

Studies of the Chesapeake Bay Impact Structure— Introduction and Discussion

By J. Wright Horton, Jr., David S. Powars, and Gregory S. Gohn

Chapter A of

Studies of the Chesapeake Bay Impact Structure— The USGS-NASA Langley Corehole, Hampton, Virginia, and Related Coreholes and Geophysical Surveys

Edited by J. Wright Horton, Jr., David S. Powars, and Gregory S. Gohn

Prepared in cooperation with the
Hampton Roads Planning District Commission,
Virginia Department of Environmental Quality, and
National Aeronautics and Space Administration Langley Research Center

Professional Paper 1688

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

Contents

Abstract	A1
Introduction	1
Previous Work	3
The Chesapeake Bay Impact Structure	5
Form and Structure	5
Character of the Target	7
Land Surface Features	7
The USGS-NASA Langley Core	9
Significant Results	11
Crystalline Basement Rocks	11
Impact-Modified and Impact-Generated Sediments	11
Postimpact Sediments	13
Water Depths—Impact and Postimpact	14
Dating the Impact Event	14
Structural Interpretation of Seismic Data	15
Interpretation of Audio-Magnetotelluric (AMT) Soundings	15
Hydrologic Effects and Water-Resources Implications	16
Conceptual Model	16
Acknowledgments	18
References Cited	18
Appendix A1. Abstracts of Research on the Chesapeake Bay Impact Structure, 2001–2003	24

Figures

A1. Regional map showing the location of the Chesapeake Bay impact structure, the USGS-NASA Langley corehole at Hampton, Va., and some other coreholes in southeastern Virginia	A2
A2. Map of southeastern Virginia showing locations of recently completed coreholes and geophysical surveys in relation to the Chesapeake Bay impact structure	4
A3. Satellite image of Chesapeake Bay showing location of the buried impact structure and nearby Mesozoic to Cenozoic tectonic features	6
A4. Map of the lower Chesapeake Bay showing Pleistocene scarps and terraces in relation to the buried Chesapeake Bay impact structure	8
A5. Stratigraphic column of the USGS-NASA Langley corehole, Hampton, Va., showing selected geophysical logs	10
A6. Correlation diagram for part of the USGS-NASA Langley core comparing informal usage of the terms “Exmore beds” and “Exmore breccia” in relation to lithology and interpretation of ocean-water resurge deposits	12
A7. Schematic cross sections illustrating stages in a conceptual model of Chesapeake Bay crater formation	17

Table

A1. Stratigraphic units, ages, and contact depths below ground surface at the USGS-NASA Langley corehole, Hampton, Va.	A9
--	----

Studies of the Chesapeake Bay Impact Structure—Introduction and Discussion

By J. Wright Horton, Jr.,¹ David S. Powars,¹ and Gregory S. Gohn¹

Abstract

The late Eocene Chesapeake Bay impact structure on the Atlantic margin of Virginia is the largest known impact crater in the United States, and it may be the Earth's best preserved example of a large impact crater that formed on a predominantly siliciclastic continental shelf. The 85-kilometer-wide (53-mile-wide) crater also coincides with a region of saline ground water. It has a profound influence on ground-water quality and flow in an area of urban growth.

The USGS-NASA Langley corehole at Hampton, Va., is the first in a series of new coreholes being drilled in the crater, and it is the first corehole to penetrate the entire crater-fill section and uppermost crystalline basement rock. The Langley corehole is located in the southwestern part of the crater's annular trough. A comprehensive effort to understand the crater's materials, architecture, geologic history, and formative processes, as well as its influence on ground water, includes the drilling of coreholes accompanied by high-resolution seismic-reflection and seismic-refraction surveys, audio-magnetotelluric surveys, and related multidisciplinary research.

The studies of the core presented in this volume provide detailed information on the outer part of the crater, including the crystalline basement, the overlying impact-modified and impact-generated sediments (physical geology, paleontology, shocked minerals, and crystalline ejecta), and the upper Eocene to Quaternary postimpact sedimentary section (stratigraphy, paleontology, and paleoenvironments).

The USGS-NASA Langley corehole has a total depth below land surface of 635.1 meters (m; 2,083.8 feet (ft)). The deepest unit in the corehole is the Neoproterozoic Langley Granite. The top of this granite at 626.3 m (2,054.7 ft) depth is overlain by 390.6 m (1,281.6 ft) of impact-modified and impact-generated siliciclastic sediments. These crater-fill materials are preserved beneath a 235.6-m-thick (773.12-ft-thick) blanket of postimpact sediments.

A high-resolution seismic-reflection and seismic-refraction profile that crosses the Langley drill site is tied to the core by borehole geophysical logs, and it reveals the details of extensional collapse structures in the western annular trough. Electrical cross sections based on audio-magnetotelluric (AMT) soundings image a nearly vertical zone of high resistivity at the outer margin of the annular trough, possibly indicating fresh ground water at that location, and they show impedance trends that match the curvature of the structure. They also image the subsurface contact between conductive sediments and resistive crystalline basement, showing that the depth to crystalline basement is relatively constant in the western part of the annular trough.

Chemical and isotopic data indicate that saline ground water of the Virginia inland saltwater wedge or bulge is a mixture of freshwater and seawater, and evidence for a mixing zone at the crater's outer margin supports the concept of differential flushing of residual seawater to create the bulge. Ground-water brine in the central part of the crater was produced by evaporation, and brine production from the heat of the impact is at least theoretically possible.

Introduction

This chapter begins with an overview of the Chesapeake Bay impact structure, including its geologic setting, the history of previous work, and the status of current research. This overview provides an introduction to more detailed studies reported in the volume. These reports contain data and interpretations from the USGS-NASA Langley corehole at Hampton, Va., which is the first corehole to basement in the structure, and from related coreholes and geophysical surveys.

This chapter also explains some style conventions used in this volume. Discussions highlight some important results of each chapter, as well as scientific results and issues that transcend the scope of individual chapters.

The impact event.—Although our understanding of the impact event is likely to improve as investigations continue, researchers currently agree on the following scenario. The

¹U.S. Geological Survey, Reston, VA 20192.

A2 Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Va.

impact event occurred 35 million to 36 million years ago, when the area that became eastern Virginia was covered by the Atlantic Ocean. An asteroid or comet fragment about 3 kilometers (km; about 2 miles (mi)) in diameter collided with Earth at a velocity on the order of 20 km (12 mi) per second (Crawford, 2002). It blasted through the shallow ocean, wet sediments, and rocks to leave a cavity about 38 km (24 mi) wide in the sea floor.

This explosion, approximately 100 times greater than a detonation of Earth's entire nuclear arsenal (Poag, 2002d), vaporized the projectile and billions of tons of water, sediment, and rock (Edwards and Powars, 2003). Some rocks and sediments melted instantly, and droplets solidified in the air before raining down as tektites as far away as Texas. The shock wave left extreme deformation features similar to those caused by nuclear explosions. Enormous volumes of water, sediment, and rock shot ballistically outward and upward to high altitudes, leaving a giant short-lived cavity in the water in addition to the hole in the seabed.

Rebound of the crater floor was followed by gravitational collapse; the inward slumping and faulting of poorly consolidated, wet sediments extended the crater to a width of about 85 km (53 mi). Ejected material fell back to Earth, and the ocean water surged violently back into the open cavity, carrying a chaotic mixture of debris ranging from damaged microorganisms to house-size blocks (Edwards and Powars, 2003). Tsunamis spread outward in all directions. Fallout particles settled on the seabed, and a thick pile of sediments accumulated on top of the crater, preserving the evidence beneath the present mouth of Chesapeake Bay until the human needs for drinkable ground water led to its discovery in recent decades (Powars and Bruce, 1999).

The impact crater location and name.—The Chesapeake Bay impact crater underlies the southern part of Chesapeake Bay, its surrounding peninsulas, and a small part of the western Atlantic Ocean (fig. A1). This buried, late Eocene complex crater is the largest known impact crater in the United States and the seventh largest known on Earth (Earth Impact Database, 2003). It may be the Earth's best preserved and best studied example of a large impact structure formed in a predominantly siliciclastic continental-shelf environment. The Chesapeake Bay impact crater coincides closely with an unusual region of saline ground water originally called the Virginia inland saltwater wedge (Sanford, 1913). The impact structure, therefore, has a profound influence on ground-water flow and quality, including salinity, across one of the fastest growing urban centers on the east coast of North America that increasingly depends on ground-water resources (Hampton Roads Planning District Commission, 1999).

In this volume, the terms "Chesapeake Bay impact crater" and "Chesapeake Bay crater" refer to the actual crater depression, whereas "Chesapeake Bay impact structure" is used in a broader sense to include outlying impact-related structures, such as faults in the outer fracture zone (fig. A1). The terms can be used interchangeably where this distinction is irrelevant to the context.

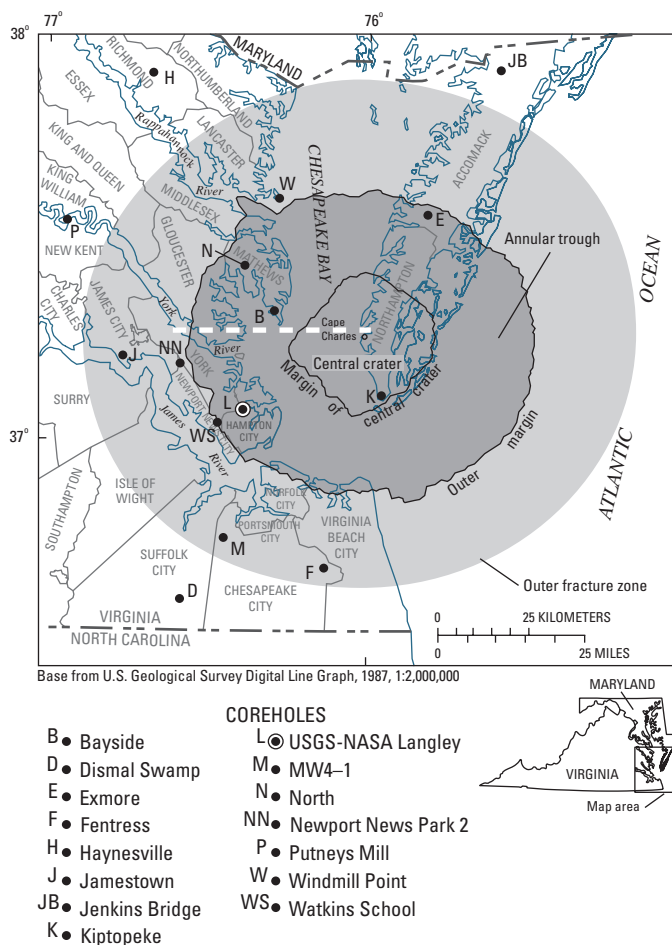


Figure A1. Regional map showing the location of the Chesapeake Bay impact structure, the USGS-NASA Langley corehole at Hampton, Va., and some other coreholes in southeastern Virginia. White dashed line indicates approximate location of schematic cross sections in figure A7. Locations of the central crater and outer margin are from Powars and Bruce (1999). The extent of the outer fracture zone (light gray) is based on Powars (2000) and Johnson and others (2001); the eastern part is speculative. Illustration modified from Powars, Johnson, and others (2002) and Edwards and Powars (2003).

The Chesapeake Bay Impact Crater Project.—The Chesapeake Bay Impact Crater Project is a multidisciplinary research collaboration begun in 2000 to understand the physical characteristics, geologic history, formative processes, and hydrologic implications of this buried structure. The project collaborators are described in the "Acknowledgments" section.

Most of the chapters in this Professional Paper discuss studies of samples from the USGS-NASA Langley corehole (fig. A1) or geophysical studies in the vicinity. This corehole was the first of four coreholes drilled for this project during the years 2000 through 2002, and it was the first corehole to penetrate the entire sedimentary section and reach uppermost crys-

talline basement rock within the crater's annular trough (fig. A1). Related studies of samples from additional coreholes, although mentioned in several chapters, are still in progress.

The four coreholes drilled for the Chesapeake Bay Impact Crater Project during 2000 through 2002 are listed below and are plotted in figures A1 and A2:

1. USGS Bayside corehole, in the western annular trough on the Middle Peninsula at Bayside, Va. (728.5 m, 2,390.2 ft total depth, year 2001)
2. USGS-NASA Langley corehole, in the western annular trough in Hampton, Va. (635.1 m, 2,083.8 ft total depth, year 2000)
3. USGS North corehole, in the western annular trough on the Middle Peninsula, Va. (435.1 m, 1,427.5 ft total depth, year 2001)
4. USGS Dorothy R. Watkins Elementary School corehole, just outside the outer margin in Newport News, Va. (300.3 m, 985.3 ft total depth, year 2002)

The Bayside, Langley, North, and Watkins School coreholes are located approximately 8, 19, 24, and 27 km (5, 12, 15, and 17 mi), respectively, outside the central crater (fig. A2). All four cores penetrated impact-generated sediments of the Exmore beds, and the cores from Bayside and Langley sampled complete postimpact and crater sections down to Neoproterozoic granites of a peri-Gondwanan basement terrane (Horton and others, this volume, chap. B). The short names "Bayside corehole," "Langley corehole," "North corehole," and "Watkins School corehole" are used in this volume.

The USGS-NASA Langley corehole is described in online drilling reports (Gohn, Clark, and others, 2001; Powars, Bruce, and others, 2001). The Langley corehole is located at lat 37°05'44.28" N., long 76°23'08.96" W. (North American Datum of 1927), at a ground-surface altitude of 2.4 m (7.9 ft) above the North American Vertical Datum of 1988. The corehole was drilled at the National Aeronautics and Space Administration (NASA) Langley Research Center in Hampton, Va. Drilling by the U.S. Geological Survey (USGS) and cooperators (see "Acknowledgments") took place in July–October 2000, and geophysical logs were run in the hole on three occasions.

Measurements in this volume.—Geophysical, paleontologic, and petrologic studies routinely use metric units for physical parameters. However, coastal plain stratigraphic and hydrologic studies, as well as the drilling industry, routinely use feet and fractions thereof as length units for stratigraphic thickness and depth. Borehole geophysical logs typically measure depth in feet, although unit systems for the measured parameters vary. To accommodate this mixture, this volume uses metric units for all measurements, with the following exceptions. Stratigraphic positions and thicknesses and general references to depths in

cores and coreholes are made in meters or decimal fractions of meters with equivalent values in feet or decimal fractions of feet listed in parentheses, as in the example 73.3 m (240.6 ft). Similarly, horizontal distances are given in kilometers or meters with miles or feet in parentheses, as in the example 11.7 km (7.3 mi). Data collected in metric units are given in the text only in metric units, whereas data collected in feet and inches (in.) are given using both systems of measurement, as in the example 25 cm (10 in.). Conversion factors are given after the volume table of contents.

Previous Work

Sanford (1913) was the first to recognize and name the Virginia inland saltwater wedge, and D.J. Cederstrom's reports included a more comprehensive delineation of this feature and attributed it to differential flushing of seawater related to an Eocene basin fill north of the James River. Cederstrom conducted a series of comprehensive regional hydrogeologic investigations of the York-James Peninsula (Cederstrom, 1945a, 1957) and related studies in the southeastern Virginia Coastal Plain (Cederstrom, 1945b,c), providing lithologic logs of wells, biostratigraphic data analyzed by J.A. Cushman (USGS), and water-quality data (Cederstrom, 1943, 1946).

Cederstrom's (1957) subsurface Mattaponi Formation (term abandoned by Ward, 1984) included what we now recognize as crater-fill deposits (the Exmore beds), as well as additional undisturbed sediments outside the crater beneath most of the central to outer Virginia Coastal Plain (Powars and Bruce, 1999). Cederstrom proposed the "James River fault zone" to account for his interpretation of the erratic distribution and abrupt changes in thickness of strata. Knowledge of subsurface geology beneath the southeastern Virginia Coastal Plain was based mostly on water-well cuttings and geophysical logs until the late 1980s (Brown and others, 1972; Lacznik and Meng, 1988; Meng and Harsh, 1988), at which time the surficial deposits had already been mapped in considerable detail (Johnson and others, 1987, and references therein).

From 1986 to 1992, the analysis of samples from coreholes drilled by the USGS and the Virginia Department of Environmental Quality (VDEQ) significantly advanced the understanding of subsurface geology in southeastern Virginia (Powars and others, 1987, 1990, 1992; Poag and others, 1992). This work, combined with results of offshore drilling at Deep Sea Drilling Project Site 612, led to the initial recognition that an offshore layer of late Eocene impact ejecta (containing coesite, glass, and shocked quartz) had a likely source in the mid-Atlantic region (Bohor and others, 1988; Glass, 1989; Obradovich and others, 1989; Poag and others, 1991, 1992).

Subsequently, the analysis of marine seismic-reflection data, in the context of borehole data, revealed the existence of a large crater (Powars and others, 1993; Poag and others, 1994).

A4 Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Va.



Figure A2. Map of southeastern Virginia showing locations of recently completed coreholes and geophysical surveys in relation to the Chesapeake Bay impact structure. AMT data are described by Pierce (this volume, chap. J), and seismic data collected near the Langley corehole are described by Catchings and others (this volume, chap. I). Seismic data (blue lines) collected on the Middle and Delmarva Peninsulas by the USGS in 2002 are being processed.

The seismic-reflection data were donated to the USGS by Texaco, Inc., and Exxon Exploration Co. in 1993 and 1994.

Structural and stratigraphic documentation of the Chesapeake Bay impact structure followed (Poag and Aubry, 1995; Koeberl and others, 1996, 2001; Poag, 1996, 1997, 2000; Poag, Hutchinson, and others, 1999; Poag, Plescia, and Molzer, 1999; Powars and Bruce, 1999; Powars, 2000). In 2000, the Virginia Museum of Natural History Foundation awarded the Thomas Jefferson Medal for Outstanding Contributions to Natural Science jointly to C.W. Poag (USGS), D.S. Powars (USGS), and T.S. Bruce (VDEQ) for their combined efforts to map, elucidate, and bring to public awareness the Chesapeake Bay impact structure.

Detailed, nontechnical accounts of the crater and its discovery are presented in Poag's (1999) book and Tennant's (2001) series of articles. Tennant's articles received the Walter Sullivan Award for Excellence in Science Journalism from the American Geophysical Union in 2002.

Significantly, until the crater was discovered, there was no satisfactory explanation for the anomalous saltwater wedge (Powars, Bruce, Poag, and Mixon, 1994; Powars and Bruce, 1999) or the region's stratigraphic and structural complexities (Powars and Bruce, 1999; Powars, 2000). The literature on the Chesapeake Bay impact structure has included interpretations based on conceptual models of craters and crater processes (Melosh, 1989), analogies to other craters, and interpretations of seismic-reflection profiles. Some of the fundamental concepts of this crater's morphology, internal structure, and formative processes, although widely cited, have remained untested hypotheses.

Accordingly, the Chesapeake Bay Impact Crater Project was undertaken in 2000 as a coordinated, multiagency effort to better understand the physical characteristics, geologic history, formative processes, hydrologic effects, and water-resource implications of this buried structure. Among specific interests are the structure's influence on ground-water quality and availability in southeastern Virginia and planetary-science implications for understanding impacts in a continental-shelf environment.

As described above, four deep coreholes for this project were completed in 2000 through 2002 (fig. A2). Various mineralogical, geochemical, isotopic, petrographic, sedimentologic, structural, and other methods of core-sample analysis are described in this volume. Nearly 23 km (14 mi) of land-based, high-resolution seismic-reflection and seismic-refraction surveys were conducted on the York-James Peninsula in 2001 and on the Middle Peninsula in 2002, both crossing the outer annular trough and outer margin, and some short surveys were conducted across parts of the central crater and its rim on the Delmarva Peninsula (fig. A2). Publications highlighting the recent studies include those by Catchings, Saulter, and others (2001), Gohn, Clark, and others (2001), Powars, Bruce, and others (2001), Poag (2002c), Poag, Plescia, and Molzer (2002), Edwards and Powars (2003), Sanford (2003), Self-Trail (2003),

and Poag and others (2004); see also the abstracts listed in appendix A1.

The Chesapeake Bay Impact Structure

The following sections provide an overview of the Chesapeake Bay impact structure's complex form and structure, asymmetric layered marine target, and spatially associated land surface features. The term "target" is used for the area that was hit by the asteroid or comet fragment.

Form and Structure

An impact crater can be classified either as a *simple crater*, implying a bowl-shaped depression, or as a *complex crater*, implying a more complicated form that commonly includes a central uplift, a generally flat floor, and an inward collapse around its rim. Craters on Earth that exceed a diameter of about 4 km (2.5 mi) are complex craters (French, 1998).

The complex crater beneath Chesapeake Bay has an average width of about 85 km (53 mi), ranging from about 80 to 95 km (50 to 59 mi), and it contains an excavated central crater also termed the inner basin (Poag, Hutchinson, and others, 1999; Powars and Bruce, 1999; Powars, 2000). The central crater is variously interpreted on the basis of geophysical data to be approximately 30–38 km (19–24 mi) in diameter and subquadrant in shape (Powars and Bruce, 1999; Powars and others, 2003) or about 35–40 km (22–25 mi) in diameter and irregular in shape (Poag, Hutchinson, and others, 1999). Interpretations of seismic-reflection data suggest that the floor of the central crater penetrated crystalline basement about 1.3 km (0.8 mi) deeper than the lip of the outer rim and 1.6 km (1.0 mi) below sea level and that a mass of crystalline rock has a diameter of 15–20 km (9–12 mi) and rises as a central peak (uplift) about 900 m (2,950 ft) above the central crater floor (Poag, Plescia, and Molzer, 2002).

The central crater is surrounded by a flat-floored annular trough about 24 km (15 mi) in width (Poag and others, 1994). The margin of the central crater is characterized by uplifted basement rocks and has been interpreted by Poag, Plescia, and Molzer (2002) as an irregular peak ring. The outer margin of the annular trough is roughly circular and is characterized by a terraced zone of inwardly slumped fault blocks (Poag, 1996; Powars and Bruce, 1999). An outer escarpment ranges in relief from ~300 m (~1,000 ft) on the northwest to ~1,000 m (~3,300 ft) or more on the southeast (Poag, 1996; Poag, Hutchinson, and others, 1999). The outer margin of the annular trough is delineated by seismic profiles, which cross it at 61 locations (Poag, Plescia, and Molzer, 2002, p. 1083), and is generally considered to be the edge of the crater.

A6 Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Va.

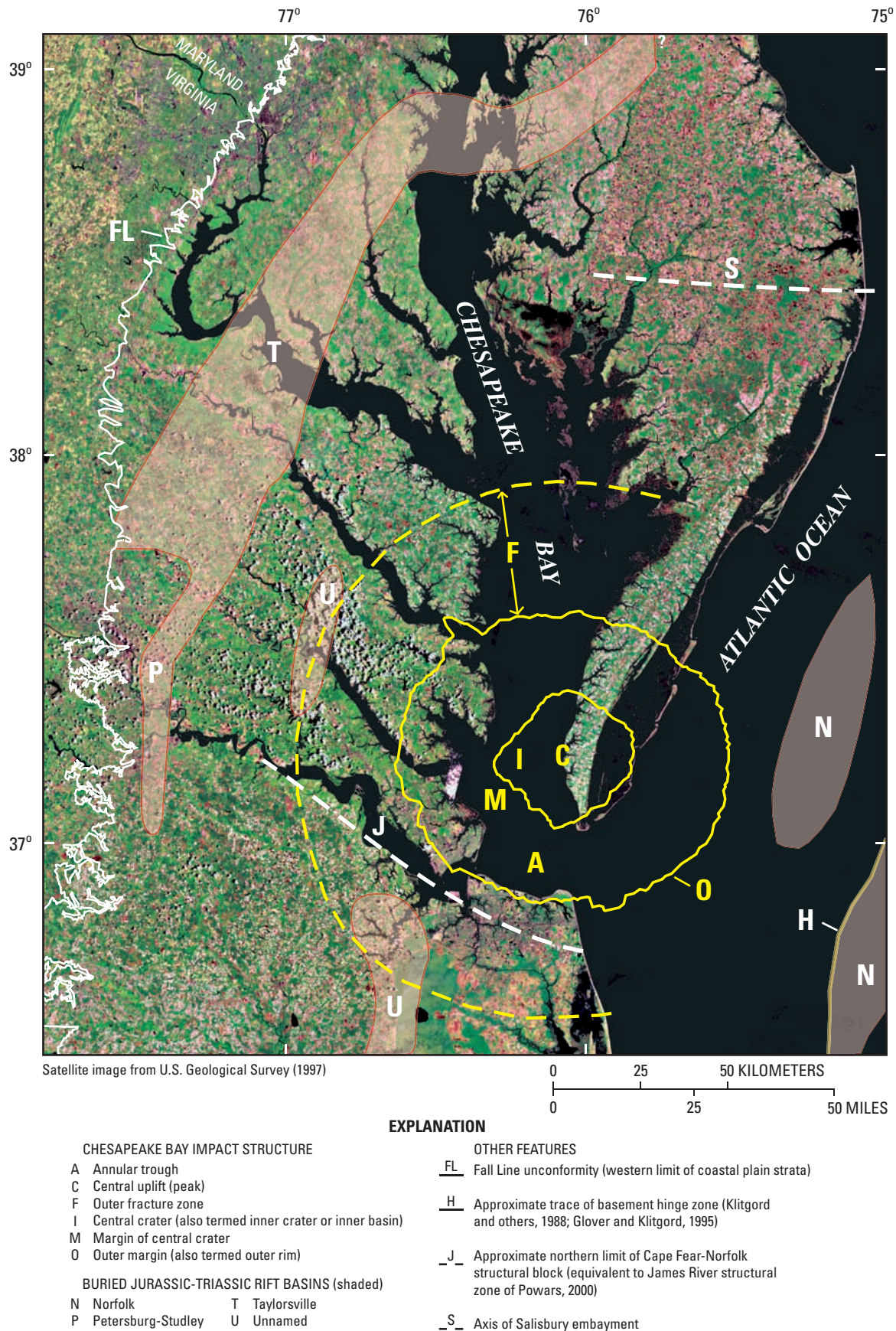


Figure A3. Satellite image of Chesapeake Bay showing location of the buried impact structure and nearby Mesozoic to Cenozoic tectonic features. Tectonic features modified from Powars and Bruce (1999, fig. 1) and Powars (2000, fig. 1).

The crater is surrounded by an outer fracture zone (F in fig. A3) about 35 km (22 mi) in width that contains discontinuous, concentric faults (Powars, 2000; Powars, Johnson, Edwards, and others, 2002) and radial faults (Johnson and others, 2000; Powars, 2000). All of the crater features are well preserved beneath a blanket of postimpact sediments that is about 150–400 m (490–1,300 ft) thick (Poag and others, 1994; Powars and Bruce, 1999).

The initial interpretations of crater structure and form relied on the seismic-reflection profiles donated to the USGS by Texaco and Exxon (Powars and others, 1993; Poag and others, 1994; Poag, 1996, 1997, 1999; Powars and Bruce, 1999). These profiles were generated from 48-fold, multichannel data collected in Chesapeake Bay and its estuaries by Teledyne Exploration in 1986. The USGS and the National Geographic Society generated more than 1,200 km (750 mi) of additional marine seismic-reflection profiles in 1996 from data acquired in a single-channel digital format using an air-gun seismic source. Poag, Hutchinson, and others (1999) based their interpretations of the crater architecture on these data as well as the earlier Texaco and Exxon data, noting that the single-channel seismic system did not resolve the basement surface in the deeper, eastern part of the crater.

Character of the Target

When the Chesapeake Bay impact structure formed on the Atlantic continental shelf of eastern North America, the marine target had three main components arranged as stacked layers: crystalline rocks, clastic sediments, and seawater. The uppermost target component consisted of seawater, estimated to have been in the range of 0–340 m (0–1,115 ft) deep at the impact site; water depths increased eastward across the structure as discussed below under the heading, “Water Depths—Impact and Postimpact.”

The middle target component consisted of stratified, unconsolidated, mostly Lower and Upper Cretaceous siliciclastic deltaic sediments capped by thinner, Upper Cretaceous to lower Tertiary shallow-shelf marine sediments. These preimpact target sediments formed an eastward-thickening wedge ranging in thickness from about 400 m (about 1,300 ft) on the west side of the structure to about 1,500 m (about 4,900 ft) on the east side (Powars and others, 2003). Beneath the coastal plain north of the impact structure in Maryland, preimpact sediments dip toward the trough of the tectonic downwarp known as the Salisbury embayment (fig. A3), where they thicken to as much as 1,800 m (5,900 ft) about 90 km (60 mi) from the outer margin (Powars and Bruce, 1999). Preimpact Cretaceous and Cenozoic deformation of the target sediments is suggested by coastal plain subsurface mapping at the northern end of the Cape Fear-Norfolk structural block (J in fig. A3), south of the crater (Powars, 2000).

The lowermost target component consisted of crystalline metamorphic and igneous rocks ranging in age from Paleozoic to Proterozoic and similar in general character to rocks exposed

in the Appalachian Piedmont (Daniels and Leo, 1985; Horton and others, 1991). The tectonic significance of this crystalline basement in the Chesapeake Bay target region has been controversial because of limited information, as exemplified by the wide range of interpretations as part of Laurentia (Sheridan and others, 1999), Gondwana (Lefort and Max, 1991), or an intervening volcanic arc (Horton and others, 1991).

The Paleozoic and Proterozoic rocks beneath the coastal plain and continental shelf, like those of the Piedmont, contain local rift basins of Triassic and Jurassic age. The outer margin of the Chesapeake Bay impact crater lies about 70 km (40 mi) east of the Petersburg-Studley rift basin, northeast of an unnamed basin, and just west of the offshore Norfolk rift basin (fig. A3). The crater lies west of a basement hinge zone, along which the upper surface of basement beneath sediments of the continental shelf deepens abruptly seaward from about 2 km (1 mi) to more than 8 km (5 mi) below sea level (Klitgord and others, 1988; Glover and Klitgord, 1995). The hinge zone is characterized by a series of half grabens bounded by seaward-dipping faults, tilted blocks bounded by landward-dipping faults, and associated sedimentary wedges, which are attributed to Jurassic rifting that preceded the opening of the Atlantic Ocean (Klitgord and others, 1988). Seismic-reflection interpretations in the region must distinguish extensional features associated with the late Eocene impact structure from those formed by the earlier rifting.

Land Surface Features

Although the Chesapeake Bay impact crater has no surface outcrops and can be sampled only by drilling, some features of the land surface are spatially associated with the buried crater. The surface geology at the USGS-NASA Langley corehole consists of shallow bay sediments that were deposited on an ancestral Chesapeake Bay floor when the late Pleistocene sea level was 5.5 m (18 ft) higher than the present sea level (Johnson, 1969). These bay-floor deposits form a flat land surface known as the Hampton flat (Coch, 1971), and their associated shoreline is the Big Bethel scarp shown in figure A4. The Big Bethel scarp is about 4 km (2.5 mi) west of the Langley drill site. The Hampton flat and similar surfaces are commonly described as terraces.

The geological literature characterizes the Virginia Coastal Plain geomorphology as a succession of terraces that descend in elevation toward the Chesapeake Bay, the Atlantic Ocean, and the large rivers (Oaks and Coch, 1973; Johnson and others, 1987; Mixon and others, 1989; Johnson and others, 2001). Each terrace is composed of a terrace tread (or flat) that terminates in a landward scarp. The terrace treads are aggradational surfaces that formed by fluvial-estuarine, bay, and shallow-marine depositional processes (Johnson, 1969; Johnson and others, 1987, 2001). The valley-facing scarps formed by fluvial and estuarine erosion, and the coast-facing scarps formed by shoreline erosion.

A8 Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Va.



Base from the U.S. Geological Survey National Elevation Dataset 30-m digital elevation model (DEM) showing land-surface elevations shaded at 2-m (6.6-ft) intervals.

EXPLANATION

PLEISTOCENE SCARPS		PLEISTOCENE TERRACE	
Scarp—Ticks point downslope		HF	Hampton Flat
A	Ames Ridge	COREHOLE	
B	Big Bethel	L	USGS-NASA Langley
C	Cheriton		
CH	Chippokes		
D	Diamond Springs		
H	Harpersville		
HK	Hickory		
K	Kingsmill		
L	Lee Hall		
M	Mappesburg		
P	Pungoteague		
S	Suffolk		
SU	Surry		



Figure A4. Map of the lower Chesapeake Bay showing Pleistocene scarp and terraces in relation to the buried Chesapeake Bay impact structure and the USGS-NASA Langley corehole. Valley-facing scarps formed by fluvial and estuarine erosion, and coast-facing scarps

formed by shoreline erosion. Sources: Johnson (1969), Coch (1971), Oaks and Coch (1973), Johnson and others (1987), Mixon and others (1989), Powars and Bruce (1999), Powars (2000), and Johnson and others (2001).

The Big Bethel, Diamond Springs, Harpersville, and Ames Ridge scarps and the northern part of the Suffolk scarp approximately overlie the outer margin of the buried crater and mimic its curvature at different locations as shown in figure A4. Johnson and others (1998) found that Miocene, Pliocene, and Pleistocene strata show draping and other evidence of differential movement near the scarps, possibly related to compaction around the buried crater's margin.

The USGS-NASA Langley Core

Table A1 and figure A5 show the stratigraphic framework of the outer annular trough as revealed by the 635.1-m-deep (2,083.8-ft-deep) USGS-NASA Langley corehole at Hampton, Va. (L in figs. A1 and A2). The crystalline basement at this location consists of Neoproterozoic granite (Horton and others, 2001; Horton, Aleinikoff, and others, 2002; Horton, Kunk and others, 2002; Horton and others, this volume, chap. B). The top of the granite at 626.3 m (2,054.7 ft) depth is overlain by 390.6 m (1,281.6 ft) of impact-modified and impact-generated siliciclastic sediments. These crater-fill materials are preserved beneath a 235.6-m-thick (773.12-ft-thick) blanket of postimpact sediments.

Cretaceous sediments that were variably disturbed by the late Eocene asteroid or comet impact include crater units A and B; crater unit A is block faulted, locally fluidized, and gradational upward into crater unit B, which shows extensive fluidization, infiltration, and mixing (Gohn and others, this volume, chap. C). These impact-modified sediments were scoured and covered by ocean-water resurge deposits of the Exmore beds (polymict, matrix-supported diamicton). The Exmore beds consist of mixed Lower Cretaceous to upper Eocene sediment clasts (up to boulder size) and minor crystalline-rock clasts floating in a matrix of glauconitic, quartz-rich, muddy sand that contains Cretaceous, Paleocene, and Eocene fossils (Edwards and Powars, 2003; Self-Trail, 2003). The Exmore beds and their crystalline clasts are discussed in chapters C (Gohn and others), D (Frederiksen and others), and E (Horton and Izett).

The oldest postimpact stratigraphic unit, the upper Eocene Chickahominy Formation, is discussed by Poag and Norris (this volume, chap. F). Chapter G by Powars and others and chapter H by Edwards and others describe the entire postimpact (upper Eocene to Quaternary) stratigraphic section.

The stratigraphic framework in figure A5 and table A1 is used throughout this volume with one exception, chapter F, in which Poag and Norris use the stratigraphic framework of Poag,

Table A1. Stratigraphic units, ages, and contact depths below ground surface at the USGS-NASA Langley corehole, Hampton, Va.

[The USGS-NASA Langley corehole has a total depth below ground surface of 635.1 meters (2,083.8 feet). The ground-surface altitude of 2.4 m (7.9 ft) is given relative to the National Geodetic Vertical Datum of 1988]

Age	Stratigraphic unit	Base (ft)	Top (ft)	Base (m)	Top (m)
late Pleistocene	Tabb Formation, Lynnhaven Member	7.2	0.0	2.2	0.0
Pliocene	Yorktown Formation	76.3	7.2	23.3	2.2
late Miocene	Eastover Formation	224.5	76.3	68.4	23.3
late Miocene	St. Marys Formation	405.5	224.5	123.6	68.4
early and middle Miocene	Calvert Formation	470.9	405.5	143.5	123.6
middle Miocene	Calvert Beach Member	456.1	405.5	139.0	123.6
middle Miocene	Plum Point Member	461.1	456.1	140.5	139.0
early Miocene	Newport News beds	470.9	461.1	143.5	140.5
late Oligocene	Old Church Formation	577.4	470.9	176.0	143.5
late early Oligocene	Drummonds Corner beds*	601.3	577.4	183.3	176.0
late Eocene	Chickahominy Formation	773.12	601.3	235.65	183.3
late Eocene	Exmore beds	884.0	773.12	269.4	235.65
Early Cretaceous (+infiltration zones)	crater unit B	1,451.7	884.0	442.5	269.4
Early Cretaceous	crater unit A	2,054.7	1,451.7	626.3	442.5
Neoproterozoic	Langley Granite*	—	2,054.7	—	626.3

*Units named and defined in this volume.

A10 Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Va.

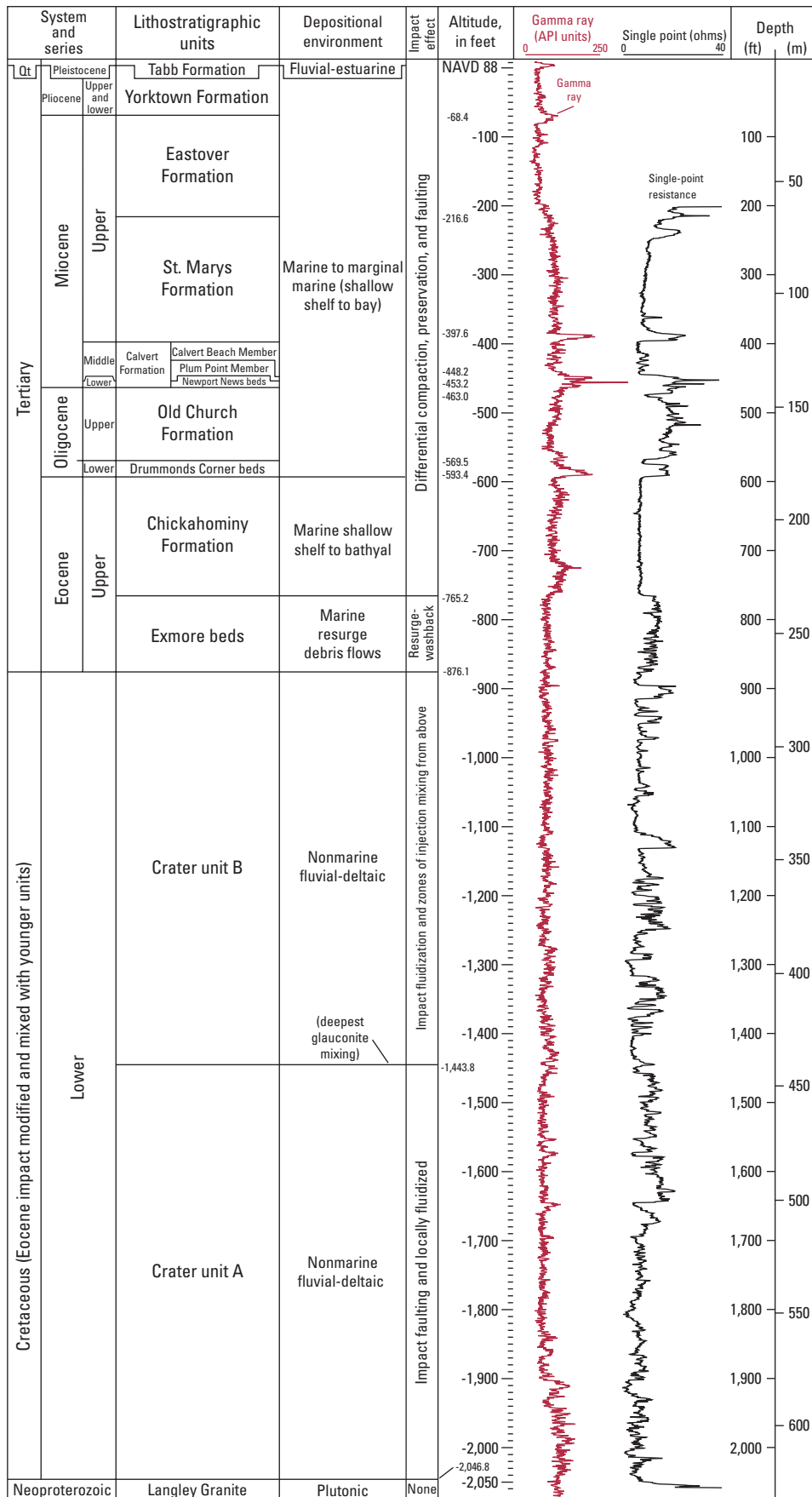


Figure A5. Stratigraphic column of the USGS-NASA Langley corehole, Hampton, Va., showing selected geophysical logs. Definitions: ft, feet; m, meters; NAVD 88, North American Vertical Datum of 1988; Qt, Quaternary.

Koeberl, and Reimold (2004). A correlation diagram for part of the USGS-NASA Langley core (fig. A6) shows the distinction between the informal Exmore beds of Gohn and others (this volume, chap. C) and the informal Exmore breccia of Poag and Norris (this volume, chap. F). Poag and Norris (p. F2) use the term “Exmore breccia” for “the brecciated sedimentary crater-fill deposits (underlain by either displaced sedimentary megablocks or crystalline basement rocks, and overlain by the fallout layer)” including all but the very top of the Exmore beds as well as crater unit B. Poag and Norris also treat thin units (their “fall-out layer” and “dead zone”) as a transitional interval distinct from the underlying Exmore breccia and overlying Chickahominy Formation. In summary, the “Exmore breccia” of Poag and Norris is a general term for impact breccias of any type anywhere in the crater, whereas the “Exmore beds” of Gohn and others is a term restricted in order to distinguish matrix-supported polymict sedimentary breccias that formed as water-resurge deposits from other kinds of impact breccias.

Significant Results

Of the ten chapters (B–K) on the Chesapeake Bay impact structure that follow this introduction, the first seven (B–H) present the results of multidisciplinary investigations of samples from the USGS-NASA Langley corehole. In chapter B, Horton and others discuss the petrography, structure, age, and thermal history of granitic basement rock beneath the Atlantic Coastal Plain at this location. The next three chapters (C–E) concentrate on impact-generated and impact-modified sediments in the Langley core. These include Gohn and others’ analysis of the physical geology in chapter C, Frederiksen and others’ interpretation of the paleontology in chapter D, and Horton and Izett’s investigation of shocked minerals and crystalline-rock ejecta in chapter E. Three additional chapters (F–H) address the postimpact sediments in the USGS-NASA Langley core. In chapter F, Poag and Norris interpret the record of early postimpact deposition and paleoenvironments in the upper Eocene Chickahominy Formation. Powars and others discuss the physical stratigraphy of the postimpact, upper Eocene to Quaternary sedimentary section in chapter G. In chapter H, Edwards and others present the paleontology of the upper Eocene to Holocene stratigraphic section.

Two chapters (I and J) use recent geophysical investigations to decipher the subsurface geology in the western annular trough and outer margin of the impact structure. In chapter I, Catchings and others interpret the data from a land-based, high-resolution seismic-reflection and seismic-refraction profile on the York-James Peninsula. In chapter J, Pierce discusses subsurface information gained from audio-magnetotelluric soundings across the marginal area of the structure on the York-James Peninsula and the Middle Peninsula in southeastern Virginia.

The volume concludes with chapter K by McFarland and Bruce on the distribution, origin, and relations to flow of ground-water salinity along the western margin of the Chesapeake Bay impact crater in eastern Virginia. These hydrologic studies show how the structure, distribution and properties of materials, and formative processes of the impact crater directly influence ground-water flow and quality in a region of major urban development that depends heavily on ground-water resources.

Crystalline Basement Rocks

The stratigraphic section revealed by the USGS-NASA Langley corehole at Hampton, Va. (fig. A5), includes the basement rock concealed beneath 626.3 m (2,054.7 ft) of sedimentary deposits and designated the Langley Granite of Horton and others (this volume, chap. B). The Langley Granite, newly described in that chapter and discussed in related abstracts (Horton and others, 2001; Horton, Aleinikoff, and others, 2002; Horton, Kunk, and others, 2002), is a peraluminous monzogranite of Neoproterozoic age that is pervasively chloritized and nonfoliated. In chapter B, Horton and others point out that the absence of shocked minerals and discernible impact heating in the Langley Granite at this location provides boundary constraints for computational models of the impact. The top of the granite is weathered, but not saprolitized, and is nonconformably overlain by the Cretaceous sediments.

Recent tectonic models of eastern North America have interpreted little-known basement rocks in the Chesapeake Bay target region alternatively as a northern extension of the Roanoke Rapids volcanic-arc terrane (Horton and others, 1991), as a remnant of Gondwanan Archean crust now in northwest Africa that was left behind when the Atlantic Ocean opened (Lefort and Max, 1991), or as Mesoproterozoic (Grenvillian) basement of Laurentia (Sheridan and others, 1999). Horton and others (this volume, chap. B) present evidence that the Langley Granite is Neoproterozoic in age and that it formed in a peri-Gondwanan magmatic arc.

Impact-Modified and Impact-Generated Sediments

The Lower Cretaceous fluvial sediments are nearly pristine just above the granite. The study by Gohn and others (this volume, chap. C) indicates that, as confining pressure due to the thickness of overburden decreased upward, the water-saturated sand beds became increasingly fluidized, and the clay beds became more intensely fractured. Preimpact Upper Cretaceous and lower Tertiary marine sediments are missing from their normal stratigraphic position, but their disaggregated remnants are mixed into the upper part of the Lower Cretaceous sedimentary section. The overlying Exmore beds contain a mixture of clasts, including re-sedimented Cretaceous and Tertiary sediment clasts as well as sparse shocked minerals and crystalline ejecta.

A12 Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Va.

Lithology	Depth, in feet	Depth, in meters	Poag and Norris, this volume, chap. F	Gohn and others, this volume, chap. C	Interpretation
Silty clay	773.12	235.65	Chickahominy Formation		Marine postimpact
Thinly laminated silt			Dead zone		Final settling of suspended matter from resurge and fallout, currents active
Pyrite lattices	773.75	235.84	Fallout layer		
Clayey silt	773.85	235.87			
Matrix-supported polymict diamicton	774.03	235.92	Exmore breccia		Resurge submarine debris flows

Interpretation	Poag and Norris, this volume, chap. F	Gohn and others, this volume, chap. C	Depth, in feet	Depth, in meters	Lithology
Marine postimpact	Chickahominy Formation		773.12	235.65	Silty clay
Marine resurge		Exmore beds	800	250	Matrix-supported polymict diamicton
Nonmarine fluvial-deltaic sediments with impact fluidization and zones of sediment injection from above	Exmore breccia	Crater unit B	884.0	269.4	Block-supported diamicton
			300		
			1,000		
			1,100	350	
					(Deepest glauconite mixing)
Nonmarine fluvial-deltaic, impact faulted, locally fluidized	Megablocks	Crater unit A	1,451.7	442.5	Clay, sand, silt, and gravel

Figure A6. Correlation diagram for part of the USGS-NASA Langley core comparing informal usage of the terms “Exmore beds” and “Exmore breccia” in relation to lithology and interpretation of ocean-water resurge deposits. The stratigraphic terms defined in chapter C (Gohn and others) are used throughout this volume except in chapter F (Poag and Norris), which follows the stratigraphy of Poag, Koeberl, and Reimold (2004).

The mixture suggests scouring and erosion of the nearfield ejecta and underlying sediments by the resurge of seawater and debris flows into the crater.

The study by Frederiksen and others (this volume, chap. D) indicates that spore-pollen samples from crater units A and B are derived from the Cretaceous Potomac Group and that the upper part of crater unit B also contains microfossils derived from lower Tertiary formations. Their study of microfossils shows that the Exmore beds contain clasts that range in age from Early Cretaceous to late Eocene. Significantly, the Exmore contains microfossil species known only from the lower part of the middle Eocene and others known only from the uppermost middle Eocene and lowermost upper Eocene. Strata of these ages have never been recovered in the subsurface of the Virginia Coastal Plain but were once present and possibly have since been eroded away. In addition, some dinoflagellate cysts from the Exmore are fused, curled, fragmented, or otherwise degraded, and this damage is attributed to heat and abrasion during the oceanic impact, as also discussed by Edwards and Powars (2003). Some calcareous nannofossils appear to have impact-induced fractures (Self-Trail, 2003).

Horton and Izett (this volume, chap. E) confirm the presence of rare shocked quartz grains in the sandy matrix of the Exmore beds and in reworked crystalline-rock clasts in and just below the Exmore in the Langley core. Some crystalline-rock clasts are interpreted to be derived from ejecta because they contain shocked quartz and associated cataclastic fabrics. In the Langley core, nearly all of these clasts consist of variably porphyritic felsite. The contrast between relatively uniform crystalline-ejecta compositions at this site and more varied compositions at the Bayside and North sites suggests that the ejecta were distributed unevenly, perhaps in rays (Horton and Izett, this volume, chap. E). The impact event provided a remarkable sampling tool by excavating an enormous volume of target rock, including little-known basement terranes (Horton and others, 1991; Rankin, 1994; Sheridan and others, 1999), and scattering fragments where they can be retrieved at shallower levels.

Resurge deposits of the Exmore beds apparently were injected and mixed into variably liquefied, slumped sediments in the upper part of crater unit B, where Horton and Izett (this volume, chap. E) found shocked quartz in a single clast of felsic impact breccia (at 275.8 m (905.0 ft) depth), and where Frederiksen and others (this volume, chap. D) reported the only two matrix samples from crater unit B found to contain Tertiary microfossils. These include one dinocyst sample (at 278.4 m (913.4 ft) depth) and one calcareous nannofossil sample (at 298.5 m (979.3 ft) depth) that contain specimens of mixed Paleocene and Eocene ages (Frederiksen and others, this volume, chap. D), although the nannofossil sample is from the top of a drilling run and could be contaminated (Gohn and others, this volume, chap. C). However, zones containing glauconite of marine origin, presumably of Late Cretaceous and Tertiary age, occur at irregular intervals throughout crater unit B in the matrix

between blocks derived from the older Cretaceous Potomac Formation.

Postimpact Sediments

Three chapters decipher the depositional environments, physical stratigraphy, and paleontology of postimpact sediments in the Langley core. In chapter F, Poag and Norris use stable-isotope, foraminifera, and bolboformid analyses of cores from several sites inside the crater (including the USGS-NASA Langley, Bayside, and North cores) and a variety of geophysical data to interpret the regional record of early postimpact deposition and paleoenvironments of the upper Eocene Chickahominy Formation. They also propose that the uppermost and latest syn-impact fallout deposit is contained in a thin, pyrite-bearing layer overlain by a thin postimpact “dead zone” as illustrated in figure A6. The oxygen and carbon isotopic data characterize three warm pulses that occurred during the deposition of the Chickahominy Formation. They interpret this climate history as possible evidence for the Chesapeake Bay impact and other late Eocene impacts collectively exerting long-term influence on global climate that led to the early Oligocene mass extinction event.

In chapter G, Powars and others use borehole geophysical logs to correlate lithostratigraphy of the Langley core with the land-based, high-resolution seismic-reflection data. They apply the correlated lithologic and geophysical data to characterize the physical stratigraphy of the postimpact, upper Eocene to Quaternary sedimentary section of the Langley core. Their correlation with the seismic data indicates that the postimpact units have distinct seismic signatures and that they are faulted. Significantly, most of the postimpact deposits are fine-grained sediments that slowly filled and buried the crater and therefore preserved several upper Eocene to lower Miocene stratigraphic units not found in the Virginia Coastal Plain outside the structure. A newly recognized Oligocene stratigraphic unit, the Drummonds Corner beds (informal name) (fig. A5), is described in chapter G by Powars and others.

In chapter H, Edwards and others present the paleontology of the postimpact upper Eocene to Quaternary stratigraphic section in the Langley core and include data on dinoflagellates, diatoms, mollusks, silicoflagellates, calcareous nannofossils, ostracodes, foraminifera and bolboformids, and vertebrate remains. They characterize the depositional and paleoenvironmental record of the postimpact sediments and discuss sediment accumulation rates, the paleontology of the newly recognized Drummonds Corner beds (informal name), and the reworking of impact-damaged microfossils into postimpact units. Variations in the rate of sediment accumulation indicate at least two episodes of rapid filling at about 20 meters per million years (~20 m/m.y.; ~66 ft/m.y.) during the late Eocene and late Miocene and several unconformities during the early and middle Miocene at this site.

Water Depths—Impact and Postimpact

The impact target was located on a gently sloping continental shelf where water depths increased seaward. Interpreted water depths for the western outer margin of the crater and estimated seabed gradients are used to project water depths at the eastern outer margin.

Target-water depth at the western outer margin of the crater.—At the crater's western outer margin near Newport News, Va. (fig. A1, locality NN), the estimated late Eocene water depth of the target is between minimum and maximum limits of about 0 and 170 m (0 and 560 ft). This depth range is interpreted on the basis of data from three coreholes: one updip of the crater at Putneys Mill, Va. (P in fig. A1), one updip at Haynesville, Va. (H in fig. A1), and one north of the crater at Solomons Island, Md. (north of the area shown in fig. A1). Benthic and planktonic foraminifera from the uppermost preimpact unit, the Piney Point Formation, in these cores indicate middle Eocene paleodepths of about 20–150 m (about 60–490 ft) (Poag, 1989; Bybell and Gibson, 1994; Gibson and Bybell, 1994). Projections from these locations (because the Piney Point is not intact in the crater) along the paleoshelf slope indicate middle Eocene water depths of about 20–170 m (about 60–560 ft) at the western outer margin. Subtracting 0–50 m (0–164 ft) from the middle Eocene depths to account for eustatic sea-level decline (Haq and others, 1988; Kominz and others, 1998) indicates late Eocene target-water depths of about 0–170 m (about 0–560 ft) at the western outer margin.

Target-seabed gradient.—The target seabed probably had a gradient between minimum and maximum limits of about 1:1,000 and 1:500; this range of gradients is based on Tertiary and modern analogs. A continental shelf gradient of 1:1,000 is approximately equivalent to the landward part of Tertiary reconstructions (for example, by Pekar and others, 2001) and the modern shelf as measured from Emery and Uchupi (1972). A gradient of 1:500 is approximately equivalent to the steeper, seaward part of Tertiary reconstructions (for example, by Steckler and others, 1999; Pekar and others, 2001).

Projected water depths across impact target.—The seabed gradients are used here to project target-water depth limits from the western outer margin to the center and to the eastern outer margin of the 85-km-diameter (53-mi-diameter) impact target. Projection of water paleodepths of 0–170 m (0–560 ft) from the western outer margin along a 1:1,000 gradient across the target yields paleodepths of 42.5–212.5 m (139–697 ft) at the center and 85–255 m (279–837 ft) at the eastern outer margin, whereas projection along a 1:500 gradient yields paleodepths of 85–255 m (279–837 ft) at the center and 170–340 m (560–1,115 ft) at the eastern outer margin. The metric numbers are rounded in 10-m increments and summarized below.

On the basis of these projections, the estimated target-water depths are in the range of about 0–170 m (0–560 ft) (mean value 85 m, 280 ft) at the western outer margin, about 40–260

m (131–853 ft) (mean value 150 m, 492 ft) at the center, and about 80–340 m (263–1,115 ft) (mean value 210 m, 689 ft) at the eastern outer margin of the crater target. If the paleoshelf steepened abruptly at an undetermined clinoform rollover point between a landward gradient approaching 1:1,000 and a seaward gradient approaching 1:500 as in some Tertiary reconstructions (Steckler and others, 1999; Pekar and others, 2001), the water depths would be within these limits.

Water depth after impact.—The postimpact Chickahominy Formation was deposited in a circular depression over the crater as illustrated on the isopach map in chapter F (Poag and Norris, this volume, chap. F, fig. F11), and so the water paleodepth probably exceeded that of the preimpact target seabed. Benthic and planktonic foraminiferal assemblages in the Chickahominy indicate a seabed paleodepth of about 300 m (984 ft), which is the outer neritic to upper bathyal environment (150–500 m (500–1,600 ft) depth) with restricted oxygen availability and high flux of organic carbon (Poag and Norris, this volume, chap. F). Ostracodes also indicate that the Chickahominy Formation was mainly outer neritic to upper bathyal (Edwards and others, this volume, chap. H).

Dating the Impact Event

Chapters D, F, and H on paleontology of the Langley core agree that the age of the late Eocene Chesapeake Bay impact event is approximately 35.7 to 35.8 Ma (million years before the present). However, in chapter E, Horton and Izett present a weighted mean total fusion $^{40}\text{Ar}/^{39}\text{Ar}$ age of 35.3 Ma (± 0.1 Ma at 1σ , ± 0.2 Ma at 2σ) for 19 analyses of 4 North American tektites, and they interpret this as the age of the impact event.

Frederiksen and others (this volume, chap. D) determined from calcareous nannofossils that the Exmore beds belong to Zone NP 19/20 and that the impact occurred during the early part of the time represented by that zone at approximately 35.7–35.8 Ma. Poag and Norris (this volume, chap. F) give an extrapolated age of impact of about 35.78 Ma in their figures F6 and F26, while recognizing a range of uncertainty from 35.2 to 36.0 as shown in gray in their figure F3.

Edwards and others, in chapter H, independently calculated limits on sediment accumulation rates in the postimpact Chickahominy Formation based on zone boundaries and the Eocene-Oligocene boundary from the time scale of Berggren and others (1995); they note that Poag and Norris (this volume, chap. F) arrived at nearly identical rates by using slightly different assumptions. Then, as shown in figure H10, Edwards and others projected the base of the Chickahominy Formation in the Langley core into the time scale of Berggren and others (1995), using these zone boundaries and sediment accumulation rates to yield a value of 35.7–35.8 Ma for the age of impact. They note that this value is ultimately based on the geomagnetic reversal time scale of Cande and Kent (1995), which is calibrated to iso-

topic ages of 33.7 ± 0.4 and 46.8 ± 0.5 Ma; the calibration uses a cubic spline fit that does not take the age uncertainties into account (M.J. Kunk, USGS, written commun., 2003).

For ages determined by different methods and having various accuracies, the age of impact of 35.7–35.8 Ma based on microfossil zones calibrated to Berggren and others' (1995) time scale is not significantly different from the 35.3 ± 0.2 Ma (2σ) age of tektites reported in chapter E by Horton and Izett.

Structural Interpretation of Seismic Data

The first parts of the crater to be subjected to more intensive study in the current phase of deep coring and high-resolution seismic-reflection surveying are the outer annular trough and its outer margin. In 2001, the USGS completed a 9-km-long (5.6-mi-long) high-resolution, land-based seismic-reflection and seismic-refraction survey (common-depth-point interval 2.5 m (8.2 ft)) on the York-James Peninsula (Catchings, Powars, and others, 2001; Catchings, Saulter, and others, 2001; Catchings and others, 2002). This seismic survey is linked to the adjacent Langley and Watkins School coreholes shown in figure A2 by borehole geophysical logs. The USGS investigators completed a similar 9-km-long (5.6-mi-long), high-resolution seismic survey along the Middle Peninsula (also crossing the outer annular trough and outer margin) in 2002 and obtained 4.6 km (2.9 mi) of data on the southern Delmarva Peninsula across the inner rim and central part of the crater (fig. A2). The data processing and interpretation of these profiles are still in progress.

In chapter I, Catchings and others (this volume) correlate a 1-km-long (0.62-mi-long) high-resolution seismic-reflection and seismic-refraction profile with lithologic and geophysical logs from the adjacent Langley corehole to decipher subsurface stratigraphic and structural details in the western annular trough. A stratabound, extensional collapse structure in that part of the impact-disturbed sedimentary section is generally confined to crater units A and B, with only a few minor offsets in the top of the Langley Granite, as shown by Catchings and others (this volume, chap. I). The abundance of faults in this interval increases upward, suggesting that extension increased in proportion to the decrease in overburden confining pressure. The top of the stratabound extensional fault system appears to be truncated at the base of the Exmore beds, except for a few faults that may be younger or reactivated, implying that formation of the extensional collapse structure largely preceded deposition of the water-resurge debris flows. More structural analysis of the faults is needed to determine if they formed by vertical extension due to rebound or lateral extension associated with inward slumping of sediments in the annular trough.

The high-resolution seismic data also provide guidance for interpreting the lower resolution marine seismic data, enabling the recognition of numerous collapse structures across the west-

ern annular trough (Powars and others, 2003). Most of these structures disrupt parautochthonous Cretaceous sediments, ocean-water resurge sediments, and postimpact sediments, thereby suggesting detachment zones within the sedimentary section. Many extensional collapse structures are formed by abundant short-displacement faults rather than a few normal faults of large displacement.

The marine seismic data and preliminary interpretation of the high-resolution land-based seismic data can be used to distinguish the discontinuous, locally inclined or offset reflectors interpreted to be slumped fault blocks from overlying resurge deposits of the Exmore beds; these data can also be used to distinguish the more continuous horizontal reflectors that represent little-disturbed Cretaceous sediments outside the crater (Powars and others, 2003). These sediments appear to be faulted to a much lesser degree than the slump blocks. Inward-dipping normal faults and antithetic faults define the typically rotated slump blocks. A few major normal faults displace the sediment-crystalline rock contact, indicating that they are relatively deep seated.

Resurge-tsunami and overlying postimpact sediments buried the irregular upper surface of the slump blocks. Observed thickness variations, dip reversals, and fault displacements of these sediments probably result from differential compaction across the underlying irregular surface. The impact-generated resurge deposits are up to 100 m (330 ft) thick in the annular trough but abruptly thin to 7.5 m (24.6 ft) just outside the outer margin in the Watkins School corehole (Powars and others, 2003).

Interpretation of Audio-Magnetotelluric (AMT) Soundings

Pierce (this volume, chap. J) discusses 18 tensor audio-magnetotelluric soundings that were collected in 2000 and 2001 to provide cross-section images of the electrical-response variations in traverses across the western outer margin of the crater (fig. A2). These soundings use the electromagnetic signals from distant lightning or atmospheric disturbances to determine variations in electrical resistivity of the earth as a function of depth (Vozoff, 1991). The orthogonal magnetic and electrical fields are measured to determine impedance tensors that account for anisotropy. Chapter J explains how resistivities were calculated from these impedances and used to construct two cross sections that show electrical-response variations in the structure as a function of depth on the York-James Peninsula and on the Middle Peninsula.

The audio-magnetotelluric soundings and resultant electrical cross sections of the York-James Peninsula and Middle Peninsula in Pierce's chapter J show a nearly vertical zone of high resistivity at the outer margin of the annular trough, which can be used to map the structure. The high resistivity may be caused

by fresh ground water discharging from the Lower Cretaceous sediments at the outer margin, by cementation along the fault zone, or by compaction of the sediments as a result of the impact event. Impedance trends to the northwest on the York-James Peninsula and to the northeast on the Middle Peninsula match the curvature of the structure. The electrical cross sections also image the lateral contact between conductive sediments and resistive basement, which is close to the technique's depth limit of resolution.

Hydrologic Effects and Water-Resources Implications

The Chesapeake Bay impact crater coincides approximately with Virginia's inland saltwater wedge in which saline ground water extends about 50 km (30 mi) landward of its normally expected position along the coast of southeastern Virginia. Powars and others (this volume, chap. G) describe it as a bulge rather than a wedge, because the saline ground water extends into shallower depths than in the region surrounding the crater. McFarland and Bruce (2002; this volume, chap. K) studied chemical analyses of water squeezed from sediment cores and pumped out of water wells in order to understand the relations between crater structure and ground-water salinity. These analyses included chloride, bromide, and chlorine-36, as well as stable hydrogen and oxygen isotopes and specific conductance.

In chapter K, McFarland and Bruce present chemical and isotopic analyses of ground-water samples from the USGS-NASA Langley, Bayside, and North cores and from water wells on the western margin of the impact structure. These analyses indicate that the high ground-water salinities of the Virginia inland saltwater wedge, or bulge, were more likely produced by mixing of freshwater and seawater than by other possible mechanisms. Vertical profiles of specific conductance and chloride concentrations indicate a zone of mixing along the western margin of the structure. These profiles also support the concept that the crater structure has caused differential flushing of residual seawater, older than 2 Ma and possibly as old as 35 Ma, to create the saltwater bulge.

Some chloride concentrations in ground water from the interior part of the crater (Kiptopeke well) exceed those of modern seawater. Stable hydrogen and oxygen isotopic ratios indicate that these brines probably were produced by evaporation (McFarland and Bruce, this volume, chap. K). Sanford (2002, 2003) has demonstrated that brine production from the escape of steam caused by the heat of the impact is at least theoretically possible. Future discovery of hydrothermal mineralization along pathways for escaping steam would favor this interpretation, whereas discovery of ground-water brines beneath the Atlantic Coastal Plain outside the crater would favor alternative explanations.

Ground water is expected during the next several decades to provide much of the required increase in water supply for southeastern Virginia, one of the most rapidly growing areas on the Atlantic Coast. The potential influence of the Chesapeake Bay impact crater on the future of this region's ground-water resource is profound.

Conceptual Model

A conceptual model of the Chesapeake Bay crater formation in stages, illustrated in figure A7, is derived from a synthesis of the chapters in this volume and concepts of the cratering process as summarized by French (1998). The preimpact target on the Atlantic continental shelf consisted of three main components as illustrated in figure A7A: (1) crystalline basement rocks deepening eastward; (2) poorly consolidated, water-saturated siliciclastic sediments, including nonmarine Upper Cretaceous and Lower Cretaceous beds and a veneer of marine Upper Cretaceous and Paleocene to upper Eocene beds; and (3) ocean water ranging in depth from about 0–170 m (0–560 ft) on the west side to about 80–340 m (263–1,115 ft) on the east side. Contact of the projectile produced shock waves in the target and projectile, vaporizing the projectile and causing vaporization, melting, and shock deformation in the target.

Figure A7B illustrates the crater excavation stage in which shock-wave expansion into the target forced material outward, upward (ejecting high-velocity particles), and downward to form a bowl-shaped *transient cavity* or *transient crater*. The shock wave also caused shock deformation and associated faults and fractures, melts lining the transient cavity, outward excavation flow of material forming an ejecta curtain, and an uplifted rim.

The transient *water cavity* is interpreted to have had about the same diameter as the transient cavity in underlying rocks and sediments on the basis of numerical simulations of marine-target craters (Ormö and others, 2002; Shuvalov and others, 2002). The numerical models indicate that the growing crater rim and ejecta curtain pushed the water aside to form a water surge, which eventually broke up and initiated tsunamis.

As soon as the transient cavity ceased to expand, crater modification by gravity-driven processes occurred as illustrated in figure A7C. Rebound and collapse of the central crater and central uplift were accompanied by inward slumping of water-saturated sediments within the annular trough beyond the central crater and by the resurgence of seawater and submarine debris flows into the cavity as documented in other marine craters (von Dalwigk and Ormö, 2001). The collapse structures are illustrated by images of seismic profiles in chapters F and I, and the impact-modified and impact-generated sediments are described and illustrated in chapters C, D, and E. The high-energy resurgence debris flows were followed by settling of fallout particles and

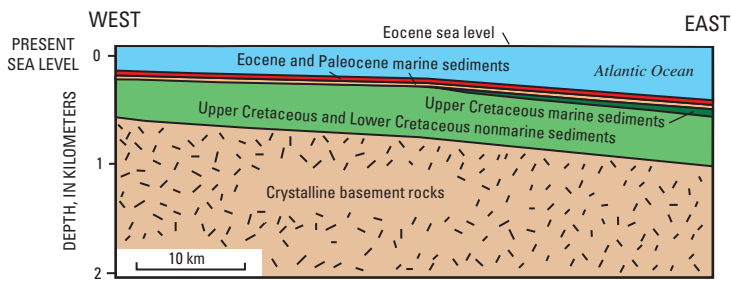
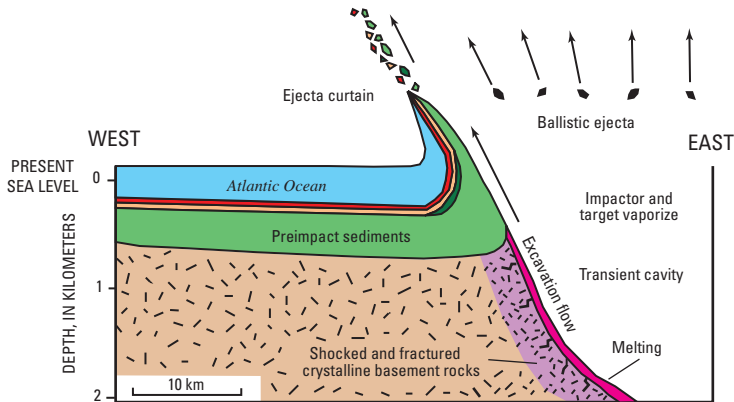
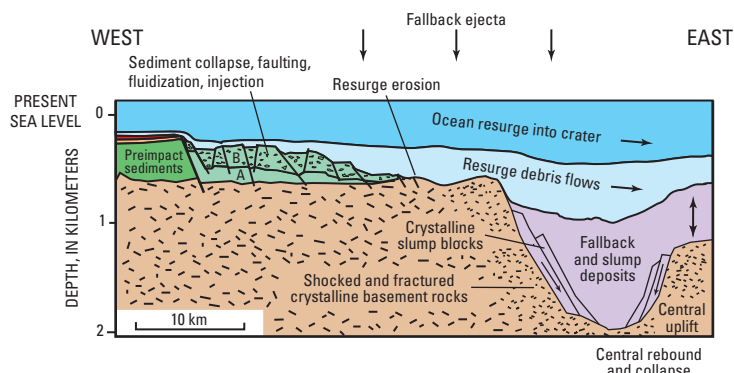
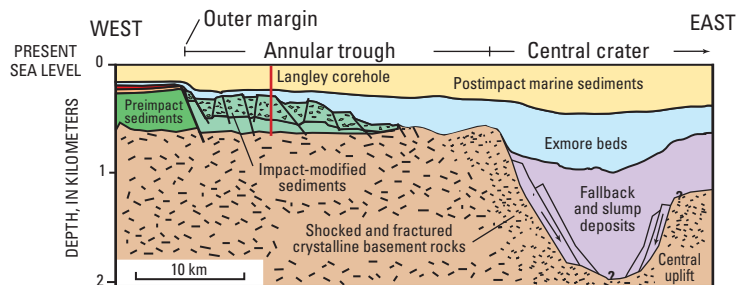
A. Preimpact target**B. Contact compression followed by excavation****C. Crater modification (collapse, slump blocks, and water resurge)****D. Postimpact burial**

Figure A7. Schematic cross sections illustrating stages in a conceptual model of Chesapeake Bay crater formation. Diagrams show western half of crater along west-to-east profile as located approximately in figure A1. Modified from Edwards and Powars (2003). **A, Preimpact target:** Before the projectile hit, the ocean site consisted of three main layers: crystalline basement rocks (deepening eastward), siliciclastic sediments (thickening eastward), and ocean water deepening eastward from about 0–170 m (0–560 ft) to about 80–340 m (263–1,115 ft).

B, Contact compression followed by excavation: Contact of the projectile produced shock waves, vaporizing the projectile and causing vaporization, melting, and shock metamorphism in the target. Expansion of the shock wave excavated a bowl-shaped transient cavity in the target, producing shock metamorphism, melts, ejecta, and an ejecta curtain (drawn approximately as modeled to occur in about 30 seconds; Crawford, 2002).

C, Crater modification (collapse, slump blocks, and water resurge): Collapse of the transient cavity was accompanied by inward collapse of slump blocks in poorly consolidated sediments of the annular trough (for example, to form crater units A and B; see A and B in diagram). The collapse expanded the crater beyond the central excavation to a total width of about 85 km (53 mi). A violent resurge of ocean water and submarine debris flows filled the open cavity with water and debris.

D, Postimpact burial: After the resurge currents deposited the Exmore beds, the crater was buried by marine sediments. The USGS-NASA Langley corehole is projected onto the section line.

other material suspended in the water column, which led to a resumption of normal marine sedimentation. Figure A7D illustrates subsequent burial of the crater by postimpact sedimentation as documented in chapters F, G, and H.

The studies in this volume are consistent with a model for internal structure of the sedimentary section of the annular trough of the Chesapeake Bay impact crater as consisting of slumped, normal-fault-bounded megablocks overlain by water-resurge debris flows (Exmore beds). This model likely remains accurate for the large slump blocks at the outer margin. The shallow collapse structures are similar to shallow extensional features recently observed in the Silverpit crater of the North Sea (Stewart and Allen, 2002).

Acknowledgments

This Professional Paper is a contribution to the Chesapeake Bay Impact Crater Project. Investigations of the Chesapeake Bay impact structure under this project are conducted by the U.S. Geological Survey (USGS) in cooperation with the Hampton Roads Planning District Commission, the Virginia Department of Environmental Quality, and the National Aeronautics and Space Administration (NASA) Langley Research Center. The Hampton Roads Planning District Commission and the USGS provided funds for the drilling of the USGS-NASA Langley corehole. The NASA Langley Research Center provided extensive operational and logistical support for the drilling operation. The Virginia Department of Environmental Quality and the Department of Geology of the College of William and Mary provided extensive operational support at the drill site.

We wish to acknowledge USGS organizational units of both the Geology Discipline and the Water Resources Discipline for their contributions to the project. Those from the Geology Discipline include the Eastern Earth Surface Processes Team (geology, paleontology, drilling, project management), the Eastern Mineral Resources Team (audio-magnetotelluric electrical sounding), the Central Mineral Resources Team (uranium-lead geochronology), the Crustal Imaging and Characterization Team (argon geochronology), the Coastal and Marine Geology Team (geology, paleontology), the Western Earthquake Hazards Team (seismic reflection and refraction surveys), and the Astrogeology Research Program (geophysics). Participants from the USGS Water Resources Discipline include the Virginia District (hydrology, project management), the Maryland District (geophysical logging), the Rocky Mountain Drilling Unit (core drilling), and the Central Regional Research Branch (geophysical logging). The principal USGS funding sources are the National Cooperative Geologic Mapping Program, the Coastal and Marine Geology Program, and the Cooperative Water Program.

Reviewers (all USGS) for chapters in this volume include Robert A. Ayuso, Thomas M. Brocher, Harry J. Dowsett, Joseph S. Duval, Lucy E. Edwards, Norman O. Frederiksen, Jeffrey N. Grossman, Michael J. Kunk, James E. Landmeyer, E. Randolph McFarland, Daniel J. Milton, Charles W. Naeser, Wayne L. Newell, Douglas J. Nichols, C. Wylie Poag, Douglas W. Rankin, Nicholas M. Ratcliffe, Ward E. Sanford, J. Stephen Schindler, Jean M. Self-Trail, Joseph P. Smoot, C. Scott Southworth, and Jeffrey C. Wynn. These individuals contributed significantly to the scientific quality of the book. We thank Lucy E. Edwards, E. Randolph McFarland, and Charles W. Naeser for reviewing earlier drafts of this chapter, and we are particularly grateful to Edwards for encouragement and assistance on the estimates of target-water depth. We thank Theodore B. Samsel, R. Brent Banks, Anita M. Cotton, and Peter G. Chirico (all USGS) for help with the computer graphics in this chapter and other chapters in the volume.

References Cited

- Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995, A revised Cenozoic geochronology and chronostratigraphy, *in* Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, Jan, eds., *Geochronology, time scales and global stratigraphic correlation: SEPM (Society for Sedimentary Geology) Special Publication 54*, p. 129–212.
- Bohor, B.F., Betterton, W.J., and Foord, E.E., 1988, Coesite, glass, and shocked quartz at DSDP Site 612; Evidence for nearby impact in the late Eocene [abs.]: *Lunar and Planetary Science Conference*, 19th, Houston, Tex., March 14–18, 1988, Abstracts, p. 114–115.
- Brown, P.M., Miller, J.A., and Swain, F.M., 1972, Structural and stratigraphic framework and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U.S. Geological Survey Professional Paper 796, 79 p.
- Bybell, L.M., and Gibson, T.G., 1994, Paleogene stratigraphy of the Putneys Mill, New Kent County, Virginia, corehole: U.S. Geological Survey Open-File Report 94–217, 38 p.
- Cande, S.C., and Kent, D.V., 1995, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic: *Journal of Geophysical Research*, v. B100, no. 4, p. 6093–6095.
- Catchings, R.D., Powars, D.S., Gohn, G.S., and Goldman, M.R., 2002, High-resolution seismic reflection survey of the southwestern margin of the Chesapeake Bay impact structure, Virginia [abs.]: *Eos, Transactions, American Geophysical Union*, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A–05, p. S352. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- Catchings, R.D., Powars, D.S., Gohn, G.S., Goldman, M.R., Gandhok, G., and Johnson, G.H., 2001, Subsurface images of

- the annular trough of the Chesapeake Bay impact structure, Virginia, from seismic reflection/refraction data [abs.]: Lunar and Planetary Science Conference, 32d, Houston, Tex., March 12–16, 2001, Abstract 1937, available online at <http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1937.pdf>
- Catchings, R.D., Saulter, D.E., Powars, D.S., Goldman, M.R., Dingler, J.A., Gohn, G.S., Schindler, J.S., and Johnson, G.H., 2001, High-resolution seismic reflection/refraction images near the outer margin of the Chesapeake Bay impact crater, York-James Peninsula, southeastern Virginia: U.S. Geological Survey Open-File Report 01–407, 18 p., available only online at <http://geopubs.wr.usgs.gov/open-file/of01-407/>
- Cederstrom, D.J., 1943, Chloride in ground water in the coastal plain of Virginia: Virginia Geological Survey Bulletin 58, 36 p.
- Cederstrom, D.J., 1945a, Geology and ground-water resources of the coastal plain in southeastern Virginia: Virginia Geological Survey Bulletin 63, 384 p.
- Cederstrom, D.J., 1945b, Selected well logs in the Virginia Coastal Plain north of James River: Virginia Geological Survey Circular 3, 81 p.
- Cederstrom, D.J., 1945c, Structural geology of southeastern Virginia: American Association of Petroleum Geologists Bulletin, v. 29, no. 1, p. 71–95.
- Cederstrom, D.J., 1946, Chemical character of ground water in the coastal plain of Virginia: Virginia Geological Survey Bulletin 68, 62 p.
- Cederstrom, D.J., 1957, Geology and ground-water resources of the York-James Peninsula, Virginia: U.S. Geological Survey Water-Supply Paper 1361, 237 p.
- Coch, N.K., 1971, Geology of the Newport News South and Bowers Hill quadrangles, Virginia: Virginia Division of Mineral Resources Report of Investigations 28, 26 p., 2 over-size maps.
- Crawford, D.A., 2002, A computational model of the Chesapeake Bay impact [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 465.
- Daniels, D.L., and Leo, G.W., 1985, Geologic interpretation of basement rocks of the Atlantic Coastal Plain: U.S. Geological Survey Open-File Report 85–655, 45 p., 4 over-size pls.
- Earth Impact Database, 2003 [a resource maintained by the Planetary and Space Science Centre at the University of New Brunswick, Canada]: available online at <http://www.unb.ca/passc/ImpactDatabase/> (Accessed June 2, 2003.)
- Edwards, L.E., Frederiksen, N.O., Self-Trail, J.M., and Poag, C.W., 2002, Paleontology of crater-fill deposits, Chesapeake Bay impact structure, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 465–466.
- Edwards, L.E., and Powars, D.S., 2003, Impact damage to dinocysts from the late Eocene Chesapeake Bay event: *Palaios*, v. 18, no. 3, p. 275–285. (Also available online at <http://www.bioone.org/pdfserv/i0883-1351-018-03-0275.pdf>)
- Edwards, L.E., and Self-Trail, J.M., 2002, Shocking news—Impact effects on marine microfossils, Chesapeake Bay impact structure, Virginia [abs.]: Eos, Transactions, American Geophysical Union, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A–04, p. S351. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- Emery, K.O., and Uchupi, Elazar, 1972, Western North Atlantic Ocean; Topography, rocks, structure, water, life, and sediments: American Association of Petroleum Geologists Memoir 17, 532 p.
- Emry, Scott, McFarland, E.R., and Powars, D.S., 2002, Societal implications of an impact crater—Chesapeake Bay impact structure, Virginia [abs.]: Eos, Transactions, American Geophysical Union, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A–01, p. S351. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- French, B.M., 1998, Traces of catastrophe; A handbook of shock-metamorphic effects in terrestrial meteorite impact structures: Houston, Tex., Lunar and Planetary Institute, LPI Contribution No. 954, 120 p.
- Gibson, T.G., and Bybell, L.M., 1994, Paleogene stratigraphy of the Solomons Island, Maryland corehole: U.S. Geological Survey Open-File Report 94–708, 39 p.
- Glass, B.P., 1989, North American tektite debris and impact ejecta from DSDP Site 612: *Meteoritics*, v. 24, no. 4, p. 209–218.
- Glass, B.P., 2002, Distal impact ejecta from the Chesapeake Bay impact structure [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 466.
- Glover, Lynn, III, and Klitgord, K.D., chief compilers, 1995, Continent-ocean transect E–3, southwestern Pennsylvania to Baltimore Canyon trough: Boulder, Colo., Geological Society of America, 78-p. pamphlet, 2 sheets, scale about 1:625,000.
- Gohn, G.S., Bruce, T.S., Catchings, R.D., Emry, S.R., Johnson, G.H., Levine, J.S., McFarland, E.R., Poag, C.W., and Powars, D.S., 2001, Integrated geologic, hydrologic, and geophysical investigations of the Chesapeake Bay impact structure, Virginia, USA; A multi-agency program [abs.]: Lunar and Planetary Science Conference, 32d, Houston, Tex., March 12–16, 2001, Abstract 1901, available online at <http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1901.pdf>
- Gohn, G.S., Clark, A.C., Queen, D.G., Levine, J.S., McFarland, E.R., and Powars, D.S., 2001, Operational summary for the USGS-NASA Langley corehole, Hampton, Virginia: U.S. Geological Survey Open-File Report 01–87–A, 21 p., available online at <http://pubs.usgs.gov/of/2001/of01-087/>
- Gohn, G.S., Powars, D.S., Bruce, T.S., Quick, J.E., and Catchings, R.D., 2002, Geologic constraints on modeling of complex-crater collapse; Data from the Chesapeake Bay impact structure, Virginia [abs.]: Eos, Transactions, American Geophysical Union, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A–07, p. S352. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- Gohn, G.S., Powars, D.S., Bruce, T.S., Self-Trail, J.M., Weems, R.E., Edwards, L.E., Horton, J.W., Jr., Izett, G.A., and Johnson, G.H., 2001, Preliminary interpretation of the USGS-NASA Langley corehole, Chesapeake Bay impact

- structure, York-James Peninsula, Hampton, VA [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 2, p. A-24.
- Gohn, G.S., Powars, D.S., Quick, J.E., Horton, J.W., Jr., and Catchings, R.D., 2002, Variation of impact response with depth and lithology, outer annular trough of the Chesapeake Bay impact structure, Virginia Coastal Plain [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 465.
- Hampton Roads Planning District Commission, 1999, 35 million year-old meteor crater affects the region's ground water: Chesapeake, Va., Hampton Roads Planning District Commission, Environmental Planning Special Report, Issue 2, October 1999, p. 2-5. (Also available online at <http://www.hrpdc.org/publications/specialreports/groundwater.pdf>)
- Haq, B.U., Hardenbol, Jan, and Vail, P.R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, in Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H.W., Van Wagoner, John, and Kendall, C.G.St.C., eds., Sea-level changes—An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 71-108.
- Horton, J.W., Jr., Aleinikoff, J.N., Izett, G.A., Naeser, C.W., and Naeser, N.D., 2001, Crystalline rocks from the first corehole to basement in the Chesapeake Bay impact structure, Hampton, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A-448.
- Horton, J.W., Jr., Aleinikoff, J.N., Izett, G.A., Naeser, N.D., Naeser, C.W., and Kunk, M.J., 2002, Crystalline basement and impact-derived clasts from three coreholes in the Chesapeake Bay impact structure, southeastern Virginia [abs.]: Eos, Transactions, American Geophysical Union, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A-03, p. S351. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- Horton, J.W., Jr., Drake, A.A., Jr., Rankin, D.W., and Dallmeyer, R.D., 1991, Preliminary tectonostratigraphic terrane map of the central and southern Appalachians: U.S. Geological Survey Miscellaneous Investigations Series Map I-2163, scale 1:2,000,000.
- Horton, J.W., Jr., Gohn, G.S., Edwards, L.E., Self-Trail, J.M., Powars, D.S., Kunk, M.J., and Izett, G.A., 2003, Recent research in the Chesapeake Bay impact crater, USA—Part 2. Reworked ejecta and impact debris [abs.]: International Conference on Large Meteorite Impacts, 3d, Noerdlingen, Germany, August 5-7, 2003, Abstract 4051, available online at <http://www.lpi.usra.edu/meetings/largeimpacts2003/pdf/4051.pdf>
- Horton, J.W., Jr., Kunk, M.J., Naeser, C.W., Naeser, N.D., Aleinikoff, J.N., and Izett, G.A., 2002, Petrography, geochronology, and significance of crystalline basement rocks and impact-derived clasts in the Chesapeake Bay impact structure, southeastern Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 466.
- Johnson, G.H., 1969, Guidebook to the geology of the lower York-James Peninsula and south bank of the James River: Williamsburg, Va., College of William and Mary, Department of Geology Guidebook 1, 33 p.
- Johnson, G.H., Kruse, S.E., Vaughn, A.W., Lucey, J.K., Hobbs, C.H., III, and Powars, D.S., 1998, Postimpact deformation associated with the late Eocene Chesapeake Bay impact structure in southeastern Virginia: Geology, v. 26, no. 6, p. 507-510.
- Johnson, G.H., Powars, D.S., and Bruce, T.S., 2000, Stratigraphic and geohydrologic anomalies around the Chesapeake Bay impact structure, eastern Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 32, no. 2, p. A-28.
- Johnson, G.H., Powars, D.S., Bruce, T.S., Beach, T.A., Harris, M.S., and Goodwin, B.K., 2001, Post-impact effects of the Eocene Chesapeake Bay impact, lower York-James Peninsula, Virginia: Virginia Geological Field Conference, 31st, Williamsburg, Virginia, October 19 and 20, 2001 [Guidebook], 40 p.
- Johnson, G.H., Ward, L.W., and Peebles, P.C., 1987, Stratigraphy and paleontology of Pliocene and Pleistocene deposits of southeastern Virginia, in Whittecar, G.R., ed., Geological excursions in Virginia and North Carolina—Geological Society of America, Southeastern Section, 36th Annual Meeting, 1987, Guidebook, Field Trips nos. 1-7: Norfolk, Va., Old Dominion University, Department of Geological Sciences, p. 189-218.
- Klitgord, K.D., Hutchinson, D.R., and Schouten, Hans, 1988, U.S. Atlantic continental margin; Structural and tectonic framework, in Sheridan, R.E., and Grow, J.A., eds., The Atlantic continental margin, U.S., v. 1-2 of The geology of North America: Boulder, Colo., Geological Society of America, p. 19-56.
- Koeberl, Christian, Kruger, F.J., and Poag, C.W., 2001, Geochemistry of surficial sediments near the Chesapeake Bay impact structure and the search for source rocks of the North American tektites [abs.]: Lunar and Planetary Science Conference, 32d, Houston, Tex., March 12-16, 2001, Abstract 1333, available online at <http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1333.pdf>
- Koeberl, Christian, Poag, C.W., Reimold, W.U., and Brandt, Dion, 1996, Impact origin of the Chesapeake Bay structure and the source of the North American tektites: Science, v. 271, no. 5253, p. 1263-1266.
- Kominz, M.A., Miller, K.G., and Browning, J.V., 1998, Long-term and short-term global Cenozoic sea-level estimates: Geology, v. 26, no. 4, p. 311-314.
- Lacznia, R.J., and Meng, A.A., III, 1988, Ground-water resources of the York-James Peninsula of Virginia: U.S. Geological Survey Water-Resources Investigations Report 88-4059, 178 p.
- Lefort, J.-P., and Max, M.D., 1991, Is there an Archean crust beneath Chesapeake Bay?: Tectonics, v. 10, no. 1, p. 213-226.

- McFarland, E.R., 2002, Hydrochemical evidence for the origin of the elevated ground-water salinity in the Chesapeake Bay impact structure, southeastern Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 466.
- McFarland, E.R., and Bruce, Scott, 2002, Distribution, origin, and relations to flow of salty ground water along the western margin of the Chesapeake Bay impact structure in eastern Virginia [abs.]: Eos, Transactions, American Geophysical Union, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A-08, p. S352. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- Melosh, H.J., 1989, Impact cratering—A geologic process: New York, Oxford University Press, 245 p.
- Meng, A.A., III, and Harsh, J.F., 1988, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1404-C, p. C1-C82, 4 oversize pls.
- Mixon, R.B., Berquist, C.R., Newell, W.L., Johnson, G.H., Powars, D.S., Schindler, J.S., and Rader, E.K., 1989, Geologic map and generalized cross sections of the Coastal Plain and adjacent parts of the Piedmont, Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I-2033, 2 sheets, scale 1:250,000.
- Oaks, R.Q., Jr., and Coch, N.K., 1973, Post-Miocene stratigraphy and morphology, southeastern Virginia: Virginia Division of Mineral Resources Bulletin 82, 135 p.
- Obradovich, J.D., Snee, L.W., and Izett, G.A., 1989, Is there more than one glassy impact layer in the late Eocene? [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A134.
- Ormö, Jens, Shuvalov, V.V., and Lindström, Maurits, 2002, Numerical modeling for target water depth estimation of marine-target impact craters: Journal of Geophysical Research, v. 107, no. E12, 9 p. (5120). (Also available online at <http://www.agu.org/pubs/crossref/2002/2002JE001865.shtml>)
- Pekar, S.F., Christie-Blick, Nicholas, Kominz, M.A., and Miller, K.G., 2001, Evaluating the stratigraphic response to eustasy from Oligocene strata in New Jersey: Geology, v. 29, no. 1, p. 55-58.
- Poag, C.W., 1989, Foraminiferal stratigraphy and paleoenvironments of Cenozoic strata cored near Haynesville, Virginia, chap. D of Mixon, R.B., ed., Geology and paleontology of the Haynesville cores—Northeastern Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1489, p. D1-D20, 5 pls.
- Poag, C.W., 1996, Structural outer rim of Chesapeake Bay impact crater—Seismic and borehole evidence: Meteoritics & Planetary Science, v. 31, no. 2, p. 218-226.
- Poag, C.W., 1997, The Chesapeake Bay bolide impact; A convulsive event in Atlantic Coastal Plain evolution: Sedimentary Geology, v. 108, no. 1-4, p. 45-90.
- Poag, C.W., 1999, Chesapeake invader; Discovering America's giant meteorite crater: Princeton, N.J., Princeton University Press, 183 p.
- Poag, C.W., 2000, Nature and distribution of deposits derived from the Chesapeake Bay submarine impact [abs.]: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-163.
- Poag, C.W., 2002a, Biospheric consequences of the Chesapeake Bay bolide impact [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 467.
- Poag, C.W., 2002b, Structure and morphology of the Chesapeake Bay submarine impact crater [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 465.
- Poag, C.W., 2002c, Synimpact-postimpact transition inside Chesapeake Bay crater: Geology, v. 30, no. 11, p. 995-998.
- Poag, C.W., 2002d, Tsunamis and hypercanes; Late-stage impact depositional systems at Chesapeake Bay [abs.]: Eos, Transactions, American Geophysical Union, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A-06, p. S352. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- Poag, C.W., and Aubry, M.-P., 1995, Upper Eocene impactites of the U.S. East Coast; Depositional origins, biostratigraphic framework, and correlation: Palaios, v. 10, no. 1, p. 16-43.
- Poag, C.W., and the Chesapeake Coring Team, 2001, Drilling to basement inside the Chesapeake Bay crater [abs.]: Lunar and Planetary Science Conference, 32d, Houston, Tex., March 12-16, 2001, Abstract 1203, available online at <http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1203.pdf>
- Poag, C.W., Gohn, G.S., and Powars, D.S., 2001, From shocked basement to fallout spherules; The coring record at the Chesapeake Bay crater [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A-433.
- Poag, C.W., Gohn, G.S., and Powars, D.S., 2002, Chesapeake Bay impact crater; Seismostratigraphy and lithostratigraphy of displaced sedimentary megablocks [abs.]: Lunar and Planetary Science Conference, 33d, League City, Tex., March 11-15, 2002, Abstract 1019, available online at <http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1019.pdf>
- Poag, C.W., Hutchinson, D.R., Colman, S.M., and Lee, M.W., 1999, Seismic expression of the Chesapeake Bay impact crater; Structural and morphologic refinements based on new seismic data, in Dressler, B.O., and Sharpton, V.L., eds., Large meteorite impacts and planetary evolution; II: Geological Society of America Special Paper 339, p. 149-164.
- Poag, C.W., Koeberl, Christian, and Reimold, W.U., 2004, The Chesapeake Bay crater—Geology and geophysics of a late Eocene submarine impact structure: New York, Springer-Verlag, 522 p. plus CD-ROM.
- Poag, C.W., Plescia, J.B., and Molzer, P.C., 1999, Chesapeake Bay impact structure; Geology and geophysics [abs.], in Gersonde, Rainer, and Deutsch, Alexander, eds., Oceanic impacts; Mechanisms and environmental perturbations; ESF-IMPACT Workshop, April 15-April 17, 1999, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, Abstracts: Berichte zur Polarforschung (Reports on Polar Research), v. 343, p. 79-83.
- Poag, C.W., Plescia, J.B., and Molzer, P.C., 2002, Ancient impact structures on modern continental shelves; The Ches-

- peake Bay, Montagnais, and Toms Canyon craters, Atlantic margin of North America: Deep-Sea Research Part II—Topical Studies in Oceanography, v. 49, no. 6, p. 1081–1102.
- Poag, C.W., Powars, D.S., Mixon, R.B., Edwards, L.E., Folger, D.W., Poppe, L.J., and Bruce, Scott, 1991, An upper Eocene impact-wave(?) deposit beneath Chesapeake Bay [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A460.
- Poag, C.W., Powars, D.S., Poppe, L.J., and Mixon, R.B., 1994, Meteoroid mayhem in Ole Virginny—Source of the North American tektite strewn field: Geology, v. 22, no. 8, p. 691–694.
- Poag, C.W., Powars, D.S., Poppe, L.J., Mixon, R.B., Edwards, L.E., Folger, D.W., and Bruce, Scott, 1992, Deep Sea Drilling Project Site 612 bolide event—New evidence of a late Eocene impact-wave deposit and a possible impact site, U.S. East Coast: Geology, v. 20, no. 9, p. 771–774.
- Powars, D.S., 2000, The effects of the Chesapeake Bay impact crater on the geologic framework and the correlation of hydrogeologic units of southeastern Virginia, south of the James River: U.S. Geological Survey Professional Paper 1622, 53 p., 1 oversize pl. (Also available online at <http://pubs.usgs.gov/prof/p1622/>)
- Powars, D.S., and Bruce, T.S., 1999, The effects of the Chesapeake Bay impact crater on the geological framework and correlation of hydrogeologic units of the lower York-James Peninsula, Virginia: U.S. Geological Survey Professional Paper 1612, 82 p., 9 oversize pls. (Also available online at <http://pubs.usgs.gov/prof/p1612/>)
- Powars, D.S., Bruce, T.S., Bybell, L.M., Cronin, T.M., Edwards, L.E., Frederiksen, N.O., Gohn, G.S., Horton, J.W., Jr., Izett, G.A., Johnson, G.H., Levine, J.S., McFarland, E.R., Poag, C.W., Quick, J.E., Schindler, J.S., Self-Trail, J.M., Smith, M.J., Stamm, R.G., and Weems, R.E., 2001, Preliminary geologic summary for the USGS-NASA Langley corehole, Hampton, Virginia: U.S. Geological Survey Open-File Report 01–87–B, 20 p., available online at <http://pubs.usgs.gov/of/2001/of01-087/>
- Powars, D.S., Bruce, Scott, Poag, C.W., and Mixon, R.B., 1994, Virginia's coastal plain inland saltwater wedge; A geohydrologic response to the Chesapeake Bay bolide impact [abs.]: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A–410.
- Powars, D.S., Gohn, G.S., Bruce, T.S., Johnson, G.H., Catchings, R.D., Frederiksen, N.O., Edwards, L.E., Self-Trail, J.M., and Pierce, H.A., 2002, Distribution and origin of impact-generated debris; Western annular trough, Chesapeake Bay impact crater [abs.]: Eos, Transactions, American Geophysical Union, v. 83, no. 19, spring meeting supplement of 7 May 2002, Abstract T21A–02, p. S351. (Also available online at <http://www.agu.org/meetings/waissm02.html>)
- Powars, D.S., Gohn, G.S., Catchings, R.D., Horton, J.W., Jr., and Edwards, L.E., 2003, Recent research in the Chesapeake Bay impact crater, USA—Part 1. Structure of the western annular trough and interpretation of multiple collapse structures [abs.]: International Conference on Large Meteorite Impacts, 3d, Noerdlingen, Germany, August 5–7, 2003, Abstract 4053, available online at <http://www.lpi.usra.edu/meetings/largeimpacts2003/pdf/4053.pdf>
- Powars, D.S., Gohn, G.S., Catchings, R.D., McFarland, E.R., Bruce, T.S., Johnson, G.H., Izett, G.A., Emry, S.R., and Edwards, L.E., 2001, Deep corehole and seismic reflection data provide insights into crater-filling processes and the hydrogeology of the outer margin of the Chesapeake Bay impact structure, eastern Virginia Coastal Plain, USA [abs.]: Lunar and Planetary Science Conference, 32d, Houston, Tex., March 12–16, 2001, Abstract 2183, available online at <http://www.lpi.usra.edu/meetings/lpsc2001/pdf/2183.pdf>
- Powars, D.S., Gohn, G.S., Edwards, L.E., Bruce, T.S., Catchings, R.D., Emry, S.R., Johnson, G.H., Levine, J.S., Poag, C.W., and Pierce, H.A., 2001, Structure and composition of the southwestern margin of the buried Chesapeake Bay impact structure, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A–203.
- Powars, D.S., Gohn, G.S., Edwards, L.E., Catchings, R.D., Bruce, T.S., Johnson, G.H., and Poag, C.W., 2002, Lithostratigraphic framework of the crater-fill deposits; Western annular trough, Chesapeake bay impact crater [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 465.
- Powars, D.S., Johnson, G.H., Bruce, T.S., and Edwards, L.E., 2001, The relation between the Chesapeake Bay impact structure and the structure and stratigraphy of Cenozoic deposits in eastern Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 2, p. A–76.
- Powars, D.S., Johnson, G.H., Edwards, L.E., Horton, J.W., Jr., Gohn, G.S., Catchings, R.D., McFarland, E.R., Izett, G.A., Bruce, T.S., Levine, J.S., and Pierce, H.A., 2002, An expanded Chesapeake Bay impact structure, eastern Virginia; New corehole and geophysical data [abs.]: Lunar and Planetary Science Conference, 33d, League City, Tex., March 11–15, 2002, Abstract 1034, available online at <http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1034.pdf>
- Powars, D.S., Mixon, R.B., and Bruce, Scott, 1992, Uppermost Mesozoic and Cenozoic geologic cross section, outer coastal plain of Virginia, in Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey Workshop on the Geology and Geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 85–101.
- Powars, D.S., Mixon, R.B., Edwards, L.E., Andrews, G.W., and Ward, L.W., 1987, Evidence for Paleocene and lower Eocene pinch-outs on the north flank of the Norfolk arch, Eastern Shore of Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 2, p. 124.
- Powars, D.S., Mixon, R.B., Edwards, L.E., Poag, C.W., and Bruce, Scott, 1990, Cross section of Cretaceous and Cenozoic strata, Norfolk arch to Salisbury basin, outer coastal plain of Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 4, p. 57.
- Powars, D.S., Poag, C.W., and Mixon, R.B., 1993, The Chesapeake Bay "impact crater," stratigraphic and seismic evi-

- dence [abs.]: Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A-378.
- Powars, D.S., Quick, J.E., Bruce, T.S., Catchings, R.D., Emry, S.R., Gohn, G.S., Izett, G.A., Johnson, G.H., Levine, J.S., McFarland, E.R., and Poag, C.W., 2001, Structure and composition of the southwestern margin of the buried Chesapeake Bay impact structure [abs.], in Morgan, M.L., and Warme, J.E., Bolide impacts on wet targets: Geological Society of America Field Forum, Nevada and Utah, April 2001, not paginated.
- Rankin, D.W., 1994, Continental margin of the eastern United States; Past and present, in Speed, R.C., ed., Phanerozoic evolution of North American continent-ocean transitions—The Decade of North American Geology summary volume to accompany the DNAG continent-ocean transect series: Boulder, Colo., Geological Society of America, p. 129–218.
- Reimold, W.U., Koeberl, Christian, and Poag, C.W., 2002, Chesapeake Bay impact crater; Petrographic and geochemical investigations of the impact breccia fill [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 466.
- Sanford, Samuel, 1913, The underground water resources of the Coastal Plain Province of Virginia: Virginia Geological Survey Bulletin 5, 361 p., 1 pl.
- Sanford, W.E., 2002, Possible hydrothermal activity following the Chesapeake Bay bolide impact [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 466.
- Sanford, W.E., 2003, Heat flow and brine generation following the Chesapeake Bay bolide impact: *Journal of Geochemical Exploration*, v. 78–79, p. 243–247.
- Self-Trail, J.M., 2003, Shock-wave-induced fracturing of calcareous nannofossils from the Chesapeake Bay impact crater: *Geology*, v. 31, no. 8, p. 697–700.
- Sheridan, R.E., Maguire, T.J., Feigenson, M.D., Patino, L.C., and Volkert, R.A., 1999, Grenville age of basement rocks in Cape May, N.J. well—New evidence for Laurentian crust in U.S. Atlantic Coastal Plain basement Chesapeake terrane: *Journal of Geodynamics*, v. 27, no. 4–5, p. 623–633.
- Shuvalov, V.V., Dypvik, H., and Tsikalas, F., 2002, Numerical modeling of the Mjølner marine impact event [abs.]: Lunar and Planetary Science Conference, 33d, League City, Tex., March 11–15, 2002, Abstract 1038, available online at <http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1038.pdf>
- Steckler, M.S., Mountain, G.S., Miller, K.G., and Christie-Blick, Nicholas, 1999, Reconstruction of Tertiary progradation and clinoform development on the New Jersey passive margin by 2-D backstripping: *Marine Geology*, v. 154, no. 1–4, p. 399–420.
- Stewart, S.A., and Allen, P.J., 2002, A 20-km-diameter multi-ringed impact structure in the North Sea: *Nature*, v. 418, no. 6897, p. 520–523.
- Tennant, Diane, 2001, A cosmic tale, reprinted from *The Virginian-Pilot*, June 24–30, 2001: Hampton Roads, Va., *The Virginian-Pilot*, 16 p.
- U.S. Geological Survey, 1997, The Chesapeake Bay watershed [an image mosaic compiled from Landsat Thematic Mapper images collected from 1990 through 1994]: Reston, Va., U.S. Geological Survey poster, 1 sheet. (Also available online at <http://chesapeake.usgs.gov/poster.html>)
- von Dalwigk, Ilka, and Ormö, Jens, 2001, Formation of resurge gullies at impacts at sea; The Lockne crater, Sweden: *Meteoritics & Planetary Science*, v. 36, no. 3, p. 359–369.
- Vozoff, Keeva, 1991, The magnetotelluric method, chapter 8 in Nabighian, M.N., and Corbett, J.D., eds., *Electromagnetic methods in applied geophysics: Society of Exploration Geophysicists Investigations in Geophysics* no. 3, v. 2 (Applications), pt. A, p. 641–712.
- Ward, L.W., 1984, Stratigraphy of outcropping Tertiary beds along the Pamunkey River, central Virginia Coastal Plain, in Ward, L.W., and Krafft, Kathleen, eds., *Stratigraphy and paleontology of the outcropping Tertiary beds in the Pamunkey River region, central Virginia Coastal Plain—Guidebook for Atlantic Coastal Plain Geological Association Field Trip*, October 6–7, 1984: Atlantic Coastal Plain Geological Association, p. 11–77, 12 pls.

Appendix A1. Abstracts of Research on the Chesapeake Bay Impact Structure, 2001–2003

Citations for the listed abstracts are in the “References Cited.”

Year 2001

Catchings, Powars, and others (2001)
Gohn, Bruce, and others (2001)
Gohn, Powars, and others (2001)
Horton and others (2001)
Poag and the Chesapeake Coring Team (2001)
Poag, Gohn, and Powars (2001)
Powars, Gohn, Catchings, and others (2001)
Powars, Gohn, Edwards, Bruce, and others (2001)
Powars, Johnson, Bruce, and Edwards (2001)
Powars, Quick, and others (2001)

Year 2002

Catchings, Powars, Gohn, and Goldman (2002)
Crawford (2002)
Edwards and Self-Trail (2002)

Edwards and others (2002)
Emry and others (2002)
Glass (2002)
Gohn, Powars, Bruce, and others (2002)
Gohn, Powars, Quick, Horton, and Catchings (2002)
Horton, Aleinikoff, and others (2002)
Horton, Kunk, and others (2002)
McFarland (2002)
McFarland and Bruce (2002)
Poag (2002a,b,d)
Poag, Gohn, and Powars (2002)
Powars, Gohn, Bruce, and others (2002)
Powars, Gohn, Edwards, Catchings, and others (2002)
Powars, Johnson, Edwards, and others (2002)
Reimold and others (2002)
Sanford (2002)

Year 2003

Horton and others (2003)
Powars and others (2003)