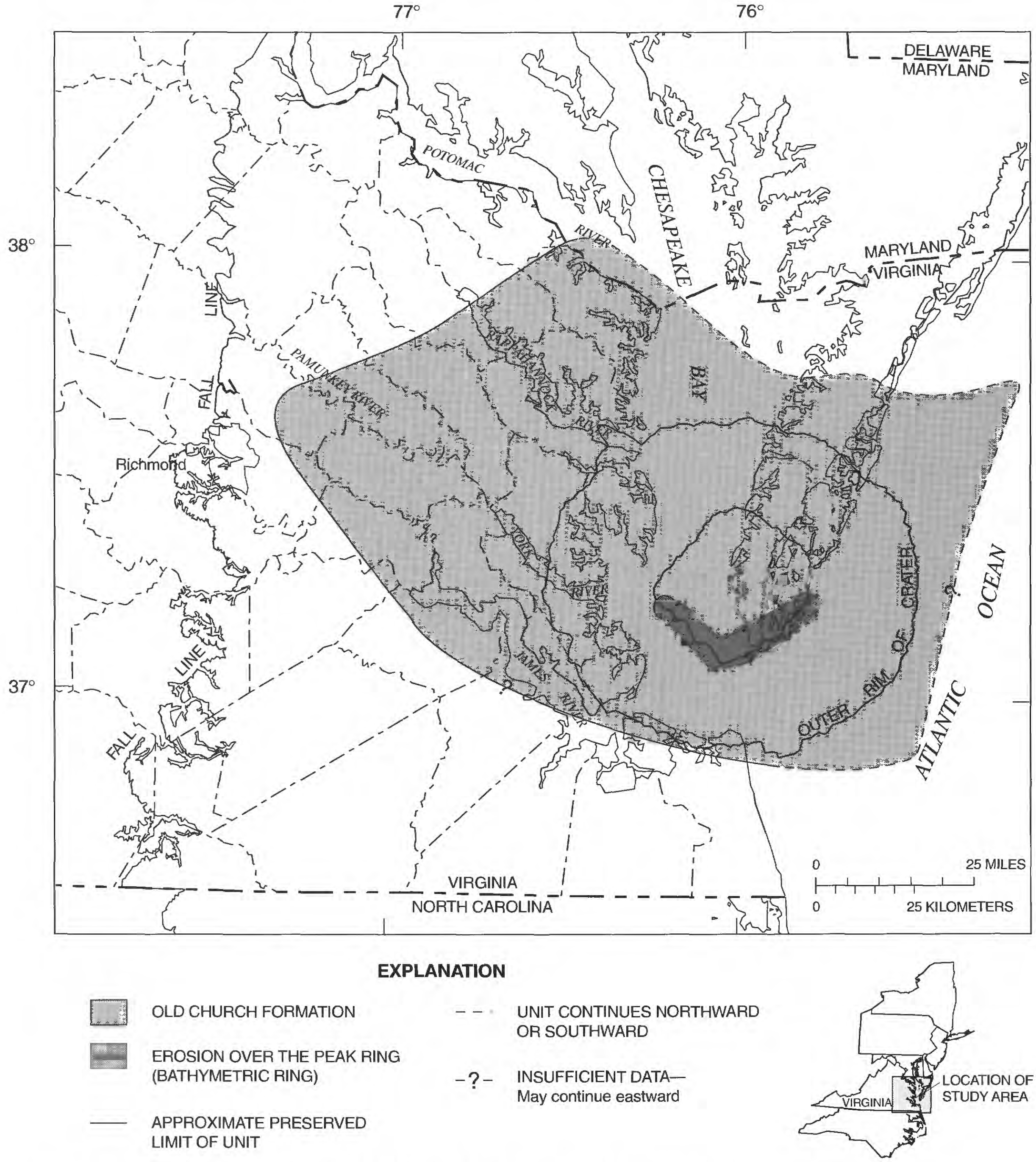


Figure 10. Distribution of the post-impact Old Church Formation (upper Oligocene).

Fairhaven Members are available, we will name the lower Miocene deposits found in Virginia the Newport News unit of the Calvert Formation. These lower Miocene beds contain distinctive marine bioclastic sands that were deposited along the outer rim and western side of the annular trough. Inside the crater, very thin (8.8 ft), much finer grained, clayey, lower Miocene beds have been identified in the Exmore corehole. The lower Miocene age is based on diatom, dinocyst and foraminiferal data (Powars and others, 1992; C.W. Poag, USGS, written commun., 1993; L. de Verteuil, University of Toronto, written commun., 1994; Verteuil and Norris, 1992, 1996; L. Edwards, USGS, written commun., 1998, 1999), which suggest an equivalence to the Fairhaven Member or lower one-half of the Plum Point Member of the Calvert Formation. These lower Miocene beds have a limited, very patchy distribution, as shown in figure 11, and range in thickness from a feather edge to about 30 ft outside the outer rim and up to about 40 ft inside the crater.

The lower Miocene bioclastic sand facies consist of olive to olive-gray to dark-olive-gray, very poorly sorted, very shelly, medium to pebbly, glauconitic and phosphatic quartz sand to shell hash. These deposits often include medium-gray, semi-indurated to indurated (calcium carbonate cement) layers and minor

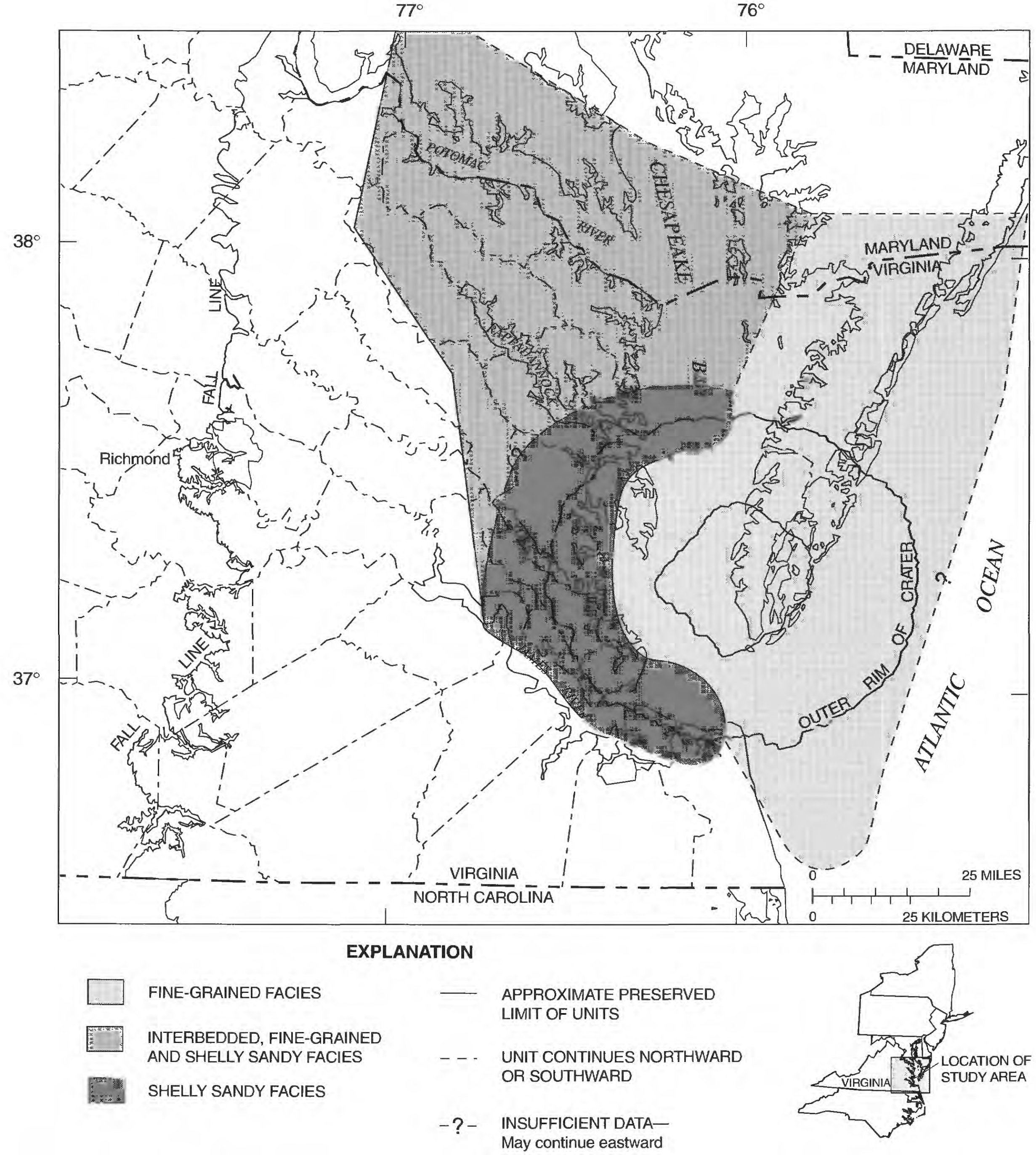


Figure 11. Distribution of the post-impact Newport News unit of the Calvert Formation (lower Miocene).

clay, silt, very fine to fine sand, sharks' teeth and bone. The quartz and phosphate pebbles range up to 0.4 in. and burrowing sometimes creates a mottled appearance with various shades of olive. The finer grained beds encountered in the Exmore corehole contain two thin (4.2- and 4.9-ft) fining-upward sequences. These sequences consist of about 1 ft of olive-gray, clayey, silty, very fine to fine sand with scattered, black, fine to medium grains and chips of phosphate and glauconite that fine upward into clayey silt to silty clay. Diatoms in these clayey beds are visible using a hand lens. The base of each sequence is sharp with sand-filled burrows into silty clay.

The shelly, sandy facies exhibit a high resistivity-log signature that contrasts strongly with that of the overlying clayey middle Miocene Calvert Formation. The coarse-grained phosphate and glauconite are responsible for giving this unit one of the most elevated gamma-log signatures of all the stratigraphic units in the study area and helps differentiate the unit from the shelly, sandy facies of the underlying Old Church Formation. The fine-grained lower Miocene beds exhibit clayey resistivity-log signatures (deflection to the left) that dramatically contrast with the high resistivity-log signatures typical of the more sandy Delmarva beds, but are similar to the overlying fine-grained middle Miocene Calvert Formation deposits (pl. 5).

Seismic resolution of these relatively thin lower Miocene beds of the Calvert Formation is very difficult, and therefore they are grouped together with the underlying Old Church Formation and Delmarva beds as a single seismic stratigraphic unit (pl. 3).

Plum Point and Calvert Beach Members of the Calvert Formation

The middle Miocene Calvert Formation is predominately a light- to dark-olive-gray, very fine, sandy clay silt to diatomaceous silty clay and diatomite. These clayey beds comprise the majority of the section, which commonly contains 2–10 fining-upward sequences. The base of each sequence has a few feet of light- to dark-olive-gray, clayey and silty, very fine to fine sand that commonly contains medium to coarse sand with scattered quartz and phosphate pebbles, phosphate and glauconite chips and grains, and very sparse to abundant shells. The clayey beds commonly contain abundant Foraminifera and scattered shells. Cores from these beds contain a distinct microfossil assemblage that indicates a middle Miocene age, spanning planktonic Foraminifera zones N8 through N9-10? (Powars and others, 1992; Verteuil and Norris, 1992, 1996) and, therefore, represent the Plum Point Member (upper two-thirds) and Calvert Beach Member of the Calvert Formation.

The Calvert Formation's middle Miocene beds are distributed across nearly the entire Virginia Coastal Plain north of the James River (fig. 12). These beds appear to be absent in a small area north of the James River and west of the Chickahominy River and are very thin (less than 15 ft) in the Norfolk to Virginia Beach area. The middle Miocene beds show the widest variation in thickness of all the post-impact deposits and generally thicken and prograde into the crater, especially from the north side, which suggests a northern source. Northeast of the crater, toward the axis of the Salisbury Embayment (a tectonic structural low), the middle Miocene beds were encountered in the Jenkins Bridge corehole at depths similar to those at which they were encountered in the crater; the beds are even a little thicker (550 ft) in the corehole (fig. 18.4 in Powars and others, 1992). This greater thickness is in agreement with a northern source. Beneath the lower York-James Peninsula, the middle Miocene beds are up to 65 ft thick outside the crater's outer rim and range from about 45 to 207 ft thick inside the crater.

The overall fine-grained composition of the middle Miocene Calvert Formation is reflected in the low, fairly flat, resistivity-log signature (deflection to the left), whereas the basal sands are only locally distinct. In the Newport News Park 2 corehole, the basal 6 ft of section contains enough glauconite and phosphate to cause a sharp kick to the right on the gamma log (one of the "hottest" responses). This hot response often continues downward into the lithically similar, shelly, sandy facies of the lower Miocene Calvert Formation. The high resistivity-log signature and very high gamma-log signature of the sandy Old Church and lower Miocene strata contrast with those of the overlying and underlying fine-grained deposits and make this unit an excellent marker bed that can be followed across the region (pl. 4). In the Kiptopeke corehole (pl. 5), the gamma and resistivity logs reflect the fining-upward sequences of the middle Miocene Calvert Formation, with the relatively thin basal sands having relatively thin high resistivity- and gamma-log signatures. In contrast, the thicker clayey intervals have low resistivity- and relatively high gamma-log signatures.

The lack of biostratigraphic data from inside the crater beneath the lower York-James Peninsula makes it difficult to differentiate between the middle Miocene Calvert Formation and the lithologically similar overlying St. Marys Formation. As shown on plate 4, the St. Marys Formation is interpreted as a much thicker unit that truncates and overlaps the middle Miocene Calvert Formation in this area. These interpretations were influenced, in part, by the thick sections of the St. Marys Formation strata encountered in the Jamestown corehole (app. 4b) and the Dismal Swamp and Fentress coreholes. However, because middle Miocene deposits are much thicker farther toward the center (Kiptopeke corehole, pls. 3 and 5) and northern part of the crater (Exmore corehole) and because of uncertainty in correlating these similar-looking sequences, a "?" is included on plate 4 at some of the contacts.

The seismic signature of the middle Miocene Calvert Formation is ill-defined outside the crater's outer rim (pl. 3). Across the outer rim, this section thickens and slopes into the crater. On the York River seismic line (pl. 3), the homogeneous lithology of the section here

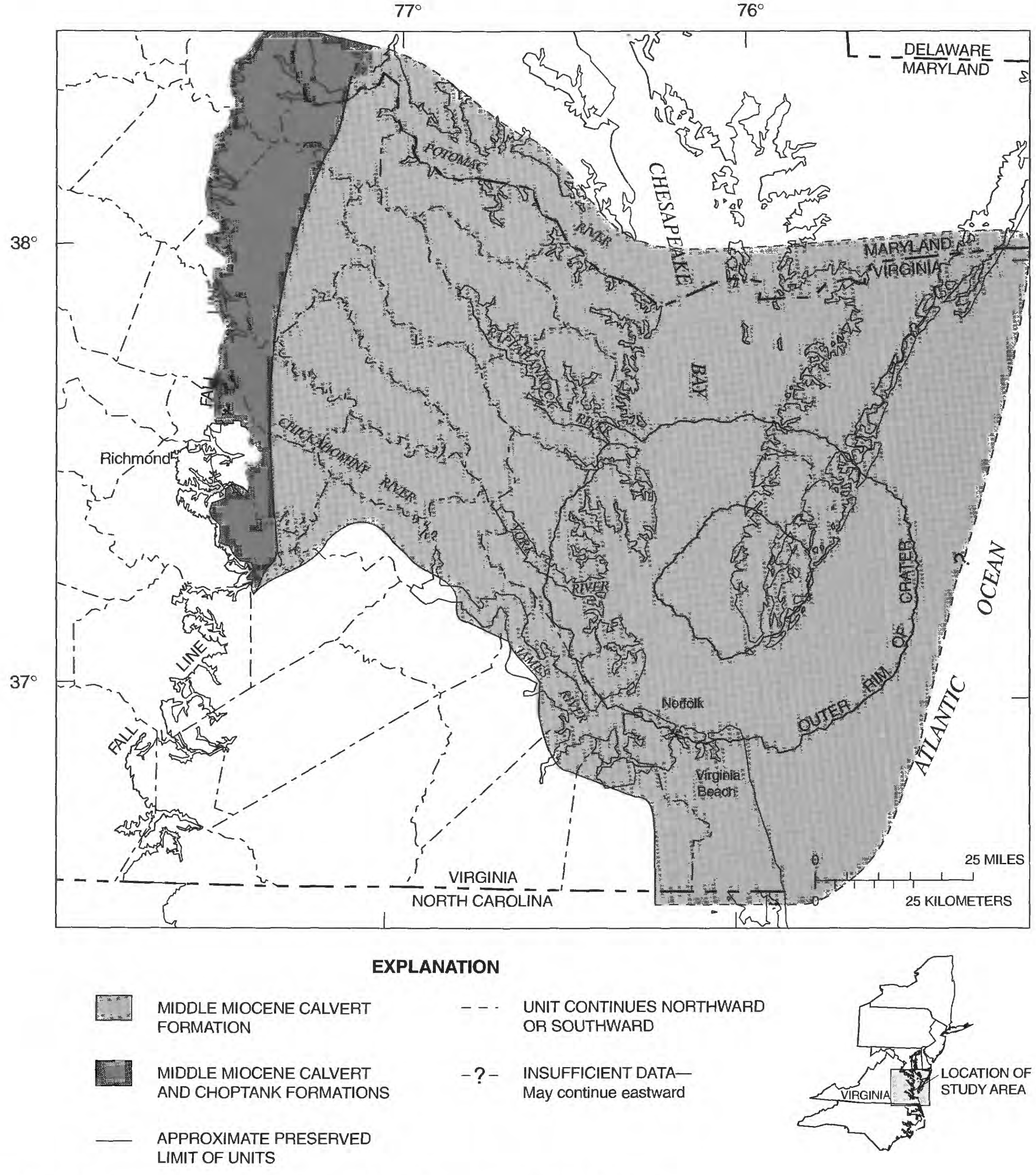


Figure 12. Distribution of the post-impact Calvert Formation (middle Miocene).

apparently causes the wide spacing of high-amplitude reflectors. Farther into the crater, the section consists of closer spaced, long, continuous, parallel, high-amplitude reflections typical of marine beds that have numerous sand-over-clay contacts (commonly representing an unconformity).

St. Marys Formation

The St. Marys Formation (upper Miocene) is the first post-impact unit that extends across the entire region (fig. 13), progressively onlapping and truncating older units west to southwest of the crater. The St. Marys consists of massive, mostly dense, well-sorted, dark-greenish-gray to dark-gray, micaceous, clayey silt to very fine, sandy clay and silt containing scattered shells, sparse to abundant burrows, fairly abundant iron sulfide (pyrite and chalcopyrite), and finely disseminated organic matter. The thickness of the unit ranges from about 30 to 100 ft outside the outer rim of the crater and from about 70 to 250 ft inside 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. The St. Marys exhibits a predominately clayey facies across the southern and western parts of the region (both inside and outside the crater). North of the crater and beneath the Delmarva Peninsula, the unit consists of a relatively thick (up to twice as thick as the clayey facies), predominantly sandy, shelly facies. Beneath the lower York-James Peninsula, the St. Marys exhibits a gradational change from the lower clayey facies to the upper, sandy, shelly facies. These changes are reflected in the resistivity logs by the gradual change from a clayey log signature (deflection to the left) to a sandy log signature (deflection to the right; pl. 4). The lower clayey facies commonly contains two fining-upward sequences that have thin (less than 5 ft), shelly, phosphatic, sandy basal lag deposits. The base of the unit, like most of the marine unconformities found in the Oligocene and Miocene sequence, contains a basal lag deposit of poorly sorted, shelly, woody, pyritic, very fine to very coarse sand, with scattered phosphate pebbles (up to 0.4 in.).

Dinocyst data (L. DeVerteuil, University of Toronto, written commun., 1994; Verteuil and Norris, 1992, 1996) from the St. Marys clayey facies encountered in the Exmore corehole suggest an equivalence to the Windmill Point beds (Ward, 1984) and are extrapolated to upper zone N16 to lower zone N17 (planktonic foram zones). C.W. Poag (USGS, written commun., 1988 and 1993) reported these same beds contain Foraminifera indicating foram zone N18. Dinocyst data from the Jamestown corehole also indicate an equivalence to the Windmill Point beds (see app. 4b). Strontium-isotope data from the Kiptopeke and Newport News Park coreholes suggest that the age of the St. Marys strata ranges from about 6.7 to 5.5 Ma (P.J. Sugarman and K.G. Miller, Rutgers University, written commun., 1995), which extrapolates to zone N17. Similar ages (6.2–5.5 Ma) were found in the overlying Eastover Formation and indicate that the unconformity separating these units represents a relatively short interval of time.

Above the St Marys, the base of the Eastover is marked by a shelly, sandy basal lag deposit that generally lacks phosphatic material outside the crater's outer rim and, therefore, shows a sandy resistivity-log signature with a low gamma-log signature. Inside the crater's outer rim, the basal sands include phosphatic material and, therefore, produce high gamma-log signatures (deflection to the right). One of the keys for differentiation is that these basal sands are at the base of the Eastover Formation's overall coarsening-upward trend. Problems with differentiating the St. Marys from the underlying clayey middle Miocene Calvert Formation were discussed in the last section (including geophysical log signatures). Farther to the west (Jamestown corehole), shelly basal sands of the St. Marys overlie the lithologically similar lower Miocene deposits, making differentiation very difficult.

Due to the lack of shallow seismic data, the St. Marys Formation is combined with all the overlying post-impact deposits into an upper Miocene to Quaternary seismic stratigraphic unit. Inside the crater, where the St. Marys strata are at much deeper depths, it is possible, through correlation to the coreholes, to assign some of the long, thin, parallel, marine reflectors to the St. Marys.

Eastover Formation

The Eastover Formation (upper Miocene) consists of massive to laminated, dark-gray to greenish-gray and dark-greenish-gray, muddy, fine sand interbedded with finer and coarser grained beds. The Eastover is sparsely to abundantly shelly and burrowed; contains some shell hashes and indurated beds; and is, in part, glauconitic and micaceous. The pearly luster, tabular-shaped mollusk *Isognomon maxillata* is a common species and is abundant in the upper part of the Eastover but not present in the overlying Yorktown Formation. Throughout the study area, the lower part of the Eastover consists of a clayey, fine-grained facies and the upper part is a shelly, coarser grained, sandy facies. This report does not separate the Claremont Manor and Cobham Bay Members of the Eastover Formation

(Ward, 1984) because ostracode and foraminiferal analysis from the Dismal Swamp and Fentress coreholes indicates that the Eastover includes a thick younger section that has no correlative units in outcrop (T. Cronin and S. Ishman, USGS, written commun., 1995).

In the lower York-James Peninsula area, the Eastover ranges in thickness from about 35 to 110 ft outside the crater's outer rim and from about 100 to 210 ft inside the crater, except where truncated by Quaternary deposits. Similar to the St. Marys Formation, the Eastover appears to be relatively thicker in the southern one-half of the region, both in and outside the crater (up to 266 ft thick in the Kiptopeke corehole). Strontium-isotope dates from the Kiptopeke and New-

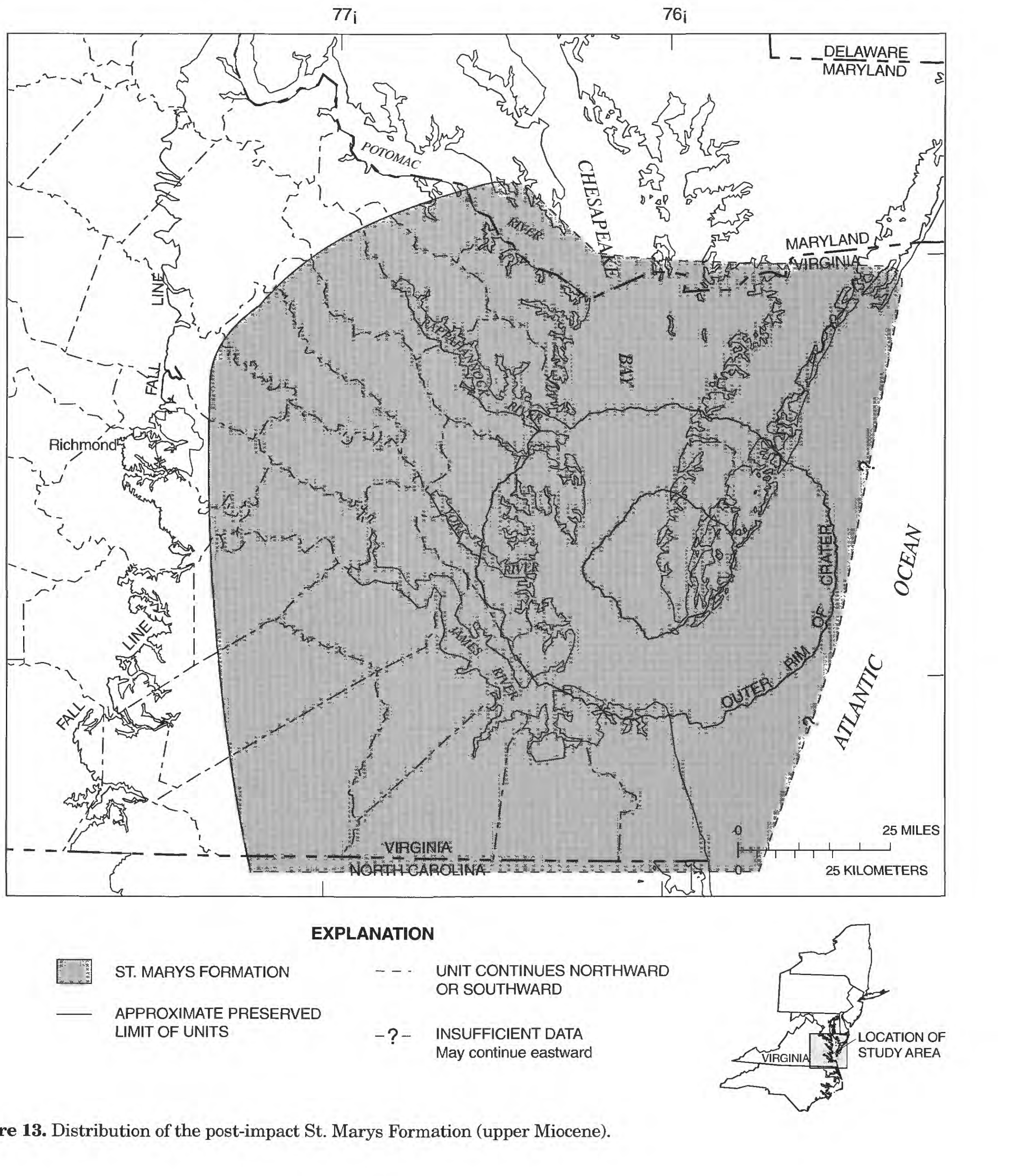


Figure 13. Distribution of the post-impact St. Marys Formation (upper Miocene).

port News Park 2 coreholes suggest the age of the Eastover Formation ranges from 6.2 to 5.5 Ma, which extrapolates to Foraminiferal zone N17.

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). Figure 14 shows the present-day distribution of the Eastover Formation, which onlaps older Coastal Plain stratigraphic units westward toward the Fall Line. The means by which the Eastover is distinguished from the underlying St. Marys is discussed in the previous section, which includes a description of the Eastover Formation's basal sand. The Eastover Formation is overlain by the Yorktown Formation across the entire study area, except where the Yorktown has been cut out by Pleistocene channeling. The lithology at the top

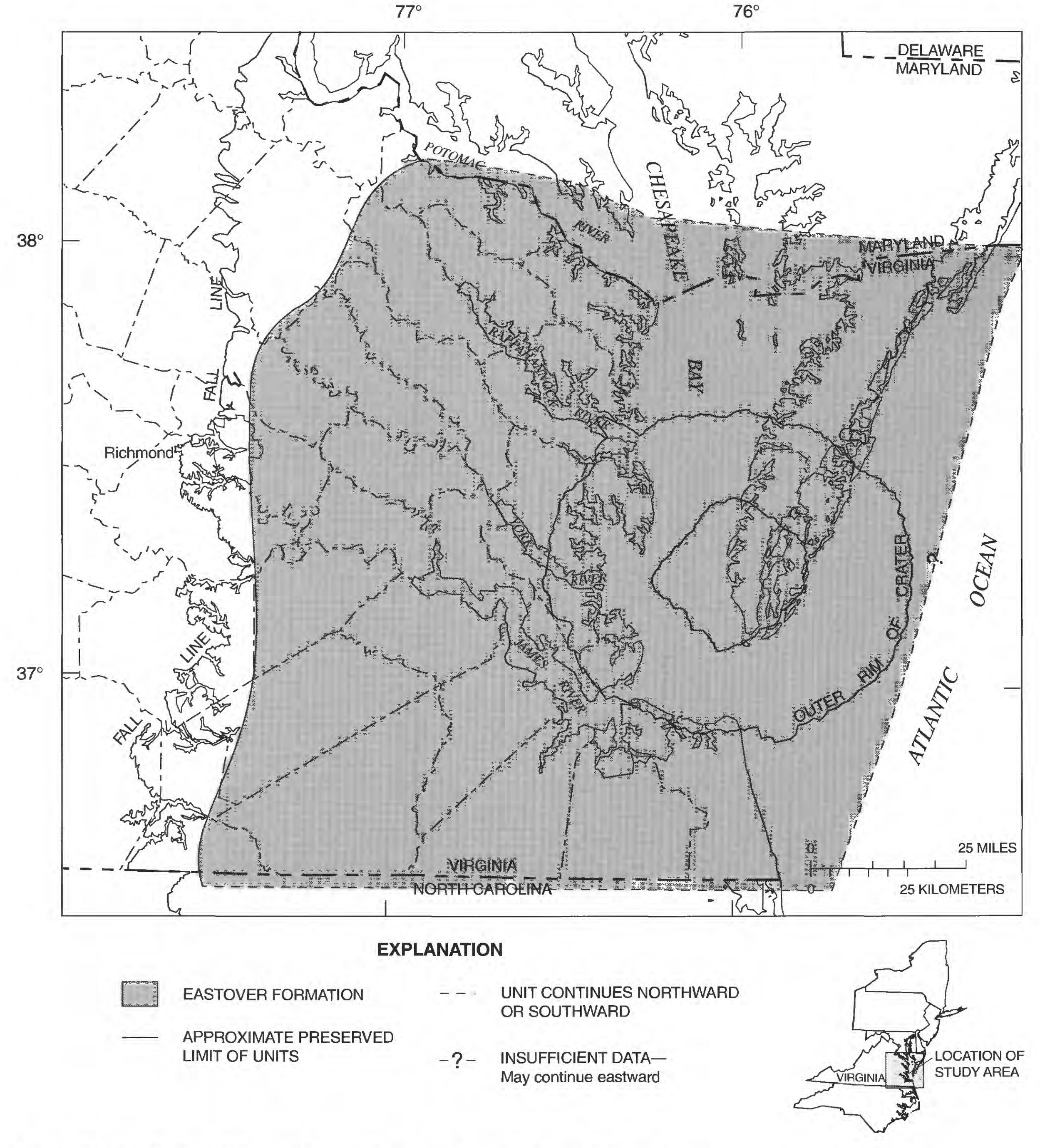


Figure 14. Distribution of the post-impact Eastover Formation (upper Miocene).

of the Eastover is quite variable across the region, but a thin clay layer in the Eastover is locally persistent in the study area (pl. 4) and makes differentiation from the Yorktown relatively easy on the resistivity logs. Biostratigraphic documentation of this contact is lacking, and the contact may be within the overlying shelly coarse-grained sands as it is in outcrops along the James River.

Because of the lack of shallow seismic data, the Eastover Formation is lumped with the upper Miocene to Quaternary post-impact deposits. Similar to the St. Marys Formation, the Eastover is deep enough inside the crater to be resolved and is represented by long, thin, parallel marine reflectors.

Yorktown Formation

The Yorktown Formation (lower and upper Pliocene) extends across the entire study area (fig. 15) and is overlain by late Tertiary fluvial to nearshore marine deposits of the Bacons Castle Formation on the middle Coastal Plain and primarily by Quaternary fluvial-estuarine deposits on the lower Coastal Plain. Locally, on the lower Coastal Plain, the Yorktown Formation is overlain by shallow marine deposits of the Chowan River Formation (late Pliocene). In the lower York-James Peninsula, the Yorktown strata range in thickness up to about 60 ft outside the outer rim of the crater and up to about 115 ft inside the crater. The thickest section (115 ft) documented in the region is near the edge of the inner basin, in the Kiptopeke corehole (pl. 5). Similar to the Oligocene and Miocene post-impact deposits, the Yorktown strata generally become finer grained, thicken, and sag into the crater. Detailed mapping of the Yorktown Formation over the last 30 years (Johnson, 1969, 1972, 1976; Johnson and others, 1982; Johnson, Kruse, and others, 1998; Johnson, Powars, and others, 1998) and other recent investigations (Brockman and Richardson, 1992; Brockman and others, 1997), however, have documented complex lithofacies distribution and thickness patterns. Synchronous deposition and deformation of beds have greatly influenced the finer to coarser grained lithofacies distribution patterns within 12.4 mi of the crater's outer rim (Johnson, Powars, and others, 1998; Powars and others, 1998). These patterns are now attributable to episodic differential movement of the bounding faults around the buried outer rim of the crater and the rotation of slump blocks near the perimeter of the outer rim (Johnson, Kruse, and others, 1998; Johnson, Powars, and others, 1998; Powars and others, 1998).

The complex distribution and truncation of lithofacies, documented by the relatively abundant outcrops and shallow subsurface data of the Yorktown, may be typical of many of the underlying post-impact units for which very little data are available. The deposition of shoaling bioclastic sand bodies near the edge of the outer rim in several of these underlying units suggests that they might have units similar to the lenticular bioclastic sand bodies of the Yorktown Formation (0.6 to 1.2 mi wide, 1.9 to 3.7 mi long) that are parallel and concentrical to the crater's outer rim.

The Yorktown Formation consists of bluish-gray to greenish-gray and dark-greenish-gray, commonly shelly (locally a bioclastic sand, typically crossbedded), very fine to coarse quartz sand, in part glauconitic and phosphatic, interbedded with gray and blue-gray, sparsely fossiliferous, sandy and silty clay to clay silt. The basal part of the Yorktown coarsens downward into a pebbly, shelly, glauconitic, and phosphatic quartz sand sharply overlying and burrowed into a locally clayey or shelly sandy deposit of the Eastover. 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. As shown on plate 4, many of the resistivity logs start below the Yorktown Formation, which also hampers subdivision. For details about these members and their geophysical borehole signatures, the reader is referred to the recent shallow groundwater investigations by Brockman and Richardson (1992) and Brockman and others (1997).

Because of the lack of shallow seismic data, the Yorktown strata are combined into the upper Miocene to Quaternary seismic stratigraphic unit. Inside the crater, this unit is too shallow to be resolved. West of the Chesapeake Bay, recent, land-based, shallow seismic (down to about 0.15 second twt) and ground-penetrating radar investigations tied to detailed outcrop mapping indicate that Miocene and Pliocene deposits dip radially away from the center of the impact structure (Riddle and others, 1996; Johnson, Kruse, and others, 1998; Johnson, Powars, and others, 1998). This occurs over regions several miles in width and results in dips that are discordant from the typical eastward regional dip of Cenozoic strata (Riddle and others, 1996; Johnson, Kruse, and others, 1998; Johnson, Powars, and others, 1998). These dip reversals are generally less than 1 degree and often include fan-like interformational 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, Powars, and others, 1998).

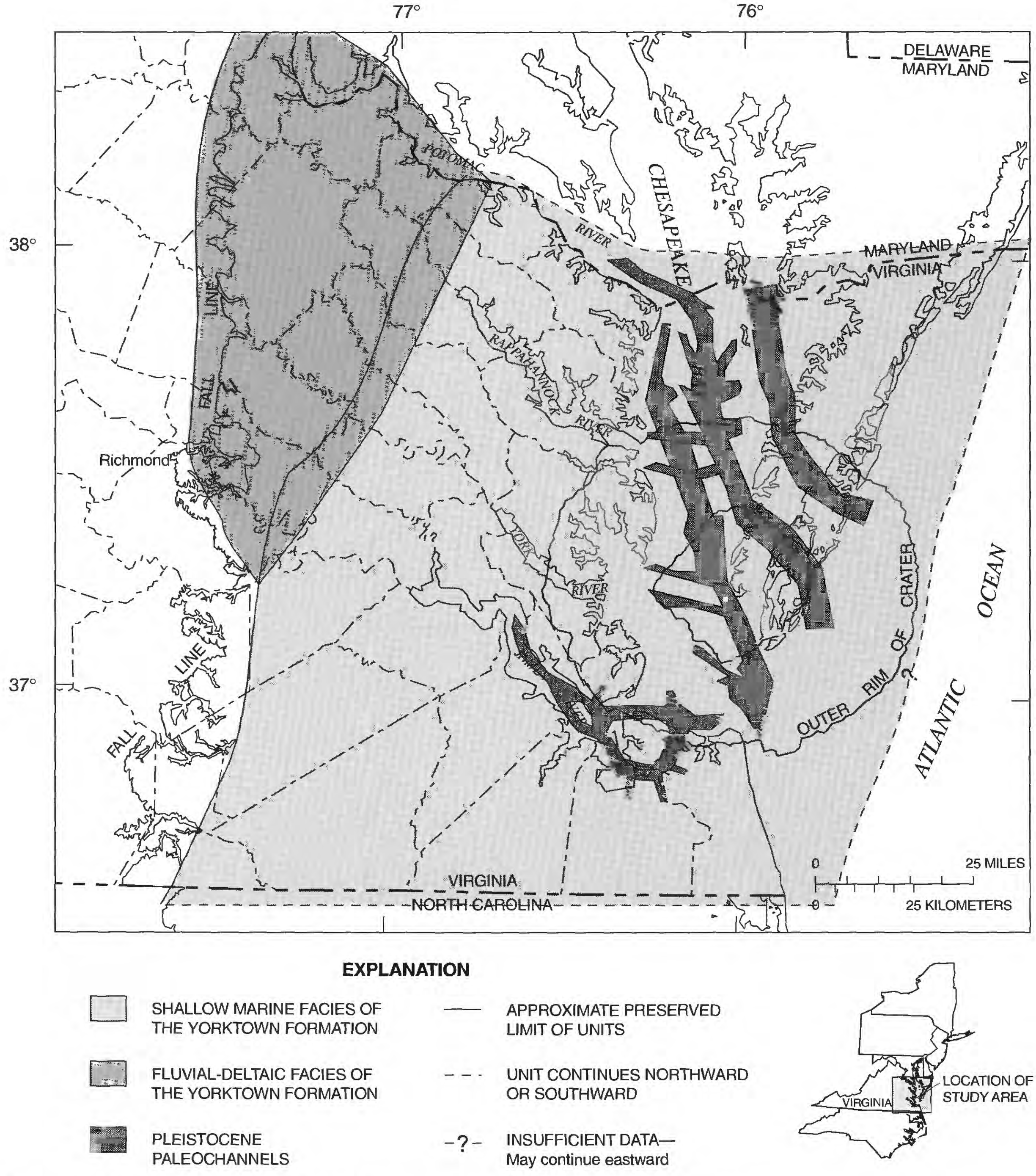


Figure 15. Distribution of the post-impact Yorktown Formation (lower and upper Pliocene).

Chowan River Formation

The Chowan River Formation (upper Pliocene) has a very limited, sporadic distribution across the southeastern part of the study area and locally is found only in the lower York-James Peninsula. It consists of interbedded, silty, fine sand, clayey silt, and bioclastic sand that ranges in thickness from a feather edge to about 51 ft in the downdip Virginia Beach area. The Chowan River Formation is documented in the Kiptopeke corehole from −48 to −72 ft bsl and consists of dark-greenish-gray, interbedded, bioclastic to shelly, silty, fine sand and muddy fine sand containing a few medium to coarse grains. This suggests that the Chowan River also dips into the crater. Where present, this unit unconformably overlies the Yorktown Formation and is truncated by Quaternary fluvial to estuarine and marginal-marine deposits. Similar lithologies in the Chowan River and the underlying Yorktown Formation make differentiation difficult, requiring chronostratigraphic data. Except for the Kiptopeke and Fentress coreholes and the borehole in the town of Cape Charles, no attempt was made to differentiate the Chowan River from the Yorktown.

Bacons Castle Formation

The Bacons Castle Formation (upper Pliocene) is the surficial unit in the western uplands part of the study area, primarily outside the buried outer rim of the crater. In this area, the Bacons Castle is mapped as the fine-grained upper Barhamsville Member of the Bacons Castle Formation, which consists primarily of gray to yellowish-orange and reddish-brown, thinly bedded to laminated, clayey silt to silty fine sand (Johnson and Ramsey, 1987; Mixon, Berquist, and others, 1989). Johnson and Ramsey (1987) mapped the lithologic facies and interpreted the following depositional sequence in this area: (1) fluvial to tidal-flat and estuarine deposits on a fluvial-dissected landscape incised into the top of the Yorktown Formation; (2) shallow marine deposits; and (3) a prograding tidal-flat complex. Brockman and others (1997) report that a medium to coarse gravelly sand and silt found on the uplands of the Naval Weapons Station at Yorktown, Va., also is part of the Bacons Castle. The base of the unit commonly coarsens downward to a pebbly to coarse sand that rests with angular unconformity on the Yorktown Formation.

Quaternary Deposits

Quaternary strata in the study area include fluvial, estuarine, marginal-marine, and nearshore-shelf sediments deposited during the Pleistocene glacial-interglacial period. The Pleistocene (early, middle, and late) 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 toward the coast and major streams. The Quaternary strata in the lower York-James Peninsula include early, middle, and late Pleistocene deposits, which generally exhibit a fining-upward sequence, and Holocene deposits. 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 peat. 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 (Colman and Mixon, 1988; Johnson, 1969, 1972; Johnson and Ramsey, 1987). Johnson (1972) mapped the distribution and thickness of the post-Yorktown strata for most of the lower York-James Peninsula, showing the existence of an extensive paleodrainage network beneath the lower York-James Peninsula. Near the Hampton Roads tunnel, the James River paleochannel cuts down to nearly 160 ft bsl beneath the modern James River. The Pleistocene scarps were formed by fluvial, 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 parallelism of the coast-facing scarps and their proximity to the outer rim of the crater, the stacked nature of some of the scarps near the outer rim, and the fact that primarily late Pleistocene and Holocene deposits are the only surficial units found inside the buried outer rim of the crater strongly suggest they have been influenced by the episodic differential movement around the buried outer rim and continued higher subsidence rates inside the crater. Figure 16 shows the location of segments of the Suffolk, Harpersville, Big Bethel, and Diamond Springs scarps, and Ames Ridge (also a scarp), in relation to the crater's buried outer rim.

Paleochannels of the Susquehanna River beneath the present-day Chesapeake Bay either trend southward to the crater or cut across the lower Delmarva Peninsula south of Salisbury, Md. (Johnson and Powars, 1996). The southerly course of the Susquehanna River paleochannels to the crater is, in part, the result of the formation of the Delmarva Peninsula. The surficial backbone of this peninsula (as far south as Salisbury, Md.) was formed during the late Tertiary from deposition by the Pensauken fluvial-deltaic complex into the northern end of the Salisbury tectonic low by the ancestral Hudson-Delaware River system. Subsequent southward progradation of sediments along this headland during interglacial sea-level high formed the lower Delmarva Peninsula and resulted in the southward temporal progression of the Susquehanna paleochannels. Major paleochannels (Exmore, Eastville, Cape Charles, James and York Rivers) exhibit course changes at the outer rim and turn into the crater. The channels exit across the eastern side of the crater, which subsided at a faster rate, probably because of an underlying tectonic hinge zone. The configuration of the Chesapeake Bay and its tributaries resulted from drowning of the Susquehanna River system during the Holocene, and the bay's location was greatly influenced by the differential compaction and subsidence of sediments in and over the crater.

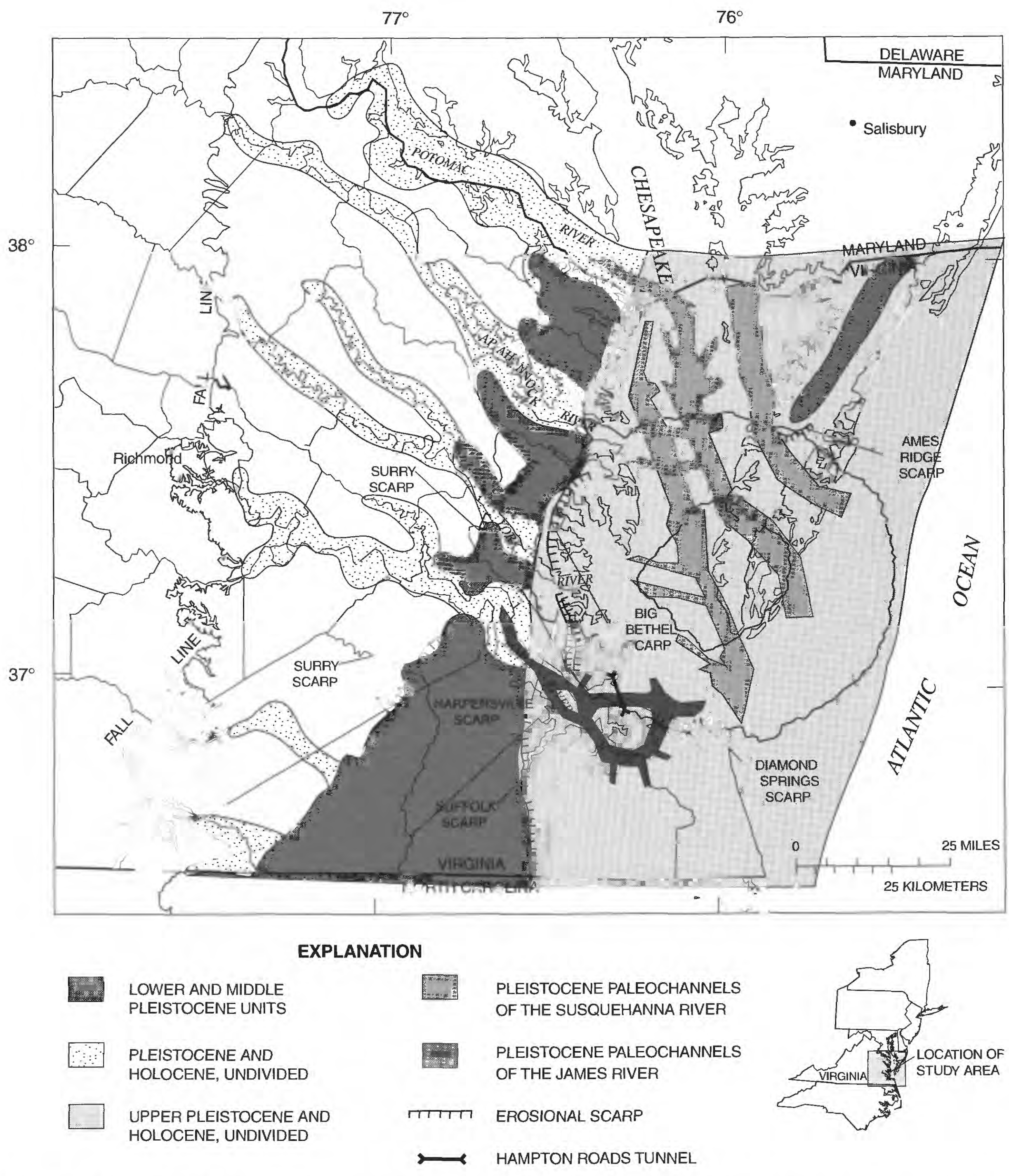


Figure 16. Generalized distribution of the post-impact Quaternary surficial stratigraphic units, including the location of some major scarps and paleochannels.

A generalized subdivision of the Quaternary surficial units is shown in figure 16. For more information about individual Quaternary units, the reader is referred to the geological 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 LITHIC UNITS TO HYDROGEOLOGIC UNITS

On the basis of lithology, biostratigraphy, and borehole geophysical logs, we have attempted to correlate the geological units described in this report with the hydrogeologic units of the Virginia Coastal Plain Regional Aquifer System Analysis (RASA) study (Meng and Harsh, 1988) (table 2). The 56-mi-wide CBIC has truncated the lower half of the seven aquifers and seven confining units that were identified by the RASA study in the lower York-James Peninsula area (Meng and Harsh, 1988). The St. Marys-Choptank aquifer, an important aquifer to the north 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). Recently, investigators have refined the hydrogeology of the shallow aquifer system of York County (the top two aquifers and one confining unit of the RASA study) into a more local aquifer-confining unit subdivision, adding one more aquifer and confining unit beneath the Lackey Plain (Brockman and others, 1997) (pl. 4).

The information displayed on the plates of this report provides a geological framework data base on which the hydrogeologic framework will be built. The litho-stratigraphic fence diagram is easily transformed into aquifers and confining units (pl. 4), and the structure contour and isopach maps (pls. 6*A* and *B*, 7*A* and *B*) of the possibly low permeability Exmore tsunami-breccia and the overlying fine-grained Chickahominy Formation (confining unit) can be readily incorporated into the current ground-water model.

Figures 17 and 18 graphically show this report's geological framework in relation to the cross sections of Meng and Harsh (1988) and Laczniak and Meng (1988) that traverse the lower York-James Peninsula. As would be expected, formational contacts do not match up with aquifer-confining unit contacts (especially where basal sands of one stratigraphic unit overlie sands of another).

Table 3 shows the wide variability between the distribution of stratigraphic units in this report and that of the hydrogeologic units of Cederstrom (1957) and Meng and Harsh (1988).

The structural and stratigraphic features created by the CBIC have dramatically influenced the hydrogeologic framework, ground-water flow system, and regional water quality of the Virginia Coastal Plain. Previous ground-water investigators recognized a salt-water wedge extending westward beneath the York-James and Middle Peninsulas (Cederstrom, 1943, 1946; Larson, 1981; Focazio and others, 1993; Richardson, 1994) (fig 19). Cederstrom (1943, 1946) proposed that this salt-water wedge was the product of incomplete flushing of ancient seawater along a structural depression. Back (1966) and Focazio and others (1993) suggested that the source of the chloride was probably submergence of the sediments during marine transgressions. Another explanation offered by Back (1966) and followed by Richardson (1994) was that the higher inland salinity resulted from low topographic altitude of the recharge area located along the Fall Line. The structural depression of Cederstrom (1943), however, has been identified as the CBIC (Powars and others, 1993, 1994). Loading and compaction of the Exmore tsunami-breccia is considered a possible explanation for the very high concentrations of chloride (up to 25,700 mg/L, or approximately 1.3 times that of average seawater) found in the Exmore tsunami-breccia at the VDEQ Kiptopeke Research Station (Bruce and Powars, 1995). Differential flushing of the sub-basin created by the crater also must have contributed to the creation of this inland salt-water wedge. Emplacement and mixing of the lithically heterogeneous Exmore tsunami-breccia with seawater and its subsequent burial, primarily by very fine-grained deposits (in the structural low), has apparently altered regional flow paths, possibly causing differential flushing of freshwater over and/or around the primarily fine-grained deposits filling the crater. Compaction also may have contributed to the Exmore tsunami-breccia's relatively low permeability. 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 and have apparently retarded the flushing of salt water from inside the crater.

Salt water has been defined by the amount of solute dissolved in the water, as measured by concentrations of dissolved solids in milligrams per liter or parts per million (Krieger and others, 1957) (see fig. 19). Following this classification, freshwater would be defined as water having dissolved-solids concentrations less than

Table 2. Correlation of geological units to hydrogeologic units

[U, upper; M, middle; L, lower, RASA, regional aquifer-system analysis]

SYSTEM	SERIES		Group	Formation	Geological units this report	Hydrogeologic units: Meng and Harsh (1988)	Hydrogeologic units: Virginia RASA model unit	Hydrogeologic units: Laczniak and Meng (1988)	Hydrogeologic units: Brockman and others (1997), York County shallow aquifer system: Lackey Plain	Hydrogeologic units: Brockman and others (1997), York County shallow aquifer system: Croaker Flat
QUATERNARY	Holocene				Alluvium, swamp, + beach	Columbia aquifer	AQ10	Columbia aquifer	Columbia aquifer	Columbia aquifer
	Pleistocene	U			Tabb Formation					
		M			Shirley Formation					
		M			Chuckatuck Formation					
		L			Charles City Formation				Columbia aquifer	Yorktown confining unit[2]
		L			Windsor Formation					
TERTIARY	Pliocene	U			Bacons Castle Formation	Yorktown confining unit	CU9	Yorktown confining unit	Cornwallis Cave confining unit; Cornwallis Cave aquifer	
		U	CHESAPEAKE GROUP	Yorktown Formation	Moore House Member	Yorktown-Eastover aquifer	AQ9		Yorktown confining unit	
		U			Mogarts Beach Member					Yorktown confining unit
		U			Rushmere Member			Yorktown-Eastover aquifer	Yorktown-Eastover aquifer	
		L			Sunken Meadow Member					
	Miocene	U		Eastover Formation	Unnamed beds[1]					
		U			Cobham Bay Member ?					
		U			Claremont Manor Member	St. Marys confining unit	CU8	St. Marys confining unit	Eastover-Calvert confining unit	
		U			St. Marys Formation					
		M		Calvert Formation	Choptank Formation (not present in study area)	St. Marys-Choptank aquifer	AQ8	Calvert confining unit		
		M			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	Not covered in report	
	Oligocene	U			Old Church Formation					

[1]Unpublished data D.S. Powars and T. Cronin (1995).
[2]Yorktown-Eastover aquifer.

Table 2. Correlation of geological units to hydrogeologic units—Continued

[U, upper; M, middle; L, lower, RASA, regional-aquifer system analysis]

SYSTEM	SERIES		Geological units this report	Hydrogeologic units: Meng and Harsh (1988)	Virginia RASA model unit	Laczniak and Meng (1988)	Brockman and others (1997)
TERTIARY	Miocene	M	Plum Point Member of the Calvert Fm	Calvert confining unit	CU7	Calvert confining unit	Eastover-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	Not covered in report ↓
	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	
	Paleocene	U	Marlboro Clay				
		U	Aquia Formation	Aquia aquifer	AQ6	Aquia aquifer	
		L	Brightseat Formation	Brightseat confining unit	CU3	Upper Potomac confining unit	
				Brightseat aquifer	AQ3	Upper Potomac aquifer	
CRETACEOUS	Upper		Upper Cretaceous beds	Upper Potomac confining unit	CU3	Virginia Beach confining unit (CU4)	
						Virginia Beach aquifer (AQ4)	
			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	
MESOZOIC	Lower		Rift-basin deposits				
PALEOZOIC AND PROTEROZOIC			Crystalline basement rocks				

[1]Unpublished data Powars and Cronin (1995).

[2]Yorktown-Eastover aquifer.

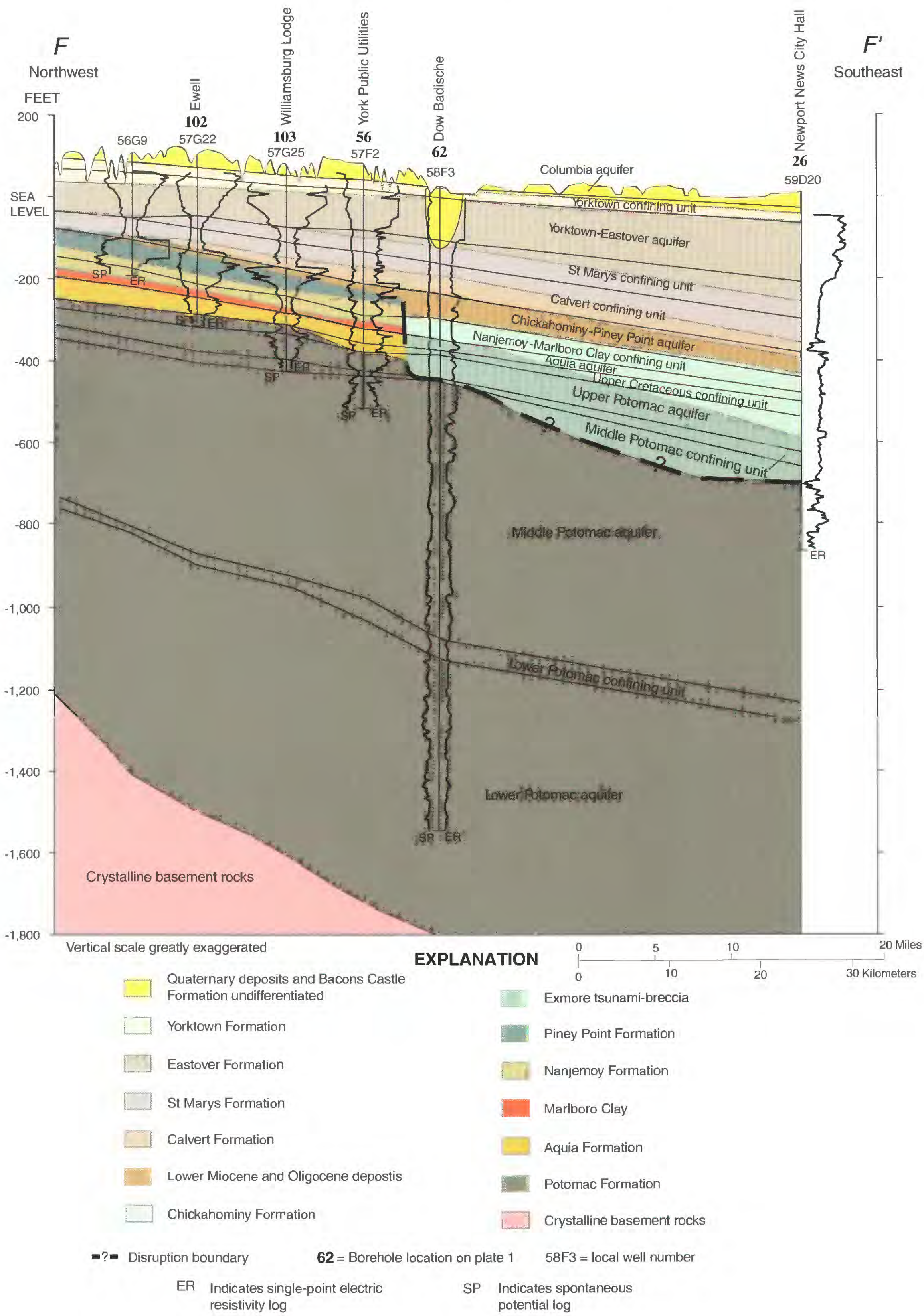


Figure 17. Hydrogeologic section across the lower York-James Peninsula (from Meng and Harsh, 1988) and geological reinterpretation overlain in color (line of section shown on pl. 1).

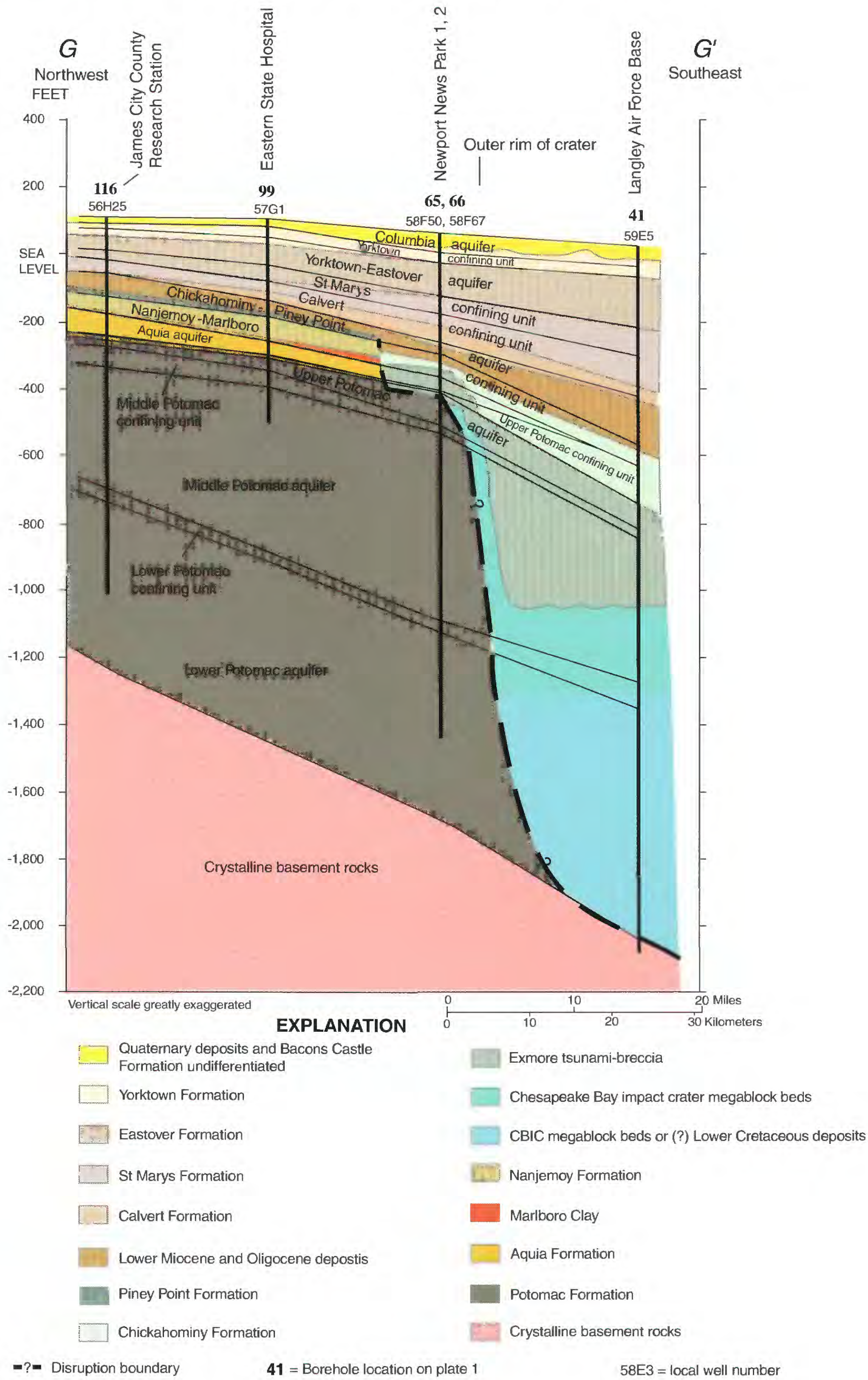


Figure 18. Hydrogeologic section across the lower York-James Peninsula (from Laczniak and Meng, 1988) and geological reinterpretation overlain in color (line of section shown on pl. 1).

Table 3. Correlation of this report's distribution of stratigraphic units, Cederstrom's (1957) distribution of stratigraphic units, and Meng and Harsh's (1988) distribution of hydrogeologic units

[RASA, regional aquifer-systems analysis; Cu, confining unit; Aq, aquifer; UPot, upper Potomac; MPot, middle Potomac; LPot, lower Potomac; Chic-PP,

Cederstrom (1957)	This report	RASA hydrogeologic units (Meng and Harsh, 1988)
Columbia Group	Quaternary undifferentiated	Columbia aquifer
Columbia Group	Bacons Castle Formation	Yorktown Cu + Yorktown-Eastover Aq + ? Columbia Aq
Yorktown Formation[1]	Chowan River Formation	Yorktown-Eastover Aq + ? Columbia Aq
Yorktown Formation[1]	Yorktown Formation	Yorktown Cu + Yorktown-Eastover Aq
Yorktown + St. Marys Formations[1]	Eastover Formation	Yorktown-Eastover Aq + St. Marys Cu[2]
St. Marys Formation[1]	St. Marys Formation	St. Marys Cu + Calvert Cu
St. Marys + Calvert Formations[1]	Upper + middle Calvert Formation	Calvert Cu
Calvert[1] + Chickahominy Formations	Newport News unit of the Calvert Formation	Chickahominy-Piney Point Aq
Calvert[1] + Chickahominy Formations	Old Church Formation	Chickahominy-Piney Point Aq + UPot Aq
Chickahominy Formation	Delmarva beds	Chickahominy-Piney Point Aq + UPot Aq
Chickahominy + Nanjemoy Formations	Chickahominy Formation	Nanjemoy-Marlboro Clay Cu ⋮[3] UPot Aq, MPot Cu, MPot Aq[2]
Chickahominy + ? Aquia + Mattaponi Formations	Exmore tsunami-breccia	Aquia Aq + UPot Cu + UPot Aq ⋮[3] MPot Aq
Nanjemoy Formation	Piney Point Formation	Chickahominy-Piney Point Aq
Nanjemoy Formation	Nanjemoy Formation	Chic-PP Aq + Nanj-Marl Cu
Nanjemoy Formation	Marlboro Clay	Nanjemoy-Marlboro Clay Cu
Aquia + Mattaponi Formations	Aquia Formation	Chic-PP Aq + Aquia Aq
Aquia + Mattaponi Formations	Brightseat Formation	Aquia Aq + Brightseat Cu + ? Brightseat Aq
Mattaponi Formation + Potomac Group (Upper Cretaceous)	Unnamed Upper Cretaceous beds	Chic-PP Aq, Nanj-Marl Cu, Aquia Aq, UPot Cu
Potomac Group (Upper Cretaceous)	Upper Cenomanian beds	UPot Cu + UPot Aq
Potomac Group (Lower Cretaceous)	Potomac Formation	UPot Aq, MPot Cu, MPot Aq, LPot Cu, LPot Aq
Basement	Basement	? Impermeable boundary

[1]Mostly reported as undifferentiated Chesapeake Group.
[2]Only the uppermost part of unit.
[3]To the right of this symbol ⋮ = units equivalent downdip.

1,000 mg/L; seawater generally has concentrations near 35,000 mg/L. In figure 19, the limit of freshwater is, therefore, delineated by the 1,000-mg/L contour line adjacent to the outer rim of the crater north of the James River. The correlation between the CBIC's outer rim and the steep gradient (transition zone) of dissolved-solids concentrations is excellent. This transition zone separates saltier ground water inside the crater from fresher ground water present outside the outer rim. A similar transition zone aligning ground-water quality with the crater's outer rim is seen in all the RASA aquifers, except the Yorktown-Eastover and Columbia aquifers. This water-quality information was compiled before the discovery of the impact crater and, therefore, determined independently (Focazio and others, 1993). It should be noted, however, that data from inside the crater are limited (fig. 19).

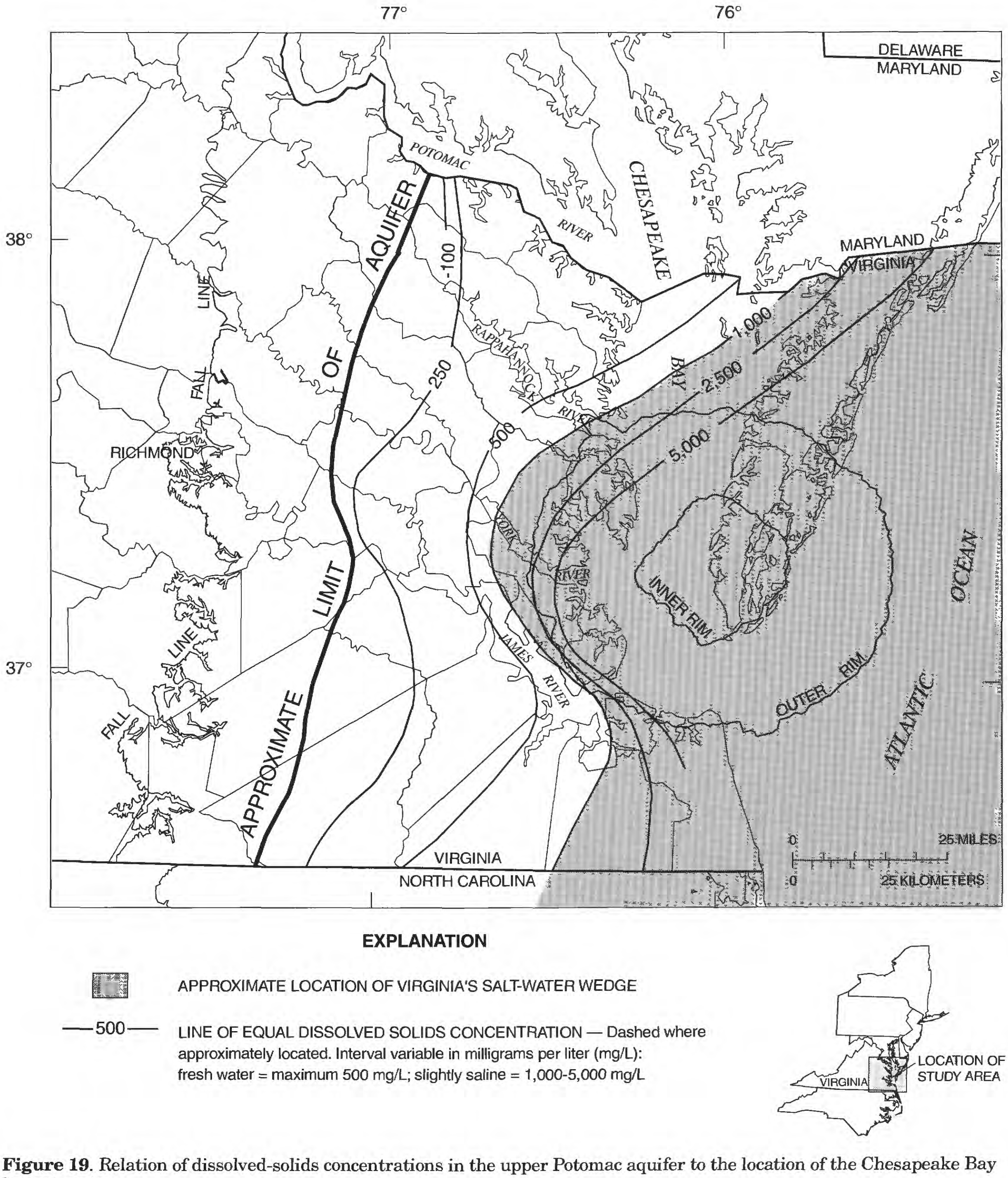


Figure 19. Relation of dissolved-solids concentrations in the upper Potomac aquifer to the location of the Chesapeake Bay impact crater.

In ground-water modeling of the lower York-James Peninsula, Laczniak and Meng (1988) achieved the best fit of simulated to measured water levels by lowering the transmissivity values of the sediments in the area now mapped as the crater. More recently, a two-dimensional, density-dependent, solute-transport model was developed by the USGS, in cooperation with the Hampton Roads Planning District Commission (as part of the Chloride Monitoring Project), and a no-flow boundary was placed a few miles inside the outer rim of the crater (Smith, 1999). This was an attempt to account for the possible effect of the crater's outer rim on the ground-water flow system. At present, there is not enough information to identify the type, if any, of flow boundary that exists along the crater's outer rim and whether the faulting at the edge of the crater causes flow barriers and/or conduits. There also is not enough information to define the flow regime inside the crater or to determine the permeabilities of the Exmore tsunami-breccia or the CBIC megablock beds. This information is needed to more accurately model and evaluate the potential movement of salty water within and around the crater to nearby well fields.

SUMMARY AND CONCLUSIONS

The Chesapeake Bay impact crater (CBIC) has greatly influenced the structural, stratigraphic, and hydrogeologic framework of the central and southern parts of the Virginia Coastal Plain. The CBIC also has influenced the development of the late Cenozoic landscape of this region.

The CBIC was created approximately 35 million years ago when a comet or meteorite struck the inner continental shelf, ejecting debris, producing a complex crater, and generating a series of gigantic tsunamis. The impactor penetrated the full thickness of existing Coastal Plain sediments (Cretaceous to Eocene), slammed into basement rock, and left an about 1.2-mi-deep by 56-mi-wide crater that was immediately filled with chaotically mixed sediments that were eventually buried by younger sediments. The town of Cape Charles, Va., overlies the center of the crater. The CBIC is a complex peak-ring crater with an inner and outer rim, a relatively flat-floored annular trough, and a central depression basin that penetrates into the basement. In the central basin, seismic-reflection data display a very irregular, broken double reflector that possibly represents the top of a melt sheet or disrupted basement. This surface suggests the presence of a central uplift surrounded by a series of concentric ridges and valleys. Post-impact deposits show the presence of two structural troughs running along the outer part of the inner basin's northwestern and southeastern sides.

Lithostratigraphic and biostratigraphic data from cores and well cuttings, borehole geophysics, and seismic-reflection data were compiled and analyzed to refine the geological framework of the lower York-James Peninsula. On the basis of correlation of borehole and seismic data, a cross section was constructed to show the stratigraphic and structural configuration of the western part of the crater (Jamestown to Kiptopeke, Va.). Correlations were compiled into a lithostratigraphic cross section and structure contour and isopach maps to illustrate the structural and stratigraphic relations of geological units inside, and adjacent to, the outer rim of the impact crater.

Syn-impact deposits consist of the upper Eocene Exmore tsunami-breccia and the seismically defined Chesapeake Bay impact crater megablock beds (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 deposits of upper Eocene to Holocene age buried the crater and its syn-impact deposits with approximately 1,300 to 1,600 ft of sediment, which explains the distribution and abrupt thickening of stratigraphic units north of the James River. Seismic profiles show numerous compaction faults that offset most post-impact deposits around the outer rim and inside the crater.

The outer rim is characterized by an escarpment zone with normal-faulted slump blocks that encircle and have been down-thrown and rotated into the annular trough. The relief on the escarpment ranges from about 1,000 to nearly 4,000 ft, and the width of the escarpment varies from 0.53 to 1.9 mi. The geometry and slope of the escarpment vary; in some places, it can be characterized as a steep wall, whereas in other places, it resembles stairs stepping into the annular trough. A narrow band of preserved Exmore tsunami-breccia deposits around the outside of the crater's outer rim is affected by the bounding fault zone and other faults apparently produced or reactivated by the impact. Adding the dimensions of this faulted zone outside the outer rim to the crater's diameter results in a 75.5-mi-wide structure referred to as the Chesapeake Bay impact structure (CBIS) (Powars and others, 1998).

The crater's structural depression has determined the post-impact depositional history and stratigraphic relations among formations beneath the lower York-James Peninsula. Transformation of the depositional environment during late Eocene time from inner neritic (shallow) to bathyal (deep) depths, compounded by the creation of a persistent low due to post-impact loading and compaction, has resulted in the deposition of geological units that are preserved only within the disruption boundary of the impact.

Outside the outer rim and disruption boundary of the CBIC, the stratigraphic sequence beneath the lower York-James Peninsula consists of the following geological units: Lower Cretaceous Potomac Formation; upper Paleocene Aquia Formation; uppermost Paleocene to lowermost Eocene Marlboro Clay; lower Eocene Nanjemoy Formation; middle Eocene Piney Point Formation; lower Oligocene Delmarva beds; upper Oligocene to lower Miocene (?) Old Church Formation; lower and middle Miocene Calvert Formation; upper Miocene St. Marys Formation; upper Miocene Eastover Formation; lower and upper Pliocene Yorktown Formation; upper Pliocene Bacons Castle Formation; and Quaternary deposits undifferentiated. Notably, Upper Cretaceous deposits are absent beneath the lower York-James Peninsula.

Syn-impact deposits present within the disruption boundary and outer rim of the CBIC beneath the lower York-James Peninsula include the seismically defined CBIC megablock beds and the upper Eocene Exmore tsunami-breccia. The post-impact upper Eocene Chickahominy Formation caps the Exmore tsunami-breccia within the disruption boundary; the lower Oligocene Delmarva beds appear to be the first post-impact unit preserved across the disruption boundary south of the crater; the upper Oligocene Old Church Formation is the first post-impact unit preserved across the disruption boundary west of the crater.

Lateral contacts between undisturbed stratigraphic units and syn-impact units are complex. The geometry and slope of the escarpment vary greatly around the perimeter of the CBIC due to hydraulic erosion created by oceanic water collapse and subsequent tsunamis. The competency of the various pre-impact sediments—for example, the partially lithified Piney Point Formation—also may have influenced the shape of the escarpment and disruption boundary.

Pre-impact sediments of Early Cretaceous to middle Eocene age abut laterally syn-impact Exmore tsunami-breccia and megablock beds along the faulted escarpment of the outer rim of the CBIC and the outer edge of the disruption boundary. Generally, the CBIC megablock beds and Exmore tsunami-breccia are in lateral contact with the Lower Cretaceous Potomac Formation just inside the outer rim of the CBIC. Outside the crater rim, the Exmore tsunami-breccia laterally abuts the upper part of the Potomac Formation and the Aquia Formation. The Chickahominy Formation is generally in lateral contact with the Marlboro Clay, Nanjemoy and Piney Point Formations.

Post-impact units deposited across the disruption boundary thicken into the annular trough. The Delmarva beds, Old Church Formation, and lower Miocene part of the Calvert Formation also become coarser grained beneath the lower York-James Peninsula, but become finer grained farther into the annular trough (also in the northern and eastern part of the trough, which apparently was farther from a sediment source). The middle Miocene part of the Calvert Formation and the upper Miocene St. Marys and Eastover Formations exhibit only minor lithologic changes across the outer rim into the annular trough.

Pliocene to Quaternary deposits show complex lithofacies distribution and thickness patterns that include thin to thick and fine to coarse beds within 12.5 mi. of the crater's outer rim. 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 Cenozoic strata. These dip reversals are generally less than 1 degree and commonly include fan-like interformational 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. The parallelism and proximity of Quaternary coast-facing scarps to the outer rim of the crater, the stacked nature of some scarps near the crater's outer rim, and the fact that primarily late Pleistocene and Holocene deposits are the only surficial units found inside the buried outer rim of the crater strongly suggest a connection to episodic differential movement around the buried outer rim of the crater and continued higher subsidence rates inside the crater.

These structural and stratigraphic features created by the impact also have influenced our understanding of the hydrogeologic framework, ground-water flow system, and regional water quality of the Virginia Coastal Plain. Results of this study indicate that the lower one-half of the seven aquifers and confining units previously identified in the region have been disrupted, and the physical properties of the ground-water flow system have been significantly altered. Emplacement of a mixture of the lithically heterogeneous Exmore tsunami-breccia with seawater, and its subsequent burial by fine-grained deposits in the structural low, likely altered regional flow paths, resulting in differential flushing of freshwater over and/or around the primarily fine-grained deposits found inside the crater. The distribution of Virginia's inland salt-water wedge coincides quite well with the CBIC's location. In the absence of alternative 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 are poorly understood, and additional data are needed to precisely locate and delineate the outer rim. The outer rim conforms well to the transition zone that separates ground water of high salinity inside the outer rim from fresher water outside the outer rim. Additional land-based seismic-reflection profiles, cores, and borehole geophysical logs, especially a sonic velocity log for accurate depth correlation between borehole and seismic data, would provide the information needed to locate this boundary accurately. Hydrologic data, such as flow direction, water quality, and permeability within the crater are limited, and information about the depositional processes associated with such a large impactor into water-saturated, unconsolidated sediments is sparse. Obtaining cores and placing monitoring 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 movement of salty water to well fields in the vicinity of the impact crater. As ground-water use increases in the Hampton Roads region and public water utilities increasingly tap into 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 1A. 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 Polytech Institute; VEPCO, Virginia Electric Power Company; --, local number not assigned]

Bore-hole location number on plate 1	Local number	Identifying name, owner, or organization, and some references	Latitude	Longitude	Surface altitude	Bottom altitude
1	58A76	Dismal Swamp Corehole (Powars and others,1992; unpublished data, D.S. Powars, USGS and T.S. Bruce, VDEQ)	36 36 55	76 33 20	33	–1,857
2	61B11	Fentress Corehole (Powars and others, 1992; unpublished data, D.S. Powars, USGS and T.S. Bruce, VDEQ)	36 42 27	76 07 47	15	–2,005
3	58C6	Well #8 (Cederstrom, 1945a) Chuckatuck-Cedarbrook Farm	36 51 16	76 33 26	15	–535
4	58C5	Well #37 (Cederstrom, 1945a) Drivers-Monogram Farm	36 49 04	76 32 50	20	–520
5	59C2	Virginia Division of Forestry	36 48 08	76 23 15	20	–633
6	59C28	City of Chesapeake-Bowers Hill-Production Well #1	36 47 02	76 24 55	21	–979
7	58B11	NAN-P-8 (Brown and others, 1972)	36 44 28	76 33 32	20	–634
8	59C2	POR-P-10 (Brown and others, 1972)	36 48 08	76 23 15	15	–638
9	59C6	CHE-P-11 (Brown and others, 1972)	36 52 41	76 23 17	3	–597
10	59C39	MW4-1 Corehole (Powars and others, 1992)	36 47 10	76 26 52	17	–983
11	60C6	Lone Star Cement Corp.	36 48 53	76 17 09	5	–790
12	60C7	City of Portsmouth	36 51 15	76 19 17	10	–1,144
13	60B2	CHE-P-5 (Brown and others, 1972)	36 41 49	76 20 19	14	–806
14	63C1	VB-P-3 (Brown and others, 1972)	36 52 00	75 58 51	5	–1,583
15	--	Airfield Pond Corehole (unpublished data, J.S. Schindler, R. Weems, and D.S. Powars, USGS)	36 54 48	77 01 28	91	–130
16	57D1	IW-P-13 (Brown and others, 1972)	36 59 42	76 37 53	40	–414
17	57D28	VPI geothermal well #26,Town of Isle of Wight	36 54 29	76 42 07	75	? –930
18	57D2	Well #81 (Cederstrom, 1945a) Smithfield Ice Plant	36 59 05	76 37 21	10	–311
19	58D6	Rescue Water Company	36 59 39	76 33 30	22	–528
20	58D7	Town of Smithfield-Red Point Heights	36 59 12	76 36 50	35	–477
21	58C8	Nimmo Well, Chuckatuck, Va.	36 52 18	76 31 30	20	–558
22	58D9	Tidewater Virginia Properties-Graymor Estates	36 57 27	76 31 39	15	–541
23	58D2	Well #54 (Cederstrom, 1945a) Battery Park Water Co.	36 59 32	76 29 44	13	–333
24	58D3	Well #108 (Cederstrom, 1945a) Carrolton	36 58 02	76 34 48	8	–382
25	59D1	Tidewater Water Co.	36 52 55	76 23 11	15	–573
26	59D20	City of Newport News-City Hall Complex	36 58 40	76 25 50	30	–870
27	--	NAN-P-13 (Brown and others, 1972)	36 52 30	76 28 25	22	–633
28	--	Well #13 (Cederstrom, 1957) Buxton Hospital	36 59 08	76 23 33	11	–809
29	59D4	Well #44 (Cederstrom, 1957) Newport News; Virginia Public Service Company (Gas Works)	36 58 28	76 25 52	12	–1,070
30	59D5	Well #46 (Cederstrom, 1957) Newport News; Levinson Meat Packing	36 59 08	76 25 07	8	–892
31	60D7	VPI geothermal well #c24 -Willoughby Bay	36 57 27	76 29 19	5	1,030
32	--	Well #9 (Cederstrom, 1945a) Lamberts Point-Norfolk & Western Railway Co.	36 52 26	76 18 56	10	–606
33	61C1	NOR-T-12 (Brown and others, 1972)	36 52 23	76 12 21	15	–2,567
34	61C1	Well #20 (Cederstrom, 1945a) Moores Bridge	36 52 21	76 12 13	10	–1,730
35	62D2	VB-T-4 (Brown and others, 1972)	36 57 59	76 06 47	–35	–1,500
36	57E10	VDEQ	37 02 36	76 42 59	85	–615

Appendix 1A. 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 Polytech Institute; VEPCO, Virginia Electric Power Company; --, local number not assigned]

Borehole location number on plate 1	Local number	Identifying name, owner, or organization, and some references	Latitude	Longitude	Surface altitude	Bottom altitude
37	--	Well #3a (Cederstrom, 1945a) Rushmere	37 04 34	76 40 05	5	–381
38	--	Well #7 (Cederstrom, 1945a) Burwells Bay	37 03 23	76 40 13	15	–306
39	--	Well #25 (Cederstrom, 1945a) Lone Star Cement Co., near Mogarts Beach	37 00 29	76 36 24	12	–324
40	--	Well #42a (Cederstrom, 1945a) Bacons Castle Test Well	37 06 10	76 44 13	70	–985
41	59E5	NASA Research Center-Langley Air Force Base	37 05 38	76 22 43	9	–2,084
42	59E6	Big Bethel Water Plant	37 05 11	76 24 54	15	–990
43	60E42	VPI geothermal well #c27-Langley Air Force Base	37 05 32	76 22 12	5	–1,000
44	60E43	VPI geothermal well #c60-Bunny's bar	37 02 12	76 19 03	10	–1,000
45	60E1	Well #8 (Cederstrom, 1957)-Fort Monroe	37 00 05	76 18 25	3	–2,251
46	60E2	Well #9 (Cederstrom, 1957) Old Point Comfort: Hotel Chamberlain	37 00 03	76 18 40	4	–941
47	60E3	Well #24 (Cederstrom, 1957) North End Point	37 06 30	76 17 25	3	–1,169
48	55F20	Well #2, Town of Claremont	37 13 21	76 57 06	90	–313
49	--	Well #4 (Cederstrom, 1945a) 1 mile west of Claremont	37 14 20	76 58 32	17	–270
50	56F16	First Colony	37 14 34	76 48 15	30	–464
51	56F42	Surry Court House #2	37 08 32	76 50 27	103	–375
52	--	Well #26 (Cederstrom, 1957) Jamestown; 4-H Club	37 13 41	76 47 28	10	–265
53	--	Well #27a (Cederstrom, 1957) Jamestown	37 13 57	76 47 32	33	–287
54	--	Well #51 (Cederstrom, 1957) James City County: Williamsburg, Carolyn Tourist Court	37 17 13	76 43 22	90	–258
55	--	Jamestown Corehole (unpublished data, D.S. Powars, USGS)	37 13 05	76 46 37	1	–272
56	57F2	York Public Utilities	37 14 21	76 38 28	80	–586
57	57F5	Hog Island Nuclear Power Plant	37 09 50	76 41 52	34	–386
58	57F7	Busch Gardens	37 13 43	76 40 08	53	–457
59	57F8	Busch Gardens	37 14 06	76 38 43	85	–435
60	57F25	Hog Island (unpublished data, T.S. Bruce, VDEQ and D.S. Powars, USGS)	37 11 33	76 40 53	5	–1,235
61	57F26	VEPCO	37 09 51	76 41 57	35	–385
62	58F3	Dow Badische (JC-T-11) (Brown and others, 1972)	37 11 20	76 36 54	20	–1,540
63	58F18	US Naval Mine Depot (Magazine #8) = #35 (Cederstrom, 1957) = YK-T-6 (Brown and others, 1972)	37 14 15	76 35 39	50	–490
64	58F38	Grove	37 12 50	76 36 52	40	–455
65	58F50	Newport News Park 1 corehole (Meng and Harsh, 1988; unpublished data, T.S. Bruce, VDEQ and D.S. Powars, USGS)	37 12 08	76 34 11	55	–1,423
66	58F67	Newport News Park 2 Corehole (unpublished data, T.S. Bruce, VDEQ and D.S. Powars, USGS)	37 12 08	76 34 11	52	–570
67	58F57	City of Newport News Golf Course	37 11 14	76 31 21	20	–487
68	58F81	LH-3-8 (Lee Hall Treatment Plant) (Russnow, Kane and Associates, Inc., 1995)	37 10 01	76 33 16	35	–1,315
69	58F82	LH-3-7 (Upper Potomac monitor well) (Russnow, Kane and Associates, Inc., 1995)	37 11 29	76 30 38	56	–1,244

Appendix 1A. 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 Polytech Institute; VEPCO, Virginia Electric Power Company; --, local number not assigned]

Borehole location number on plate 1	Local number	Identifying name, owner, or organization, and some references	Latitude	Longitude	Surface altitude	Bottom altitude
70	58F89	LH-1 (Upper Potomac production well) (Russnow, Kane and Associates, Inc., 1997)	37 10 41	76 35 17	30	–1,120
71	58F91	LH-2 (Middle Potomac production well) (Russnow, Kane and Associates, Inc., 1997)	37 11 12	76 34 13	35	–1,113
72	58F92	LH-1 (Upper Potomac monitor well) (Russnow, Kane and Associates, Inc., 1997)	37 10 41	76 35 17	40	–560
73	58F127	Virginia Peninsula Economic Development Council	37 11 49	76 35 34	50	–530
74	58F2	Well #3 (Cederstrom, 1957) Lee Hall (Skiffes Creek)	37 11 54	76 35 00	10	–517
75	58F5	Well #8 (Cederstrom, 1957) Lee Hall Reservoir	37 10 09	76 33 17	15	–455
76	58F6	Well #17 (Cederstrom, 1957)	37 08 42	76 34 09	7	–440
77	58F7	Well #20 (Cederstrom, 1957)	37 09 08	76 34 35	31	–512
78	58F8	Well #21 (Cederstrom, 1957)	37 09 19	76 35 04	34	–658
79	58F9	Well #22 (Cederstrom, 1957)	37 09 40	76 34 50	37	–513
80	58F10	Well #23 (Cederstrom, 1957)	37 08 23	76 34 50	10	–455
81	58F11	Well #29 (Cederstrom, 1957)	37 08 32	76 30 15	30	–462
82	58F13	Well #39 (Cederstrom, 1957)	37 13 36	76 30 33	50	–722
83	59F1	US Naval Supply Center (correlation to Yorktown Battlefield borehole; unpublished data, T.S. Bruce, VDEQ and D.S. Powars, USGS)	37 13 04	76 29 19	50	–396
84	59F2	US Navy Tank Farm-York River	37 12 51	76 27 08	10	–440
85	59F3	Well #30 Warwick County (Cederstrom, 1957)	37 08 09	76 29 30	30	–524
86	--	Well #41 York County (Cederstrom, 1957)	37 11 58	76 28 13	51	–431
87	--	Well #49 York County (Cederstrom, 1957) J. Levinson Subdivision	37 08 45	76 29 41	80	–355
88	63F50	Kiptopeke Corehole (Powars and others, 1992; unpublished data, D.S Powars, USGS and T.S. Bruce, VDEQ)	37 08 07	75 57 08	7	–1,993
89	63F	Well #82 (Cederstrom, 1945b) Cape Charles, Phil. & Norfolk RR	37 15 56	76 00 44	20	–1,790
90	55G4	Charles City County	37 18 45	76 56 13	35	–303
91	56G5	Water James City Service Authority	37 16 10	76 45 43	90	–307
92	56G52	Water James City Service Authority-Powhatan Enterprise	37 16 25	76 46 20	90	–220
93	56G73	Powhatan Village Corporation-east of Chickahominy River	37 16 04	76 52 24	32	–414
94	56G57	Powhatan Village Corporation	37 21 45	76 49 32	84	–726
95	56G65	Water James City Service Authority	37 21 48	76 46 10	100	–736
96	56G68	Water James City Service Authority	37 18 37	76 47 41	109	–742
97	56G69	Water James City Service Authority	37 22 01	76 46 17	112.5	–188
98	56G72	Water James City Service Authority	37 21 48	76 46 10	100	–200
99	57G1	Eastern State Hospital	37 17 49	76 44 18	90	–501
100	57G20	Carven Gardens	37 15 02	76 39 24	90	–501
101	57G21	James River Estates	37 15 38	76 40 06	80	–422
102	57G22	Ewell	37 19 34	76 44 14	100	–330
103	57G25	Williamsburg Lodge	37 16 05	76 42 03	70	–430

Appendix 1A. 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 Polytech Institute; VEPCO, Virginia Electric Power Company; --, local number not assigned]

Bore-hole location number on plate 1	Local number	Identifying name, owner, or organization, and some references	Latitude	Longitude	Surface altitude	Bottom altitude
104	57G30	Williamsburg Motor House	37 16 56	76 41 51	55	–445
105	57G3	Well #7 (Cederstrom, 1957) Camp Perry	37 18 36	76 38 52	74	–390
106	57G4	Well #13 (Cederstrom, 1957) Camp Perry	37 19 07	76 40 59	84	–359
107	57G5	Well #20 (Cederstrom, 1957) Camp Perry	37 19 25	76 39 13	41	–393
108	57G6	Well #22 (Cederstrom, 1957) Waller Pond Housing Development	37 18 07	76 42 08	10	–458
109	57G7	Well #23 (Cederstrom, 1957) Williamsburg	37 17 53	76 40 31	25	–340
110	57G8	Well #24 (Cederstrom, 1957) Pennimen Fuel Depot, US Navy	37 16 33	76 38 04	83	–450
111	58G1	Well #26 (Cederstrom, 1957) Pennimen Fuel Depot US Navy	37 16 58	76 36 33	20	–515
112	58G5	GLO-P-1 (Brown and others, 1972)	37 21 10	76 36 48	7	–417
113	59G2	Well #45 (Cederstrom, 1945b) Severn	37 17 39	76 25 00	8	–602
114	55H1	City of Newport News	37 24 28	76 56 15	10	–768
115	55H6	Southern Properties	37 23 59	76 54 04	95	–183
116	56H25	James City County Research Station	37 24 51	76 51 33	90	–905
117	56H38	Water James City Service Authority	37 23 12	76 48 06	106	–701
118	57H6	Yorkview Plantation	37 23 10	76 41 14	50	–503
119	57H20	West End Station	37 26 21	76 40 42	10	–914
120	58H4	Gloucester (unpublished data, D.S. Powars, USGS and T.S. Bruce, VDEQ)	37 23 31	76 31 26	75	–1,775
121	60H1	Well #46 (Cederstrom, 1945b) Mathews-Elkins Oil and Gas Co.	37 25 55	76 19 18	7	–2,318
122	56J5	West Point-Chesapeake Corporation	37 32 46	76 48 30	27	–1,252
123	56J11	West Point-Chesapeake Corporation	37 31 26	76 45 41	15	–1,255
124	57J3	Chesapeake Corporation	37 30 08	76 42 56	51	–100
125	58J5	Barnhardt Farms	37 36 30	76 31 26	40	–702
126	58J11	Rappahannock Community College	37 33 52	76 37 28	110	–590
127	60J7	Windmill Point Corehole (unpublished data, D.S. Powars, USGS)	37 36 50	76 16 55	4	–744
128	64J14	Exmore Corehole (Powars and others, 1992; unpublished data, D.S. Powars, USGS)	37 35 08	75 49 09	30	–1,366
129	59K17	West Irvington Well #2	37 39 41	76 25 48	15	–655
130	59K19	Town of Kilmarnock Well #3	37 42 12	76 23 09	65	–707
131	--	Essex Mill Pond Corehole (unpublished data, D.S. Powars and L.W. Newell, USGS)	37 52 30	76 51 04	11	–214
132	60L2	Well #21 (Cederstrom, 1945b) Reedsville	37 50 07	76 17 02	5	–865
133	--	Haynesville Corehole (Mixon, Berquist, and others, 1989)	37 57 14	76 40 10	87	–469
134	--	Clarks Mill Pond Corehole (unpublished data, D.S. Powars and L.W. Newell, USGS)	37 55 52	76 28 05	46	–299
135	66M23	Jenkins Bridge Corehole (unpublished data, D.S. Powars, USGS and T.S. Bruce, VDEQ)	37 56 10	75 36 18	6	–1,314
136	66M1	Taylor #1, Oil test well	37 53 03	75 31 01	42	–6,237
137	57G66	Waller Mill Park	37 18 59	76 42 02	70	–435
138	57E3	Well #40 (Cederstrom, 1945a) Bacons Castle Estate	37 06 33	76 43 22	19	–348
139	59C40	VPI geothermal well #25	36 51 01	76 28 49	22	–1,978

Appendix 1B. 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'* shown on plate 3; Fm., Formation]

Bore-hole location number on plate 1	Potomac Fm.	Upper Cretaceous beds	Aquia Fm.	Marlboro Clay	Nanjemoy Fm.	Piney Point Fm.	Chesapeake Bay megablock beds	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.	Chowan River Fm.	Bacons Castle Fm.	Pleistocene beds	Holocene beds
1	–560	–308	–289	–273	–269	--	--	--	--	--	--	--	--	–167	–27	15	--	--	33	--
2	–1,035	–687	–645	–635	–620	--	--	--	--	–612	--	--	–600	–346	–172	–65	–52	--	15	--
3	–535	–415	?–365	?	?	--	--	--	--	nd	nd	nd	nd	nd	nd	nd	nd	--	15	--
4	–489	–334	??	??	??	--	??	?–295	?–285	?	?	–271	--	?	?	?–25	nd	--	8	--
6	–526	–407	–386	–378	–367	--	--	--	--	?	?	–349	–330	–186	–45	6	--	--	21	--
10	–540	–397	–384	–372	–350	--	--	--	--	--	??	–339	–325	–186	–43	–23	??	--	17	--
14	–1,110	–859	??	??	??	??	??	??	??	??	??	??	?	?	?	?	??	--	?	??
15	–69	--	–42	--	--	--	--	--	--	--	--	--	--	–20	33	68	--	--	--	--
16	–356	?–300	??	??	??	??	??	??	??	??	??	?–218	?	?–124	?–36	?18	--	--	?40	--
18	–310	–280	?	?	–230	--	--	--	--	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
19	–468	–276	–255	–246	–208	--	--	--	--	nd	?	?–191	?	–149	–34	22	--	--	--	--
20	–425	–294	–247	–227	–219	--	--	??	??	??	??	?–215	?	–144	–40	–4	--	--	35	--
22	–409	–294	–280	–262	–245	--	--	??	??	??	?–241	?–235	?	–182	–43	15	--	--	--	--
23	–297	–272	–247	?	?	nd	??	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
24	–378	–252	?	?	?	nd	??	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
26	–700	--	--	--	--	--	??	–574	–410	–392	–378	–368	–323	–228	–35	12	--	--	30	--
27	–456	?–400	??	??	??	??	??	??	?–370	??	??	??	??	?–195	?–36	1	--	--	22	--
29	–694	--	--	--	--	--	??	–592	–413	?	?	–391	?	–238	–84	–22	--	--	12	--
30	–722	--	--	--	--	--	??	–592	–467	?	?	–401	?	?	?	–12	--	--	8	--
31	nd	--	--	--	--	--	??	–769	–654	–623	–613	–603	–540	–240	–85	–15	--	--	5	--
32	nd	–524	??	??	??	--	??	?–397	–387	?	?	–367	?	?	?	–7	--	--	10	--
33	–777	–667	--	--	--	--	??	?–618	–610	?	?	?–595	?–490	?–230	?–140	–72	--	--	15	--
34	–775	–695	?	?	?	--	??	–675	–625	?	?	–615	?	?	?	?	--	--	10	--
35	–991	–870	--	--	--	--	??	?	–830	?	?	–810	?–508	? –290	? –160	?	nd	--	nd	nd
37	–294	?	?	?	–225	--	--	--	--	?	?	?–214	nd	nd	nd	nd	nd	nd	nd	nd
38	–290	?	?	?	–245	nd	??	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
39	–283	?	–253	?	?	nd	??	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
40	–334	–250	–231	?	?	?	--	--	--	?	–169	–167	--	–105	?–18	49	--	--	70	--
41	–1,279	--	--	--	--	--	–1,077	–735	–585	–520	–467	–438	–390	–210	–67	?–4	--	--	9	--
42	–868	--	--	--	--	--	–868	–671	–519	–459	–423	–409	–357	–219	–70	2	--	--	15	--
43	nd	--	--	--	--	--	nd	–765	–612	–510	–469	–440	–412	–201	–69	?	--	--	5	--
44	nd	--	--	--	--	--	nd	–777	–646	–591	–545	–532	–407	–262	–81	?4	--	--	10	--
45	??	--	--	--	--	--	–1,457	–837	–637	?–628	?–618	–607	?–400	–292	–95	–47	--	--	?3	?
47	--	--	--	--	--	--	–1,077	–917	–737	?	–623	–597	–390*	–272	–87	–72	--	--	?3	?
49	–130	--	–95	--	?–63	--	--	--	--	--	?–45	--	--	?–13	17	--	--	--	--	--

Appendix 1B. 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'* shown on plate 3; Fm., Formation]

Bore-hole loca-tion number on plate 1	Potomac Fm.	Upper Creta-ceous beds	Aquia Fm.	Marlboro Clay	Nan-jemoy Fm.	Piney Point Fm.	Chesa-peake Bay mega-block beds	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.	Chowan River Fm.	Bacons Castle Fm.	Pleisto-cene beds	Holo-cene beds
50	–258	--	–217	–202	–158	–140	--	--	--	--	–114	–100	?94	?–57	?–30	??	--	--	30	--
52	–263	--	?	?	–160	–135	--	--	--	--	?	–100	nd	?	?10	--	--	--	nd	--
53	–256	--	–218	–206	–165	–149	--	--	--	--	?–136	?–120	?–117	?–57	–22	nd	--	--	33	--
54	nd	nd	nd	nd	nd	?–207	--	--	--	nd	nd	nd	nd	?	?	?	--	--	?	--
55	–258	--	–217	–203	–159	–152	--	--	--	--	–139	–120	?–115	–55	–24	--	--	--	–14	1
56	–380	--	–320	–302	–256	–244	--	--	--	–233	–223	–216	–176	–104	0	40	--	??	80	--
57	–333	--	–270	–254	–212	–205	--	--	--	–196	–187	–168	? –162	–92	–66	--	--	--	34	--
58	–345	--	–301	–287	–237	–227	--	--	--	–217	–207	–200	–177	–95	1	34	--	--	53	--
59	–352	--	–325	–315	–255	–245	--	--	--	–235	–215	–208	–172	–99	–3	42	--	??	85	--
60	–330	--	–300	–286	–232	–215	--	--	--	?	–200	–185	–166	–125	??	--	--	--	–15	5
62	–437	--	--	--	--	--	--	–344	–291	?	–264	–233	–194	–123	–102	--	--	--	20	?
63	–356	--	--	--	--	--	--	–277	–244	–221	–209	–202	–144	–102	8	50	--	--	?	--
64	–354	--	--	--	--	--	--	–320	–279	–263	–250	–238	–191	–119	–14	14	--	--	40	--
66	–411	--	--	--	--	--	--	–357	–323	–308	–293	–279	–216	–127	–19	25	--	--	52	--
67	nd	--	--	--	--	--	nd	–460	–404	–379	–360	–333	–250	–160	–44	2	--	--	20	--
68	–430	--	--	--	--	--	--	–395	–303	?	–285	–279	–225	–125	–25	35	--	--	?	--
69	–1,094	--	--	--	--	--	?–984	–588	–408	–378	–355	–336	–261	–194	–37	36	--	--	56	--
70	–462	--	--	--	--	--	--	–381	–312	–286	–264	–255	–205	–112	–17	30	--	--	?	--
71	–480	--	--	--	--	--	--	–369	–308	–295	–285	–274	–209	–119	–25	35	--	--	?	--
73	–382	--	--	--	--	--	--	–332	–293	–274	–261	–252	–200	–130	–22	30	--	--	50	--
74	–397	--	--	--	--	--	--	–366	–317	?	–282	–276	–200	–142	–20	–10	--	--	10	--
75	–429	--	--	--	--	--	--	–395	–307	?	–296	–287	–215	?	–20	0	--	--	15	--
76	–430	--	--	--	--	--	--	?	?	?	–274	–252	?	?	?	--	--	--	7	--
77	–429	--	--	--	--	--	--	–364	–324	?	–284	–259	?	–134	?	–6	--	--	31	--
78	–576	--	--	--	--	--	--	–352	–321	?	?	–262	?	–146	–29	–4	--	--	34	--
79	–438	--	--	--	--	--	--	–354	–294	?	?	–274	?	?	?	7	--	--	37	--
80	–405	--	--	--	--	--	--	–372	–329	?	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
81	nd	--	--	--	--	--	nd	–395	?–360	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
82	nd	--	--	--	--	--	nd	–524	–375	–362	–350	–315	?	–145	? –50	35	--	--	50	--
83	nd	nd	nd	nd	nd	nd	nd	nd	nd	?	–365	–356	–248	–158	–22	42	--	nd	50	--
84	nd	nd	nd	nd	nd	nd	nd	nd	–427	–410	–372	–352	–254	–182	–38	?–9	--	--	10	--
85	nd	--	--	--	--	--	nd	–400	–350	?	?	?	?	–170	?	18	--	--	30	--
86	nd	nd	nd	nd	nd	nd	nd	nd	–410	–393	–380	–370	–257*	–187*	–38*	32*	??	--	51	--
87	?	--	--	--	--	--	nd	–300	?–215	?	?	–190	?	?	–15	?	--	80	--	--
88	--	--	--	--	--	--	–1,700	–1,279	–1,077	–1,063	--	?–1,028	–613	–455	–189	–74	–49	--	7	--

Appendix 1B. 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'* shown on plate 3; Fm., Formation]

Bore-hole loca-tion number on plate 1	Potomac Fm.	Upper Creta-ceous beds	Aquia Fm.	Marlboro Clay	Nan-jemoy Fm.	Piney Point Fm.	Chesa-peake Bay mega-block beds	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.	Chowan River Fm.	Bacons Castle Fm.	Pleisto-cene beds	Holo-cene beds
89	--	--	--	--	--	--	?–1,700	–1,210	–1,080	?	?	?	?	?–290	?–212	?	?–26	--	20	--
92	?	--	–184	–174	–144	–120	--	--	--	?	–110	–95	–86	–54	50	70	--	90	--	--
93	–222	--	–177	–165	–120	–103	--	--	--	--	–85	–64	??	–33	–12*	?	--	--	?32	?
99	–294	--	–265	–248	–192	–180	--	--	--	–169	–164	–149	–130	–80	29	65	--	90	--	--
100	–370	--	–312	–294	–246	–237	--	--	--	–224	–216	–206	–166	–94	8	48	--	90	--	--
101	–350	--	–318	–303	–225	–217	--	--	--	–212	–202	–195	–158	–92	10	30	--	80	--	--
102	–288	--	–252	–234	–190	–164	--	--	--	?	–154	–142	–124	–80	44	65	--	100	--	--
103	–317	--	–288	–273	–222	–200	--	--	--	–190	–186	–181	–155	–94	8	46	--	--	70	--
104	–331	--	–295	–275	–224	–210	--	--	--	–203	–191	–181	–156	–97	15	35	--	--	55	--
105	–352	--	–308	–298	? –286	–271	--	--	--	? –236	?	?	–160	? –66	? 14	39	--	74	--	--
106	–330	--	–296	–276	? –235	? –234	--	--	--	?	–201	–186	–156	–31	?	54	--	84	--	-
107	–351	--	–305	–303	–264	? –246	--	--	--	?	?	?–229	–154	–23	? 31	--	--	--	41	--
108	–345	--	–290	?	?–220	?	--	--	--	?	? –188	? –170	? –137	?	?	? –20	--	--	10	--
109	–321	--	–300	–280	?	?	--	--	--	?	?	?–177	?	?	?	? –25	--	--	25	--
110	–395	--	–332	–317	? –290	?	--	--	--	?	? –242	?	?	?	?	42	--	83	--	--
111	–420	--	nd	nd	nd	nd	--	nd	nd	nd	nd	nd	nd	nd	nd	–10	--	--	20	--
112	–395	--	--	--	--	--	--	?–305	–269	?–261	?–254	?–243	?–190	? –111	? –14	?	--	--	7	--
113	nd	--	--	--	--	--	nd	–567	–432	?	?–417	?	?	?	? –62	0	--	--	8	--
118	–342	--	–298	–280	–222	–210	--	--	--	–206	–192	–172	–144	–76	32	?	--	--	50	--
119	–358	--	–314	–305	–180	–175	--	--	--	?	?	–160	?	?	–10	--	--	--	–20	--
120	?–795	--	--	--	--	--	??	–545	–395	–365	–345	–325	–235	–145	–9	48	--	--	75	--
121	?–1,483	--	--	--	--	--	??	? –858	?–583	?	?	? –483	?	?	?	?2	--	--	7	--
127	–593	--	--	--	--	--	?–573	–514	–448	?	–438	–429	–222	–163	–92	?	--	--	?	4
128	nd	--	--	--	--	--	nd	–1,179	–1,080	–1,039	–995	?–986	–477	–296	–151	--	--	--	30	--
131	nd	nd	nd	nd	–169	–118	--	--	--	--	–92	--	–5	12	--	--	--	--	--	--
133	–450	--	–331	–330	–240	–185	--	--	--	--	–181	--	–49	–12	43	87	--	--	--	--
134	nd	nd	nd	nd	nd	?	--	--	--	--	–250	--	–93	?	?	--	--	--	--	--
135	–1,292	–1,173	?	?	?–1,144	--	--	?–1,144	?–1,106	–1,058	–1,030	?	–486	–334	–144	–22	--	--	6	--
137	–318	--	–270	–260	–214	–203	--	--	--	–198	–181	–170	–143	–88	16	36	--	70	--	--
138	–316	–296	–266	?	?	--	--	--	--	?	?	?	--	?	?	19	--	--	--	--
139	?	–398	??	??	? –338	??	??	??	??	??	??	??	??	??	??	??	??	--	?22	--

Appendix 2. Selected lithic logs from Cederstrom (1945a, 1957) and this report's stratigraphic reinterpretations of portions of these logs

Drillers' log Altitude, 7 feet	Thickness (feet)	Depth (feet)	This report's interpretation
Well no. 46. (Cederstrom, 1945a) Mathews, Mathews County, Elkins Oil and Gas Co. Borehole location #121 on plate 1; GWSI #60H1.			
Columbia Group:			Pleistocene
Sand and surface soil	5	5	
Chesapeake Group:			Pliocene and Miocene undivided
Sand	78	83	
Sand and shell	16	99	
Shell	1	100	
Sand and shell	100	200	
Shale	10	210	
Sand	20	230	
Gummy shale	170	400	
Sticky shale	90	490	–483 = top lower Miocene and Oligocene undivided
Driller reports sand; cored sample is gray shell marl containing minor glauconite, fish bones, and pyrite	10	500	
Sand and gravel	60	560	
Pamunkey Group:			
Sand, shell, and boulders	30	590	–583 = top Chickahominy Formation (upper Eocene)
Sandy shale	5	595	
Gumbo	205	800	
Shale	10	810	
Gummy shale	55	865	–858 = top of Exmore tsunami-breccia (upper Eocene)
Green glauconitic quartz sand	7	872	
Hard sand and pyrites	1	873	
Green sand	5	878	
Sand	3	881	
Gumbo	14	895	
Coarse glauconitic quartz sand	7	902	
Sand	8	910	
Gumbo	7	917	
Sand	118	1,035	
Shale	15	1,050	
Sand	35	1,085	
Shale	5	1,090	
Shale and sand	20	1,110	
Driller reports sand; core is light-green glauconite in limy matrix	12	1,122	
Gumbo	38	1,160	
Sand	5	1,175	
Gumbo	40	1,215	
Shell and black sand	5	1,220	
Sandy shale and shell	60	1,280	

Appendix 2. Selected lithic logs from Cederstrom (1945a, 1957) and this report's stratigraphic reinterpretations of portions of these logs—Continued

Drillers' log Altitude, 7 feet	Thickness (feet)	Depth (feet)	This report's interpretation
Well no. 46. (Cederstrom, 1945a) Mathews, Mathews County, Elkins Oil and Gas Co. Borehole location #121 on plate 1; GWSI #60H1—Continued			
Pamunkey Group—Continued:			
Gumbo	54	1,334	
Sand	1	1,335	
Sand, trace of glauconite	75	1,410	
Shale	78	1,488	
Sand	2	1,490	–1,483 = top of CBIC megablock beds (? upper Eocene)
Potomac Group:			
Red gumbo	62	1,552	
Sand	118	1,670	
Red shale, sticky	10	1,680	
Sand	125	1,805	
Shale	65	1,870	
Salt water and sand	40	1,910	
Sand	20	1,930	
Shale	15	1,945	
Salt water and sand	5	1,950	
Sand	75	2,025	
Shale	40	2,065	
Sand	20	2,085	
Sand and gravel	90	2,175	
Sand	35	2,210	
Sandy chalk	16	2,236	
Sand and shale	4	2,240	
Sand and gravel	67	2,307	–2,300 = top of crystalline basement
Precambrian (?):			
Rock	6	2,313	
Red and green rock	5	2,318	
Broken rock and shale	2	2,320	
Granite	5	2,325	
Well no. 79. (Cederstrom, 1945a) Well no. 44. (Cederstrom, 1957) Newport News, Virginia Public Service Company, Gas Works Borehole location #29 on plate 1; GWSI #59D4. Log by Layne-Atlantic Co. and D.J. Cederstrom. Well drilled by the Layne-Atlantic Co. Foraminifera determined by J.A. Cushman. Log to 372 feet from cuttings collected by the Layne-Atlantic Co.; below 372 feet the well was logged by D.J. Cederstrom. Altitude, 12 feet			
Columbia Group:			
Sand, fine, clayey	34	34	–27 = Pleistocene/Pliocene contact
Chesapeake Group:			
Sand, fine, clayey	30	64	Yorktown Formation (Pliocene)
Shelly marl, very sandy, gray	32	96	–89 = top of Eastover Formation (upper Miocene)
Sand, fine, gray	30	126	
Shelly marl, slightly sandy, gray	30	156	
Shelly marl, sandy, gray	10	166	
Sand and shells	24	190	

Appendix 2. Selected lithic logs from Cederstrom (1945a, 1957) and this report's stratigraphic reinterpretations of portions of these logs—Continued

Drillers' log Altitude, 7 feet	Thickness (feet)	Depth (feet)	This report's interpretation
Well no. 79. (Cederstrom, 1945a) Well no. 44. (Cederstrom, 1957) Newport News, Virginia Public Service Company, Gas Works Borehole location #29 on plate 1; GWSI #59D4. Log by Layne-Atlantic Co. and D.J. Cederstrom. Well drilled by the Layne-Atlantic Co. Foraminifera determined by J.A. Cushman. Log to 372 feet from cuttings collected by the Layne-Atlantic Co.; below 372 feet the well was logged by D.J. Cederstrom. Altitude, 12 feet—Continued			
Chesapeake Group—Continued:			
Clay, sandy, gray	30	220	
Shelly marl	30	250	–243 = top of St. Marys Formation (upper Miocene)
Clay, dark-gray	92	342	
Clay, tough, gray	30	372	(? Calvert Formation)
Clay, slightly glauconitic, gray	31	403	–396 = top of lower Miocene and Oligocene
Pamunkey Group (Cederstrom, 1945a)			
Chickahominy Formation (Eocene) (Cederstrom, 1957):			
Sand, medium- to fine-grained glauconite, quartz; water	22	425	–418 = top of Chickahominy Formation (upper Eocene)
Clay, glauconitic, gray	78	503	
Mattaponi Formation (Upper Cretaceous and Paleocene):			
Clay, glauconitic, gray; Nanjemoy foraminifera	67	570	
Clay, slightly glauconitic, gray; drills rather slowly	34	604	–597 = top of Exmore tsunami-breccia (upper Eocene)
Clay, sandy, gray; grades down to hard-packed glauconitic sand; Aquia (?) foraminifera	40	644	
Alternating streaks of glauconite and quartz sand and soft mottled (pink, brown, green) clay	31	675	
Sand, glauconitic quartz; contains about 35 percent mottled clay	10	685	
Clay, mottled; contains about 35 percent glauconitic quartz sand	21	706	–699 = top of Potomac Formation (Lower Cretaceous)
Clay, mottled; with streaks of more sandy clay	31	737	
Clay, mottled; drills very slowly	23	760	
Clay, sandy, mottled	26	786	
Sand, quartz, medium-grained, gray, slightly glauconitic; water	18	804	
Sand, slightly clayey	4	808	
Sand, quartz, medium-grained; contains very little clay, water	27	835	
Clay, sandy	2	837	
Sand; water	2	839	
Clay, slightly sandy, green	14	853	
Clay; drills very slowly	5	858	

Appendix 2. Selected lithic logs from Cederstrom (1945a, 1957) and this report's stratigraphic reinterpretations of portions of these logs—Continued

Drillers' log Altitude, 7 feet	Thickness (feet)	Depth (feet)	This report's interpretation
Sand, gray, slightly glauconitic, medium-grained; water	14	872	
Well no. 79. (Cederstrom, 1945a) Well no. 44. (Cederstrom, 1957) Newport News, Virginia Public Service Company, Gas Works Borehole location #29 on plate 1; GWSI #59D4. Log by Layne-Atlantic Co. and D.J. Cederstrom. Well drilled by the Layne-Atlantic Co. Foraminifera determined by J.A. Cushman. Log to 372 feet from cuttings collected by the Layne-Atlantic Co.; below 372 feet the well was logged by D.J. Cederstrom. Altitude, 12 feet—Continued			
Mattaponi Formation (Upper Cretaceous and Paleocene)—Continued:			
Clay, sandy	39	911	
Sand, loose; contains thin streaks of clay; good water-bearing formation	18	929	
Sand, quartz, clayey, slightly glauconitic	10	939	
Clay	9	948	
Sand, quartz, slightly glauconitic medium-grained; water	3	951	
Clay, mottled (pink, brown, green)	4	955	
Sand, medium-grained; water	4	959	
Sand, clayey, slightly glauconitic	9	968	
Sand, medium-grained; contains traces of glauconite and clay; water	21	989	
Sand, clayey	9	998	
Sand, loose; with thin clay streaks; water	12	1,010	
Clay, hard; drills very slowly	3	1,013	
Sand, quartz, gray, medium-grained; trace of glauconite; water	22	1,035	
Sand, slightly clayey	10	1,045	
Sand, trace of glauconite, coarse at 1,082 feet; water	37	1,082	
Well no. 81. (Cederstrom, 1945a) Well no. 8c. (Cederstrom, 1957) Fort Monroe, Elizabeth City County, U.S. Army. Borehole location #45 on plate 1; GWSI #60E1. (Log originally from Folio 8, U.S. Geological Survey) Altitude, 3 feet			
Columbia Group:			
Sand	50	50	–43 = Pleistocene/Pliocene contact
Chesapeake Group:			
Clay	40	90	Yorktown Formation (Pliocene)
Sand, gray	40	130	–123 = top of Eastover Formation (upper Miocene)
Clay	30	160	
Sand	25	185	
Clay, sandy	25	210	
Clay	30	240	
Sand	15	255	
Rock and boulders	20	275	
Sand; water	20	295	
Clay	230	525	–518 = top of St. Marys Formation (upper Miocene)
Clay and sand; forams	85	610	–603 = top of lower Miocene and Oligocene

Appendix 2. Selected lithic logs from Cederstrom (1945a, 1957) and this report's stratigraphic reinterpretations of portions of these logs—Continued

Drillers' log Altitude, 7 feet	Thickness (feet)	Depth (feet)	This report's interpretation
Well no. 81. (Cederstrom, 1945a) Well no. 8c. (Cederstrom, 1957) Fort Monroe, Elizabeth City County, U.S. Army. Borehole location #45 on plate 1; GWSI #60E1. (Log originally from Folio 8, U.S. Geological Survey) Altitude, 3 feet—Continued			
Pamunkey Group (Cederstrom, 1945a):			
Chickahominy Formation (Eocene) (Cederstrom, 1957)			
Sand and boulders; Eocene forams; water	30	640	–633 = top of Chickahominy Formation
Clay, glauconitic and pyritic; Eocene at forams; residue of sample at 698 ft contains glauconite and pyrite782 to 784 feet much glauconite, at 835 feet quartz with less glauconite and some pyrite	200	840	–833 = top of Exmore tsunami-breccia (upper Eocene)
Clay and gravel; washed residue of sample at 863 to 877 feet contains some glauconite and pyrite, at 877 feet some glauconite, at 885 feet residue largely glauconite, at 890 feet and 900 feet quartz and less glauconite	80	921	
Sand, gravel, and boulders	25	945	
Clay	35	980	
Sand; water	5	985	
Clay; residue of samples taken at 1,020 to 1,030 feet contains about 3 percent glauconite; at 1,050 to 1,058 feet about 20 percent glauconite	105	1,090	
Boulders	5	1,095	
Sand and clay	30	1,125	
Boulders	5	1,130	
Sand and clay; residue contains 3 percent glauconite	20	1,150	
Sandstone	5	1,155	
Sand and clay; trace of glauconite	25	1,180	
Clay and small gravel; residue contains about 20 percent glauconite	20	1,200	
Sand	18	1,218	
Sand and clay	2	1,220	
Hard sand	30	1,250	
Sand with some clay and boulders	5	1,255	
Sand, gravel, and boulders; sample at 1,280 feet contains trace of glauconite	65	1,320	
Potomac Group (Lower and Upper Cretaceous) (Cederstrom, 1957):			
Sand and clay	45	1,365	
Sand, mostly coarse, with some clay; at 1386 feet residue contains quartz, feldspar and minor glauconite, pyrite and rock; at 1,435 feet quartz, feldspar and 1 percent glauconite; Eocene forams	70	1,435	

Appendix 2. Selected lithic logs from Cederstrom (1945a, 1957) and this report's stratigraphic reinterpretations of portions of these logs—Continued

Drillers' log Altitude, 7 feet	Thickness (feet)	Depth (feet)	This report's interpretation
Well no. 81. (Cederstrom, 1945a) Well no. 8c. (Cederstrom, 1957) Fort Monroe, Elizabeth City County, U.S. Army. Borehole location #45 on plate 1; GWSI #60E1. (Log originally from Folio 8, U.S. Geological Survey) Altitude, 3 feet—Continued			
Potomac Group (Lower and Upper Cretaceous) (Cederstrom, 1957)—Continued:			
Clay, red; and sand; residue contains quartz, mica and trace of glauconite; Eocene forams and macrofossils	5	1,440	–1,437 = top of CBIC megablock beds (upper Eocene)
Potomac Group (Cederstrom, 1945a):			
Sand, coarse, trace of glauconite; water	98	1,538	
Clay	20	1,558	
Clay and sand	17	1,575	
Sand, coarse	45	1,620	
Sand and clay; water at 1,630 feet	100	1,720	
Sand and boulders	10	1,730	
Clay	20	1,750	
Sand	50	1,800	
Sand and clay	20	1,820	
Sand and pebbles	10	1,830	
Clay and white sand	50	1,880	
Sand with minor amount of clay; water at 1,915 feet and 1945 feet	120	2,000	
Sand, coarse	60	2,060	
Clay	5	2,065	
Sand, coarse	115	2,180	
Clay	66	2,246	–2,251 = top of crystalline basement
Precambrian (?) :			
Rock, crystalline	8	2,254	
Well no. 82. (Cederstrom, 1945a) Cape Charles, Northampton County, New York, Philadelphia and Norfolk Railroad Company. Borehole location #89 on plate 1. Geologic boundaries are only Cederstrom's interpretations and were not based on a study of well cuttings or other data. Altitude, about 20 feet			
Columbia Group:			
Clay, sandy, soft, yellow	40	40	
Sand, soft, yellow	6	46	–26 = Pleistocene/Pliocene contact
Chesapeake Group:			
Clay, soft, dark-gray	54	100	
Marl, soft, greenish	45	145	
Sand, soft, dark-gray	17	162	
Clay, soft, blue	13	175	
Marl, soft, green	12	187	
Sand, soft, gray	2	189	
Clay, soft, gray	15	204	
Sand, loose, glauconitic, quartz	28	232	–212 = ? top Eastover Formation (upper Miocene)
Clay, soft, green	6	238	
Shells, soft rock	1	239	
Sand, loose, gray	39	278	
Clay, soft, dark-gray	3	281	

Appendix 2. Selected lithic logs from Cederstrom (1945a, 1957) and this report's stratigraphic reinterpretations of portions of these logs—Continued

Drillers' log Altitude, 7 feet	Thickness (feet)	Depth (feet)	This report's interpretation
Well no. 82. (Cederstrom, 1945a) Cape Charles, Northampton County, New York, Philadelphia and Norfolk Railroad Company. Borehole location #89 on plate 1. Geologic boundaries are only Cederstrom's interpretations and were not based on a study of well cuttings or other data. Altitude, about 20 feet—Continued			
Chesapeake Group—Continued:			
Sand, soft, dark-gray	39	310	–290 = ? top of St Marys Formation (upper Miocene)
Clay, soft, lead-colored	70	380	
Clay, sticky, light-green	95	475	
Clay, soft, dark-green	20	495	
Clay, rather tough, dark-green	395	890	–870 = ? near top of lower Miocene
Pamunkey Group:			
Clay, green with black specks	60	950	
Clay, soft and hard layers, light-green	150	1,100	–1,080 = top of Chickahominy Formation (upper Eocene)
Clay, gray	32	1,132	
Clay, soft, gray	16	1,148	
Clay, hard and soft layers, gray	17	1,165	
Sand, compact, greenish	65	1,230	–1,210 = top of Exmore tsunami-breccia (upper Eocene)
Rock, sandy, hard, gray	7	1,237	
Sand and gravel, compact, gray	13	1,250	
Mixed brown and gray sandy clay, hard and soft layers	20	1,270	
Sand, hard, green	49	1,319	
Sand, gravel and clay mixed, hard and soft layers	12	1,331	
Mottled clay, sand and gravel, hard and soft layers	254	1,585	-1,565 = ? top of CBIC megablock beds (upper Eocene)
Clay, sandy, hard, green	22	1,607	
Clay, sandy, pale-pink	73	1,680	
Clay, gray, with crusts of sandstone	60	1,740	
Potomac Group:			
Clay, sticky, reddish-brown, no sand	70	1,810	

Appendix 3. Seismic field data and digital processing information

	FIELD DATA			
Recorded by	Teledyne Exploration party 724			
Date	October 1986			
Instruments	DFS IV			
Filter	08-128 Hertz			
No. of channels	96			
Record length	6.0 seconds			
Sample rate	2 milliseconds			
Sample array	410–4,305 feet			
Shotpoint interval	82 feet			
Group interval	41 feet			
Energy source	6 air guns (984 cubic inches, 2,000 pounds per square inch)			
	DIGITAL PROCESSING INFORMATION			
Date processed	December 1986			
Sample rate	4 milliseconds			
Datum plane	Sea level			
Stack mutes	Time	0.05 second	Distance	431 feet
	Time	0.05 second	Distance	595 feet
	Time	0.70 second	Distance	4,285 feet
Data Reduction Sequence				
1. Gain recovery				
3. Divergence correction				
4. Deconvolution				
Operator length (1)	256 milliseconds			
Prediction length (1)	4 milliseconds			
Correlation Gate (2)	0.5–2.5 seconds	Distance	431 feet	
Correlation Gate (2)	1.0–2.8 seconds	Distance	4,285 feet	
Band limit (1)	out-out	Time	Correlation Gates	
Operator length (2)	256 milliseconds			
Prediction length (2)	4 milliseconds			
Correlation Gate (2)	0.5–2.5 seconds	Distance	431 feet	
Correlation Gate (2)	1.0–2.8 seconds	Distance	4,285 feet	
Band limit (1)	out-out	Time	Correlation Gates	
5. Velocity analysis				
6. Normal moveout				
7. Stack	48 Fold CDP (common depth point)			
10. Digital filter				
Band limit	15–60 Hertz	Time	0.0–6.0 seconds	
Program gain				
9. Migration	97-percent velocity adjustment			
Amplitude enhancement				
Signature processing				
2. Other	2 trace composite			
8. Other	Post stack deconvolution			

Remarks: 128 traces per mile; a positive reflection coefficient is a negative number on tape and is displayed as a peak.

Appendix 4a. Calcareous nannofossil occurrences in the Jamestown core, with age and formation correlation (L.M. Bybell)

[X, present; (.), not present; 1, 1 specimen observed; ?, possibly present; ??, very questionably present; depth of sample is in feet; Abundance: C, common or 1-10 specimens per field of view at X640; F = frequent or 1 specimen per 1-10 fields of view at X640; R, rare or 1 specimen per more than 20 fields of view at X640; B, barren of calcareous nannofossils; Preservation: F = fair;
P = poor]

Species[1,2]	Formation													
	Potomac	Aquia	Aquia	Aquia	Nanjemoy	Nanjemoy	Nanjemoy	Nanjemoy	Piney Point	Old Church	Calvert	Calvert	Calvert	St. Marys
	Age													
	??	??	late Paleocene	late Paleocene	early Eocene	early Eocene	early Eocene	early Eocene	middle Eocene	late Oligocene-early Miocene	early Miocene	early Miocene	early Miocene	??
	Calcareous nannofossil zone													
	BARREN	BARREN	NP 8	NP 9	NP 10	NP 12-14	NP 12-14	NP 12-14	NP 16?	??	NN 2-3	NN 2-3	NN 2-4	BARREN
	Depth													
	273.7	255.9	241.5	220	201.8	196.2	186.6	168.8	157	149.3	137.1	128.3	121.3	105.1
Braarudosphaera bigelowii	.	.	.	.	.	.	.	.	.	X	.	.	X	.
Cepekiella lumina	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Chiasmolithus bidens	.	.	X	X	.	X	X	X	X	.	.	.	.	.
Coccolithus eopelagicus	.	.	.	.	.	.	X	.	.	.	X	.	.	.
Coccolithus pelagicus	.	.	X	X	.	.	X	X	X	X	.	X	X	.
Cribrocentrum reticulatum	.	.	.	.	.	.	.	.	.	.	.	1	.	.
Cruciplacolithus tenuis	.	.	?	.	.	.	.	.	.	.	.	.	.	.
Cyclococcolithus formosus	.	.	.	.	.	.	X	X	X	.	.	.	.	.
Cyclococcolithus leptoporus	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Discoaster barbadiensis	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Discoaster lenticularis	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Discoaster deflandrei	.	.	.	.	.	.	.	X	.	.	X	.	.	.
Discoaster druggii	.	.	.	.	.	.	.	.	.	.	.	X	.	.
Discoaster kuepperi	.	.	.	.	.	.	X	?	.	.	.	.	.	.
Discoaster lodoensis	.	.	.	.	.	.	X	1	.	.	.	.	.	.
Discoaster multiradiatus	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Discoaster woodringii	.	.	.	.	.	.	.	.	.	X	.	X	?	.
Ellipsolithus distichus	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Ericsonia subpertusa	.	.	X	.	X	.	.	.	.	.	.	.	.	.
Fasciculithus tympaniformis	.	.	X	.	.	.	.	.	.	.	.	.	.	.
Helicosphaera ampliaperta	.	.	.	.	.	.	.	.	.	.	X	X	X	.
Helicosphaera carteri	.	.	.	.	.	.	.	.	.	.	.	.	X	.

Appendix 4a. Calcareous nannofossil occurrences in the Jamestown core, with age and formation correlation (L.M. Bybell)—Continued

[X, present; (.), not present; 1, 1 specimen observed; ?, possibly present; ??, very questionably present; depth of sample is in feet; Abundance: C, common or 1-10 specimens per field of view at X640; F = frequent or 1 specimen per 1-10 fields of view at X640; R, rare or 1 specimen per more than 20 fields of view at X640; B, barren of calcareous nannofossils; Preservation: F = fair; P = poor]

Species[1,2]														
Formation	Potomac	Aquia	Aquia	Aquia	Nanjemoy	Nanjemoy	Nanjemoy	Nanjemoy	Piney Point	Old Church	Calvert	Calvert	Calvert	St. Marys
Age	??	??	late Paleocene	late Paleocene	early Eocene	early Eocene	early Eocene	early Eocene	middle Eocene	late Oligocene-early Miocene	early Miocene	early Miocene	early Miocene	??
Calcareous nannofossil zone	BARREN	BARREN	NP 8	NP 9	NP 10	NP 12-14	NP 12-14	NP 12-14	NP 16?	??	NN 2-3	NN 2-3	NN 2-4	BARREN
Depth	273.7	255.9	241.5	220	201.8	196.2	186.6	168.8	157	149.3	137.1	128.3	121.3	105.1
Helicosphaera intermedia	.	.	.	.	.	.	.	.	.	X	.	.	.	.
Helicosphaera lophota	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Helicosphaera seminulum	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Heliolithus riedelii	.	.	X	.	.	.	.	.	.	.	.	.	.	.
Hornibrookina arca	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Lithostromation operosum	.	.	.	.	.	.	.	.	X	.	.	.	X	.
Lophodolithus nascens	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Markalius inversus	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Markalius sp.	.	.	X	.	.	.	.	.	.	.	.	.	.	.
Nannotetrina alata	.	.	.	.	.	.	.	??	.	.	.	.	.	.
Neochiastozygus concinnus	.	.	X	X	.	.	.	.	.	.	.	.	.	.
Neococcolithes dubius	.	.	.	.	.	.	X	X	.	.	.	.	.	.
Neococcolithes spp.	.	.	.	.	.	.	.	.	X	.	.	.	X	.
Pemma rotundum	.	.	.	.	.	.	.	.	?	.	.	.	.	.
Placozygus sigmoides	.	.	X	.	.	.	.	.	.	.	.	.	.	.
Pontosphaera multipora	.	.	.	.	.	.	.	X	.	?	.	X	.	.
Pontosphaera spp.	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Reticulofenestra abisecta	.	.	.	.	.	.	.	.	.	X	X	X	.	.
Reticulofenestra floridana	.	.	.	.	.	.	X?	.	X	X	.	.	.	.
Reticulofenestra pseudo-umbilicus	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Reticulofenestra umblicus	.	.	.	.	.	.	.	?	?	.	.	1?	.	.
Reticulofenestra sp. aff. *R. umbilicus*	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Reticulofenestra spp. small	.	.	.	.	.	X	.	.	.	X	X	.	.	.
Rhabdosphaera perlonga	.	.	.	.	.	.	?	.	.	.	.	.	.	.

Appendix 4a. Calcareous nannofossil occurrences in the Jamestown core, with age and formation correlation (L.M. Bybell)—Continued

[X, present; (.), not present; 1, 1 specimen observed; ?, possibly present; ??, very questionably present; depth of sample is in feet; Abundance: C, common or 1-10 specimens per field of view at X640; F = frequent or 1 specimen per 1-10 fields of view at X640; R, rare or 1 specimen per more than 20 fields of view at X640; B, barren of calcareous nannofossils; Preservation: F = fair; P = poor]

Species[1,2]	Formation													
	Potomac	Aquia	Aquia	Aquia	Nanjemoy	Nanjemoy	Nanjemoy	Nanjemoy	Piney Point	Old Church	Calvert	Calvert	Calvert	St. Marys
	Age													
	??	??	late Paleocene	late Paleocene	early Eocene	early Eocene	early Eocene	early Eocene	middle Eocene	late Oligocene-early Miocene	early Miocene	early Miocene	early Miocene	??
	Calcareous nannofossil zone													
	BARREN	BARREN	NP 8	NP 9	NP 10	NP 12-14	NP 12-14	NP 12-14	NP 16?	??	NN 2-3	NN 2-3	NN 2-4	BARREN
	Depth													
	273.7	255.9	241.5	220	201.8	196.2	186.6	168.8	157	149.3	137.1	128.3	121.3	105.1
Rhomboaster bramlettei	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Sphenolithus moriformis	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Sphenolithus radians	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Sphenolithus spp.	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Thoracosphaera spp.	.	.	.	.	.	.	.	X	X	.	.	.	.	.
Toweius callosus	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Toweius eminens eminens	.	.	X	X	.	.	.	.	.	.	.	.	.	.
Toweius eminens tovae	.	.	X	X	.	.	.	.	.	.	.	.	.	.
Toweius occultatus	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Toweius pertusus	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Transversopontis pulcher	.	.	.	.	.	.	X	X	X	.	.	.	.	.
Transversopontis pulcheroides	.	.	.	.	.	.	X	X	.	.	.	.	.	.
Zygodiscus herlyni	.	.	.	X	X	.	.	.	.	.	.	.	.	.
Zygrhablithus bijugatus	.	.	.	.	.	.	X	X	X	.	.	.	.	.
Abundance	B	B	C	C	F	R	F	F	F	F	F	F	F	B
Preservation			F	F	P	P	F	F	F	F	F	F	F	

Appendix 4a. Calcareous nannofossil occurrences in the Jamestown core, with age and formation correlation (L.M. Bybell)—Continued

[1]**Cenozoic calcareous nannofossil species considered in this report (in alphabetical order by genus).**
Braarudosphaera bigelowii (Gran & Braarud 1935) Deflandre 1947
Cepekiella lumina (Sullivan 1965) Bybell 1975
Chiasmolithus bidens (Bramlette & Sullivan 1961) Hay & Mohler 1967
Coccolithus eopelagicus (Bramlette & Riedel 1954) Bramlette & Sullivan 1961
Coccolithus pelagicus (Wallich 1877) Schiller 1930
Cribrocentrum reticulatum (Gartner & Smith 1967) Perch-Nielsen 1971
Cruciplacolithus tenuis (Stradner 1961) Hay & Mohler in Hay and others, 1967
Cyclococcolithus formosus Kamptner 1963
Cyclococcolithus leptoporus (Murray & Blackman 1898) Kamptner 1954
Discoaster barbadiensis Tan Sin Hok 1927
Discoaster deflandrei Bramlette & Riedel 1954
Discoaster druggii Bramlette & Wilcoxon 1967
Discoaster kuepperi Stradner 1959
Discoaster lenticularis Bramlette & Sullivan 1961
Discoaster lodoensis Bramlette & Riedel 1954
Discoaster multiradiatus Bramlette & Riedel 1954
Discoaster woodringii Bramlette & Riedel 1954
Ellipsolithus distichus (Bramlette & Sullivan 1961) Sullivan 1964
Ericsonia subpertusa Hay & Mohler 1967
Fasciculithus tympaniformis Hay & Mohler in Hay and others, 1967
Helicosphaera ampliaperta Bramlette & Wilcoxon 1967
Helicosphaera carteri (Wallich 1877) Kamptner 1954
Helicosphaera intermedia Martini 1965
Helicosphaera lophota (Bramlette & Sullivan 1961) Locker 1973
Helicosphaera seminulum Bramlette & Sullivan 1961
Heliolithus riedelii Bramlette & Sullivan 1961
Hornibrookina arca Bybell & Self-Trail 1995
Lithostromation operosum (Deflandre in Deflandre and Fert, 1954) Bybell 1975
Lophodolithus nascens Bramlette & Sullivan 1961
Markalius inversus Bramlette & Martini 1964
Nannotetrina alata (Martini 1960) Haq & Lohman 1975
Neochiastozygus concinnus (Martini 1961) Perch-Nielsen 1971c
Neococcolithes dubius (Deflandre in Deflandre and Fert, 1954) Black 1967
Pemma rotundum Klumpp 1953
Placozygus sigmoides (Bramlette & Sullivan 1961) Romein 1979b
Pontosphaera multipora (Kamptner ex Deflandre 1959) Roth 1970
Reticulofenestra abisecta (Müller 1970) Roth & Thierstein 1972
Reticulofenestra floridana (Roth & Hay in Hay and others, 1967) Theodoridis 1984
Reticulofenestra pseudoumbilicus (Gartner 1967) Gartner 1969
Reticulofenestra umbilicus (Levin 1965) Martini & Ritzkowski 1968
Rhabdosphaera perlonga (Deflandre in Grassé, 1952) Bramlette & Sullivan 1961
Rhomboaster bramlettei (Brönnimann & Stradner 1960) Bybell & Self-Trail 1995
Sphenolithus moriformis (Brönnimann & Stradner 1960) Bramlette & Wilcoxon 1967
Sphenolithus radians Deflandre in Grassé, 1952
Toweius callosus Perch-Nielsen 1971b
Toweius eminens var. *eminens* (Bramlette & Sullivan 1961) Gartner 1971
Toweius eminens var. *tovae* Bybell & Self-Trail 1995
Toweius occultatus (Locker 1967) Perch-Nielsen 1971
Toweius pertusus (Sullivan 1965) Romein 1979b
Transversopontis pulcher (Deflandre in Deflandre and Fert, 1954) Perch-Nielsen 1967
Transversopontis pulcheroides (Sullivan 1964) Báldi-Beke 1971
Zygodiscus herlyni Sullivan 1964
Zygrhablithus bijugatus (Deflandre in Deflandre and Fert, 1954) Deflandre 1959

Appendix 4a. Calcareous nannofossil occurrences in the Jamestown core, with age and formation correlation (L.M. Bybell)—Continued

[2]Useful Cenozoic calcareous nannofossil datums.

The following calcareous nannofossil species can be used to date sediments of Paleocene to early Miocene age. Many, but not all, of these species are present in the Jamestown core. FAD is a first appearance datum, and LAD is a last appearance datum. Zonal markers for the Martini (1971) NP zones are indicated with an *, and a # indicates a zonal marker for the Bukry (1973, 1978) and Okada and Bukry (1980) CP zones. L.M. Bybell has found the remaining species to be biostratigraphically useful in the Gulf of Mexico and Atlantic Coastal Plains.

FAD *Reticulofenestra pseudoumbilicus* - early Miocene
FAD *Cyclococcolithus leptoporus* - early Miocene
LAD *Helicosphaera ampliaperta* - within Zone NN 4, early Miocene
FAD *Helicosphaera ampliaperta* - within Zone NN 2, early Miocene
FAD *#*Discoaster druggii* - base of Zone NN 2, early Miocene
LAD *Zygrhablithus bijugatus* - top of Zone NP 25, late Oligocene
LAD *#*Reticulofenestra umbilicus* - top Zone NP 22, top of Zone CP 16c
LAD **Cyclococcolithus formosus* - top of Zone NP 21, early Oligocene
LAD *#*Chiasmolithus bidens* - top of Zone NP 16, middle Eocene
FAD *Reticulofenestra* spp. - within upper Zone NP 12 or lower Zone NP 13
FAD *Helicosphaera lophota* - near top of Zone NP 12
LAD *Toweius callosus* - within Zone NP 12 - not exact
FAD *Helicosphaera seminulum* - mid Zone NP 12
FAD *#*Discoaster lodoensis* - base of Zone NP 12, base CP 10
LAD *Zygodiscus herlynii* - within Zone NP 11 - not exact
LAD *Discoaster lenticularis* - upper Zone NP 10
LAD *Rhomboaster bramlettei* - upper Zone NP 10
LAD *Hornibrookina* spp. - lower Zone NP 10
FAD **Rhomboaster bramlettei* - base of Zone NP 10, early Eocene
LAD *Toweius eminens tovae* (consistent occurrence) - upper Zone NP 9
FAD *Toweius occultatus* - within upper Zone NP 9
FAD *Toweius callosus* - within Zone NP 9
FAD *Toweius callosus* - within Zone NP 9
FAD *Discoaster lenticularis* - near base of Zone NP 9
FAD *#*Discoaster multiradiatus* - base of Zone NP 9, base CP 8a
FAD **Heliolithus riedelii* - base of Zone NP 8

Appendix 4b. Dinocyst occurrences in the Jamestown core, with age and formation correlation (L.E. Edwards)

[X, present; (.), not present; ?, questionably present; R, reworked; C, contaminated from above, probably burrowing; ?R, present, questionably reworked; ?C, present, questionably a contaminant; depth of sample is in feet; dinocyst zonation from Verteuil and Norris, 1996]

Species	Formation							
	Old Church			Calvert			St. Marys	
	Age							
	late Oligocene			early Miocene		early or middle Miocene	late Miocene	
	Dinocyst zone							
				DN 2	DN 2	DN 3-5	DN 8-9	DN 8-9
	Depth							
	158	149	142	135	124	117	104	61.4
Achomosphaera andalousiensis	.	.	.	.	.	.	X	X
Apteodinium spiridoides	X	.	X	X	X	.	.	.
Apteodinium tectatum	.	.	.	.	X	X	.	.
Barssidinium evangelineae	.	.	.	.	.	.	X	X
Batiacasphaera sphaerica	.	?	X	X	X	.	.	.
Chiropteridium galea	X	.	.	.	.	.	.	.
Chiropteridium lobospinosum	X	X	X	.	.	.	.	.
Chiropteridium sp.	.	.	.	.	?R	.	.	
Corrudinium sp.	X	X	.	.	.	.	.	.
Cousteaudinium aubryae	.	.	.	.	X	.	.	.
Cribroperidinium tenuitabulatum	X	.	.	X	.	.	.	.
Cyclopsiella sp.	.	.	.	X	.	.	.	.
Dapsilidinium pseudocolligerum	.	X	.	X	.	.	.	.
Deflandrea phosphoritica var. *spinulosa*	.	.	X	.	.	.	.	.
Dinopterygium cladoides sensu Morgenroth (1966)	.	X	.	.	.	.	.	.
Distatodinium biffii	X	X	.	.	.	.	.	.
Distatodinium sp.	.	.	.	.	X	.	.	.
Erymnodinium delectabile	.	.	.	.	.	.	?	X
Exochosphaeridium insigne	.	.	.	X	X	.	.	.
Habibacysta tectata	.	.	.	.	.	.	.	X
Homotryblium plectilum	X	X	X	.	.	.	.	.
Hystrichokolpoma rigaudiae	.	.	X	X	.	X	.	.
Hystrichokolpoma sp.	.	X	X	X	.	.	.	.
Hystrichosphaeropsis obscura	.	.	.	X	X	X	.	.
Impagidinium spp.	.	.	X	.	.	.	X	X
Invertocysta lacrymosa	.	.	.	.	.	.	.	X
Labyrinthodinium truncatum subsp. *truncatum*	.	.	.	.	.	.	X	X
Lejeunecysta spp.	X	.	.	X	X	.	.	X
Lingulodinium machaerophorum	X	X	X	.	X	X	.	.
Lingulodinium multivirgatum	.	.	.	.	?	.	.	.

Appendix 4b. Dinocyst occurrences in the Jamestown core, with age and formation correlation (L.E. Edwards)—Continued

[X, present; (.), not present; ?, questionably present; R, reworked; C, contaminated from above, probably burrowing; ?R, present, questionably reworked; ?C, present, questionably a contaminant; depth of sample is in feet; dinocyst zonation from Verteuil and Norris, 1996]

Species	Formation							
	Old Church			Calvert			St. Marys	
	Age							
	late Oligocene			early Miocene		early or middle Miocene	late Miocene	
	Dinocyst zone							
				DN 2	DN 2	DN 3-5	DN 8-9	DN 8-9
	Depth							
	158	149	142	135	124	117	104	61.4
Melitasphaeridium choanophorum	.	.	.	.	X	.	X	X
Operculodinium piaseckii	.	.	.	.	.	.	X	.
Operculodinium spp.	.	X	X	X	X	X	X	X
Palaeocystodinium golzowense	.	X	X	X	X	.	.	.
Pentadinium imaginatum	X	X	.	.	.	.	.	.
Pentadinium laticinctum subsp. *laticinctum*	X	X	.	.	.	.	.	.
Pentadinium sp. cf. *P. laticinctum granulatum*	.	.	X	X	X	X	.	.
Pentadinium sp. I of Edwards (1986)	?C	?C	?C	X	.	.	.	.
Polysphaeridium zoharyi	.	.	X	X	.	.	.	.
Quadrina? condita	.	.	.	.	.	.	.	X
Reticulatosphaera actinocoronata	X	X	.	.	X	.	X	X
Riculacysta perforata	X	X	.	.	.	.	.	.
Selenopemphix brevispinosa	.	.	.	.	X	.	X	X
Selenopemphix nephroides	X	X	.	X	.	.	.	.
Selenopemphix quanta	.	.	.	X	.	.	.	X
Spiniferites mirabilis	.	.	.	.	.	X	.	X
Spiniferites pseudofurcatus	X	.	X	X	X	X	.	.
Spiniferites spp.	X	X	X	X	X	X	X	X
Sumatradinium druggii	.	.	.	.	.	X	.	.
Sumatradinium soucouyantiae	.	.	C	X	X	X	.	.
Sumatradinium sp.	.	.	.	.	X	.	.	.
Systematophora placacantha	.	X	X	X	X	X	.	.
Tectatodinium pellitum	X	.	.	.	X	.	X	.
Thalassiphora pelagica	X	.	.	.	.	.	.	.
Trinovantedinium spp.	.	.	.	.	.	X	.	X
Tuberculodinium rossignoliae	.	.	X	.	.	.	.	.
Tuberculodinium vancampoae	X	.	.	X	X	X	X	X
Charlesdowniea coleothrypta	.	.	R	.	.	.	.	.
Wetzeliella sp.	.	R	.	.	.	.	.	.
freshwater alga *Pediastrum*	.	.	.	.	.	.	.	X

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