Physical Stratigraphy of the Upper Eocene to Quaternary Postimpact Section in the USGS-NASA Langley Core, Hampton, Virginia

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Chapter G 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

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Hampton Roads Planning District Commission,
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U.S. Geological Survey

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Abstract

In 2000 a corehole at the National Aeronautics and Space Administration (NASA) Langley Research Center, Hampton, Va., was continuously cored through the entire coastal plain section into crystalline basement rock by the U.S. Geological Survey (USGS) and its cooperators; a high-resolution seismic-reflection and seismic-refraction survey across the York-James Peninsula was simultaneously conducted. The core and land-based seismic data were needed to interpret the Chesapeake Bay impact crater's effects on the geological and hydrogeological framework of the lower York-James Peninsula. This kind of information is required to determine the location of the crater's buried outer margin escarpment.

The USGS-NASA Langley corehole reached a total depth of 635.1 meters (m; 2,083.8 feet (ft)); the hole penetrated 235.65 m (773.12 ft) of postimpact sediments overlying 390.63 m (1,281.6 ft) of synimpact debris and 8.9 m (29.1 ft) of crystalline basement rock. The synimpact and postimpact stratigraphic units of the new corehole correlate well with units interpreted by Powars and Bruce (1999, USGS Professional Paper 1612) from geophysical logs and descriptions of cuttings from a preexisting test well that was located about 520 m (1,700 ft) east of the new corehole.

The postimpact deposits recovered in the USGS-NASA Langley core include, in ascending order, the following units: the very clayey, calcareous Chickahominy Formation (upper Eocene); the glauconitic, phosphatic, and partly shelly lithologies of both the Drummonds Corner beds (a newly recognized upper lower Oligocene stratigraphic unit) and the Old Church Formation (upper Oligocene); the shelly and sandy beds of the Calvert Formation (lower Miocene); the primarily siliciclastic, fine-grained part of the Calvert Formation (middle Miocene), the St. Marys Formation (upper Miocene), and the lower part of the Eastover Formation (upper Miocene); the siliciclastic, locally glauconitic, fine- to coarse-grained, fossiliferous upper part of the Eastover (upper Miocene) and the Yorktown Formation (lower and upper Pliocene); and the fluvial to estuarine Tabb Formation (upper Pleistocene).

The land-based seismic-reflection survey was run adjacent to the Langley corehole to correlate velocities and reflectors with the lithology of the core. The seismic profile also shows that most of the synimpact crater debris consists of highly fractured and fault-bounded, blocky material with distinctive anisotropy and reflection patterns. The overlying postimpact deposits show disruption zones suggesting fracturing and faulting; the scale of deformation in the postimpact deposits is orders of magnitude less than the scale of deformation within the synimpact deposits. Recovery of several angled fractures with slickensides and a fault filled with gouge within the postimpact section provides supportive evidence for their signature on the seismic images. These postimpact fractures and faults may be related to continued compaction and megablock movement. The existence of a preimpact James River structural zone along the southern and southwestern margin of the crater has an apparent additive effect to synimpact and postimpact structural adjustments of the region.

The structural depression of the crater has greatly influenced the postimpact depositional history, sedimentary patterns, and stratigraphic relations of the units that have buried it. Initially the crater's depression transformed parts of the preimpact inner neritic (shallow) shelf depositional environment into a bathyal (deep) depositional environment. Postimpact loading and compaction, possibly along with structural adjustments, have helped the crater to maintain a persistent bathymetric low so that postimpact stratigraphic units dip into and thicken

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toward the center of the crater. This low has resulted in the deposition and preservation of postimpact stratigraphic units (upper Eocene, Oligocene, and lower Miocene) that are found only within the Chesapeake Bay impact structure. Delineation of the types of structural features and stratigraphic affinities created by the impact is essential to development of the hydrogeologic framework to be used in the modeling of the ground-water flow system and regional water quality of the Virginia Coastal Plain.

Introduction

The discovery of a large impact crater beneath the Chesapeake Bay and its apparent effects on the regional ground-water resources has prompted a revision of the structural, stratigraphic, and hydrogeologic framework of a large part of the Virginia Coastal Plain (Powars and Bruce, 1999). The revision process began with the analysis of borehole and marine seismic-reflection data that revealed the existence of a large crater (Powars and others, 1993; Poag, Powars, Mixon, and Bruce, 1994; Poag, Powars, Poppe, and Mixon, 1994). This analysis was followed by structural and stratigraphic documentation of the 85-kilometer-wide (53-mile-wide) Chesapeake Bay impact crater (Koeberl and others, 1996; Poag, 1996, 1997, 2000; Poag and others, 1999; Powars and Bruce, 1999; Powars, 2000). Recently, Johnson, Powars, and others (1998, 2001), Powars (2000), and Powars, Johnson, and others (2002) have presented evidence for an outer fracture zone that surrounds the crater and that is as much as 35 kilometers (km; 22 miles (mi)) wide (fig. G1). The whole structure is referred to as the Chesapeake Bay impact structure and is located beneath the lower Chesapeake Bay, its adjacent peninsulas, and a small part of the Atlantic Ocean east of the lower part of the Delmarva Peninsula. The approximate center of the crater is beneath the town of Cape Charles, Va., as shown in figure G1.

The Chesapeake Bay impact structure formed approximately 35.7 to 35.8 million years ago (Ma) (Horton and others, this volume, chap. A) when a large comet or asteroid crashed into shallow continental shelf waters of the western Atlantic Ocean, penetrated several hundred meters of unconsolidated, seaward-dipping, water-saturated sediments, and blasted a hole into the crystalline basement rocks. At this time during the late Eocene, the Earth was warmer than it is today, and sea level was about a hundred meters (about 300 feet) higher than it is today. The Virginia coastline was located somewhere on the Piedmont, west of the present Fall Zone, and the land was covered by a tropical forest.

The explosion caused by the impact created an initial water-column splash that probably reached the upper atmosphere (H.J. Melosh, University of Arizona, Tucson, oral com-

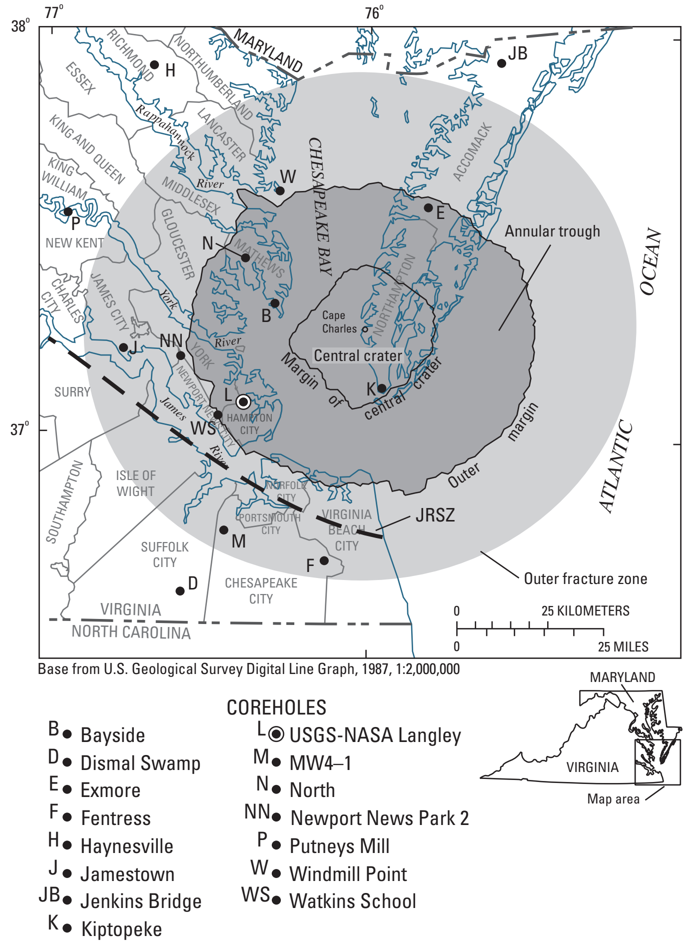


Figure G1. Regional map showing the location of the Chesapeake Bay impact structure, the USGS-NASA Langley corehole at Hampton, Va., and some other coreholes in southeastern Virginia. Locations of the central crater and outer margin are from Powars and Bruce (1999). The extent of the outer fracture zone (light gray) is based on Powars (2000) and Johnson, Powars, and others (2001); the eastern part is speculative. Illustration modified from Powars, Johnson, and others (2002) and Edwards and Powars (2003). JRSZ, James River structural zone of Powars (2000).

mun., 2002). The impact produced an inverted, sombrero-shaped, complex crater that was immediately filled by a forceful resurge of ocean water containing chaotically mixed submarine debris (similar to debris in the Lockne impact crater in Sweden described by von Dalwigk and Ormö, 2001), rim-collapse material, and fluidized and slumped material. The initial resurge was followed by trains of debris-loaded tsunamis; their deposits were capped by the settling out of suspended and fallout particles. Younger postimpact sedimentary deposits have buried the crater since this catastrophic event. Walled terraces, central peaks, and flat floors characterize complex craters (Melosh, 1989), and the Chesapeake Bay impact crater appears to have all these features buried at depth.

The regional ground-water flow paths apparently were altered by truncation and disruption of preimpact aquifers, by emplacement of the synimpact deposits, and by subsequent postimpact deposition of mostly very fine grained deposits in the crater's structural low. Powars and others (1994) and Bruce and Powars (1995) recognized that the western part of the buried crater generally coincided with Virginia's inland saltwater wedge as mapped by Cederstrom (1943, 1945a,b,c, 1957). Cederstrom suggested that the wedge was created by differential flushing of a sediment-filled Eocene basin. The present interpretation is that the buried crater created a large region where seawater has not been flushed from the coastal plain sediments in and around the crater. The western outer margin of the crater appears to act as a mixing (transition) zone separating ground water of high salinity (brackish) inside the outer margin from lower salinity water outside the outer margin (Powars and Bruce, 1999). It should be emphasized that this salinity transition area is a zone and that brackish water is found west of the crater's margin in some of the sediments within the outer fracture zone (for details, see McFarland and Bruce, this volume, chap. K). Until the crater was discovered, there was no satisfactory explanation for the anomalous saltwater wedge (which is better defined as a bulge because it rises to shallow depths) (Powars and others, 1994; Powars and Bruce, 1999) or the region's stratigraphic and structural complexities.

The location and geometry of the outer margin of the Chesapeake Bay impact crater beneath the lower York-James Peninsula are poorly defined. Additional data are needed to locate and delineate the outer margin precisely. Hydrologic data (such as flow direction, water quality, and permeability within the crater) are limited. Information about the depositional processes associated with such a large impactor into water-saturated, unconsolidated sediments is sparse. The societal need for water across the Hampton Roads region has led several municipalities to develop brackish-water desalination plants just outside the crater, but geologic and hydrologic information is needed to model more accurately and evaluate the ground-water flow and the potential for movement of salty water into well fields in the vicinity of the impact crater.

To further investigate the geology and hydrology of this structure, in the year 2000, the U.S. Geological Survey (USGS) and cooperating institutions (see "Acknowledgments") drilled a deep corehole in the southwestern part of the structure's annular trough and completed high-resolution seismic-reflection and seismic-refraction surveys (Catchings, Powars, and others, 2001, 2002; Catchings, Saulter, and others, 2001; Catchings and others, this volume, chap. I) and audio-magnetotelluric surveys (Pierce, this volume, chap. J) across its southwestern margin. A suite of geophysical borehole logs was obtained, including a sonic velocity log for correlation with the seismic data.

The deep corehole, called the USGS-NASA Langley corehole, was drilled on the York-James Peninsula at the National Aeronautics and Space Administration (NASA) Langley Research Center in Hampton, Va., within the northeast quarter of the Newport News North 7.5-min quadrangle (USGS, 1986) (figs. G2 and G3). The site is a short distance north of Langley Boulevard and southwest of Building 1190 in an open grassy area. The coordinates for the Langley corehole, as determined by using a high-accuracy Global Positioning System, are lat 37°05'44.28" N., long 76°23'08.96" W. (North American Datum of 1927); the hole was begun at a ground-surface altitude of 2.4 meters (m; 7.9 feet (ft)) above the North American Vertical Datum of 1988 (NAVD 88). The Langley corehole has a total depth of 635.1 m (2,083.8 ft).

The core site is approximately 8 km (5 mi) inside the outer margin of the buried Chesapeake Bay impact structure as mapped in the Hampton-Newport News area by Powars and Bruce (1999), and it is approximately 36.8 km (22.9 mi) from the center of the impact structure at Cape Charles, Va. The surficial geology at the core site represents shallow paleo-Chesapeake Bay floor sediments deposited in the late Pleistocene when sea level was 5.5 m (18 ft) above today's level. These bay-floor deposits formed a flat topographic surface that Coch (1971) named the Hampton Flat; its associated shoreline, the Big Bethel scarp, is 4 km (2.5 mi) west of the drill site (see Horton and others, this volume, chap. A, fig. A4).

The stratigraphic interval sampled by the USGS-NASA Langley corehole is physically distinguished by three primary geologic units (presented below with thickness and boundary altitudes relative to the NAVD 88):

- Crystalline rock (Neoproterozoic peraluminous granite), 8.9 m (29.1 ft) thick, between altitudes of –632.74 and –623.87 m (–2,075.9 and –2,046.8 ft); see Horton and others (this volume, chap. B)
- Impact-modified and impact-generated crater debris, 390.63 m (1,281.6 ft) thick, between altitudes of –623.87 and –233.23 m (–2,046.8 and –765.2 ft); see Gohn and others (this volume, chap. C), Frederiksen and others (this volume, chap. D), and Horton and Izett (this volume, chap. E)
- Postimpact shallow-marine and coastal plain deposits, 235.65 m (773.12 ft) thick, between –233.32 m (–765.2 ft) and the top of the corehole at +2.4 m (+7.9 ft); see this chapter (G) and Edwards and others (this volume, chap. H) and Poag and Norris (this volume, chap. F)

A variety of paleontological data for the USGS-NASA Langley core confirmed Powars and Bruce's (1999) stratigraphic interpretation of the 1974 NASA Langley test well located only about 520 m (about 1,700 ft) east of the Langley corehole (comparison shown in fig. G4). The USGS-NASA Langley corehole provides key information for understanding the formative processes that occurred in the Chesapeake Bay impact structure's southwestern annular trough.

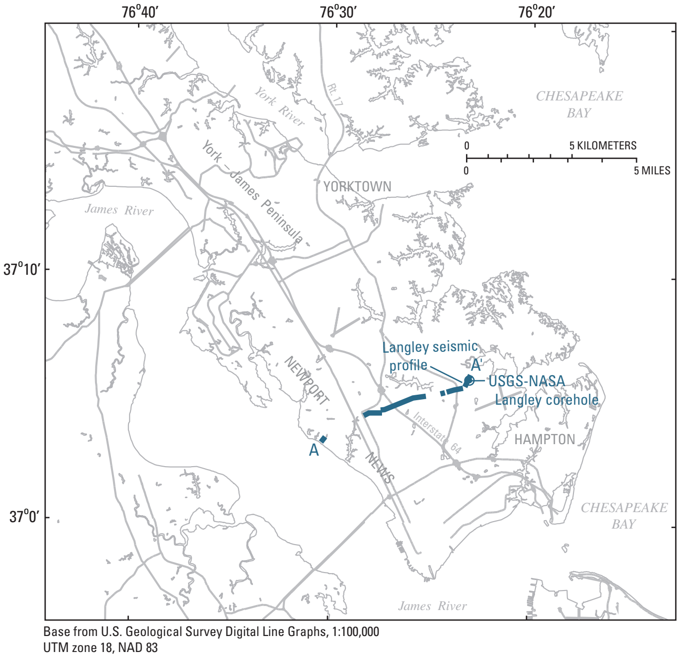


Figure G2. Map of the lower York-James Peninsula showing the location of the USGS-NASA Langley corehole and the land-based high-resolution seismic transect (black line; gaps show areas skipped). The final segment of the transect, the 1-km-long (0.62-mi-long) Langley seismic profile, is described by Catchings and others (this volume, chap. I).

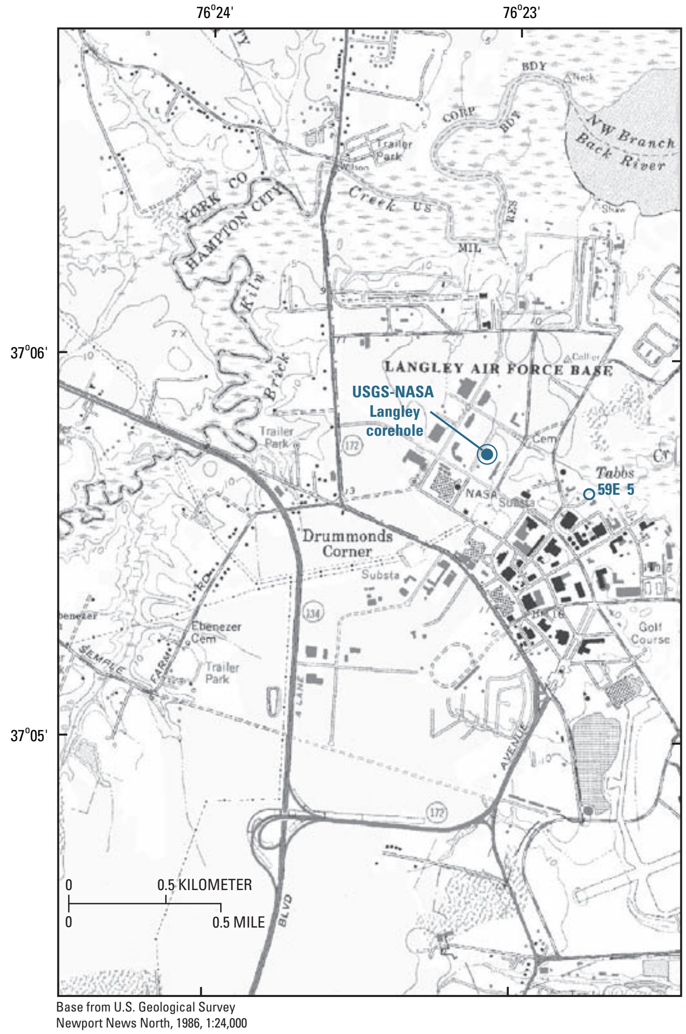


Figure G3. Detailed map showing the location of the USGS-NASA Langley corehole (59E 31) and the 1974 NASA Langley test well (59E 5) at the NASA Langley Research Center, Hampton, Va.

Figure G4 (facing page). Stratigraphic columns and geophysical logs for the USGS-NASA Langley corehole (*A*, this report) and the 1974 NASA Langley test well (*B*, Powars and Bruce, 1999). See figure G3 for hole locations. Colors in bands indicate equivalent units.

Purpose and Scope

This chapter describes the physical geology of the 235.65 m (773.12 ft) of postimpact deposits penetrated in the USGS-NASA Langley corehole and summarizes the paleontological data (Edwards and others, this volume, chap. H). Lithic descriptions of the Langley core are provided in appendix G1. The lithostratigraphy of the core is correlated with borehole geophysical logs and the land-based high-resolution seismic-reflection data to characterize the physical properties of the stratigraphic units and their geophysical signatures. The correlation of the core and borehole geophysical logs provides the supportive evidence required for accurate interpretation of earlier water-well geophysical logs and descriptions of borehole cuttings. This information makes possible a better understanding of the Chesapeake Bay impact structure's effects on the geological and hydrological framework of southeastern Virginia over approximately the last 35.7 to 35.8 million years (m.y.).

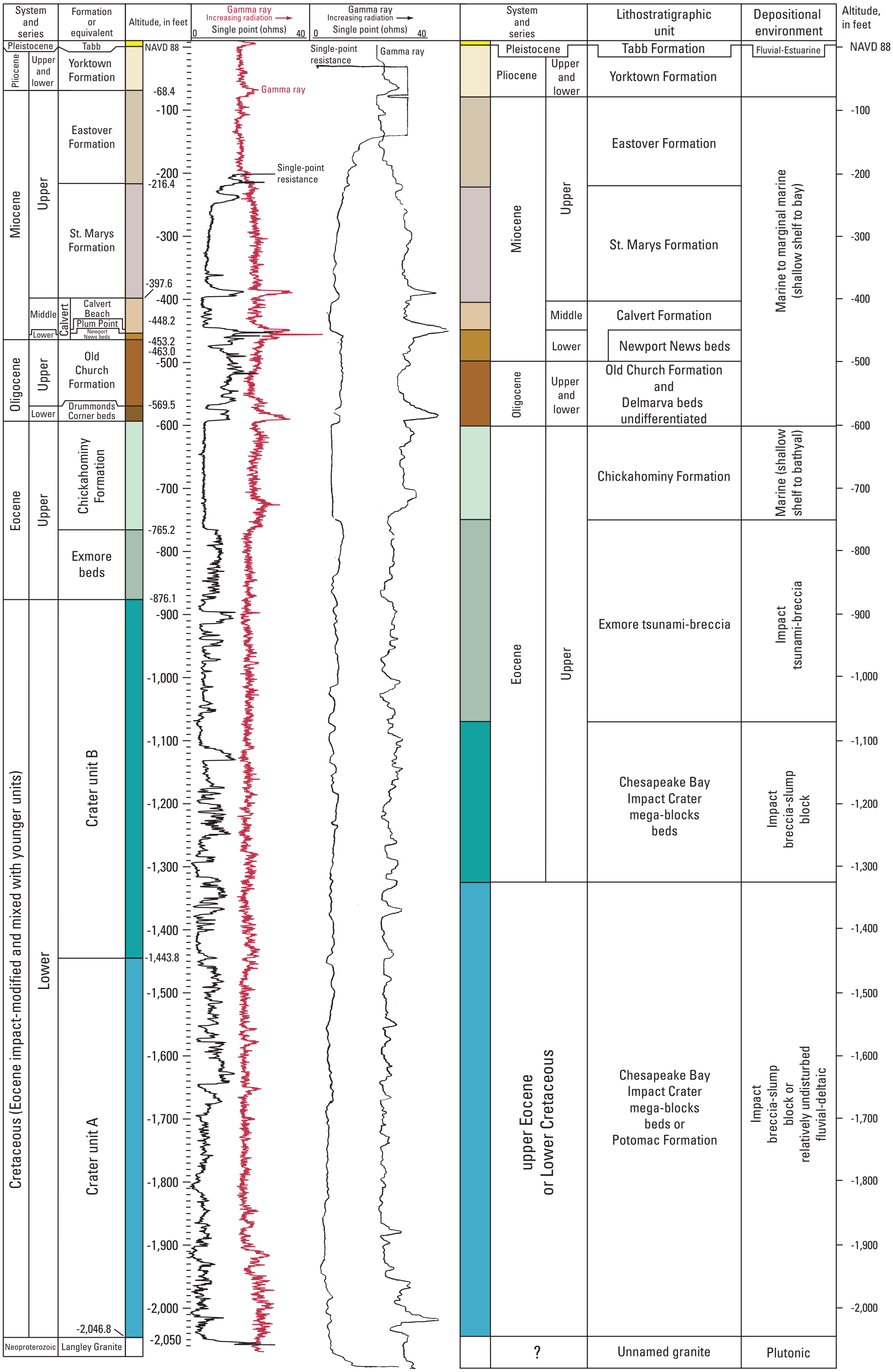
Recent Previous Investigations

Table G1 lists some of the products that have come from the combined efforts of the U.S. Geological Survey, the Hampton Roads Planning District Commission, and the Virginia Department of Environmental Quality from 1987 through the year 2002. These publications have greatly changed our understanding of the subsurface geologic and hydrologic framework of southeastern Virginia.

Methods of Investigation

Compilation of Lithologic Data from Core

Compilation of the onsite graphical representation and written descriptions of the lithology of the USGS-NASA Langley core was supplemented by additional postdrill inspection



A. USGS-NASA Langley corehole (59E 31), 2000

B. NASA Langley test well (59E 5), 1974

Table G1. Key Chesapeake Bay impact crater publications from 1987 through 2002.

[Many of the listed publications result from cooperative work by the U.S. Geological Survey, the Hampton Roads Planning District Commission, and the Virginia Department of Environmental Quality. Publications are listed by year within each group]

Contributions to regional geologic framework, 1987–2000
Powars, Mixon, Edwards, Andrews, and Ward, 1987
Powars, Mixon, Edwards, Poag, and Bruce, 1990
Poag, Powars, Mixon, Edwards, Folger, Poppe, and Bruce, 1991
Powars, Poag, and Bruce, 1991
Poag, Poppe, Powars, and Mixon, 1992
Poag, Powars, Poppe, Mixon, Edwards, Folger, and Bruce, 1992
Powars, Mixon, and Bruce, 1992
Poag and Aubry, 1995
Poag and Commeau, 1995
Powars and Bruce, 1999
Powars, 2000
Crater discovery, 1993–94
Powars, Poag, and Mixon, 1993
Poag, Powars, Mixon, and Bruce, 1994
Poag, Powars, Poppe, and Mixon, 1994
Crater's association with Virginia's inland saltwater wedge, 1994–2002
Powars, Bruce, Poag, and Mixon, 1994
Bruce and Powars, 1995
Powars, Bruce, and Johnson, 1998
Powars and Bruce, 1999
Powars, 2000
McFarland, 2002
McFarland and Bruce, 2002
Crater's structural and stratigraphic effects on postimpact deposits and geomorphology, 1993–2000
Powars, Poag, and Mixon, 1993
Poag, Powars, Mixon, and Bruce, 1994
Poag, Powars, Poppe, and Mixon, 1994
Johnson and Powars, 1996
Koeberl, Poag, Reimold, and Brandt, 1996
Poag, 1996, 1997, 2000
Riddle, Vaughn, Lucey, Kruse, Johnson, and Hobbs, 1996
Johnson, Kruse, Vaughn, Lucey, Hobbs, and Powars, 1998
Johnson, Powars, Bruce, Vaughn, Lucey, and Kruse, 1998
Powars, Bruce, and Johnson, 1998
Poag, Hutchinson, Colman, and Lee, 1999
Powars and Bruce, 1999
Powars, 2000
Powars, Edwards, Bruce, and Johnson, 2000

Table G1. Key Chesapeake Bay impact crater publications from 1987 through 2002.—Continued

Preliminary descriptions of the USGS-NASA Langley corehole data, 2001
Gohn, Clark, Queen, Levine, McFarland, and Powars, 2001
Powars, Bruce, Bybell, Cronin, Edwards, and others, 2001
Interpretations of the crater's structure and synimpact and postimpact crater-filling processes, 2001–2002
Catchings, Powars, Gohn, Goldman, Gandhok, and Johnson, 2001
Catchings, Saulter, Powars, Goldman, Dingler, Gohn, Schindler, and Johnson, 2001
Gohn, Powars, Bruce, Self-Trail, Weems, Edwards, Horton, Izett, and Johnson, 2001
Horton, Aleinikoff, Izett, Naeser, and Naeser, 2001
Johnson, Powars, Bruce, Beach, Harris, and Goodwin, 2001
Poag and the Chesapeake Coring Team, 2001
Powars, Gohn, Catchings, McFarland, Bruce, Johnson, Izett, Emry, and Edwards, 2001
Powars, Gohn, Edwards, Bruce, Catchings, Emry, Johnson, Levine, Poag, and Pierce, 2001
Powars, Johnson, Bruce, and Edwards, 2001
Catchings, Powars, Gohn, and Goldman, 2002
Gohn, Powars, Bruce, Quick, and Catchings, 2002
Gohn, Powars, Quick, Horton, and Catchings, 2002
Horton, Aleinikoff, Izett, Naeser, Naeser, and Kunk, 2002
Horton, Kunk, Naeser, Naeser, Aleinikoff, and Izett, 2002
Johnson, Powars, and Bruce, 2002
Poag, 2002a,b,c
Poag, Gohn, and Powars, 2002
Poag, Plescia, and Molzer, 2002
Powars, Edwards, Bruce, and Johnson, 2002
Powars, Gohn, Bruce, Johnson, Catchings, Frederiksen, Edwards, Self-Trail, and Pierce, 2002
Powars, Gohn, Edwards, Catchings, Bruce, Johnson, and Poag, 2002
Powars, Johnson, Edwards, Horton, Gohn, Catchings, McFarland, Izett, Bruce, Levine, and Pierce, 2002

(10x hand lens and binocular microscope) and sampling. A variety of paleontological data (Edwards and others, this volume, chap. H) provided confirmation of preliminary stratigraphic assignments and the guidance for the stratigraphic assignment and recognition of units. Colors are described with reference to the color charts of Munsell Color Company (1988) and Goddard and others (1948). This chapter mostly uses depth from the surface of the corehole in meters followed by feet in parentheses. Depth and altitude are provided on the stratigraphic columns.

Analysis of Borehole Geophysical Logs

Stephen E. Curtin (USGS) and Richard E. Hodges (USGS) ran a suite of geophysical logs in the USGS-NASA Langley borehole using a Century logging system with a Model 8043 multi-tool probe. Different suites of geophysical logs were run on several different dates to different depths. The deepest suite of logs reached 634.9 m (2,083 ft), almost the total depth of the hole (635.1 m; 2,083.8 ft); this suite included natural-gamma-ray, multipoint-resistivity, 6-ft lateral-resistivity, caliper, acoustic televiewer (ATV), induction-resistivity, single-point-resistance, spontaneous-potential, and sonic velocity logs. Other suites included long-normal-resistance and short-normal-resistance logs. Borehole geophysical logs, especially the resistivity and natural-gamma-ray logs, were interpreted by establishing geophysical signatures for the various lithic units observed in the core. The lithostratigraphy in this chapter is largely based on interpretation of the lithic descriptions and geophysical logs supplemented by paleontological data (Edwards and others, this volume, chap. H).

Correlation with High-Resolution Seismic Images

Both marine- and land-based seismic data reveal numerous faults that displace the top of basement and overlying sediments in the annular trough and the outer fracture zone (Poag and others, 1999; Powars and others, 2003). The existence of a preimpact James River structural zone (fig. G1) along the southern and southwestern margin of the crater has an apparent additive effect to synimpact and postimpact structural adjustments of the region (Powars, 2000). A 1-km-long (0.62-mi-long), high-resolution, land-based seismic image (Catchings and others, this volume, chap. I, fig. I9) was collected adjacent to the USGS-NASA Langley corehole to allow correlation with the core and geophysical logs (especially the sonic velocity log). Figure G5 shows how the seismic reflections correlate directly with the corehole stratigraphy and geophysical logs. Abrupt shifts in the sonic velocity log correspond to density changes across lithic contacts and produce high-amplitude positive seismic reflections (black in fig. G5). Within the postimpact units, lower amplitude positive reflections appear to relate to subtle changes in lithology, which are also reflected in most of the geophysical logs (the Chickahominy Formation is a good example of very subtle lithic changes creating noticeable changes in seismic reflections; see fig. G5).

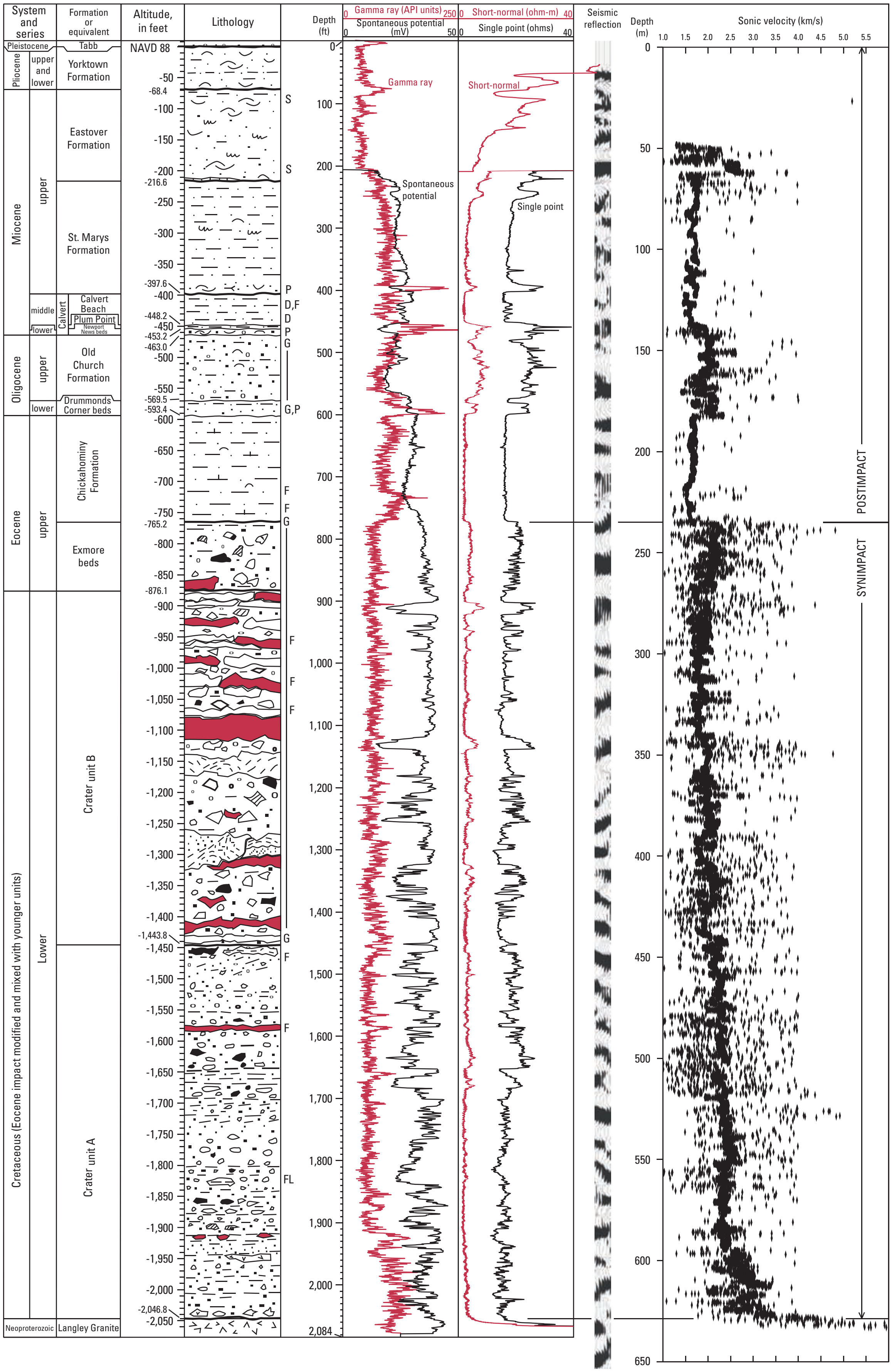
The high-resolution seismic-reflection data having a common-depth-point (CDP) interval of 2.5 m (8.2 ft) indicate that most of the synimpact crater debris consists of highly fractured and fault-bounded blocks of Lower Cretaceous fluvial-deltaic deposits (Catchings and others, this volume, chap. I; Gohn and others, this volume, chap. C). The overlying postimpact deposits also show fracturing and faulting, but the deformation is an order of magnitude less than the deformation within the synimpact deposits. The postimpact stratigraphic units at and near the Langley site have relatively horizontal continuous reflections typical of marine strata; the stratigraphic units with contrasting lithologies (primarily sand vs. clay) appear to have distinct seismic signatures and positive reflections at their contacts (fig. G5; see also Catchings and others, this volume, chap. I, figs. I9 and I11).

Figure G5 shows that the contact between the synimpact and postimpact deposits is marked by an abrupt major change in the velocity, from high (top synimpact) to low (first postimpact); this velocity change creates the positive seismic reflection at the top of the synimpact sediments. The upper part of the synimpact deposits clearly shows three strong positive reflections and, when correlated with the marine seismic data, indicates that Powars and Bruce's (1999) seismic interpretation of the first postimpact unit, the Chickahominy Formation, actually represents the uppermost synimpact deposits.

All the marine seismic images across the crater's western annular trough show that most of the postimpact sediments have a low dip toward the central crater (fig. G6) and that numerous extensional collapse structures disrupt synimpact and postimpact sediments (Poag and others, 2003). Most of the collapse structures are bounded by zones of faulting that appear to extend down into the basement, and some appear to be rooted by detachment zones within the slumping sedimentary section. Powars and others (2003) suggested that these structures appear to be concentrated into three structural rings in the annular trough and that their inner edges are at about 8, 15, and 22 km (5, 9, and 14 mi) from the margin of the central crater. The high-resolution seismic survey (Catchings and others, this volume, chap. I) shows that the Langley corehole is almost centered on one of these extensional collapse structures; at the corehole site, only the synimpact sediments beneath the multiple tsunami and postimpact sediments appear to be significantly deformed.

Physical Stratigraphy of Postimpact Deposits in the USGS-NASA Langley Corehole

The postimpact deposits in the USGS-NASA Langley core consist of 235.65 m (773.12 ft) of upper Eocene to Quaternary deposits that buried the crater and the synimpact deposits. Except for some Pleistocene fluvial-estuarine deposits, the postimpact deposits are primarily marine shallow-shelf clays,



System and series
Formation or equivalent
Altitude, in feet
Lithology
Depth (ft)
Gamma ray (API units)
Spontaneous potential (mV)
Short-normal (ohm-m)
Single point (ohms)
Seismic reflection
Depth (m)
Sonic velocity (km/s)
Pleistocene
Tabb
Pliocene
upper and lower
Yorktown Formation
Miocene
upper
Eastover Formation
St. Marys Formation
middle
Calvert
Calvert Beach
Plum Point
lower
Newport News beds
Oligocene
upper
Old Church Formation
lower
Drummonds Corner beds
Eocene
upper
Chickahominy Formation
Exmore beds
Cretaceous (Eocene impact modified and mixed with younger units)
Lower
Crater unit B
Crater unit A
Neoproterozoic
Langley Granite
NAVD 88
-68.4
-216.6
-397.6
-448.2
-453.2
-463.0
-569.5
-593.4
-765.2
-876.1
-1,443.8
-2,046.8
S
P
D,F
D
G
G,P
F
FL
Gamma ray
Short-normal
Spontaneous potential
Single point
POSTIMPACT
SYNIMPACT

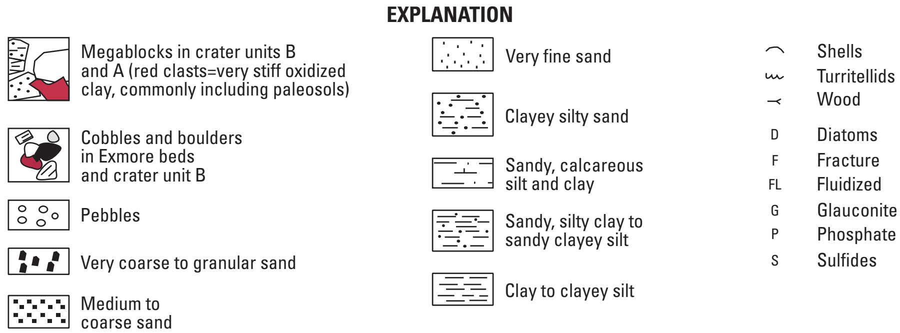
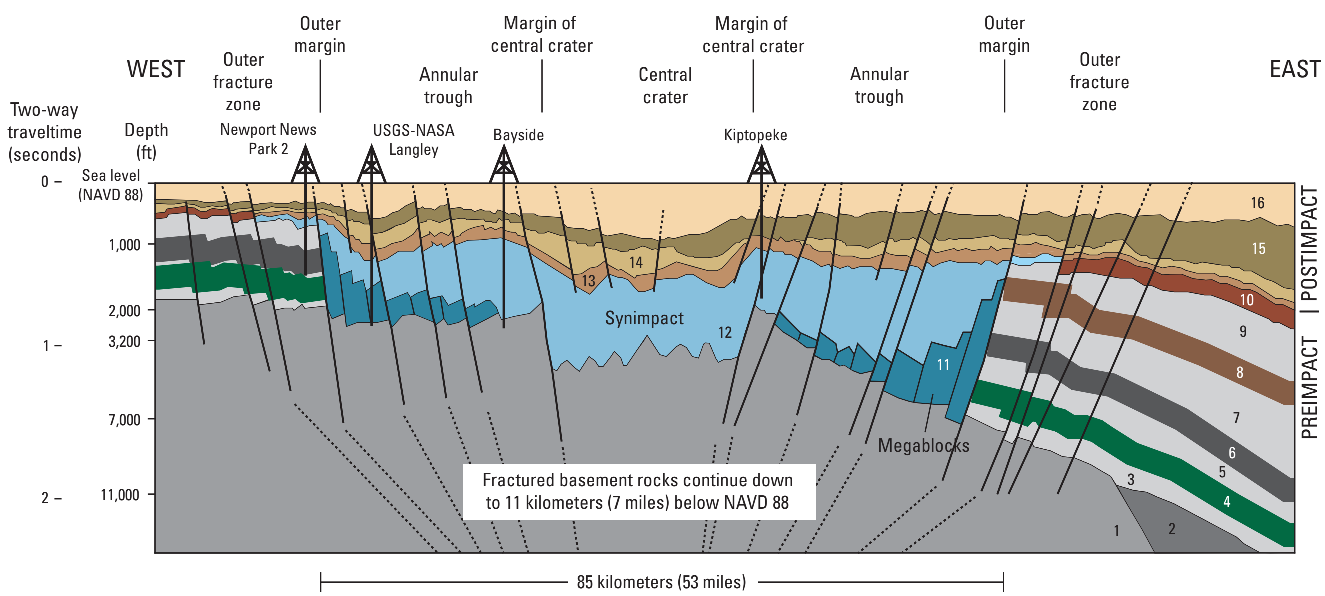


Figure G5 (above and facing page). Stratigraphic column for the USGS-NASA Langley corehole showing correlation with high-amplitude positive seismic reflections and geophysical logs, including gamma-ray, spontaneous-potential, single-point-resistance, short-normal-resistance, and sonic velocity logs. The seismic-reflection column is from Catchings and others (this volume, chap. I, fig. I9); high-amplitude positive reflections are black. Definitions: ft, feet; km/s, kilometers per second; m, meters; mV, millivolts; NAVD 88, North American Vertical Datum of 1988; ohm-m, ohm-meters.



LAYERS

1	Crystalline basement	13	Uppermost synimpact deposits and postimpact upper Eocene clays and silts
2	Norfolk rift basin (Triassic)	14	Postimpact Oligocene to lower Miocene deposits
3–9	Preimpact Cretaceous deposits	15	Postimpact middle Miocene deposits
10	Preimpact lower Tertiary deposits	16	Postimpact upper Miocene to Holocene deposits
11	Synimpact slumped megablocks		
12	Synimpact resurge deposits mixed with slumped megablocks		

Figure G6. Generalized cross section of the buried Chesapeake Bay impact structure; postimpact sediment geometry and distribution are generalized from scaled marine seismic images and corehole stratigraphic data modified from Powars and Bruce (1999). Corehole locations are shown in figure G1.

silts, and very fine to very coarse sands that may include diatomaceous, glauconitic, shelly, and thin calcium-carbonate-cemented intervals. Microfauna, macrofauna, and flora indicate marine to restricted-marine paleoenvironments.

Correlation of the postimpact units with a 1-km-long (0.62-mi-long) high-resolution seismic-reflection profile at the NASA Langley Research Center indicates (1) that the postimpact stratigraphic units here produce relatively horizontal continuous reflections typical of marine strata, (2) that a good correlation exists between positive black reflections and lithic changes that correspond to stratigraphic contacts, and (3) that stratigraphic units having different lithologies are indicated by obvious to subtle changes in the seismic character of the reflections (seismic signature). Some disturbed zones (fractures and faults) are present in the postimpact section, but they are much less common than in the underlying synimpact deposits.

The postimpact stratigraphic record in the Langley core shows numerous cycles of deposition, erosion, and periods of high and low sedimentation rates. These cycles were created by the interactions among global sea level, sediment supply, accommodation, regional to local tectonic activity, and impact (structural subsidence or uplift) influences. Because the impact was on a dipping shallow shelf, it created a unique depositional environment with a deepwater circular basin surrounded mostly by a shallow-shelf setting. For the first few million years, a bathyal depositional environment existed inside the crater.

In the Langley corehole, which is located on the southwestern updip side of the outer annular trough, the bathyal deposits are mostly overlain by postimpact deposits that represent transgressive and highstand depositional environments in inner to middle neritic water depths; these postimpact deposits include evidence for periods of continuous deposition and for other periods punctuated by changes resulting in numerous unconformities. Such unconformities are generally created when sea level rises and high-energy waves erode and rework the previous highstand deposits. The most resistant material (bone, teeth, phosphate, wood, and shells) is generally concentrated into the basal lag deposit formed after a rise in sea level. Most of the unconformable contacts between postimpact stratigraphic units in the Langley core are marked by sandy basal lag deposits that sharply overlie and are burrowed down into much finer grained clay and silt deposited during a previous highstand.

Postimpact deposits in the USGS-NASA Langley core include, in ascending order, the following units: the very clayey, calcareous Chickahominy Formation (upper Eocene); the glauconitic, phosphatic, and partly shelly lithologies of both the Drummonds Corner beds (upper lower Oligocene) and the Old Church Formation (upper Oligocene); the shelly and sandy beds of the Calvert Formation (lower Miocene); the primarily siliciclastic, fine-grained part of the Calvert Formation (middle Miocene), the St. Marys Formation (upper Miocene), and the lower part of the Eastover Formation (upper Miocene); the siliciclastic, locally glauconitic, fine- to coarse-grained, fossiliferous upper part of the Eastover Formation (upper Miocene) and the Yorktown Formation (lower and upper Pliocene); and the fluvial to estuarine Tabb Formation (upper Pleistocene). The stratigraphy of the Langley core's postimpact sedimentary units above the synimpact sedimentary debris is provided in table G2 and figure G7, and the lithology is described in appendix G1. The ages indicated for these units are derived primarily from biostratigraphic analyses of microfossils from the Langley core (Edwards and others, this volume, chap. H).

Chickahominy Formation (Upper Eocene)

The upper Eocene Chickahominy Formation is the oldest postimpact deposit found above synimpact deposits throughout the southern Chesapeake Bay area. In the Langley core, the Chickahominy Formation extends from a sharp but conformable contact with the underlying Exmore beds at 235.65 m (773.12 ft) (fig. G8) upward to a burrowed contact with the overlying upper lower Oligocene Drummonds Corner beds at 183.3 m (601.3 ft) (fig. G9); accordingly, the Chickahominy section in the Langley core is 52.3 m (171.8 ft) thick.

At the lower contact, very tight clay with scattered horizontal thin (millimeter-scale) silt to very fine sand laminae of the Exmore beds contains only reworked, mixed-age microfossils and is overlain by massive silty clay of the Chickahominy, which contains in situ and reworked macrofossils and microfossils. The silt-laminated clay represents the final settling of sediments disturbed by the impact and, thus, constitutes the uppermost part of the synimpact Exmore beds (for more details, see figure G9; Poag and Norris, this volume, chap. F; and Edwards and others, this volume, chap. H).

The upper contact of the Chickahominy is lithologically sharp and strongly burrowed. Coarse-grained phosphatic and glauconitic quartz sand of the Drummonds Corner beds fills burrows that extend down 0.7 m (2.2 ft) into the silty clay of the Chickahominy.

The Chickahominy Formation in the Langley core consists primarily of homogeneous, generally bioturbated, very compact, massive to thin-bedded, olive-gray, clayey silt to silty clay, which contains abundant microfossils and scattered macrofossils. It contains variable amounts of fine-sand- to silt-sized, primarily black to dark-green glauconite, mica, finely crystalline iron sulfides, and coarser grained pyrite. The Chickahominy section in the Langley core is generally similar lithologically to other Chickahominy sections found throughout the region (Powars and Bruce, 1999).

A pyrite-filled fracture dipping moderately at about 45° was found in the core at 230.0 to 229.9 m (754.7 to 754.4 ft) depth (fig. G10). This is the first core sample that recovers actual fractures and faults seen in the seismic-reflection images of the postimpact section (for example, in Poag and others, 1999, and Powars and Bruce, 1999). Several other similarly

Table G2. Stratigraphic contact depths and thicknesses of the postimpact sediments in the USGS-NASA Langley core.

Stratigraphic unit	Top (m)	Top (ft)	Base (m)	Base (ft)	Thickness (m)	Thickness (ft)	Series
Lynnhaven Member of Tabb Formation.........	0.0	0.0	2.2	7.2	2.2	7.2	upper Pleistocene
Yorktown Formation.......................................	2.2	7.2	23.3	76.3	21.1	69.1	Pliocene
Eastover Formation...	23.3	76.3	68.4	224.5	45.2	148.2	upper Miocene
St. Marys Formation.......................................	68.4	224.5	123.6	405.5	55.2	181.0	upper Miocene
Calvert Formation..	123.6	405.5	143.5	470.9	19.9	65.4	lower and middle Miocene
Calvert Beach Member...........................	123.6	405.5	139.0	456.1	15.4	50.6	middle Miocene
Plum Point Member................................	139.0	456.1	140.5	461.1	1.5	5.0	middle Miocene
Newport News beds................................	140.5	461.1	143.5	470.9	3.0	9.8	lower Miocene
Old Church Formation...................................	143.5	470.9	176.0	577.4	32.5	106.5	upper Oligocene
Drummonds Corner beds...............................	176.0	577.4	183.3	601.3	7.3	23.9	upper lower Oligocene
Chickahominy Formation..............................	183.3	601.3	235.65	773.12	52.3	171.8	upper Eocene

angled fractures with slickensides were found in the Chickahominy section of the Langley core (fig. G10).

The fine-grained Chickahominy section is represented by a distinctive, flat, low-value signature on borehole resistivity logs (fig. G7); it is easily differentiated from the irregular, higher resistivity signature typical of the underlying Exmore beds (except for the thin, 0.27-m-thick (0.9-ft-thick) capping fine-grained interval in the Exmore beds discussed above). The irregular, higher resistivity signature of the overlying, much sandier Drummonds Corner beds also is relatively easy to distinguish from the flat resistivity signature of the Chickahominy. The contact with the overlying Drummonds Corner beds also is marked on the natural-gamma-ray log by an increase in radioactivity in the phosphatic basal lag deposits of the Drummonds Corner beds relative to the values recorded for the Chickahominy section (fig. G7). Variations in the natural-gamma-ray log within the Chickahominy strata reflect differences in the phosphate and glauconite content (Poag and Norris, this volume, chap. F), and the resistivity logs reflect differences in the content of silt-clay and sandy silt. The lower part (about 12 m (40 ft)) of the Chickahominy has relatively high gamma-ray-log values indicating increased phosphate. This higher gamma-ray signature for the lower Chickahominy is prevalent in all of the corehole and water-well logs from the southwestern outer annular trough and the surrounding outer fracture zone.

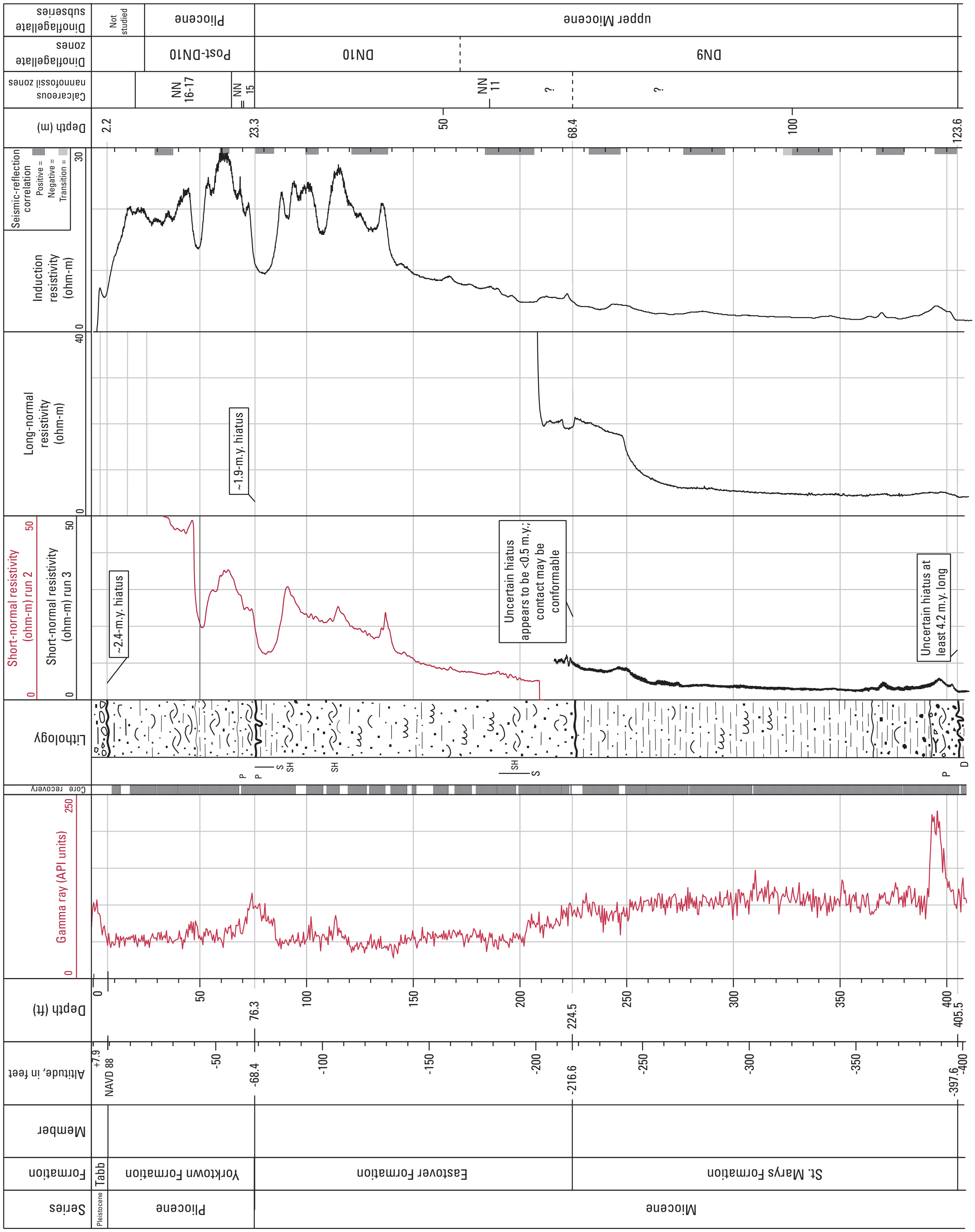
A distinctive suite of microfossils is found in the Chickahominy Formation, indicating a late Eocene age for this unit, which is based on calcareous nannofossil Zones NP 19/20 and NP 21 and planktonic foraminiferal Zones P15, P16, and P17 (Edwards and others, this volume, chap. H; Poag and Norris, this volume, chap. F). The Chickahominy section in the Langley core represents continuous bathyal deposition from the cessation of synimpact deposition at 35.2±0.3 Ma (age based on argon-40/argon-39 plateau ages of tektites inferred to result from the Chesapeake Bay impact; Obradovich and others, 1989; Poag, Powars, Poppe, and Mixon, 1994) to 35.3±0.1 Ma (age from Horton and Izett, this volume, chap. E) to 33.7 Ma or before (age from the time scale of Berggren and others, 1995). The lower contact of the Chickahominy is conformable, whereas the upper contact is an unconformity that represents a hiatus of 3.8 m.y. (Edwards and others, this volume, chap. H).

Paleoenvironmental analysis of the Chickahominy fauna and flora in the Langley core (see Poag and Norris, this volume, chap. F; and Edwards and others, this volume, chap. H) indicates that the Chickahominy sediments were deposited in a quiet-water, low-oxygen, marine environment with water depths of approximately 300 m (984 ft). The deepest water paleodepth detected from the fossil assemblages appears to be at a depth of 221.7 m (727.4 ft) in the core.

Drummonds Corner Beds (Upper Lower Oligocene)

Lower Oligocene deposits are present in the Langley core from the unconformable contact with the Chickahominy strata at 183.3 m (601.3 ft) depth to a burrowed unconformity with the overlying upper Oligocene Old Church Formation at 176.0 m (577.4 ft) depth (figs. G9, G11, and G12). The Drummonds Corner beds (upper lower Oligocene) are herein described and informally named to distinguish them from the stratigraphically older and lithically similar lower Oligocene Delmarva beds of Powars and others (1992).

Oligocene units in general, and lower Oligocene units in particular, are poorly known from the Virginia Coastal Plain.



Dinoflagellate subseries
Not studied
Pliocene
upper Miocene
Dinoflagellate zones
Post-DN10
DN10
DN9
Calcareous nannofossil zones
NN 16-17
NN 15
NN 11
Depth (m)
2.2
23.3
50
68.4
100
123.6
Seismic-reflection correlation
Positive =
Negative =
Transition =
Induction resistivity (ohm-m)
Long-normal resistivity (ohm-m)
~1.9-m.y. hiatus
Short-normal resistivity (ohm-m) run 2
Short-normal resistivity (ohm-m) run 3
~2.4-m.y. hiatus
Uncertain hiatus appears to be <0.5 m.y.; contact may be conformable
Uncertain hiatus at least 4.2 m.y. long
Lithology
Core recovery
Gamma ray (API units)
Depth (ft)
76.3
224.5
405.5
Altitude, in feet
+7.9
NAVD 88
-68.4
-216.6
-397.6
Member
Formation
Tabb
Yorktown Formation
Eastover Formation
St. Marys Formation
Series
Pleistocene
Pliocene
Miocene

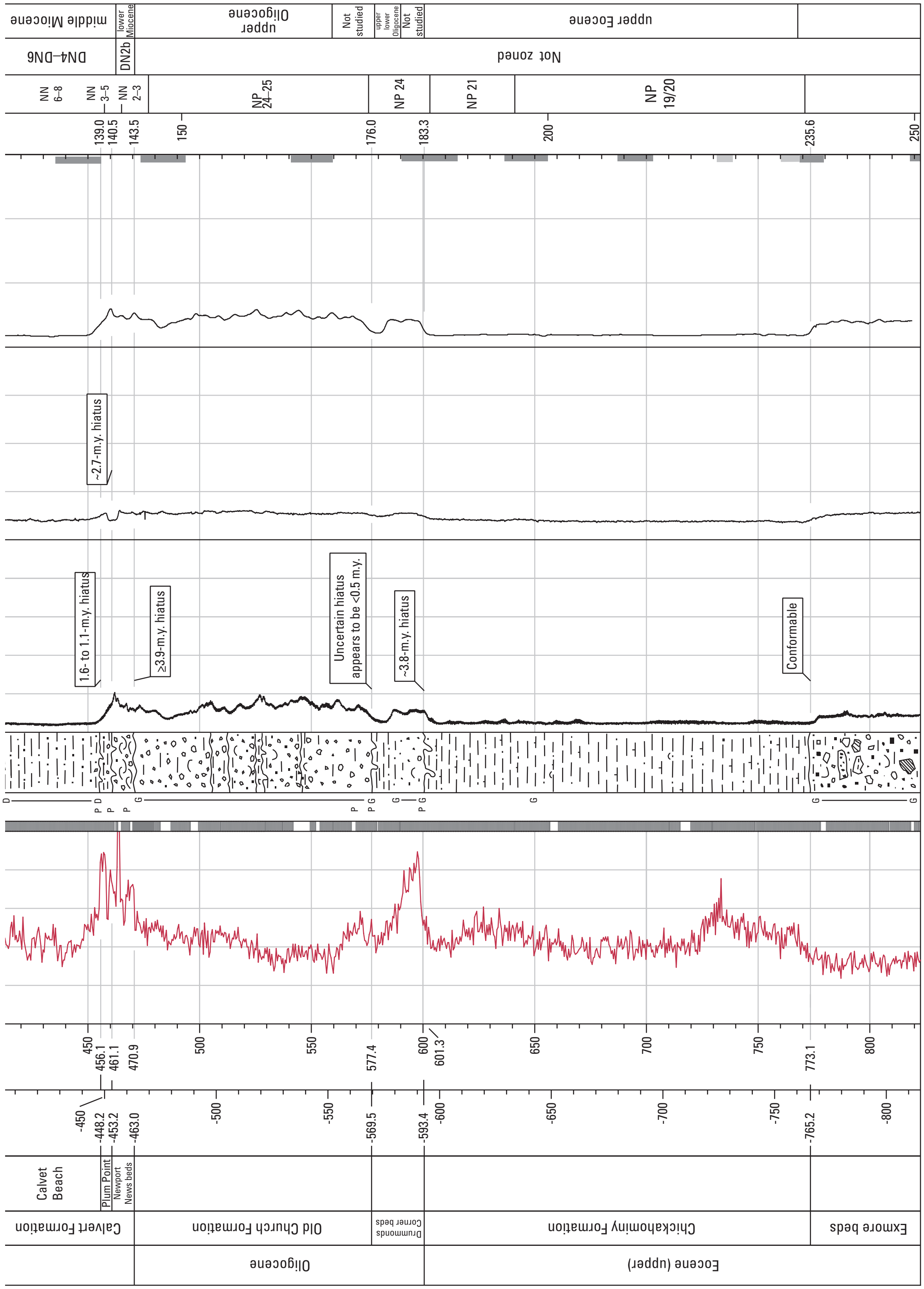


Figure G7. Lithostratigraphic column and selected geophysical logs of the postimpact section of the USGS-NASA Langley corehole showing major lithic breaks. Key nannofossil and dinoflagellate age data and hiatus lengths are from Edwards and others (this volume, chap. H). Definitions: ft, feet; m, meters; m.y., million years; NAVD 88, North American Vertical Datum of 1988; ohm-m, ohm-meters.

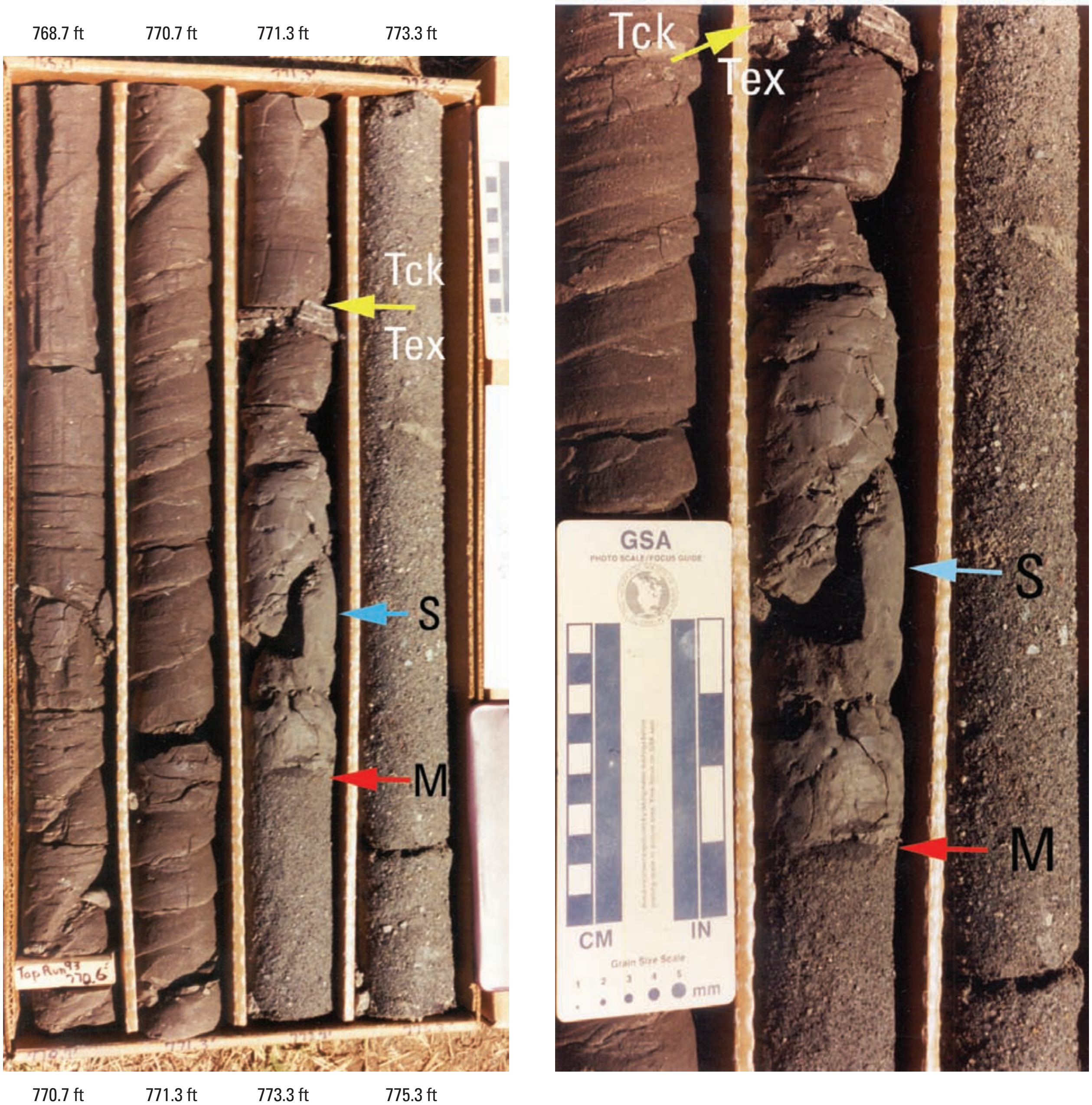


Figure G8. Photographs of the USGS-NASA Langley core showing the conformable contact at 235.65 m (773.12 ft) depth (top arrow) between the synimpact Exmore beds (Tex) and the overlying Chickahominy Formation (Tck). The photograph on the right is a closeup view of part of the core shown in the photograph on the left. In this core, the top of the Exmore beds includes a thin, fine-grained interval that is 0.27 m (0.9 ft) thick. Millimeter-scale pyrite lattices (labeled S for sulfides) were described by Poag (2002b) near the top of a 0.085-m-thick (0.28-ft-thick) basal silt layer between depths of 236.0 and 235.9 m (774.03 and 773.75 ft). Above the basal silt layer, the sediments abruptly change to very tight gray clay (which changes to dark-green-gray clay in the uppermost 0.19 m (0.63 ft)); the clay contains scattered horizontal, very thin (millimeter-scale) silt to very fine sand laminae and a few burrows(?) filled by coarser grained "Exmore matrix"; apparently, the matrix was moved from below by an early postimpact burrowing organism. The silt layer overlies the typical polymict matrix of the Exmore beds (labeled M); note dark-gray clast at contact. Top of core is at upper left. Depths handwritten on the core boxes in feet are repeated in type for clarity.

Figure G9. Composite and closeup photographs of the USGS-NASA Langley core showing the burrowed contact interval between the Chickahominy Formation (Tck) and the unconformably overlying Drummonds Corner beds (Tdc). This unconformity represents a 3.8-m.y. hiatus. The photograph on the right is a closeup view of part of the core shown in the photograph on the left; the core was slightly turned between photographs. Fine-grained marine sediments of the Chickahominy are overlain by quartz-glauconite sand of the Drummonds Corner beds. The arrow is at the formation contact at 183.3 m (601.3 ft) depth. Top of core is at upper left. Nominal core diameter is 6.1 centimeters (cm; 2.4 inches (in.)). Depths handwritten on the core boxes in feet are repeated in type for clarity.

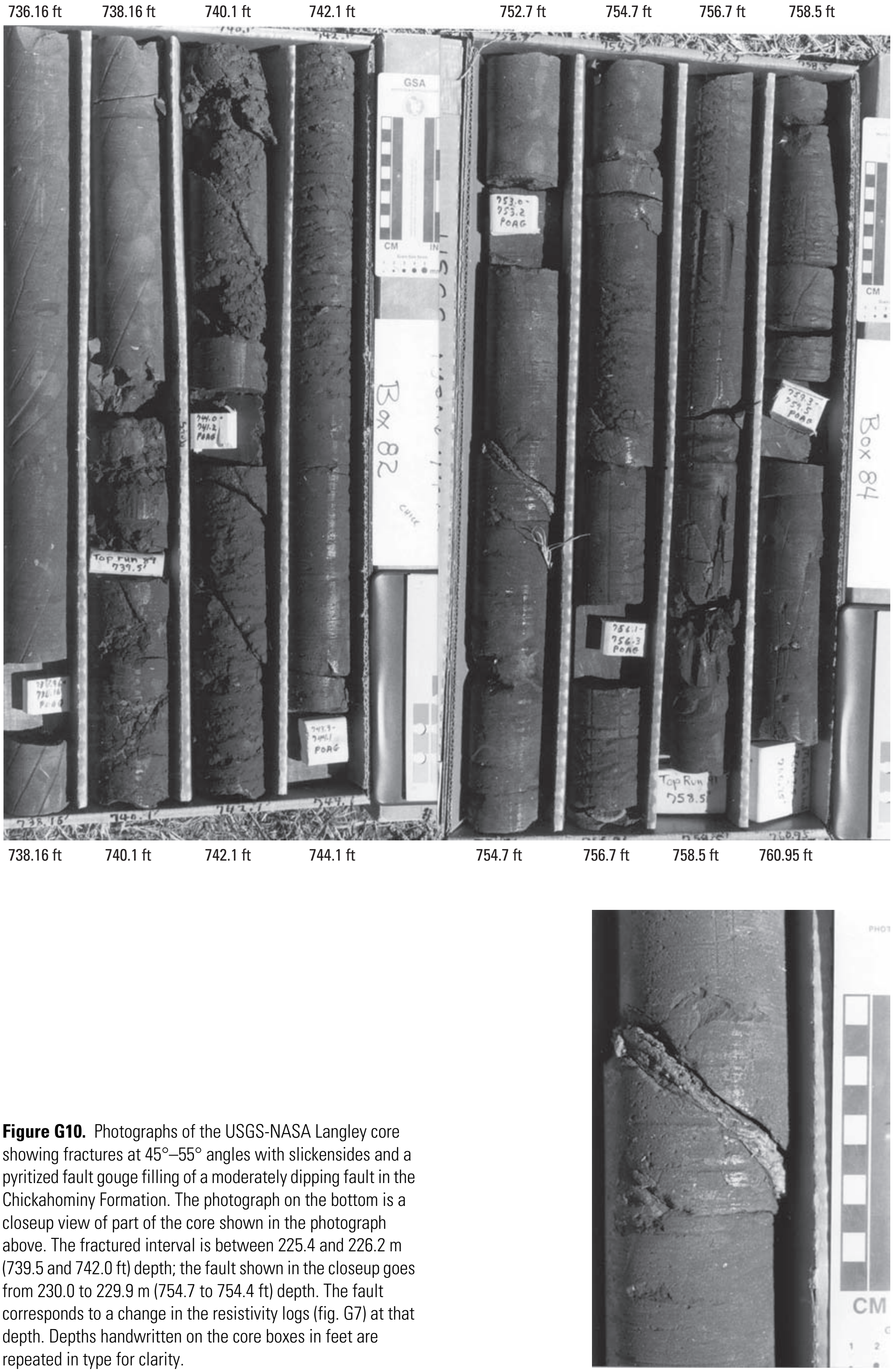


Figure G10. Photographs of the USGS-NASA Langley core showing fractures at 45°–55° angles with slickensides and a pyritized fault gouge filling of a moderately dipping fault in the Chickahominy Formation. The photograph on the bottom is a closeup view of part of the core shown in the photograph above. The fractured interval is between 225.4 and 226.2 m (739.5 and 742.0 ft) depth; the fault shown in the closeup goes from 230.0 to 229.9 m (754.7 to 754.4 ft) depth. The fault corresponds to a change in the resistivity logs (fig. G7) at that depth. Depths handwritten on the core boxes in feet are repeated in type for clarity.

Figure G11. Composite photograph of the USGS-NASA Langley core from depths of 179.8 to 182.3 m (590.0 to 598.2 ft) showing highly burrowed, muddy to coarser grained quartz-glauconitic basal sands of the Drummonds Corner beds. Top of core is at upper left; core in upper left corner of box is from 3.4 m (11.3 ft) above the basal contact. Nominal core diameter is 6.1 cm (2.4 in.). Depths handwritten on the core boxes in feet are repeated in type for clarity.

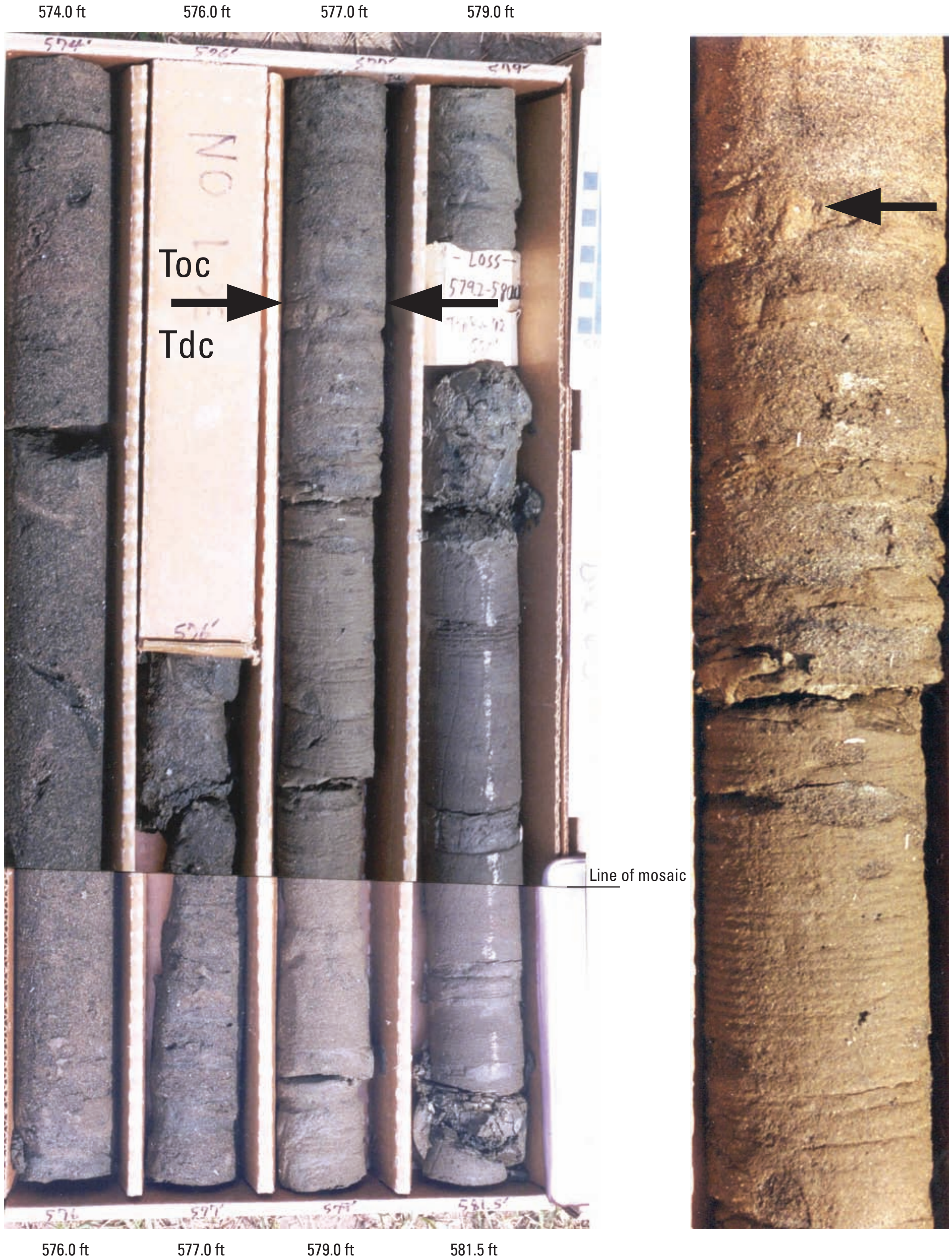


Figure G12. Composite and closeup photographs of the USGS-NASA Langley core showing (at the arrows) the unconformable burrowed contact at 176.0 m (577.4 ft) depth between the muddy finer grained sediments of the uppermost Drummonds Corner beds (Tdc) and the overlying much coarser grained quartz-glauconitic sands of the Old Church Formation (Toc). Top of core is at upper left. Nominal core diameter is 6.1 cm (2.4 in.). Depths handwritten on the core boxes in feet are repeated in type for clarity. Color differences between the composite and closeup photographs are due to lighting changes.

The first report of lower Oligocene sediments was the description of the informal Delmarva beds by Powars and others (1992) from the Exmore core, Northampton County, Va. They reported (p. 95) “as much as” 12.5 m (41 ft) of lower Oligocene sediments overlain by 13.7 m (45 ft) of incompletely recovered sediments that they tentatively assigned to the Old Church Formation. Powars and Bruce (1999) and Powars (2000) recognized the Delmarva beds in additional cores and wells in the Virginia Coastal Plain. However, in these sections, they included material that would now be placed in the Drummonds Corner beds and that in places overlies thin deposits correlative with the original Delmarva beds. In addition, the upper part of the Oligocene section in the Exmore core that they assigned to the Old Church Formation would now be placed in the Drummonds Corner beds. Powars and Bruce (1999) observed that the lower 5.2 m (17 ft) of their Old Church Formation in the Exmore core was early Oligocene in age, not late Oligocene, and suggested that this material should be included with the Delmarva beds (although they did not include it in the Delmarva beds in their tables).

In the subsurface of the Virginia Coastal Plain, we now recognize three Oligocene units; from oldest to youngest, they are the Delmarva beds, the Drummonds Corner beds, and the Old Church Formation. Determination of the biostratigraphy of all three units is complicated by the prevalence of fossil reworking within the postimpact crater section.

The lowest unit, the Delmarva beds, is present in only a few cores and is placed in the lower part of the lower Oligocene represented by planktonic foraminiferal Zones P18–P20 (undifferentiated, Powars and others, 1992). The Delmarva beds also contain palynomorphs that are restricted to the lower part of the Rupelian Stage (including the acritarch *Ascostomocystis potana,* according to L.E. Edwards, USGS, unpub. data, 1987 and 2004; the assignment of *A. potana* to the Rupelian follows Stover and Hardenbol (1993)).

The middle unit, the Drummonds Corner beds, is placed in the upper part of the lower Oligocene. It is placed in foraminiferal Zone P21a (Powars and others, 1992; Powars and Bruce, 1999) and in calcareous nannofossil Zone NP 24. It also contains palynomorphs whose overlapping ranges indicate placement in the upper part of the Rupelian Stage (Edwards and others, this volume, chap. H). Both the Delmarva beds and the Drummonds Corner beds are glauconitic, phosphatic sands and silts.

The upper unit, the Old Church Formation, is placed in the upper Oligocene (calcareous nannofossil Zone NP 24 and perhaps Zone NP 25). It contains palynomorphs that indicate placement in the upper part of the upper Oligocene (to lowest Miocene) and is therefore in the Chattian Stage (Edwards and others, this volume, chap. H).

In the Langley core, the upper lower Oligocene Drummonds Corner beds consist of microfossiliferous, quartz-glauconite sand near their base that becomes muddier upward, as indicated by the resistivity logs (fig. G7). At its base, the unit consists of very poorly sorted sand with scattered phosphate pebbles that sharply overlies and is burrowed down into the much finer grained Chickahominy strata. Figure G11 illustrates dense burrows characteristic of the Drummonds Corner beds.

Biostratigraphic analysis of the Drummonds Corner beds indicates that this unit is early Oligocene or early late Oligocene; it contains calcareous nannofossils that indicate assignment to Zone NP 24. Hence, these deposits are no older than early Oligocene (29.9 Ma) and no younger than early late Oligocene (28.5 Ma). The basal unconformity of the Drummonds Corner beds represents a 3.8-m.y. hiatus. The time span of the hiatus at the upper unconformity is uncertain, as both the Drummonds Corner beds and overlying Old Church Formation are within the same calcareous nannofossil zone (Edwards and others, this volume, chap. H); the hiatus is probably less than 0.5 m.y. long.

Paleoenvironmental analysis indicates that the Drummonds Corner beds represent deposition in shallower water and more nearshore environments than existed during deposition of the underlying Chickahominy deposits. The fish teeth in the Drummonds Corner beds are from species that are common to a subtropical climate (Edwards and others, this volume, chap. H).

Old Church Formation (Upper Oligocene)

In the Langley core, the interval from the contact at 176.0 m (577.4 ft) depth to the contact at 143.5 m (470.9 ft) depth is assigned to the Old Church Formation (figs. G12, G13, and G14). This 32.5-m-thick (106.5-ft-thick) section consists of intensely burrowed, poorly sorted, gray-olive to dark-green and black, shelly, microfossiliferous, fine to very coarse, glauconitic and phosphatic quartz sand generally in a clay-silt matrix. These beds locally include better sorted, finer grained, sandy clay-silts or thin, sandy, indurated layers. Granules of quartz, glauconite, and phosphate are scattered throughout along with minor amounts of pyrite, carbonaceous material (including wood), and occasional very small teeth from sharks. The burrows vary in size and orientation and include clay-lined, clay-filled, and sand-filled types.

The Old Church section consists of six fining-upward packages (fig. G13*A*). Burrowed sand-over-clay contacts are visible in the core at depths of 161.2 m (529.0 ft), 160.2 m (525.5 ft), 155.8 m (511.0 ft), and 154.5 m (507 ft); two are shown in figure G13*B*. Another contact is inferred to be present at 166.1 m (545.0 ft) because of the resistivity log (fig. G7). These fining-upward packages are represented on the resistivity log by upward decreases in resistivity that track the upward gradation from lower, better sorted sands to higher, clayey and silty sands.

Dinoflagellates and calcareous nannofossils indicate placement in calcareous nannofossil Zones NP 24 and NP 25 or their chronozones and, hence, a late Oligocene age for the Old

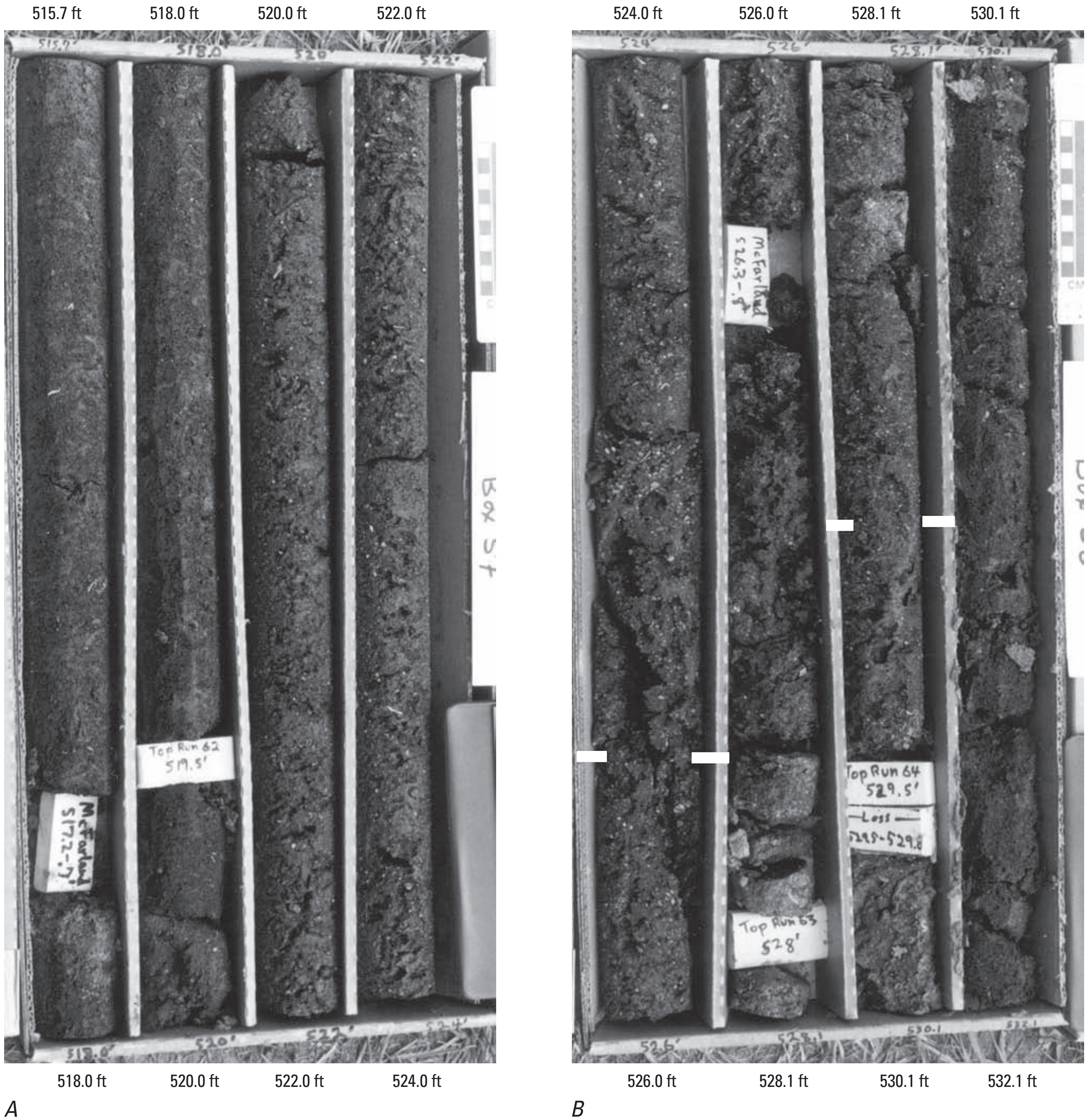


Figure G13. Photographs of the USGS-NASA Langley core showing fining-upward subunits typical of the Old Church Formation in the Langley core. Top of core is at upper left. *A*, Transition upward at about 158 m (520 ft) depth from sandier to muddier sediments within one of the subunits. *B,* Subtle lithic contacts (short lines) between subunits at 161.2 and 160.2 m (529.0 and 525.5 ft) depth, where much coarser grained quartz-glauconitic sands are overlying and burrowed down into muddy, finer grained matrix-supported sediments. Depths handwritten on the core boxes in feet are repeated in type for clarity.

465.7 ft 467.9 ft 470.9 ft 472.9 ft

467.9 ft 470.9 ft 472.9 ft 474.9 ft

Line of mosaic

Figure G14. Composite photograph of the USGS-NASA Langley core showing the unconformable contact at 143.5 m (470.9 ft) depth (arrow) between fine-grained marine deposits of the Old Church Formation and overlying shelly and locally cemented marine sediments of the Newport News beds of the Calvert Formation. Top of core is at upper left. Nominal core diameter is 6.1 cm (2.4 in.). Depths handwritten on the core boxes in feet are repeated in type for clarity.

Church Formation. The type section of the Old Church is in Zone NP 25 according to Bybell and Gibson (1994). The duration of the interval represented by the lower unconformity is uncertain but not more than 0.5 m.y.; the upper unconformity represents at least a 3.9-m.y. hiatus (Edwards and others, this volume, chap. H).

Paleoenvironmental analysis of the Old Church fauna and flora in the Langley core indicates that this unit was deposited in nearshore to middle-outer shelf water depths in a subtropical to tropical climate.

Calvert Formation (Lower and Middle Miocene)

The lower and middle Miocene Calvert Formation is present from 143.5 m (470.9 ft) depth to 123.6 m (405.5 ft) depth in the Langley core (figs. G14, G15, and G16). The Calvert Formation in the Langley core can be subdivided (in ascending order) into the lower Miocene Newport News beds, a middle Miocene portion of the Plum Point Member, and the middle Miocene Calvert Beach Member.

Newport News Beds (Lower Miocene)

Lower Miocene sediments unconformably overlie the glauconitic and phosphatic sand of the Old Church Formation in the Langley core between depths of 143.5 and 140.5 m (470.9 and 461.1 ft); they have a thickness of 3.0 m (9.8 ft). These lower Miocene sediments consist of partially indurated to indurated, poorly sorted, bioclastic, very coarse phosphatic quartz sand that is assigned to the Newport News beds of the Calvert Formation (Powars and Bruce, 1999) (figs. G14 and G15). Coarse phosphatic sand of the Plum Point Member of the Calvert Formation unconformably overlies the Newport News beds.

Differentiation of these thin, shelly, Miocene sand units from each other and from the Old Church Formation is facilitated by the analysis of the geophysical logs. Basal transgressive lag deposits of marine units typically concentrate uranium- and thorium-bearing phosphatic material (nodules, sharks' teeth, bone) that create "spikes" or "hot kicks" (high values) on natural-gamma-ray logs. These lag deposits also produce "sand kicks" (high values) on resistivity logs. Figure G7 shows this geophysical signature opposite the basal lag deposits of all stratigraphic units from the lower Oligocene Drummonds Corner beds to the upper Miocene St. Marys Formation.

Calcareous nannofossils and dinoflagellates indicate an early Miocene age for the Newport News beds in the Langley core and assignment to calcareous nannofossil Zones NN 2–4 and dinoflagellate subzone DN2b (Edwards and others, this volume, chap. H). De Verteuil (1997) calibrated subzone DN2b at 20.0 to 19.4 Ma. Powars and Bruce (1999) reported a strontium-isotope date of 20.1 Ma for shells in correlative strata from the nearby Newport News Park 2 corehole. Data indicate (Edwards and others, this volume, chap. H) that the basal unconformity represents at least a 3.9-m.y. hiatus and that the upper unconformity represents an apparent 2.7-m.y. hiatus.

The fauna and flora indicate deposition of the Newport News beds in nearshore to shallow-shelf water depths during a paleoclimate period that was somewhat warmer than the present climate at the Langley site.

Plum Point Member (Middle Miocene Part)

In the Langley core, the Plum Point Member of the Calvert Formation consists of a 1.5-m-thick (5.0-ft-thick), unconformity-bounded, fining-upward interval of shelly, poorly sorted, muddy, fine to very coarse phosphatic quartz sand that grades upward into a 0.3-m-thick (1.0-ft-thick) section of bioturbated, microfossiliferous silt and silty clay. The lower contact at 140.5 m (461.1 ft) depth is at the top of the partially indurated shelly sand of the Newport News beds (fig. G15). The truncated upper contact at 139.0 m (456.1 ft) depth (fig. G15) is between clayey silt to silty clay of the Plum Point Member and very coarse sand with sharks' teeth in the overlying Calvert Beach Member. Burrows filled with Calvert Beach sand penetrate the top of the Plum Point Member.

The Plum Point Member in the Langley core is middle Miocene in age and is assigned to calcareous nannofossil Zones NN 3–5 and to dinoflagellate Zone DN4. The lower unconformity represents an apparent 2.7-m.y. hiatus, and the upper unconformity represents a hiatus of 1.1 to 1.6 m.y. (for details, see Edwards and others, this volume, chap. H). The lower Miocene portion of the Plum Point Member that was present in the Exmore core (Powars and Bruce, 1999) is not present at the Langley site.

Paleoenvironmental analysis of fossil assemblages from the Plum Point Member in the Langley core indicates deposition in nearshore to shallow-shelf water depths and a paleoclimate somewhat warmer than the present climate at the Langley site.

Calvert Beach Member (Middle Miocene)

The Calvert Beach Member of the Calvert Formation in the Langley core is an unconformity-bounded marine unit that consists of dark-greenish-gray to olive-gray, homogeneous, massive to thinly bedded, microfossiliferous, silty clay to clayey silt. Diatoms and foraminifera are abundant and relatively easy to see with a 10x hand lens. Most of the section contains only sparse grains of very fine, angular quartz and pyrite and small percentages of wood fragments, sponge spicules, fish scales, and vertebrae. The Calvert Beach Member is present from depths of 139.0 to 123.6 m (456.1 to 405.5 ft) in the Langley core (figs. G15 and G16). It overlies the middle Miocene Plum Point Member of the Calvert Formation and underlies the upper Miocene St. Marys Formation.

The basal 1.8 m (6 ft) of the Calvert Beach Member fines upward from very coarse phosphatic and glauconitic quartz sand with sharks' teeth, bone, and clay-filled and sand-filled

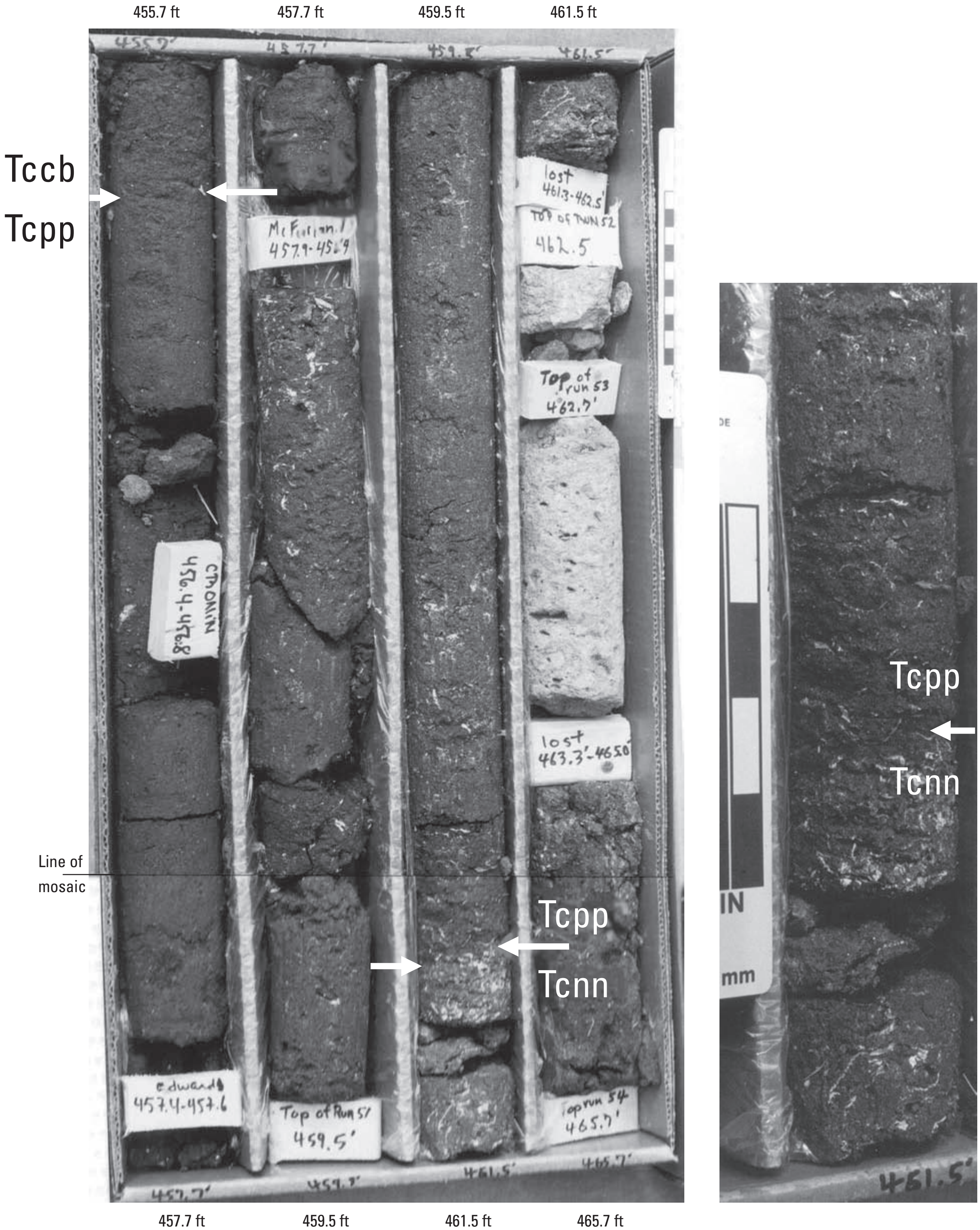


Figure G15. Composite and closeup photographs of the USGS-NASA Langley core showing unconformable Miocene contacts within the Calvert Formation at the top and base of the Plum Point Member. Arrows indicate the contact at 140.5 m (461.1 ft) depth between the Newport News beds (Tcnn, lower Miocene) and the overlying Plum Point Member (Tcpp, middle Miocene). Arrows also indicate the contact at 139.0 m (456.1 ft) depth between the Plum Point Member and the overlying Calvert Beach Member (Tccb, middle Miocene). Top of core is at upper left. The photograph at right is a closeup of the middle Miocene-lower Miocene contact (arrow) shown in the large photograph. Depths handwritten on the core boxes in feet are repeated in type for clarity.

399.5 ft

Line of mosaic

408.0 ft

Figure G16. Composite photograph of the USGS-NASA Langley core showing the location of the burrowed contact at 123.6 to 123.9 m (405.5 to 406.8 ft) depth between the finer grained middle Miocene Calvert Beach Member (Tccb) of the Calvert Formation (tray at right) and the overlying basal sands of the upper Miocene St. Marys Formation (Tsm). The contact must be within the core-loss interval indicated by arrows. Sandy burrows of the St. Marys extend down into the top 0.15 m (0.5 ft) of the recovered clay-silt of the Calvert strata. Top of core is at upper left. Nominal core diameter is 6.1 cm (2.4 in.). Depths of the top and bottom of the core box in feet are shown in type.

burrows to dark-gray, poorly sorted, clayey and silty, fine sand. This basal sand sharply overlies and is burrowed into a thin, much finer grained, sandy clay-silt layer at the top of the truncated Plum Point strata.

A 0.4-m (1.3-ft) core loss in the coring run from 124.0 to 121.8 m (406.8 to 399.5 ft) depth apparently lost the Calvert Beach-St. Marys contact, and so there is some uncertainty about the exact depth of this contact. However, the resistivity and natural-gamma-ray logs clearly indicate that the contact is at 123.6 m (405.5 ft) depth (figs. G7 and G16), which corresponds to the lowest sand recovered in this core run. This lowest sand is exactly where the drillers noted a drilling chatter that indicated vibrations caused by cutting shells or cemented layers or phosphatic bones and teeth or chunks of wood or very well sorted tight sand. There was a physical gap in the core when it first came out of the retrieval (inner) barrel separating the base of the sand at 123.6 m (405.5 ft) from much finer grained, sandy clayey silt (top of Calvert Beach Member); the silt contains small burrows filled with greenish-black, coarser sand (basal sand of the St. Marys Formation) that penetrate less than 0.3 m (1 ft) downward. The site geologist and drillers agreed that the 0.4-m (1.3-ft) missing interval was from this physical gap and therefore placed the loss at 123.6 to 124.0 m (405.5 to 406.8 ft). On the basis of the lowest sand recovered and the geophysical logs, the contact is placed at 123.6 m (405.5 ft).

The resistivity and gamma-ray logs reflect the lithic changes that occur at the upper and lower contacts. These contacts are typical marine unconformities with lag deposits of coarse phosphatic quartz sand that overlie and are burrowed into finer grained sediments below the contact. The homogeneous, fine-grained lithology of most of the Calvert Beach Member creates a low-value, flat-resistivity-log signature similar to that of the Chickahominy Formation. The gamma-ray, resistivity, and sonic logs show a major shift to higher values related to the transition from the finer grained silty clay to clayey silt of the Calvert Beach Member to its very thin basal coarse sand and the underlying coarse sand of the truncated Plum Point Member. Except for the two sand lag deposits in the lower part of the St. Marys Formation, the next shelly sand encountered upward in the Langley core occurs at about 42.7 m (140 ft) depth within the Eastover Formation.

Dinoflagellates, diatoms, and silicoflagellates indicate a middle Miocene age for the Calvert Beach Member. Calcareous nannofossils suggest a slightly younger latest middle Miocene to early late Miocene age. The base of this 15.4-m-thick (50.6-ft-thick) unit is calibrated at 14.1 Ma or a younger age (first appearance of the dinocyst *Habibacysta tectata*, according to de Verteuil and Norris, 1996); the age of the top of the unit is no younger than the top of Zone DN6 (12.7 Ma). The lower unconformity appears to represent a hiatus of 1.1 to 1.6 m.y. (Edwards and others, this volume, chap. H). The duration of the interval represented by the upper unconformity is uncertain; it is at least 4.0 m.y. in the Langley core, and stratigraphic analysis of the Newport News Park 2 core indicates that the hiatus could be as much as 4.2 m.y. long (Powars and Bruce, 1999).

The Calvert Beach Member represents a shallow-shelf to nearshore depositional environment similar to the environment for the Plum Point Member at the Langley site. Paleontologic data indicate nutrient upwelling during sedimentation and a slight to moderate cooling upward trend toward reduced paleotemperatures.

St. Marys Formation (Upper Miocene)

The upper Miocene St. Marys Formation is present from the top of the Calvert Formation at 123.6 m (405.5 ft) depth in the Langley core to a contact with the upper Miocene Eastover Formation within a poorly recovered interval at 68.4 m (224.5 ft) depth (figs. G16, G17, and G18). A deflection of the resistivity curve at 68.3 m (224 ft) from lower resistivities in the silty clays of the upper St. Marys to higher resistivities in the basal sands of the Eastover Formation supports this contact pick.

The basal 4.6 m (15.0 ft) of the St. Marys consists of greenish-black, variably shelly, woody, pyritic, very fine to medium phosphatic quartz sand with sparse fish vertebrae and teeth and faint low-angled crossbeds at the base that grades upward into a finer sand and then by 117.0 m (384.0 ft) depth becomes an olive-gray to dark-greenish-gray clayey silt to silty clay (fig. G17). The other 50.6 m (166.0 ft) of the unit consists generally of homogeneous, massive, dense, well-sorted, dark-greenish-gray to grayish-olive-green, variably micaceous and calcareous, very clayey silt to very fine sandy clay and silt. This section contains rare to moderately abundant shells, rare to abundant burrows, abundant iron sulfide (pyrite and chalcopyrite, grains to nodules to burrow fillings and linings), finely disseminated organic material, rare scattered sponge spicules, and a trace of glauconite.

Powars and Bruce (1999) reported that beneath the lower York-James Peninsula, the St. Marys exhibits a gradational change from a lower clayey facies to an upper, sandy, shelly facies. These lithological changes are reflected in the Langley corehole resistivity logs by the gradual upward change from lower to higher resistivities at 79.2 m (260 ft) depth, but these values are lower than the resistivity of the overlying sandier Eastover (fig. G7). As described by Powars and Bruce (1999), the lower clayey facies commonly contains two fining-upward sequences that have thin, shelly, phosphatic, sandy basal lag deposits that are less than 1.5 m (5 ft) thick. These lag deposits may be represented in the Langley core by 2.9-m-thick (9.4-ft-thick) sandier beds at 113.8–110.9 m (373.4–364.0 ft) depth and the 4.6-m-thick (15.0-ft-thick) basal sands.

The upper sand lacks the shells but has abundant wood and phosphate grains. The core description of the basal St. Marys agrees well with the gamma-ray-log and resistivity-log signatures that indicate the more phosphatic and sandier nature of the sediments at 1.5 m (5 ft) and 3.0 m (10 ft), respectively, above the basal contact (fig. G7). The upper lag deposits above the contact at 113.8 m (373.4 ft) are also reflected in the resistivity logs with a positive kick (deflection to the right), and the gamma-ray log is low (deflected to the left), reflecting the scar-

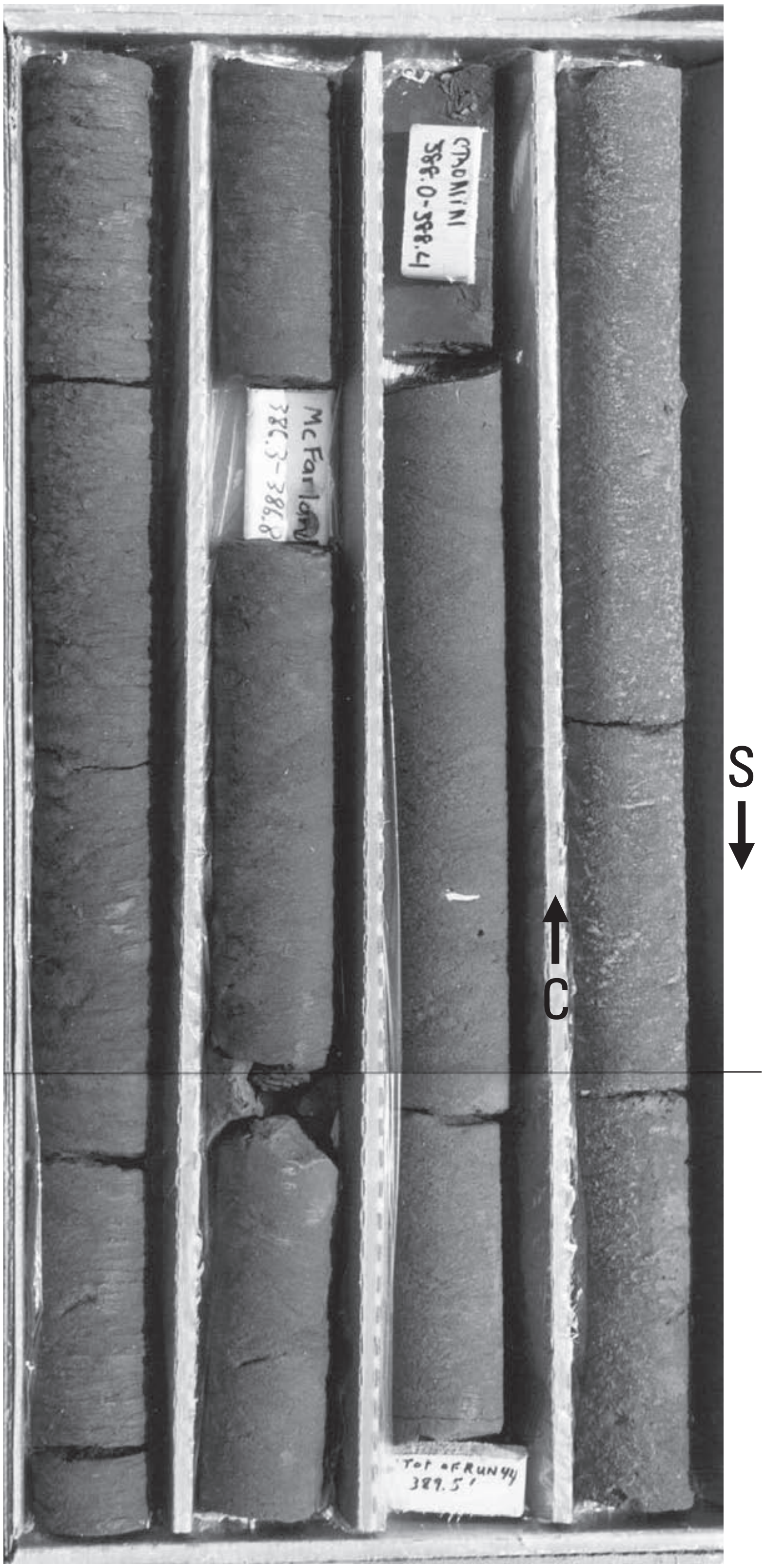


Figure G17. Composite photograph of the USGS-NASA Langley core showing the St. Marys Formation and the transition from the top of its sandy (S) basal beds, which are 4.6 m (15.0 ft) thick, to silty clay (C), which is the typical lithology of the St. Marys. White wisps in core at far right are deposits of very fine to medium quartz sand in a clay-silt matrix. Top of core is at upper left. Nominal core diameter is 6.1 cm (2.4 in.). Depths of the top and bottom of the core box in feet are shown in type.

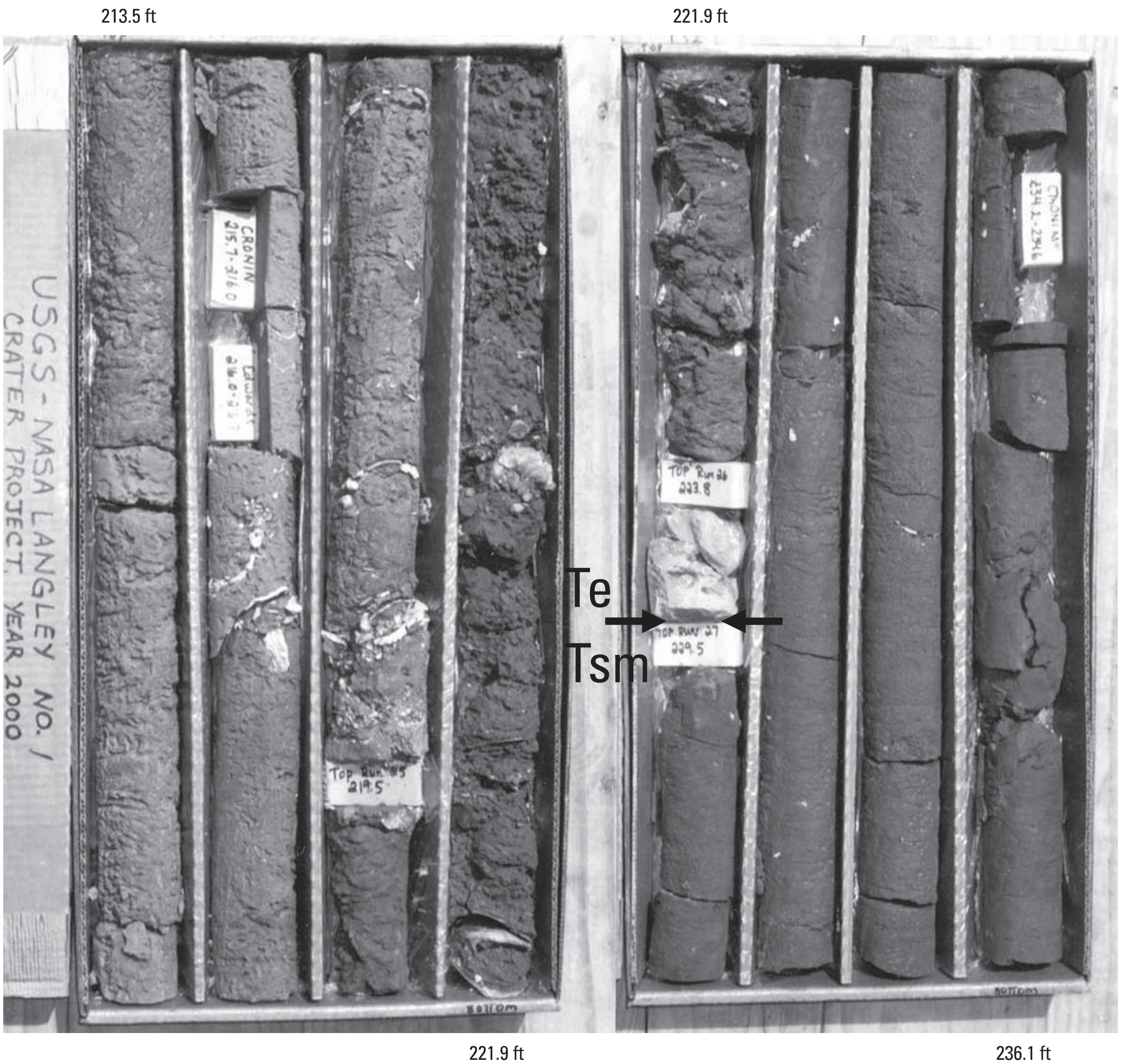


Figure G18. Photograph of the USGS-NASA Langley core showing core loss (arrows) of the presumably unconformable contact between the St. Marys Formation (Tsm) and the overlying light-colored calcite-cemented hard bed at the base of the Eastover Formation (Te). On the basis of geophysical logs, the contact is placed at 68.4 m (224.5 ft) depth and is interpreted as the base of hard bed. Top of core is at upper left. Nominal core diameter is 6.1 cm (2.4 in.). Depths of the top and bottom of the core boxes in feet are shown in type.

city of phosphate. Figure G17 shows the upward transition from the sandier beds to the silty clay beds at 119.5 to 118.6 m (392.0 to 389.0 ft) depth. Above the St. Marys, a shelly, sandy basal lag deposit at the base of the Eastover Formation lacks phosphatic material and, therefore, has a high resistivity-log signature and a low gamma-ray-log signature.

Foraminifera are the most common microfossils in the St. Marys Formation in the Langley core, and they become more abundant downward in the lower 38.1 m (125 ft) of the unit. The macrofossils are mostly clams, oysters, and *Turritella*. As in most cores across the region, *Turritella* fossils dominate the lower to middle part of the St. Marys strata from about 97.5 to 88.3 m (320.0 to 290.0 ft) depth in the Langley core; zones of concentration are at 95.1 to 94.5 m (312 to 310 ft) and 92.4 to 90.1 m (303 to 295.5 ft) depth.

Biostratigraphic analysis of the St. Marys Formation in the Langley core indicates a late Miocene age. The St. Marys is placed in dinoflagellate Zone DN9 (calibrated at 8.7–7.4 Ma according to de Verteuil and Norris, 1996), which continues into the basal Eastover (Edwards and others, this volume, chap. H). All nannofossil samples were either barren or nondiagnostic; however, Powars and Bruce (1999) reported that strontium-isotope analysis of shell material from the nearby Newport News Park 2 corehole indicates that the age of the St. Marys strata ranges from about 6.7 to 5.5 Ma, which is equivalent to the biochronozone of foraminiferal Zone N17. The lower unconformity represents at least a 4.0-m.y. hiatus, as the base of the St. Marys Formation is 8.7 Ma or younger. The upper contact may be conformable or may be a minor unconformity that represents a hiatus of less than 0.5 m.y. (Edwards and others, this volume, chap. H).

Analysis of the fauna and flora in the St. Marys Formation in the Langley core indicates a marine inner to outer shelf depositional environment with cool-water upwelling and a relatively small seasonality in temperatures. Ostracodes in the upper St. Marys indicate a temperate paleoclimate during sedimentation.

Eastover Formation (Upper Miocene)

The upper Miocene Eastover Formation is present in the Langley core from its contact with the underlying St. Marys Formation at 68.4 m (224.5 ft) depth to an unconformable contact with the overlying Yorktown Formation at 23.3 m (76.3 ft) depth (figs. G18 and G19). The base of the Eastover is within a poorly recovered 2.0-m-thick (6.7-ft-thick) interval and is placed at the base of a 0.06-m-thick (0.2-ft-thick), medium-gray, calcite-cemented, shelly sand bed that contains a few uncemented sand-filled burrows or borings. Only this indurated bed was recovered from the drill run from 68.2 to 70.0 m (223.8 to 229.5 ft) depth; it is represented by a thin, sharp high-resistivity kick at 68.4 m (224.5 ft) depth on the short-normal resistivity log (fig. G7). Another thin, sharp resistivity kick is seen on the short-normal log just slightly higher at 67.8 m (222.3 ft) depth, but this correlates with a recovered very shelly sand bed.

The contact with the overlying Yorktown Formation was completely recovered. Very shelly (large blackened oysters) and glauconitic quartz sand of the basal Yorktown sharply overlies and is burrowed at least 0.24 m (0.8 ft) down into dense, plastic, slightly sandy, silty clay of the Eastover Formation. These burrows vary from clay lined to sand filled and range from 0.12 to 0.24 m (0.4 to 0.8 ft) in width. High values on the gamma-ray and resistivity logs mark the position above the contact of the basal sand of the Yorktown Formation.

The Eastover Formation consists primarily of dark-greenish-gray to grayish-olive-gray to grayish-olive-green, bioturbated, locally macrofossiliferous, clayey and silty, very fine to medium quartz sands. Most of the Eastover apparently lacks bedding because of the high degree of bioturbation, as indicated by the mottled texture. However, some intervals have a wide variety of sparse to abundant burrows, including clay-lined sand-filled, sand-filled, clay-filled, and back-filled burrows of various sizes and orientations. The upper 3.0 m (10.0 ft) of the Eastover consists of sparingly fossiliferous, silty and sandy clay that has very thin bedding. A thin interval of laminated silty clay to clayey silt is present from 46.1 to 46.0 m (151.2 to 151.0 ft) depth.

The Eastover contains variable amounts (trace to 10 percent) of very fine grained to medium-grained, dark-green to black glauconite, which is most abundant in the upper 11.9 m (39.0 ft) of the unit. The glauconite percentage increases downward from 26.2 to 27.3 m (86.0 to 89.5 ft) depth. The glauconite is commonly concentrated in burrows. Sulfides are visible at 64.3 m (from 211.1 to 210.9 ft), from 63.8 to 61.2 m (209.3 to 200.8 ft), and from 27.1 to 23.3 m (89.0 to 76.3 ft) as irregular patches, as very fine to fine spheres, or as core surfaces that turned yellow when they dried.

No microfossils are visible in the top 10.3 m (33.7 ft), and microfossils are sparse to very sparse in the rest of the Eastover Formation. Echinoid spines are sparse throughout most of the section but are abundant from 51.8 to 48.8 m (170.0 to 160.0 ft).

The Eastover is sparsely to abundantly shelly and includes shells concentrated into layers forming shell hashes (storm deposits, marked SH in fig. G7) that are found at the following depths: 28.7 to 27.1 m (94.0 to 89.0 ft), 37.5 to 34.4 m (123.0 to 113.0 ft), 41.6 to 38.2 m (136.5 to 125.2 ft), and 61.2 to 56.8 m (200.7 to 186.2 ft). *Isognomon*, a tabular mollusk with a pearly luster, is a common species in the Eastover Formation. It is present from 64.0 to 27.4 m (210.0 to 90.0 ft) depth in the Eastover section of the Langley core, but it is not present in the overlying Yorktown Formation or in the underlying St. Marys Formation. *Turritella* is common to abundant from 58.2 to 37.8 m (191.0 to 124.0 ft).

Powars and Bruce (1999) reported that, across the region, the lower part of the Eastover Formation consists of a more clayey, fine-grained facies with characteristically low resistivity-log signatures that show an upward-coarsening trend into

Figure G19. Photograph of the USGS-NASA Langley core showing the unconformable contact at 23.3 m (76.3 ft) depth (arrows) between the Eastover Formation (Te, lower right) and the overlying Yorktown Formation (Ty). Top of core is at upper left. Depths of the top and bottom of the core boxes in feet are shown in type.

an upper shelly, coarse-grained facies with characteristically high resistivities. This configuration of Eastover strata also is found in the Langley core, with a gradual decrease in the clay and silt fraction from about 64.0 m (210.0 ft) depth upward to about 42.7 m (140.0 ft) and a corresponding change in resistivity values.

Biostratigraphic analysis indicates a late Miocene age for the Eastover Formation in the Langley core (Edwards and others, this volume, chap. H). The only clearly datable calcareous nannofossil sample comes from the lower part of the unit at 56.9 m (186.6 ft) and is assigned to Zone NN 11. The dinoflagellate data place the unit in Zones DN9 and DN10. The DN9-DN10 boundary is present in the lower part of the unit and is calibrated at 7.4 Ma (de Verteuil and Norris, 1996). This boundary is bracketed by samples at 59.9 to 52.4 m (196.5 to 171.8 ft) depth and correlates to near the top of calcareous nannofossil Zone NN 11. The top of Zone DN10 is calibrated at 5.9 Ma. Powars and Bruce (1999) reported strontium-isotope dates from shells in the correlative strata from the nearby Newport News Park 2 corehole; those dates suggest that part of the Eastover Formation ranges from 6.2 Ma to 5.5 Ma, equal to the upper part of calcareous nannofossil Zone NN 11.

The Eastover Formation's lower contact with the St. Marys Formation is not precisely dated at this point and may be a conformable contact or a minor unconformity representing a hiatus of less than 0.5 m.y. The unconformity between the Eastover Formation and the overlying Yorktown Formation represents at least a 1.9-m.y. hiatus (see Edwards and others, this volume, chap. H).

Macrofauna and microfauna and microflora in the Langley core indicate that the Eastover Formation was deposited in a shallow-shelf to nearshore, marine environment. The molluscan genera are similar to modern subtropical to warm temperate marine-shelf assemblages that live in nearshore shallow-water environments with diverse substrates. The Eastover ostracode assemblages suggest progressively diminished upwelling and a temperate climate in an inner-middle neritic shelf setting.

Yorktown Formation (Pliocene)

Marine sediments of the Pliocene Yorktown Formation are present from 23.3 to 2.2 m (76.3 to 7.2 ft) depth in the Langley core (figs. G19 and G20). The Yorktown deposits unconformably overlie similar shallow-marine deposits of the Eastover Formation. The Yorktown consists of calcareous, muddy, very fine to fine quartz sand containing common macrofossils and microfossils.

As is common at most of the other marine unconformities, the basal shelly sand of the Yorktown corresponds to a high resistivity-log deflection and a high natural-gamma-ray-log deflection (fig. G7). The contact with the underlying sandy clay of the uppermost Eastover is marked by a sharp reduction of resistivity values opposite the Eastover section.

The upper contact of the Yorktown is lithologically sharp between the dark-gray, noncalcareous (where leached by ground water) to calcareous, fine-grained sediments of the Yorktown and the oxidized medium to coarse sand of the basal part of the overlying upper Pleistocene Tabb Formation. Because core recovery was poor in this contact interval, five auger holes were made nearby. The original 2.6-m-deep (8.5-ft-deep) hand-auger hole was made in apparently undisturbed forest land about 18 m (60 ft) north-northwest of the core site. This hole provided detailed data on the Yorktown and Pleistocene sediments and the nature of the contact between them.

The Yorktown in the Langley core is composed principally of grayish-olive to greenish-gray, very fine to fine sand, silt, and clay and whole and broken shells. Quartz, aragonite, and calcite are the most abundant minerals; lesser amounts of glauconite, phosphate, and mica are present. Much of the medium to coarse sand and all of the coarser clasts are composed of aragonite and calcite. Shell material from the upper 12 cm (0.4 ft) of the Yorktown in the auger hole is partially to wholly leached.

Bedding in the Yorktown part of the core is indistinct, and variations in texture and shell content are gradational. Laminae of well-rounded and sorted fine quartzose sand occur sporadically in the core. The basal 0.5 m (1.6 ft) of the Yorktown shows a increase in shell material downward to the contact at 23.3 m (76.3 ft) (see fig. G19). Beds with shell concentrations occur at depth intervals of 19.7 to 16.8 m (64.5 to 55 ft) and 13.2 to 12.3 m (43.4 to 40.2 ft) and at about 6.7 m (22 ft). Almost all shell material, even in the shell-rich zones, is matrix supported. Although larger planar shells and shell fragments in the core are subhorizontal, especially in fossil-rich intervals, most of the other shell material is randomly oriented.

Much of the Yorktown Formation in the Langley core has been bioturbated. The fauna is dominated by gastropods, most commonly *Crepidula fornicata*, and bivalves. Scaphopods, bryozoans, barnacles, and corals are less common. Echinoid spines and plates, sponge spicules, ostracodes, and foraminifera are also found in the finer fractions. Examination of the macrofossils from the basal part of the Yorktown Formation reveals reworked Eastover fossils mixed with Yorktown fossils. A reworked Oligocene or Miocene dinocyst was found at 7.3 m (24 ft) above the contact (Edwards and others, this volume, chap. H, fig. H11).

The mollusk and ostracode data suggest that the lowest part of the Yorktown, the Sunken Meadow Member (Zone 1 of Mansfield, 1943), is missing at this site and that most of the section contains several Pliocene age-diagnostic ostracodes that place it in the *Orionina vaughani* Assemblage Zone (see Edwards and others, this volume, chap. H). This zone correlates with the Rushmere, Morgarts Beach, and Moorehouse Members (undifferentiated) of the Yorktown Formation (Ward and Blackwelder, 1980; equivalent to Mollusk Zone 2 of Mansfield, 1943).

From a subtle contact at 20.4 m (66.9 ft) downward to the top of the Eastover, the nearly 3 m (9.7 ft) of sediment contains

Figure G20. Photograph of the USGS-NASA Langley core showing the contact (short white lines) between cobbles of the Tabb Formation (Qt, upper Pleistocene) and the underlying dark, finer grained, marine strata of the Yorktown Formation (Ty, Pliocene). The contact is apparently disturbed as cobbles are pushed down a few feet below the contact. The contact was found at a depth of 2.2 m (7.2 ft) in the original nearby auger hole. Top of core is at upper left.

no diagnostic macrofossils or ostracodes; however, the calcareous nannofossils from this interval indicate an early Pliocene age, and the dinoflagellate assemblage includes a *Selenopemphix armageddonensis,* which is generally found in the Miocene but is also reported in the Pliocene. Below this subtle contact at 20.4 m (66.9 ft), the lack of mollusks that are typically found in the Sunken Meadow Member argues against this interval being assigned to the Sunken Meadow Member; however, the nannofossil data indicate that the interval could represent the Sunken Meadow Member. Above this subtle contact at 20.4 m (66.9 ft), several age-diagnostic mollusks were found, including *Chesapecten madisonius,* that indicate assignment to Zone 2 of Mansfield (1943).

The upper part of the Yorktown Formation (Zone 2 of Mansfield, 1943) was deposited under shallow-marine conditions on an unstable continental shelf (Johnson, Kruse, and others, 1998). At the time, the Langley area was surrounded on the north, west, and south by a series of large, discontinuous, arcuate, planar and crossbedded bioclastic sand shoals. There is insufficient evidence to establish their presence to the east in the eastern half of the annular trough of the Chesapeake Bay impact structure. These shoals limited the influx of terrigeneous sediment (silicate minerals) into the Langley area to silt, fine sand, and clay; skeletal carbonates and glauconite were indigenous. Because there is only one lithic break at 20.4 m (66.9 ft) within the Yorktown, sedimentation rates appear to have been relatively constant during deposition. The uppermost Yorktown has been removed by erosion at the Langley site. Ornamentation on most whole fossils in the Yorktown part of the core is well preserved, suggesting relatively rapid burial and low energy conditions. Furthermore, many species present in the Langley core favor or tolerate turbid waters and muddy bottoms. The presence of large species of the gastropod *Scaphella* and other subtropical forms in the upper part of the Yorktown south of the James River (G. Stephens, fossil collector, and G.H. Johnson, College of Willliam and Mary, oral commun., 1995) indicates significantly warmer conditions than today during the deposition of the Yorktown Formation.

Microfossil and macrofossil data acquired before the Langley corehole was drilled (Ward and Blackwelder, 1980; Gibson, 1983; Hazel, 1983; Cronin and others, 1984; Dowsett and Wiggs, 1992) indicate that the Yorktown is early and early late Pliocene in age (regionally the Yorktown has been reported to contain foraminiferal zones N18, N19, and N20). The age of the Yorktown from outcrops in southeastern Virginia extends from 4.0 Ma to 3.0 Ma according to Dowsett and Wiggs (1992). Analysis of calcareous nannofossil samples from the Langley core indicates (1) that the lower part of the Yorktown below about 20.4 m (66.9 ft) is no younger than early Pliocene (no younger than Zone NN 15) and (2) that the upper part of the Yorktown above 20.4 m (66.9 ft) is assignable to Zone NN 16-17 and, thus, is latest early or late Pliocene in age (Edwards and others, this volume, chap. H). The unconformity at the base of the Yorktown in the Langley core represents at least a 1.9-m.y. hiatus, and the upper unconformity represents about a 2.4-m.y. hiatus (Edwards and others, this volume, chap. H).

Tabb Formation (Upper Pleistocene)

In the Langley core, sediments of Pleistocene age are present from the unconformable contact with the Yorktown (fig. G20) to the top of the corehole section (land surface). These surficial sediments are assigned to the Lynnhaven Member of the Tabb Formation.

The Tabb-Yorktown contact was found in the Langley core at 3.4 m (11.0 ft) depth by Powars, Bruce, and others (2001); however, during the coring operation, pebbles and cobbles in the Tabb were pushed downward into the water-saturated, weathered Yorktown by the bit, yielding a highly disturbed sedimentary sequence in the core barrel. Five adjacent supplemental auger holes suggest that the Tabb-Yorktown contact must be higher. In the original auger hole, the contact between the Tabb and Yorktown is placed at a depth of 2.2 m (7.2 ft) and is marked by a change from a light-brown (10*YR* 6/20), well-rounded and sorted, medium to coarse, quartzose sand (Tabb) above to a strong-brown (7.5*YR* 5/6), nonfossiliferous, leached silty fine sand below. The contact is sharp to gradational over 1.8 cm (0.7 in.) and is burrowed in places.

The Tabb Formation of late Pleistocene age is the surficial stratigraphic unit on the eastern part of the York-James Peninsula (Johnson, 1976; Johnson and others, 1987; Mixon and others, 1989). In this region, it is subdivided into three members: the oldest and topographically highest Sedgefield Member, the intermediate Lynnhaven Member, and the youngest and lowest Poqouson Member. The Lynnhaven Member of the Tabb Formation is the mapped surficial unit at the Langley corehole (Johnson, 1972; Johnson and others, 1987; Mixon and others, 1989).

In the original auger hole near the Langley corehole, the Lynnhaven has a basal medium to coarse sand (34 cm (1.1 ft) thick) described above. From lowest to highest, the following layers appear above the basal sand:

- Silty clay mottled brownish yellow (18 cm (0.6 ft) thick)
- Silty clay containing well-rounded pebbles to cobbles and fining upward (18 cm (0.6 ft) thick)
- Silty clay with scattered medium and coarse sand grains and a surficial friable silt that grades upward into the next layer (58 cm (1.9 ft) thick)
- Silty clay (91.4 cm (3.0 ft) thick) (top of Pleistocene)
- Leaf litter (5 cm (2 in.) thick) (Holocene)

Except for burrows, the Lynnhaven is nonfossiliferous at Langley. The only reported fossil in this unit on the York-James Peninsula is *Crassostrea virginica* recovered from the A.B. Southall pit at the toe of the Big Bethel scarp, about 4 km (2.5 mi) west northwest of the Langley corehole (Johnson, 1976).

The Tabb Formation is considered to be late Pleistocene in age and may have been deposited in oxygen-isotope Stage 5c. Radiometric, thermoluminescence, and amino-acid age estimates on materials from the Tabb are equivocal. The Lynnhaven Member has been correlated with part of the Sandbridge Formation, Kempsville Formation, and other formations in the central Atlantic Coastal Plain (Johnson and others, 1987).

During the deposition of the Lynnhaven Member of the Tabb Formation, sea level was about +5.5 m (+18 ft) relative to present mean sea level (NAVD 88). Lynnhaven sediments were deposited in brackish waters of an ancestral Chesapeake Bay. This bay was bounded on the east by the Eastern Shore and on the west by the York-James Peninsula. It was open to the northern Chesapeake region, partially restricted on the southwest by the eastward extension of the Big Bethel scarp, and open to the south and southeast. The York River discharged fine sand, silt, and clay into this bay. The coarse clasts present in this member at Langley were derived from erosion of the Shirley Formation (middle Pleistocene) and the Sedgefield Member (lower upper Pleistocene) of the Tabb Formation. In addition to the fine sediment delivered by the York River, erosion of the upper parts of the Yorktown, Shirley, and Sedgefield Member of the Tabb yielded most of the fines in the Langley core.

Conclusions

The USGS-NASA Langley core, together with geophysical surveys, provides essential sedimentary and structural data needed for the further refinement of the geological framework of the region and clearly documents the crater's existence and effects on the regional geologic framework. This kind of information is required for the development of an accurate representation of the hydrological framework in the subsurface, which is needed for ground-water modeling.

The postimpact deposits consist of 235.65 m (773.12 ft) of upper Eocene to Quaternary deposits that buried the crater and the synimpact deposits. Except for some Pleistocene fluvial-estuarine deposits, all of the postimpact deposits are marine clays, silts, and very fine to very coarse sands that may include diatomaceous, glauconitic, shelly, and rare thin calcium-carbonate-cemented intervals. The creation of a persistent bathymetric low due to the crater's deep depression and postimpact loading and compaction have resulted in the deposition of several postimpact stratigraphic units that are preserved within the Chesapeake Bay impact structure and nowhere else beneath the Virginia Coastal Plain (Powars and Bruce, 1999; Powars, 2000). These units are the Chickahominy Formation (upper Eocene), Delmarva beds (lower Oligocene), Drummonds Corner beds (upper lower Oligocene), and Newport News beds (lower Miocene).

The postimpact sediments in the Langley core are primarily fine grained and contain about 149.6 m (491 ft) of mostly very fine to fine sand, silt, and clay and about 85.9 m (282 ft) of fine to medium sand with scattered coarser grains (commonly muddy). The Chickahominy Formation, the Calvert Formation excluding the Newport News beds, the St. Marys Formation, and the lower part of the Eastover Formation are all primarily fine grained, whereas the Drummonds Corner beds, the Newport News beds, the upper part of the Eastover Formation, the Yorktown Formation, and the Tabb Formation are generally sandier and make up the aquifer layers in this part of the system. In the western part of the crater's annular trough, there appears to be a constant layering of the finer grained postimpact layers (confining units) with the sandier layers (aquifers) according to the regional core data reported by Powars and Bruce (1999).

Correlation of the postimpact units with the seismic data indicates that the postimpact stratigraphic units appear to have some distinct seismic signatures and are clearly fractured and faulted, but to a much lesser degree than the underlying synimpact deposits. The seismic images also show that most of the postimpact deposits have a small dip toward the inner basin.

This investigation provides some of the foundation data needed to more accurately model the directions of ground-water flow and the potential for movement of salty water to well fields in the vicinity of the impact crater. As ground-water use increases in the Hampton Roads region and public water utilities increasingly tap into brackish-water aquifers as sources of drinking water, additional information about the Chesapeake Bay impact crater will be needed for future management of these ground-water resources.

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The USGS Rocky Mountain Drilling Unit drilled the USGS-NASA Langley corehole with support from the USGS Eastern Earth Surface Processes Team's drilling crew. The USGS drill crew included Arthur C. Clark (supervisor and lead driller), Jeffery D. Eman (lead driller), Stephen J. Grant (lead driller), Donald G. Queen (operations and supply), Manuel Canabal Lopez, Eugene F. Cobbs, Eugene F. Cobbs, III, Orren C. Doss, Robert Hovland, and Michael E. Williams.

Stephen E. Curtin (USGS) and Richard E. Hodges (USGS) conducted the geophysical logging of the Langley corehole.

The authors of this chapter and USGS geologists Robert G. Stamm, J. Stephen Schindler, and Laurel M. Bybell wrote the field descriptions of the Langley core at the drill site. The following members of the USGS also served as site geologists: Wilma B. Alemán Gonzalez, Noelia Baez Rodríguez, Omayra Bermudez Lugo, Karl M. Dydak, Samuel V. Harvey, Robert R. Lotspeich, Rosenelsy Marrero Cuebas, Colleen T. McCartan, E. Randolph McFarland, and Thomas Weik. Core photographs in this chapter were taken by the first author (Powars).

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Appendix G1. Lithic Summary of the Postimpact Section of the USGS-NASA Langley Core

Depth to base, in meters (feet)	Thickness, in meters (feet)	Lithology
	0.6 (2.1)	GRAVEL, clay, silt, sand, and cobbles up to 9.1 centimeters (cm; 3.6 inches (in.)) in diameter; quartz, quartzite, chert; dark yellowish orange (10*YR* 6/6).
Note: Nearby auger holes indicate that the base of the Pleistocene is at 2.2 meters (m; 7.2 feet (ft)) depth.		
		Tabb Formation, Lynnhaven Member (upper Pleistocene)
3.4 (11.0)		-----------------------------sharp unconformable contact ----------------------------
		Yorktown Formation (Pliocene)
	11.7 (38.5)	SAND (very fine to fine), muddy; primarily quartz and trace glauconite (1 percent glauconite and phosphate in upper 1 m (3 ft); less than 20 percent mollusk fragments throughout section, with an exception in the interval at 12.3–13.2 m (40.2–43.4 ft) depth containing 50–70 percent shell fragments and whole valves (pelecypods dominate with occurrence of scaphopods, turritellids, gastropods, and echinoid spines); very sparse to common microfauna throughout section; soft, poorly compacted, bioturbated; basal contact sharp with sand-filled burrows extending down 0.5 m (1.7 ft) into the silty clay below; dark greenish gray (5*GY* 4/1) in upper 0.5 m (1.7 ft), grayish olive green (5*GY* 3/2) throughout remaining interval.
15.1 (49.5)		----------------------------------sharp burrowed contact ------------------------------
	1.6 (5.3)	CLAY, silty, slightly sandy (very fine) increasing downward with lowest 0.5 m (1.7 ft) interbedded silty clay and micaceous, silty very fine to fine sand; 5 percent quartz sand, trace glauconite, 1 percent white mica; mollusk fragments (ranging from common to abundant), sparse echinoid spines; texture mottling due to bioturbation; grayish olive green (5*GY* 3/2).
16.7 (54.8)		------------------------gradational contact across 0.03 m (0.1 ft) -------------------
	3.7 (12.1)	SAND (very fine to fine), very muddy; quartz, glauconite (up to 1 percent), calcareous matrix, mollusk fragments (ranging from common to abundant), sparse echinoid spines, sponge borings, and microfauna; bioturbated, soft to slightly compacted; grayish olive green (5*GY* 3/2).
20.4 (66.9)		--------------------------------subtle sharp contact------------------------------------
	2.9 (9.4)	SAND (very fine), muddy; quartz, trace glauconite, white mica, abundant sulfides from 21.3 to 22.5 m (70 to 74 ft) depth; sparse microfauna, mollusk fragments (1 percent, very fine to fine), pelecypods (large fragments present and increasing downward at 22.0 m (72.2 ft) depth and from 22.8 to 23.3 m (74.8 to 76.4 ft) depth), abundant fragments (up to 5 cm (2 in.)) of blackened oysters in basal 0.1 m (0.4 ft); soft, poorly compacted, massive, texture mottled, bioturbated; dark greenish gray (5*GY* 4/1).

Depth to base, in meters (feet)	Thickness, in meters (feet)	Lithology
		Yorktown Formation (Pliocene)
23.3 (76.3)	--------------------sharp, burrowed unconformable contact--------------------------	
		Eastover Formation (upper Miocene)
	3.0 (10.0)	CLAY, silty, sandy (very fine, 5 percent); trace glauconite (gradually increases downward to 5 percent at 26.2 m (85.9 ft), 1 percent white mica, quartz sand (increases downward), up to 3 percent sulfide spheres and irregular masses to abundant sulfides, finely crystalline irregular masses of pyrite occur as alteration on glauconite; faintly texture mottled, bioturbated (dark, sand-filled burrows, 1.3–2.5 cm (0.5–1.0 in.) wide, from 23.3 to 23.6 m (76.4 to 77.4 ft) depth); very thin bedding from 23.9 to 24.0 m (78.5 to 79 ft) depth; dark greenish gray (5*GY* 4/1).
26.3 (86.3)	-------------------------------------gradational contact --------------------------------	
	42.1 (138.2)	SAND (very fine to medium), muddy to slightly muddy; most of the lower part of the Eastover from about 64.0 m (210.0 ft) depth upward to 42.7 m (140.0 ft) depth is a muddier fine-grained facies; generally up to 1 percent glauconite (3–5 percent in the interval of 33.4–35.1 m (109.5–115.1 ft) depth), up to 1 percent mica, quartz sand, abundant sulfides in top 0.8 m (2.7 ft); locally sparse microfauna, mollusks (sand sized to whole valve) are present variably up to 70 percent (pectens, oysters, scaphopods, and turritellids), *Isognomon* is scattered to abundant from 27.4 to 64.0 m (90.0 to 210.0 ft) depth, *Turritella* is common to abundant from 37.8 to 58.2 m (124.0 to 191.0 ft) depth, pectens are concentrated into layers forming a shell hash of stacked(?) storm deposits from 27.1 to 28.7 m (89.0 to 94.0 ft) depth, other shell hashes are at depths of 34.4–37.5 m (113.0–123.0 ft), 38.2–41.6 m (125.2–136.5 ft), and 56.8–61.2 m (186.2–200.7 ft), echinoid spines are sparse throughout most of the section but are abundant from 51.8 to 48.8 m (170.0 to 160.0 ft) depth; soft, poorly compacted, thoroughly bioturbated with sand-filled, clay-filled, and back-filled burrows, texture mottled, laminated (laminae 1 millimeter (mm) thick) shelly and carbonaceous clayey silt to silty clay from 46.0 to 46.1 m (151.0 to 151.2 ft) depth; color ranges from dark greenish gray (5*GY* 4/1) to grayish olive green (5*GY* 3/2). The base of the Eastover is within a poorly recovered 2.0-m-thick (6.7-ft-thick) interval and is placed at the base of a 0.06-m-thick (0.2-ft-thick), calcite-cemented, sand hard bed; contact placement is based on correlation with a kick at 68.4 m (224.5 ft) depth on the short-normal resistivity log (fig. G7); mollusk shell fragments and molds present, possible burrows/borings represented by uncemented sand tubes, medium gray (*N*5).
		Eastover Formation (upper Miocene)
68.4 (224.5)	------ contact not recovered; may be conformable or a minor unconformity-----	
		St. Marys Formation (upper Miocene)

Depth to base, in meters (feet)	Thickness, in meters (feet)	Lithology
	42.5 (139.5)	CLAY, silty, sandy (above 100.6 m (330.0 ft) depth very fine to fine), ranging from 2 to 15 percent, subrounded to subangular quartz, well to moderately sorted; increase in clay and microfauna below 79.2 m (260 ft) depth, increase in shells and shell material from 85.3 to 88.4 m (280 to 290 ft) depth, shells dominated by *Turritella* from 88.3 to 97.5 m (290 to 320 ft) depth, foraminifera sand at 100.6–103.5 m (330.0–339.6 ft) depth, no quartz; foraminifera sand from 103.5–110.9 m (339.6–364.0 ft) depth with sparse quartz (very fine to fine) and faint thin laminations; up to 3 percent glauconite throughout section (no occurrence at 97.4–103.5 m (319.5–339.6 ft) depth), up to 5 percent white mica, pyrite occurrence varies from trace to frequent (scattered pyritized burrows noted below 82.1 m (269.4 ft) depth, and pebble-sized pyrite chunks with reduction rims present at 103.5–106.5 m (339.6–349.4 ft) depth, trace irregular masses of sulfide noted at 70.0–76.0 m (229.6–249.3 ft) depth, up to 5 percent dark heavy minerals noted at 76.0–88.2 m (249.3–289.4 ft) depth, scattered acicular gypsum crystals noted below 106.5 m (349.4 ft) depth; sparse microfauna (benthic foraminifera and ostracodes), rare sponge spicules noted below 82.5 m (270.7 ft) depth, very sparse echinoid spines noted between 88.2 and 91.3 m (289.4 and 299.5 ft) and below 106.5 m (349.4 ft) depth, 1 percent plant fragments noted at 76.0–91.3 m (249.3–299.5 ft) depth, a fish tooth noted below 94.3 m (309.3 ft) depth, fish bone fragments between 100.4 m (329.4 ft) and 103.5 m (339.6 ft) depth; moderately dense and compact, texture mottled and bioturbated; top 4.6 m (15.1 ft) are olive gray (5*Y* 4/1), below 73.0 m (239.5 ft) depth, color ranges from grayish olive green (5*GY* 3/2) to dark greenish gray (5*GY* 4/1).
110.9 (364.0)	-------------------------------gradational contact-------------------------------------	
	2.9 (9.4)	SILT to SAND, clayey, sandy (very fine to medium); quartz (subrounded to angular), trace glauconite, white and brown mica (sparse increasing downward to abundant), pyrite (sparse increasing downward to abundant), trace acicular gypsum crystals, and abundant phosphate; rare mollusks, rare echinoid spines, sparse foraminifera, rare fish bones and teeth, a pyrite-filled tube fragment, and abundant wood chips; moderately dense and compacted, texture mottled and bioturbated; ranging from grayish olive green (5*GY* 3/2) to grayish olive (10*Y* 4/2). Subtly coarsens downward to subtle contact with underlying clay.
113.8 (373.4)	---subtle sharp contact----------------------------	
	2.2 (7.1)	CLAY, silty, sandy (very fine to medium); rare quartz, abundant white mica, and abundant pyrite; scattered thin mollusk shells (clams), abundant foraminifera, and abundant wood chips; faintly laminated; grayish olive green (5*GY* 3/2).
116.0 (380.5)	--gradational contact------------------------------	
	3.5 (11.5)	SILT, clayey, sandy (very fine to medium); quartz, 1 percent glauconite, moderately abundant white mica, and abundant pyrite; sparse clam shells, locally abundant foraminifera, rare sponge spicules, scattered wood chips, and rare bone chips; texture mottled, bioturbated; grayish olive green (5*GY* 3/2).
119.5 (392.0)	-----------------------------------gradational contact----------------------------------	

Depth to base, in meters (feet)	Thickness, in meters (feet)	Lithology
	4.1 (13.5)	SAND (very fine to medium, primarily very fine to fine), silty, clayey; dominant quartz (subangular to angular), up to 1 percent glauconite, 1–2 percent phosphate; mollusk (mostly clam) shell fragments abundant, foraminifera moderately abundant, few sponge spicules present, some wood pieces present, and sparse fish vertebrae and teeth; texture mottled and bioturbated, grading down to faintly crossbedded very fine to coarse sand; color darkens downsection, olive gray (5*Y* 3/2) to dark greenish gray (10*Y* 3/1) to greenish black (10*Y* 2.5/1).
		St. Marys Formation (upper Miocene)
123.6 (405.5)	----------------------sharp, burrowed unconformable contact -----------------------	
		Calvert Formation, Calvert Beach Member (middle Miocene)
	15.4 (50.6)	SILT, clayey, with scattered grains of sand of various mineralogies; quartz (very fine to fine), mica (very fine), pyrite (very fine to coarse), trace glauconite (very fine to coarse), and sparse rounded phosphate grains of sand size; common to abundant foraminifera, rare pyritized diatoms at top becoming more common downward, rare fish scales and vertebrae, and rare wood chips; thinly laminated, breaks apart into shalelike chips; becomes a MUDDY SAND (very fine to medium) in basal 0.6 m (2.1 ft) and has increased phosphate, abundant burrows filled by clean coarse to very coarse sand, some burrows filled by clay and silt, and includes tiny shell fragments, scattered fish vertebrae, sharks' teeth, rays' teeth and bone (phosphatized), mostly dark-greenish-gray (10*Y* 4/1) with a small portion of dark-olive-gray (5*Y* 3/2) material noted near the middle of the section and for the finer grained burrows in the basal sand.
		Calvert Formation, Calvert Beach Member (middle Miocene)
139.0 (456.1)	----------------irregular, sharp, burrowed unconformable contact ------------------	
		Calvert Formation, Plum Point Member (middle Miocene)
	0.3 (1.0)	SILT, clayey, few scattered very fine to fine sand grains, rare foraminifera; dark olive gray (5*Y* 3/2).
139.3 (457.1)	----------------------------------gradational contact-----------------------------------	
	1.2 (4.0)	SAND (fine to medium with scattered coarse to very coarse grains increasing downward to contact) varies from grain-to-grain contact to grains floating in clay-silt matrix; mostly quartz (subangular to subrounded) and mica (fine to very coarse), scattered sand-sized phosphate; abundant shells, rare foraminifera; dark olive gray (5*Y* 3/2).
		Calvert Formation, Plum Point Member (middle Miocene)
140.5 (461.1)	-------------------sharp, burrowed unconformable contact--------------------------	
		Calvert Formation, Newport News beds (lower Miocene)

Depth to base, in meters (feet)	Thickness, in meters (feet)	Lithology
	3.0 (9.8)	SAND to SHELLY SAND (fine to very coarse, primarily medium to coarse) varies from grain-to-grain contact to grains floating in clay-silt matrix; poorly sorted; primarily clear quartz (very angular to well rounded) with some smoky and blue quartz, 20–30 percent glauconite and phosphate; coarsens down to contact becoming a fine sand with scattered small pebbles; abundant shells throughout the section (in places a shell hash), shells concentrated in two separate lithified calcium-carbonate-cemented zones, each about 0.4 m (1.3 ft) thick and located near the top and bottom of the section, also semilithified at very top, scattered foraminifera; dark olive gray (5*Y* 3/2) except for the lithified segments, which are olive gray (5*Y* 4/2).
		Calvert Formation, Newport News beds (lower Miocene)
143.5 (470.9)	----------------------------sharp unconformable contact-------------------------------	
		Old Church Formation (upper Oligocene)
	32.5 (106.5)	SIX FINING-UPWARD SEQUENCES, range from 1.1 m (3.5 ft) to 11.0 m (36.1 ft) in thickness, each grades upward from better sorted sands to clay-silt-matrix-supported sands, with burrowed sand-over-clay contacts at depths of 154.5 m (507.0 ft), 155.8 m (511.0 ft), 160.2 m (525.5 ft), and 161.2 m (529.0 ft) and one contact indicated by the resistivity log at 166.1 m (545.0 ft) (fig. G7). SAND (very fine to very coarse), variable clay-silt matrix, scattered granules to small pebbles; poorly sorted, very angular to well rounded, varies from grain-to-grain contact to grains supported in clay-silt matrix (top of cycle); few scattered, indurated thin layers and patches below 149.2 m (489.5 ft) depth; abundant quartz (up to pebble size of 0.7 cm (0.3 in.)), abundant glauconite, scattered phosphate (up to pebble size of 0.5 cm (0.2 in.)), and scattered white mica flakes present below 170.7 m (560.0 ft) depth and scattered throughout with minor amounts of pyrite, carbonaceous material, and occasional very small sharks' teeth; foraminifera ranging from rare to abundant and diverse (more abundant in finer grained upper parts of the sequences), sediment-back-filled and clay-lined burrows present throughout; scattered mollusk shells and shell fragments (increase in basal sands of each sequence), small pecten at 160.0 m (524.9 ft) depth, sponge spicules present near 161.5 m (529.9 ft) depth, echinoid spines present near 162.7 m (533.8 ft) depth, and wood clast (1 cm x 3 mm (0.4 x 0.1 in.)) at 161.0 m (528.2 ft) depth; faintly bedded, by clay-silt matrix, but mostly bioturbated, scattered lenses and patches of calcite-cemented sand present near 161.0 m (528.2 ft) and below 169.0 m (554.5 ft) depth; color varies from olive (5*Y* 5/3) near top, to dark olive gray (5*Y* 3/2), olive gray (5*Y* 4/2), and black (5*Y* 2.5/1)/(5*Y* 2.5/2) below, to very dark gray (5*Y* 3/1) near bottom.
		Old Church Formation (upper Oligocene)
176.0 (577.4)	---------------------sharp, burrowed unconformable contact------------------------	
		Drummonds Corner beds (upper lower Oligocene)

Depth to base, in meters (feet)	Thickness, in meters (feet)	Lithology
	2.4 (8.0)	SILT, very clayey, sandy (very fine to fine); scattered quartz and white mica (decreasing downward), moderately abundant phosphate and glauconite, phosphate content increasing downward to abundant; moderately abundant foraminifera increasing downward to abundant, abundant burrows (some concentrated near upper boundary and filled with sand from overlying Old Church Formation), very effervescent with hydrochloric acid application; thinly bedded (1 cm (0.4 in.)) to laminated (millimeter scale); colors ranging from olive gray (5*Y* 3/2) to grayish olive green (10*Y* 4/2).
178.4 (585.4)	--------------------------------gradational contact--------------------------------------	
	4.9 (15.9)	SAND (very fine to very coarse, primarily a very fine to medium sand), silty, moderately clayey, abundant phosphate, lesser quartz and glauconite (both are subrounded to rounded); abundant foraminifera, highly burrowed; faint bedding; coarsens down to 2.2 m (7.1 ft) of basal sand with scattered granules and small quartz pebbles (up to 0.05 cm (0.02 in.)), increased phosphate, and sparse clam and snail shells; olive gray (5*Y* 3/2) with mottling (due to burrows) of olive black (5*Y* 2/1).
		Drummonds Corner beds (upper lower Oligocene)
183.3 (601.3)	----------------------sharp, burrowed unconformable contact------------------------	
		Chickahominy Formation (upper Eocene)
	52.3 (171.8)	CLAYEY SILT to SILTY CLAY throughout section with very rare sand (very fine) and silt near the top, but gradually increasing to sparse further downward; quartz, rare to sparse glauconite (silt to very fine sand sized), glauconite-rich lenses with slight increase in phosphate, quartz, and silt from 221.1 to 223.8 m (725.5 to 734.4 ft) depth overlie 0.06-m-thick (0.2-ft-thick), black (*N*1) clay layer with very dark gray (5*Y* 3/1) clayey-silt-filled burrows; throughout section rare to abundant occurrence of pyrite grains (very fine to fine), nodules, and pyrite-filled shells, sparse rounded phosphate (fine to medium) with scattered occurrence from 221.1 m (725.5 ft) depth down to basal contact; massive to laminated (millimeter scale) top 8.9 m (29.2 ft) becoming more massive with faintly visible thin bedding (1 mm to 1 cm (0.04 to 0.4 in.)) (mica flakes and shells aligned on bedding planes); matrix is very effervescent with application of hydrochloric acid, sparse to abundant foraminifera increasing downward, sparse to abundant shells (clams, scaphopods, echinoid spines, and thin-shelled oysters), increase in shell content from depths of 192.0–195.4 m (630.0–641.0 ft) and 204.5–223.8 m (671.0–734.4 ft), rare fish teeth and scales, scattered wood chips from 207.3 to 213.7 m (680.0 to 701.0 ft) depth, burrows scattered throughout section, abundant phosphate-rich sand-filled burrows from the overlying Drummonds Corner beds extending down 0.7 m (2.2 ft) into the top of the silty clay; in the lower 7.0 m (23.1 ft) increase in quartz silt with rare very fine to fine sand grains; in the lower 16.2 m (53.0 ft) are inclined fracture planes with slickensides at 219.6 m (720.5 ft) depth, several between 225.4 and 226.2 m (739.5 and 742.0 ft) depth, and a fault dipping moderately (about 45°) at 230.0–229.9 m (754.7–754.4 ft) depth (with slickensides and pyritized fault gouge; color varies from olive gray (5*Y* 4/1) to dark greenish gray (5*G* 4/1) to very dark gray (5*Y* 3/1).

Depth to base, in meters (feet)	Thickness, in meters (feet)	Lithology
		Chickahominy Formation (upper Eocene)
235.65 (773.12)	------BASE OF POSTIMPACT DEPOSITS--------sharp conformable contact--	
		Exmore beds (upper Eocene)
	0.19 (0.63)	SILTY CLAY, laminated (millimeter scale) with scattered horizontal silt to very fine sand laminae and a few burrows (including one with the typical Exmore matrix); gray changing upward to dark greenish gray.
235.84 (773.75)	----------------------------------sharp contact------------------------------------	
	0.085 (0.28)	SILT, clayey; millimeter-scale pyrite lattice at the top from 235.84 to 235.87 m (773.75 to 773.85 ft) depth; medium olive gray (5*Y* 5/1).
235.92 (774.03)	----------------------------------sharp contact------------------------------------	
		MATRIX-SUPPORTED SEDIMENTARY-CLAST DIAMICTON (typical Exmore beds)