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

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Chapter H of

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

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

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

Professional Paper 1688

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

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Abstract

The USGS-NASA Langley corehole was drilled in 2000 in Hampton, Va. The core serves as a benchmark for the study of calcareous nannofossils, dinoflagellates, diatoms and silicoflagellates, mollusks, ostracodes, planktonic foraminifera and bolboformids, and vertebrate remains in the upper Eocene, Oligocene, Miocene, and Pliocene sediments in southeastern Virginia. These sediments were deposited after the comet or asteroid impact that produced the Chesapeake Bay impact structure.

The Chickahominy Formation was deposited rapidly in outer neritic to upper bathyal marine environments during the last 2 million years of the late Eocene. The Drummonds Corner beds are newly recognized in the Langley core. These beds appear to represent shallower water or more nearshore deposition than the underlying Chickahominy deposits. Paleontology indicates an age in the later part of the early Oligocene, with a sharp floral and faunal break between the Drummonds Corner beds and the underlying Chickahominy Formation. Late Oligocene sedimentation is represented by the Old Church Formation.

The record of early and middle Miocene deposition in the Langley core is incomplete. The Calvert Formation records brief episodes of deposition in three members, which are separated by unconformities and are called the informal Newport News beds, the Plum Point Member, and the Calvert Beach Member.

A second episode of rapid deposition at the Langley site is preserved as the upper Miocene St. Marys and Eastover Formations. The Eastover is overlain unconformably by the Yorktown Formation, which is both late early and early late Pliocene. The highest unit, the Tabb Formation (Pleistocene), was not studied paleontologically.

Continued movement along faults and fractures of the crater and nearby region may have enhanced the contributions of older material into the various units filling the Chesapeake Bay impact crater, as suggested by the conspicuous reworking of microfossils in many of the samples from the upper Eocene and younger units in the USGS-NASA Langley core.

Introduction

At about 35–36 Ma (about 35 million–36 million years ago), a comet or asteroid hit in shallow marine waters where the Eastern Shore of Virginia is now located (see Horton and others, this volume, chap. A). The USGS-NASA Langley corehole (fig. H1) is near the outer margin of the crater produced by this late Eocene impact. It was drilled during the summer and fall of 2000 in the city of Hampton, Va. Drilling was done by the U.S. Geological Survey (USGS) and its partners (see "Acknowledgments"). The synimpact deposits recovered from the Langley core are discussed in chapters C and D, this volume. Here, we discuss the paleontology of the 235.65 meters (m; 773.12 feet (ft)) of sediments that were deposited subsequent to the impact (table H1; fig. H2).

The lithostratigraphy of the postimpact sediments is described in detail by Powars and others (this volume, chap. G). Upper Eocene, lower Oligocene, and upper Oligocene sediments from the Maryland-Virginia Coastal Plain are unknown or poorly known in outcrop. The Langley core provides an exceptional opportunity to detail the paleontology of these sediments. Miocene, Pliocene, and Pleistocene units have been recognized for nearly 200 years and have been studied extensively in outcrops in Virginia, Maryland, and Delaware. The Langley core provides the opportunity to relate some of these classic stratigraphic units to microfossil and megafossil studies of the

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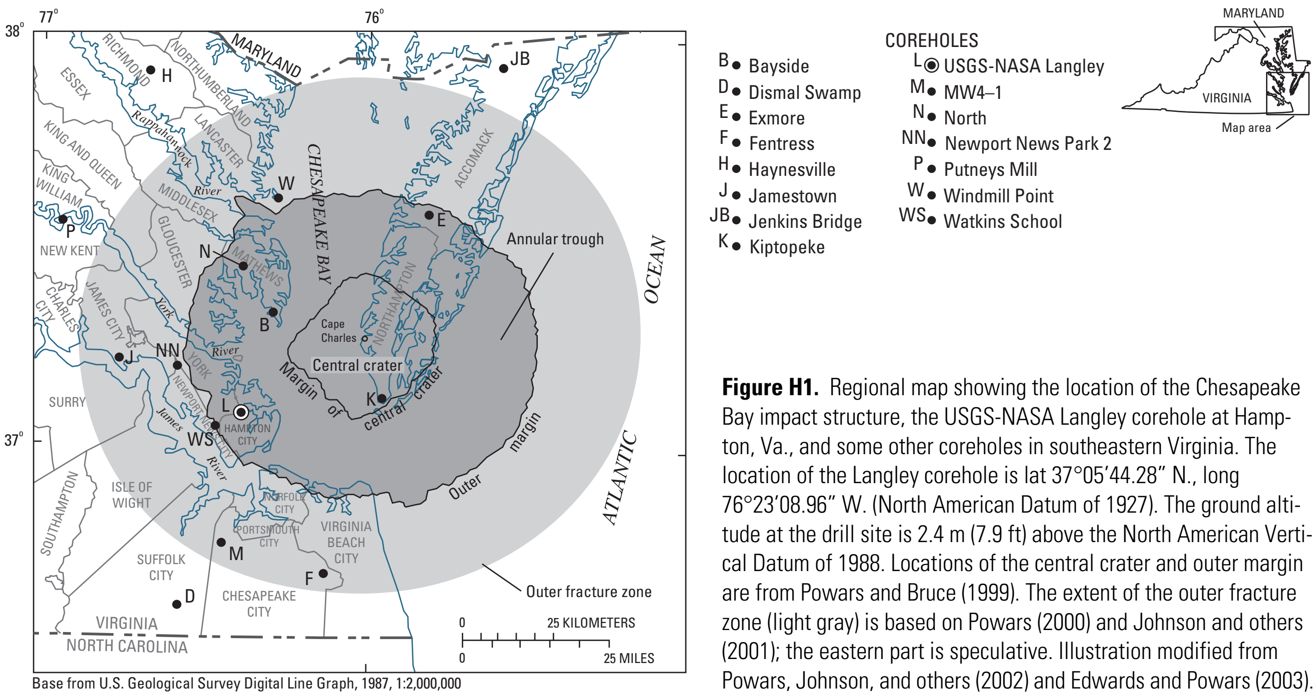


Figure H1. Regional map showing the location of the Chesapeake Bay impact structure, the USGS-NASA Langley corehole at Hampton, Va., and some other coreholes in southeastern Virginia. The location of the Langley corehole is lat 37°05′44.28″ N., long 76°23′08.96″ W. (North American Datum of 1927). The ground altitude at the drill site is 2.4 m (7.9 ft) above the North American Vertical Datum of 1988. Locations of the central crater and outer margin are from Powars and Bruce (1999). The extent of the outer fracture zone (light gray) is based on Powars (2000) and Johnson and others (2001); the eastern part is speculative. Illustration modified from Powars, Johnson, and others (2002) and Edwards and Powars (2003).

Table H1. Postimpact stratigraphic units discussed in this chapter.

Age	Stratigraphic unit	Known from outcrops?	Recognized in Langley core?	Thickness in Langley core (meters)	Thickness in Langley core (feet)
Holocene	Alluvium, swamp, beach deposits	Yes	No	–	–
Pleistocene	Tabb Formation	Yes	Yes	2.2	7.2
Pleistocene	Shirley Formation	Yes	No	–	–
Pleistocene	Chuckatuck Formation	Yes	No	–	–
Pleistocene	Charles City Formation	Yes	No	–	–
Pliocene-Pleistocene	Windsor Formation	Yes	No	–	–
Pliocene	Bacons Castle Formation	Yes	No	–	–
Pliocene	Chowan River Formation	Yes	No	–	–
Pliocene	Yorktown Formation	Yes	Yes	21.1	69.1
Miocene	Eastover Formation	Yes	Yes	45.1	148.2
Miocene	St. Marys Formation	Yes	Yes	55.2	181.0
Miocene	Choptank Formation	Yes	No	–	–
Miocene	Calvert Formation*	Yes	Yes	19.9	65.4
Oligocene	Old Church Formation	Yes; few, very thin	Yes	32.5	106.5
Oligocene	Drummonds Corner beds	No; first reported in Langley core	Yes	7.3	23.9
Oligocene	Delmarva beds	No; subsurface only	No	–	–
Eocene	Chickahominy Formation	No; subsurface only	Yes	52.4	171.82

*Three members of the Calvert Formation are mentioned in this chapter; they record brief episodes of deposition, are separated by unconformities, and are called the informal Newport News beds, the Plum Point Member, and the Calvert Beach Member.

core. Table H1 provides a summary of the stratigraphic units discussed in this chapter.

Paleontologic studies of the postimpact sediments in the USGS-NASA Langley core included work on calcareous nannofossils, dinoflagellates and acritarchs, diatoms and silicoflagellates, mollusks, ostracodes, planktonic foraminifera and bolboformids, and vertebrate remains. Complete taxonomic names are given in appendix H1. Photographs of selected fossils are shown in plates H1–H9. After summaries of previous work, lithostratigraphy, and methods, this chapter contains paleontologic interpretations for each postimpact unit in the Langley core.

Previous Work and Zonations Used

Beginning in the early 19th century, the exposures along the Chesapeake Bay and the riverbanks of Maryland and Virginia have been studied by many researchers, including Thomas Say (1822, 1824), T.A. Conrad (for example, 1832, 1833), W.B. Rogers (1884), W.B. Clark (1895), G.C. Martin (1904), and Clark and Miller (1912). In 1890, G.D. Harris did an extensive study of the bluffs at Yorktown, Va. (published in Ward, 1993). Multidisciplinary studies of the subsurface Virginia Coastal Plain include work on the Oak Grove core (Gibson and others, 1980), the Haynesville cores (Mixon, 1989), and the Fentress, Dismal Swamp, and Exmore cores (Powars and others, 1992). Paleontological data from the Chesapeake Bay impact structure are included in Powars and Bruce (1999) and Powars (2000).

Time scale.—In this chapter, we use the time scale of Berggren and others (1995). Correlation of the time scale with the relevant calcareous nannofossil, dinoflagellate, diatom, silicoflagellate, mollusk, and planktonic foraminifera zones is shown in figure H3.

Calcareous nannofossils.—The calcareous nannofossil zonation used for the upper 236 m (773 ft) of Cenozoic strata in the USGS-NASA Langley core is based upon the zonation of Martini (1971). Calcareous nannofossil biostratigraphy is based on the highest and lowest occurrences of species; FAD indicates a first appearance datum, and LAD indicates a last appearance datum. Important Cenozoic nannofossil datums are given in appendix H2.

Dinoflagellates and acritarchs.—Although there are no widely accepted worldwide zonations for the dinoflagellate cysts (dinocysts) of the Tertiary, two local zonations for the Salisbury embayment of the Atlantic Coast have been published. Edwards (1996) erected six named zones that cover the latest Paleocene to early Eocene. De Verteuil and Norris (1996) erected 10 named and numbered zones (DN1–DN10) that cover the Miocene. Miscellaneous microfossils called acritarchs are studied with dinocysts.

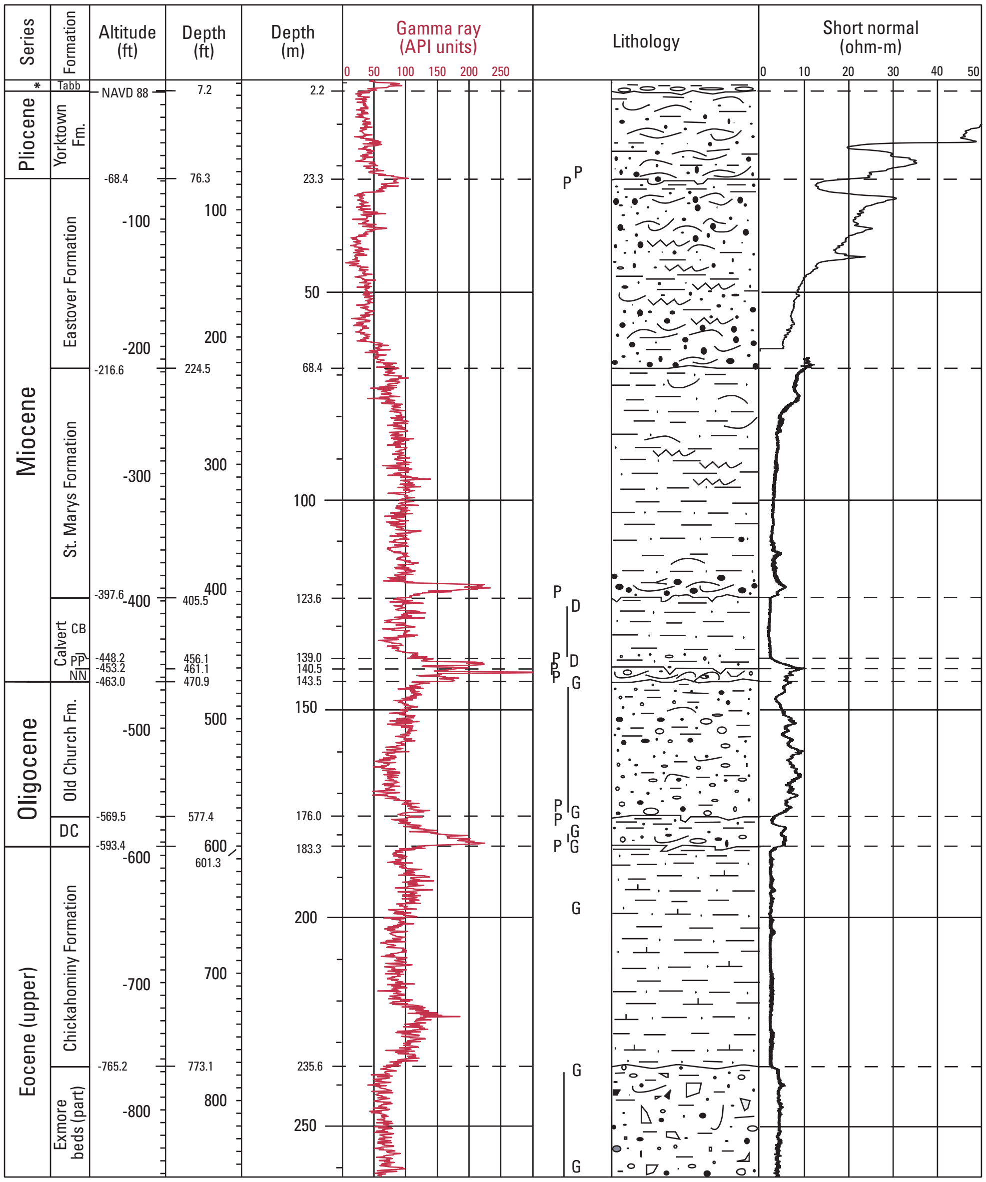
Diatoms and silicoflagellates.—Siliceous microfossils (including diatoms and silicoflagellates) have been documented for more than 100 years from the middle Miocene of the mid-Atlantic coastal region in both outcrop and core material. Earlier studies were largely descriptive, whereas the biostratigraphic studies of the past 20 years (see summaries in Andrews, 1988, and Abbott, 1984) have concentrated on correlating regional zonal schemes with deep-sea zonations and with the geological time scale.

Mollusks.—Mansfield (1943) published his research on the stratigraphy of the Miocene and Pliocene strata of Virginia in Gardner's (1943) work on the molluscan fauna. L.W. Ward and B.W. Blackwelder began extensive work on the physical stratigraphy and molluscan biostratigraphy of the mid-Atlantic Coastal Plain in the 1970s, publishing revisions of the Eocene through Pliocene units (Ward and others, 1978; Ward and Blackwelder, 1980) and establishing molluscan faunal zones (Blackwelder, 1981; Ward, 1992).

Ostracodes.—In contrast to the Gulf of Mexico region, where detailed ostracode zonations exist (see Poag, 1974; Hazel and others, 1980), only a few isolated Eocene-Oligocene ostracode faunas from the Chesapeake Bay region have been described and illustrated in the published literature (for example, Swain, 1951; Deck, 1985). Therefore, the papers of Pooser (1965) and Hazel and others (1980) and references therein were used for species identification of Eocene-Oligocene faunas. The papers of Valentine (1971), Hazel (1983), and Cronin (1990) were used for taxonomy of Miocene and Pliocene faunas. The ostracodes from the classic Miocene Calvert Cliffs of Maryland were described by Ulrich and Bassler (1904), and their taxonomy was updated by Forester (1980).

Planktonic foraminifera and bolboformids.—Previous studies of planktonic foraminifera and bolboformids from cores within or near the Chesapeake Bay impact crater include those by Poag and Aubry (1995), Poag and Commeau (1995), and Poag (1997).

Vertebrates.—No vertebrate biostratigraphic zonation has been erected yet for upper Eocene and Oligocene stratigraphic units in the Atlantic Coastal Plain. The only published vertebrate reports on this general part of the stratigraphic column in the Atlantic Coastal Plain are papers on the selachians of the upper Oligocene or lower Miocene Trent Formation of North Carolina (Case, 1980), late Eocene selachians of south-central Georgia (Case, 1981), and selachians and otoliths from the middle Eocene Piney Point Formation and upper Oligocene Old Church Formation (Müller, 1999).



*Pleistocene.

Figure H2. Stratigraphic column of postimpact units in the USGS-NASA Langley core showing selected geophysical logs, generalized lithology, and locations of samples studied for fossils. Calcareous nannofossil zonation (NP, NN numbers) is from Martini (1971), dinoflagellate zonation (DN) is from de Verteuil and Norris (1996) and de Verteuil (1997), diatom zonation, (*D. penelliptica* = *Delphineis penelliptica* Zone) is from Abbott (1980), silicoflagellate zonation (*C. t.* = *Corbisema triacantha* Zone; *D. s.* = *Distephanus stauracanthus* Subzone; *D. sch.* = *Distephanus schulzii* Subzone) is from Bukry (1981) and Perch-Nielsen (1985), molluscan zonation (M) is based on Blackwelder (1981) and Ward (1992), ostracode zonation is from Hazel (1971), and planktonic foraminiferal zonation (P) is from Berggren and Miller (1988). The Calvert Formation contains the informal Newport News beds (NN), the Plum Point Member (PP), and the Calvert Beach Member (CB). Definitions: DC = Drummonds Corner beds; ft = feet; m = meters; NAVD 88, North American Vertical Datum of 1988; ohm-m = ohm-meters.

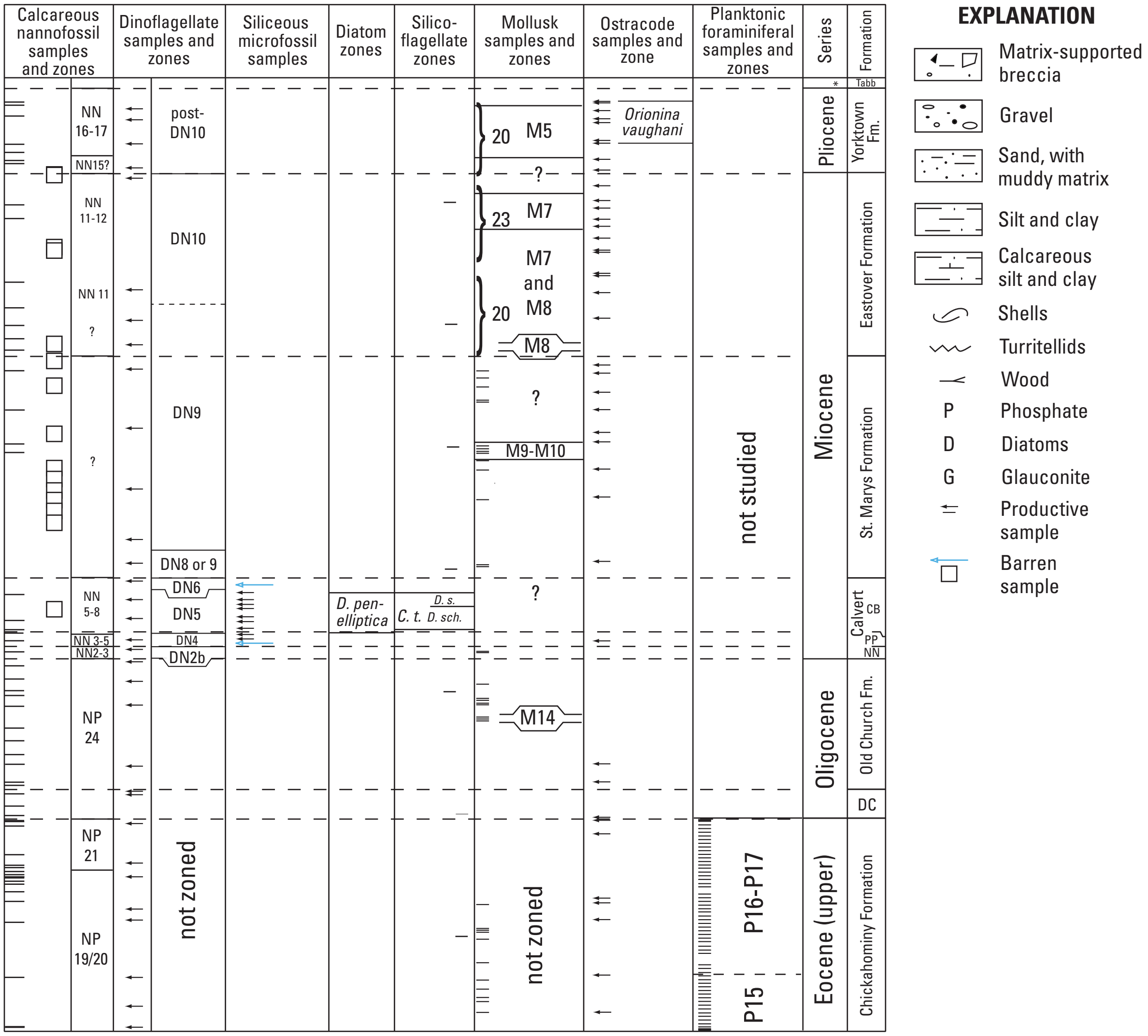
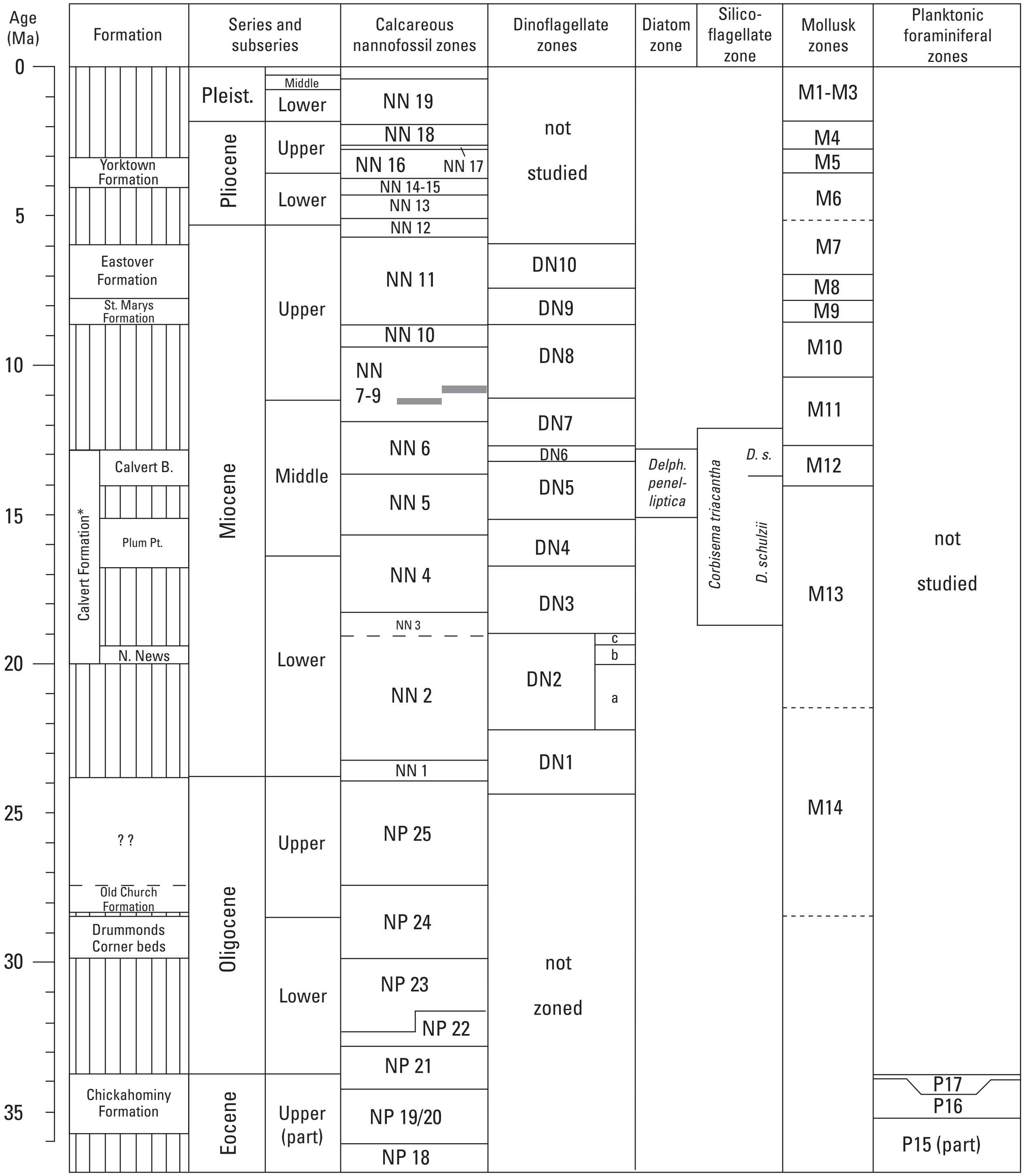


Figure H2. Continued.



* The Calvert Formation contains the informal Newport News beds, the Plum Point Member, and the Calvert Beach Member.

Lithostratigraphy of Postimpact Deposits in the USGS-NASA Langley Corehole

The physical geology of the postimpact sediments in the USGS-NASA Langley core is described in detail by Powars and others (this volume, chap. G). A brief overview is given here.

The base of the Chickahominy Formation in the Langley core represents the beginning of in-place postimpact deposition. This contact is placed at a depth of 235.65 m (773.12 ft) in the core, where massive, calcareous, marine silty clay bearing in-place microfossils overlies a horizontally laminated quartz-glauconitic silt bearing mixed and altered microfossil assemblages. The Chickahominy Formation is a thick section of calcareous clay representing late Eocene deposition.

The Chickahominy Formation is overlain by a shallower marine unit, informally termed the Drummonds Corner beds. These quartz-glauconite sands are placed in the upper part of the lower Oligocene. The lower contact of the Drummonds Corner beds is unconformable and heavily burrowed; it is at a depth of 183.3 m (601.3 ft).

Figure H3 (facing page). Correlation chart for the stratigraphic units and zonations used in the study of the postimpact deposits in the USGS-NASA Langley core. Tabb Formation is not shown. Time scale in Ma (millions of years before present) is from Berggren and others (1995). Calcareous nannofossil zonation is from Martini (1971). Calcareous nannofossil zones NN 7, NN 8, and NN 9 are grouped here. Berggren and others (1995, p. 191) noted inconsistent correlations with the magnetic polarity record, and they presented two separate correlation possibilities for Zone NN 8 (shown in gray). Dinoflagellate zonation and correlations with the time scale of Berggren and others (1995) are from de Verteuil and Norris (1996). Diatom zone is from Abbott (1980). Silicoflagellate zone and subzones are from Bukry (1981) and Perch-Nielsen (1985); abbreviations are defined in figure H2. Mollusk zones are based on Blackwelder (1981) and Ward (1992). Correlation of M zones with DN zones for the Miocene portion of the section is based on de Verteuil and Norris (1996). No data exist to correlate M14, established by Ward (1992), with either DN zones or time; the dashed line indicates an estimate of its placement based on the lithostratigraphic units in which Ward found M14 mollusks. The boundary between M6 and M7 is tentatively placed at the Miocene-Pliocene boundary where Ward (1992) placed it in his stratigraphic section, but no data exist to correlate the M7-M6 boundary with time or DN zones. M1, M2, and M3 of Blackwelder (1981) represent little time and are not present in the Langley core; therefore, they are grouped together in this section. Planktonic foraminiferal zonation is from Berggren and others (1995).

Both the Chickahominy Formation and the Drummonds Corner beds are known only from the subsurface. The Chickahominy Formation was first described from wells in York County, Va. (Cushman and Cederstrom, 1945). The Drummonds Corner beds are newly recognized in the Langley core, although they most likely have been encountered in previously drilled cores in Virginia (Powars and others, this volume, chap. G). They are stratigraphically higher than beds that were informally called the Delmarva beds in the Exmore corehole (fig. H1), located to the northeast of the Langley corehole. No sediments equivalent to the Delmarva beds are recognized in the Langley core.

The Drummonds Corner beds are overlain in the Langley core by the Old Church Formation, a glauconitic, phosphatic quartz sand of late Oligocene age. The lower contact of the Old Church is at a depth of 176.0 m (577.4 ft). The Old Church was first recognized in outcrop by Ward (1985), where it is less than 2 m (6 ft) thick. It has also been recognized in the subsurface (Mixon and others, 1989; Powars and Bruce, 1999; Powars, 2000) and is 32.5 m (106.5 ft) thick at the USGS-NASA Langley corehole site inside the impact structure.

Overlying the Old Church Formation in the Virginia Coastal Plain are Miocene and Pliocene units that may include, in ascending order, the Calvert, Choptank, St. Marys, Eastover, Yorktown, Chowan River, and Bacons Castle Formations (table H1). These are typically overlain by one or more Quaternary units. The Calvert Formation is well represented at Calvert Cliffs along the western shore of the Chesapeake Bay in Maryland and has been studied for over a century (Shattuck, 1902, 1904). The Calvert is typically fine grained and is locally diatomaceous.

In studying the Langley core, we recognize three units within the Calvert Formation (in ascending order from a depth of 143.5 m (470.9 ft)): the informal Newport News beds and two formally named members, the Plum Point Member and the Calvert Beach Member. The Newport News beds consist of 3.0 m (9.8 ft) of shelly sands of early Miocene age. The Plum Point and Calvert Beach Members consist of microfossiliferous silts and silty clays, 1.5 m (5.0 ft) and 15.4 m (50.6 ft) thick, respectively, of middle Miocene age.

The Calvert Beach Member of the Calvert Formation is overlain unconformably by the upper Miocene St. Marys Formation. Except for a basal shelly, phosphatic, quartz sand, the St. Marys consists of calcareous clayey silt to sandy clay and silt. The St. Marys Formation in the Langley core extends from 123.6 to 68.4 m (405.5 to 224.5 ft) depth. The Choptank Formation, which lies between the Calvert and St. Marys Formations elsewhere, is not recognized in the Langley core.

The St. Marys Formation in the Langley core is overlain by the upper Miocene Eastover Formation, which has a shelly, sandy basal lag and consists of clayey, silty sands. The Pliocene Yorktown Formation overlies the Eastover Formation at a heavily burrowed contact; the contact depth is 23.3 m (76.3 ft).

The Yorktown in this core is a calcareous, muddy sand that has abundant macrofossils and microfossils.

The Yorktown is overlain unconformably by 2.2 m (7.2 ft) of oxidized muddy Quaternary gravel and sand of the Lynnhaven Member of the Tabb Formation. The Tabb elsewhere has been dated as late Pleistocene (Rader and Evans, 1993). The upper Pliocene Chowan River and Bacons Castle Formations are not recognized in the Langley core, nor are additional Quaternary units.

Methods

Selected samples from postimpact sediments in the USGS-NASA Langley core were studied for calcareous nannofossils (Bybell), dinoflagellates and acritarchs (Edwards), diatoms (Barron), silicoflagellates (Bukry), mollusks (Wingard), ostracodes (Cronin), planktonic foraminifera and bolboformids (Poag; see also Poag and Norris, this volume, chap. F), and vertebrate remains (Weems). Most samples for the various fossil groups studied were taken at the drill site. Calcareous nannofossils, dinoflagellates, mollusks, and ostracodes were studied from most or all postimpact stratigraphic units. Diatoms, silicoflagellates, planktonic foraminifera and bolboformids, and vertebrates were studied from one or a few stratigraphic units. Benthic foraminifera from the Chickahominy Formation are discussed by Poag and Norris (this volume, chap. F). For the purpose of formal names of species and genera, calcareous nannofossils, dinoflagellates, diatoms, silicoflagellates, and bolboformids are classified as plants. Mollusks, ostracodes, foraminifera, and vertebrates are classified as animals. Complete taxonomic names are given in appendix H1.

For precision, endpoint depths of sampling intervals for some fossils are given in feet to the number of decimal places recorded at the time of sampling. For small samples, their locations in the core are given by only single depths.

Calcareous nannofossil samples.—Seventy-one Cenozoic calcareous nannofossil samples were examined from the upper 235.65 m (773.12 ft) of the Langley core. The sample spacing was determined by the ease or difficulty in establishing the age of the units being examined. Deeper water units with abundant calcareous nannofossils throughout were examined with a greater sample spacing than shallower water units. Sample depth in meters is a direct conversion of the sample depth in feet for the entire small sample.

For all calcareous nannofossil samples, a small amount of sediment was extracted from the central portion of a core segment (freshly broken where possible). The samples were dried in a convection oven to remove residual water, and the dry sediment was placed in vials for long-term storage in the calcareous nannofossil laboratory at the USGS in Reston, Va. Semiconsolidated or consolidated samples were ground with a mortar and pestle.

A small portion of each sample was placed in a beaker, stirred, and settled through 20 milliliters (mL) of water. An initial settling time of 1 minute (min) was used to remove the coarse fraction, and a second settling time of 10 min was used to remove the fine fraction. Smear slides were prepared from the remaining suspended material. Coverslips were attached to the slides by using Norland Optical Adhesive 61 (NOA–61), a clear adhesive that bonds glass to glass and cures when exposed to ultraviolet radiation.

Samples were primarily examined by using a Zeiss Axiophot 2 microscope. A few samples with good preservation and abundance were further examined by using a JEOL JSM–6400 scanning-electron microscope (SEM).

Dinoflagellate and acritarch samples.—Samples taken from the Langley core for dinoflagellate and acritarch studies were thoroughly scraped onsite. Sample depth in meters represents the midpoint of the interval sampled.

In the laboratory, up to 80 grams (g) of raw material was weighed and disaggregated. Each sample was treated with hydrochloric acid followed by hydrofluoric acid. Residues from the acid treatments were sieved at 10 and 200 micrometers (µm) and then separated by using a zinc chloride solution having a specific gravity of 2.0. Samples were checked under a microscope to determine if an oxidation and or ultrasonic treatment were needed, and if so, one or both of these steps were performed. All samples were resieved at 10 µm and, if enough residue remained, 20 µm. Samples were then stained with Bismark brown and mounted in glycerin jelly on a glass slide with coverslip. Slides were examined by using a light microscope.

Diatom and silicoflagellate samples.—Samples from between 125.7 and 140.4 m (412.4 and 460.6 ft) depth in the Langley core were collected for the study of diatoms and silicoflagellates. Sample depth in meters represents the midpoint of the interval sampled.

The samples were prepared by boiling them in hydrogen peroxide and later in a dilute solution of hydrochloric acid. Samples were settled for a minimum of 4 hours before excess liquid was decanted off and replaced with distilled water. This washing process was repeated four times until the suspended liquid was of neutral pH. One or two strewn slides were prepared for each sample (cover glass size 22x40 millimeters (mm)) and examined in entirety under the light microscope (at 500x for diatoms and 250x for silicoflagellates). The total silicoflagellates were counted for each slide and tabulated as percentages.

Mollusk samples.—The Langley core was examined for molluscan fauna. Occurrences of large recognizable species and any molluscan remains were noted. Fossiliferous samples were collected at selected intervals for processing and further examination. Sample depth in meters represents the direct conversion of the sample depth in feet; if a range is given, values represent endpoints in both feet and meters.

Samples were washed, the fraction >850 µm was retained, and molluscan fauna specimens recovered were sorted and identified. Generic assignments for extant groups were updated on the basis of Turgeon and others (1998).

Ostracode samples.—For ostracode samples of the Langley core, sample depth in meters represents the midpoint of the interval sampled. Approximately 50 g of sediment from each sample was processed by soaking sediment overnight in tap water and washing through 63-µm sieves. Ostracodes were picked with a fine brush from the fraction >150 µm. Because the number of individuals was limited in most units, all ostracodes were picked, including fragments. In contrast, some samples from the Eastover and Yorktown Formations contained abundant ostracodes, and about 300 individuals were picked.

Planktonic foraminifera and bolboformid samples.—For planktonic foraminifera and bolboformid samples from the Langley core, sample depth in feet and meters represents the top of the interval sampled. Samples were prepared in a standard manner (wet sieved on a 63-µm screen after 15 min of boiling in a solution of sodium hexametaphosphate). Identification is based on available literature and personal collections of Poag.

Vertebrate samples.—Because the Langley core is relatively narrow and volumetrically small, the chance of recovering any large vertebrate material was virtually nil (unless a large bone or tooth were to be sectioned during coring). Occasional bones and teeth substantially smaller than the diameter of the core could be expected, and such vertebrate remains were isolated by sieving sediment from two units (Chickahominy Formation and Drummonds Corner beds). Sample depth in meters represents the direct conversion of the sample depth in feet; if a range is given, values represent endpoints in both feet and meters.

Paleontology

Chickahominy Formation

The Chickahominy Formation at 235.65–183.3 m (773.12–601.3 ft) depth in the Langley core was studied for calcareous nannofossils (fig. H4, in pocket), dinoflagellates (fig. H5), mollusks (fig. H6, in pocket), ostracodes (fig. H7), planktonic foraminifera and bolboformids (fig. H8), and vertebrates (fig. H9). All fossil groups indicate placement in the upper Eocene. This 52-m-thick (172-ft-thick) unit represents approximately 2 million years (m.y.) of depositional accumulation. As explained below, the environment of deposition was marine. Benthic foraminifera indicate outer neritic to upper bathyal paleodepths; a nutrient-rich, oxygen-depleted environment is likely.

Calcareous nannofossils.—Eighteen samples from the Chickahominy Formation in the Langley core were examined for calcareous nannofossil content (fig. H4). Most of the samples contained abundant calcareous nannofossils with good preservation. The remainder contained common or abundant nannofossils with moderate preservation. Calcareous nannofossil assemblages were sufficient in number of specimens, diversity of taxa, and preservational state to allow placement of samples within one specific zone.

Samples from 235.0 to 196.4 m (770.9 to 644.5 ft) indicate placement in upper Eocene Zone NP 19/20 based on the presence of *Isthmolithus recurvus* (FAD defines base of Zone NP 19/20; see appendix H2) and *Discoaster saipanensis* (LAD defines the top of Zone NP 19/20), which occur in all samples within this depth range (fig. H4). *Cribrocentrum reticulatum* and *Discoaster barbadiensis* have LADs very near the top of Zone NP 19/20. *Cribrocentrum reticulatum* has its highest occurrence at 222.7 m (730.5 ft), and *D. barbadiensis* has its highest occurrence at 209.0 m (685.8 ft). Therefore, the interval between 222.7 and 196.4 m (730.5 and 644.5 ft) is placed in the very uppermost part of Zone NP 19/20, in what is assumed to be an expanded section.

Samples from 195.5 to 183.6 m (641.5 to 602.5 ft) are placed within Zone NP 21 on the basis of the absence of *D. saipanensis* (LAD defines the top of Zone NP 19/20) and the presence of *Cyclococcolithus formosus* (LAD defines the top of Zone NP 21). According to Berggren and others (1995), Zone NP 21 spans the Eocene-Oligocene boundary. Calcareous nannofossils do not clearly indicate whether the Zone NP 21 material in the Langley core is within the upper Eocene or lower Oligocene part of this zone. However, a late Eocene age is more likely because both *Chiasmolithus titus* and *Blackites tenuis* are present in parts of this interval. These two species have their LADs in the lower part of Zone NP 21. Additional evidence for a late Eocene age is the absence of a noticeable unconformity in the core between the uppermost Zone NP 19/20 material, which is very late Eocene, and the Zone NP 21 material.

The boundary between calcareous nannofossil Zone NP 19/20 and Zone NP 21 was calibrated at 34.2 Ma by Berggren and others (1995) for low and middle latitudes (fig. H3). In the Langley core, this boundary is bracketed by closely spaced samples from 196.4 and 195.5 m (644.5 and 641.5 ft).

Poag and Aubry (1995) reported an assignment of Zone NP 19/20 for Chickahominy Formation samples examined from the Exmore and Kiptopeke coreholes, which are also located within the Chesapeake Bay impact crater (fig. H1).

Dinoflagellates and acritarchs.—Eight samples from the Chickahominy Formation in the Langley core yielded highly diverse dinoflagellate assemblages of late Eocene age (fig. H5); selected specimens are shown in plates H1–H3. Sample depths range from 235.2 to 185.2 m (771.6 to 607.5 ft). Preservation ranges from fair to good.

Typical late Eocene species present include *Areosphaeridium diktyoplokus*, *Batiacasphaera baculata*, *Batiacasphaera compta*, *Trigonopyxidia fiscellata*, and *Cordosphaeridium funiculatum*. Species that are present in the Chickahominy but not to the top of the unit include *Charlesdowniea variabilis* (highest occurrence is in sample R6110 DA, 230.2 m=755.2–755.5 ft), *Diphyes colligerum* (highest occurrence is in sample R6110 AO, 209.3 m=686.4–686.8 ft), *Rhombodinium perfora-*

Unit	Chickahominy Formation								DC beds		Old Church Formation			
Depth to midpoint (m)	235.2	230.2	222.7	209.3	206.7	198.8	195.1	185.2	178.0	177.3	171.1	155.8	150.0	144.9
Depth range (ft)	771.4–771.6	755.2–755.5	730.3–730.7	686.4–686.8	677.9–678.3	652.0–652.4	639.9–640.3	607.5–607.9	583.8–584.1	581.5–581.9	561.0–561.4	511.0–511.4	492.0–492.2	475.4–475.7
Taxon Sample number R6110	DB	DA	AR	AO	AN	AL	AK	AI	AH	AG	AF	AD	AB	AA
Achilleodinium biformoides	.	.	X	X	X	X	X	X	X	X	R	.	.	.
Apteodinium spiridoides	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Areosphaeridium diktyoplokus	.	.	.	.	X	.	.	X	.	.	.	.	.	.
Batiacasphaera baculata	.	.	X	X	X	.	X	X	.	.	.	.	.	.
Batiacasphaera compta	.	.	X	X	X	.	X	X	.	.	R	.	.	.
Batiacasphaera hirsuta	.	.	.	.	.	.	.	.	?	.	.	.	.	.
Batiacasphaera sphaerica	.	.	.	.	.	.	.	.	.	.	.	X	.	X
Charlesdowniea coleothrypta	.	X	X	X	X	X	X	X	.	.	.	.	.	.
Charlesdowniea variabilis	X	X	.	.	.	.	.	.	.	.	.	.	.	.
Chiropteridium galea	.	.	.	.	.	.	.	.	.	.	X	X	X	X
Chiropteridium lobospinosum	.	.	.	.	.	.	.	.	X	X	X	X	X	X
Cleistosphaeridium placacanthum	X	.	X	X	X	X	X	X	X	X	X	X	X	X
Cordosphaeridium cantharellus	.	.	X	X	X	X	X	X	X	X	X	X	.	.
Cordosphaeridium fibrospinosum	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Cordosphaeridium funiculatum	X	X	X	X	X	X	X	X	.	.	R	.	R	.
Cordosphaeridium gracile	.	.	.	X	X	.	.	.	.	.	.	.	.	.
Corrudinium incompositum	.	.	X	.	.	.	X	?	.	.	.	.	.	.
Corrudinium sp.	.	.	.	.	.	.	.	.	.	.	.	X	.	.
Cribroperidinium spp.	X	X	X	X	X	X	X	X	.	.	X	.	X	X
Cyclopsiella vieta	.	?	X	.	.	.	X	.	.	X	.	.	.	.
Cyclopsiella sp.	.	.	.	.	.	.	.	.	.	X	.	.	.	.
Dapsilidinium pseudocolligerum	.	.	X	X	X	X	X	X	X	X	X	X	X	X
Deflandrea phosphoritica and forms intermediate with *D. heterophlycta*	X	X	X	X	X	X	X	X	.	.	R?	.	.	.
Deflandrea phosphoritica (incl. *D. phosphoritica* var. *spinulosa*)	.	.	.	.	.	.	.	.	.	.	X	X	X	X
Dinopterygium cladoides sensu Morgenroth (1966)	.	.	X	.	X	X	X	X	X	X	.	X	.	.
Diphyes colligerum	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Distatodinium ellipticum	.	.	.	.	X	?	.	X	.	.	.	.	.	.
Distatodinium spp.	.	.	X	.	.	.	X	.	.	X	X	X	.	.
Dracodinium varielongitudum	R	.	.	.	.	.	.	.	.	.	.	.	.	.
Ennaedocysta sp. or spp.	.	.	X	X	X	X	X	X	.	.	R	.	.	.
Eocladopyxis peniculata	.	.	.	.	.	.	.	.	.	.	R	.	.	.
Heteraulacacysta porosa	.	X	?	.	X	.	?	X	.	.	R	.	.	.
Histiocysta sp. of Stover and Hardenbol (1993 [1994])	.	X	.	X	X	.	X	X	.	.	.	.	.	.
Homotryblium aculeatum	.	.	.	X	X	.	.	.	.	.	.	.	.	.
Homotryblium plectilum	.	.	.	X	X	.	.	.	X	.	X	.	.	X
Homotryblium vallum	.	.	.	.	.	.	.	.	X	X	X	.	.	X
Hystrichokolpoma cinctum	.	.	.	.	.	.	X	.	X	X	X	X	.	.
Hystrichokolpoma rigaudiae	.	.	X	X	X	X	X	X	X	.	.	X	.	X
Hystrichostrogylon aff. *coninckii* of De Coninck (1995)	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Kallosphaeridium capulatum	.	.	.	.	X	.	.	X	.	.	.	.	.	.
Lejeunecysta hyalina	.	.	X	.	.	.	.	.	.	.	.	.	.	.
Lejeunecysta spp.	.	.	.	.	X	.	.	X	X	?	.	.	.	X

Lentinia serrata	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Lingulodinium machaerophorum (incl. *L. siculum*)	.	.	X	X	X	X	X	X	X	X	X	X	X	X
Lophocysta? sp. indet. of De Coninck (1986)	.	.	.	X	.	X	.	.	.	.	.	.	.	.
Membranophoridium aspinatum	.	.	.	.	X	.	.	.	X	X	X	.	X	.
Nematosphaeropsis pusulosa	.	.	X	.	.	.	X	X	.	.	.	.	.	.
Operculodinium centrocarpum	.	.	.	.	.	X	.	.	X	.	.	.	.	.
Operculodinium divergens	.	.	.	.	.	X	.	.	.	.	.	.	.	.
Operculodinium? *placitum*	.	.	.	.	.	X	.	.	.	.	.	.	.	.
Operculodinium spp.	.	X	.	.	X	.	X	X	.	.	.	X	X	X
Palaeocystodinium golzowense	X	X	X	X	X	X	X	X	X	X	X	X	.	X
Pentadinium imaginatum	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Pentadinium laticinctum subsp. *laticinctum*	X	X	X	X	X	X	X	X	X	.	.	.	.	.
Pentadinium laticinctum (grano-vermiculate forms)	.	X	.	X	X	X	X	X	X	gr	X	X	.	.
Pentadinium membranaceum	R?	.	.	.	.	.	.	.	.	.	.	.	.	.
Pentadinium sp. I of Edwards (1986)	.	.	.	.	.	.	.	.	.	.	.	X	.	.
Phthanoperidinium comatum	.	.	X	.	X	.	.	X	.	.	.	.	.	.
Reticulatosphaera actinocoronata	.	.	.	.	.	.	.	.	X	X	X	.	.	.
Rhombodinium perforatum	.	.	X	.	X	.	.	.	.	.	.	.	.	.
Rottnestia borussica	.	X	.	.	?	.	.	.	.	.	.	.	.	.
Samlandia chlamydophora	.	X	X	X	X	.	.	.	.	.	.	.	.	.
Samlandia chlamydophora sensu Stover and Hardenbol (1993 [1994])	.	.	.	.	.	X	X	X	.	.	.	.	.	.
Saturnodinium pansum	.	.	.	.	.	.	.	.	.	.	?	X	X	.
Saturnodinium sp.	.	.	X	X	X	.	X	X	.	X	R	.	? (R)	.
Selenopemphix brevispinosa subsp. *brevispinosa*	.	.	X	.	.	.	.	.	.	.	.	.	.	.
Selenopemphix nephroides	.	.	.	X	.	X	.	.	.	.	.	.	.	.
Selenopemphix sp.	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Spiniferites mirabilis	.	.	.	.	.	.	.	.	.	X	X	X	.	.
Spiniferites pseudofurcatus	X	.	X	X	X	X	X	X	X	X	X	.	.	X
Spiniferites spp.	.	.	X	X	X	X	X	X	X	X	X	X	X	X
Tectatodinium pellitum	.	X	.	X	.	.	X	X	X	.	X	.	.	X
Thalassiphora delicata	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Thalassiphora pelagica	.	.	X	X	X	X	X	X	X	X	X	.	.	.
Thalassiphora reticulata	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Trigonopyxidia fiscellata	X	.	X	.	.	.	X	X	.	.	R	.	.	.
Tuberculodinium vancampoae	.	.	.	.	.	.	.	.	.	.	X	X	.	X
Wetzeliella symmetrica	.	.	.	.	.	.	.	.	X	.		.	.	.
Wetzeliella sp.	X	.	X	.	.	.	.	.	.	X	X	.	.	.
new genus?, new species (apical archeopyle, areolig. group, with ectophragm)	.	.	.	.	.	.	.	.	.	.	.	.	.	X
miscellaneous areoligeracean forms (mostly *Glaphyrocysta* spp.)	X	X	X	X	.	X	.	.	X	:	X	.	.	.
miscellaneous peridiniacean forms	.	X	X	X	X	.	X	X	.	.	.	X	X	.
additional reworked specimens (Cretaceous, Paleocene, Eocene)	R	R	R	.	R	.	R	R	R	?	R	.	.	.
Preservation	fair	fair	fair	good	good	good	fair	fair	fair	good	var.	poor	poor	poor

Figure H5. Occurrence chart showing the presence of dinoflagellates in samples from the Chickahominy Formation, Drummonds Corner (DC) beds, and Old Church Formation in the USGS-NASA Langley core. Selected specimens are shown in plates H1–H4. Definitions: X=present, ?=questionably present, R=present but presumably reworked, R?=questionably reworked, ?(R)= questionably identified, reworked if identification is correct, gr=identified to group only, .=not present, var.=variable.

Depth	228.8 m (750.6–750.8 ft)	221.7 m (727.2–727.6 ft)	207.9 m (682.0–682.4 ft)	203.7 m (668.1–668.2 ft)	202.6 m (664.6–665.0 ft)	186.7 m (612.4–612.7 ft)	183.4 m (601.7–601.9 ft)	182.5 m (598.7–599.0 ft)	173.8 m (570.2–570.4 ft)	169.2 m (555.0–555.4 ft)	139.2 m (456.4–456.8 ft)	120.2 m (394.2–394.6 ft)	104.2 m (341.6–342.0 ft)	97.2 m (318.8–319.1 ft)	90.6 m (297.0–297.2 ft)	88.1 m (289.1–289.3 ft)	82.4 m (270.0–270.4 ft)	78.1 m (256.3–256.5 ft)	73.4 m (240.6–240.8 ft)	71.3 m (233.9–234.1 ft)	59.6 m (195.5–195.9 ft)	53.3 m (174.9–175.2 ft)	49.3 m (161.5–161.8 ft)	48.8 m (160.0–160.2 ft)	43.3 m (141.8–142.0 ft)	42.7 m (140.1–140.3 ft)	39.7 m (130.1–130.3 ft)	36.8 m (120.5–120.8 ft)	35.0 m (114.8–115.0 ft)	32.1 m (105.3–105.6 ft)	30.5 m (99.9–100.2 ft)	26.7 m (87.5–87.7 ft)	22.8 m (74.7–74.9 ft)	20.3 m (66.5–66.7 ft)	16.1 m (52.8–53.1 ft)	15.4 m (50.5–50.7 ft)	10.8 m (35.4–35.6 ft)	9.7 m (31.7–32.0 ft)	8.0 m (26.1–26.3 ft)	6.1 m (20.0–20.2 ft)	5.6 m (18.4–18.6 ft)
Unit	**Chickahominy Formation**							**DC**	**OC**		**PP**	**St. Marys Formation**									**Eastover Formation**												**Yorktown Formation**								
Genus/species																																									
Acanthocythereis sp.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Actinocythereis captionis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	X
Actinocythereis cf. *A. dacyi*	.	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Actinocythereis dawsoni	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.	X	.	.
Actinocythereis exanthemata	.	.	.	.	.	.	.	.	X?	.	.	X?	.	.	X?	X	.	X?	.	.	X?	X?	.	X?	X?	.	.	.	.	.	.	.	.	.	.	X?	.	.	.	.	.
Actinocythereis cf. *A. stenzeli*	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Actinocythereis thompsoni	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Actinocythereis sp.	.	.	.	.	.	.	.	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Alatacythere ivani	.	.	.	.	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Argilloecia sp.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Aurila laevicula	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Bensonocythere americana	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	X	X	X	X	X
Bensonocythere blackwelderi	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	X	X	X
Bensonocythere bradyi	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X
Bensonocythere calverti	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	.
Bensonocythere ricespitensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	.	X
Bensonocythere rugosa	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	.	.
Bensonocythere trapezoidalis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	.	.	.	.	.	.	.
Bensonocythere spp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.
Buntonia sp.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Campylocythere laeva	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X	X	X
Cytherella spp.	.	.	X	.	.	.	X	X	.	.	.	.	.	X	.	X	.	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cytheridea subovalis	.	.	.	.	.	.	.	.	X	.	.	X?	X?	.	.	X	.	X	.	.	X	.	.	.	X	.	.	.	.	.	.	X?	.	.	.	.	.	.	.	.	.
Cytheridea virginiensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	.	.	X
Cytheridea n. sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cytheromorpha macroincisa	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	.	.	.	.
Cytheromorpha warneri	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X	X	X	.	.	.	.	.	.	.	X	.	.	.	.	.	.	X	.	X	X	X	.	X
Cytheropteron talquinensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	X	.	X	X	X	X	X
Cytheropteron yorktownensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	.	X	X
Cytheropteron sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cytherura coryelli	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Cytherura howei	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.	.	.	.
Cytherura reticulata	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.
Digmocythere russelli	.	X	.	.	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Echinocythereis miniscula	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Echinocythereis sp.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Eucythere gibba	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.
Haplocytheridea n. sp.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Hemicytheridea cf. *H. montgomeryensis*	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Henryhowella evax	X	X	.	.	X	X	.	.	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.
Hulingsina americana	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X
Hulingsina calvertensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Hulingsina rugipustulosa	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	X	X	X	X
Hulingsina spp.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X	X	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X	.	.	.	X	X	X	X	X	X	X
Krithe sp.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Leguminocythereis sp.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Leguminocythereis cf. *L. scarabaeus*	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Loxoconcha florencensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Loxoconcha reticularis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X
Loxoconcha aff. *L. granulata*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X
Loxoconcha sp.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.	.	.
Malzella conradi	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X	X	X
Malzella evexa	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X	X
Microcytherura choctawhatcheensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X	X
Microcytherura shattucki	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Microcytherura similis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	X	X	X	X	X
Muellerina blowi	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X
Muellerina lienenklausi	.	.	.	.	.	.	.	.	X	X	.	.	X	.	X	X	X	X	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Muellerina micula	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X?	.	X	.	.	X?	.	X	X	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Muellerina ohmerti	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	X	X	X	X
Muellerina wardi	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X	X
Munseyella sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Murrayina barclayi	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	X?	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	X
Murrayina macleani	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.
Murrayina radiata	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	.	X?	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Neonesidea laevicula	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	X	X
Orionina vaughani	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X	X
Paracytheridea altila	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	X	X
Paracytheridea cf. *P. mucra*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X
Paracytheridea rugosa	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Paradoxostoma sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.
Proteoconcha gigantea	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Proteoconcha tuberculata	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	X	X
Pseudocytheretta burnsi	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	X	X	X	X	X	X	.	X	.	.	X	.	.	.	.	X	X	X	X	X	X	X
Pseudocytheretta plebeia	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X?	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Pterygocythereis americana	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Pterygocythereis inexpectata	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Puriana carolinensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Puriana rugipunctata	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X
Sahnia sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Thaerocythere schmidtae	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.
Trachyleberidea blanpiedi	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
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Preservation	P	VG	F	P	F	G	F	P	F	F	P	F	R	F	F	E	R	E	VG	VG	VG	VG	VG	G	P	F	P	F	P	P	F	P	P	F	E	E	E	E	E	E	E
Zone	none available																																?	?	*Orionina vaughani*						
Inferred age		late Eocene	late Eocene	?	Eocene-Oligocene	late Eocene-early Olig.	Oligocene	Oligocene	late Olig.-early Miocene	late Olig.-early Miocene	?	late Miocene	late Miocene	late Miocene		late Miocene	late Miocene	late Miocene	late Miocene	late Miocene	late Miocene	late Miocene	late Miocene			late Miocene		late Miocene			late Miocene			early-middle Pliocene	middle Pliocene			middle Pliocene		middle Pliocene	middle Pliocene

Figure H7. Occurrence chart showing the presence of ostracodes in samples from the USGS-NASA Langley core; samples are from the Chickahominy Formation, Drummonds Corner beds (DC), Old Church Formation (OC), Plum Point Member (PP) of the Calvert Formation, and St. Marys, Eastover, and Yorktown Formations. One sample (35 m=114.8–115.0 ft depth) is barren, and three others (139.2 m=456.4–456.8 ft; 42.7 m=140.1–140.3 ft; 22.8 m=74.7–74.9 ft) have only poorly preserved indeterminate specimens. Occurrence symbols: X=present, X?=species identity uncertain; .=not present. Preservation symbols: E=excellent, VG=very good, G=good, F=fair, P=poor, R=rare.

Series	Unit	Depth to top of sample		Taxon											Planktonic foraminiferal biochronozone
		(ft)	(m)	*Testacarinata inconspicua*	*Turborotalia cerroazulensis cocoaensis*	*Praetenuitella praegemma*	*Hantkenina alabamensis*	*Turborotalia cerroazulensis pomeroli*	*Globigerinatheka index*	*Cribrohantkenina inflata*	*Turborotalia cerroazulensis cunialensis*	Acarininids (reworked)	*Bolboforma spinosa*	*Bolboforma latdorfensis*	
Upper Eocene	Chickahominy Formation	601.30	183.28	X	.	X	.	X	.	.	.	.	.	X	P16-P17
		602.15	183.54	X	.	X	.	.	.	.	.	.	.	X	
		602.70	183.70	X	.	.	.	.	.	.	.	.	.	X	
		605.70	184.62	X	X	.	X	X	.	.	X	.	.	X	
		608.70	185.53	.	.	X	.	.	.	.	.	.	.	.	
		611.70	186.45	X	.	X	X	.	.	.	.	.	.	.	
		614.70	187.36	X	.	X	.	.	.	.	.	.	.	X	
		617.70	188.28	X	.	.	X	.	X	.	.	.	.	X	
		620.70	189.19	X	.	X	.	.	X	.	.	.	.	.	
		623.70	190.10	.	.	X	.	.	.	.	.	.	.	.	
		626.80	191.05	.	X	X	X	.	.	.	.	.	.	X	
		629.80	191.96	.	.	X	.	.	.	.	.	.	.	.	
		632.70	192.85	X	.	X	.	.	.	.	.	.	.	X	
		635.70	193.76	X	X	X	.	.	.	.	.	.	.	X	
		638.40	194.58	.	.	X	.	.	.	.	.	.	.	X	
		641.00	195.38	.	.	X	.	.	.	.	.	.	.	X	
		644.20	196.35	X	.	X	.	.	.	.	.	.	.	X	
		647.20	197.27	X	X	X	X	.	X	.	.	.	.	X	
		650.20	198.18	.	.	.	X	.	.	.	.	.	.	.	
		653.70	199.25	.	.	.	.	.	.	.	.	.	.	X	
		656.20	200.01	.	X	.	.	.	.	X	X	.	.	X	
		662.20	201.84	.	.	X	.	.	.	.	.	.	.	X	
		665.20	202.75	.	X	X	.	.	.	.	.	.	.	X	
		668.20	203.67	.	X	X	X	.	X	.	X	.	.	X	
		671.20	204.58	.	X	X	X	.	X	X	.	.	.	X	
		674.20	205.50	.	.	X	.	.	X	.	.	.	.	X	
		676.80	206.29	X	.	.	.	.	.	.	.	.	.	X	
		680.00	207.26	X	.	X	.	.	X	.	.	.	.	X	
		683.20	208.24	X	.	.	.	.	X	.	.	.	.	X	
		686.10	209.12	X	X	X	X	.	X	.	.	.	.	X	
		689.10	210.04	.	X	.	X	.	X	.	.	.	.	X	
		692.20	210.98	.	X	.	.	.	X	.	.	.	.	X	
		695.20	211.90	.	.	.	X	.	X	.	.	.	.	X	
		698.30	212.84	.	.	.	.	.	X	.	.	.	.	X	
		701.10	213.70	.	.	.	X	.	X	.	.	.	.	X	
		704.80	214.82	.	.	X	X	.	.	.	.	.	.	X	
		708.00	215.80	.	X	X	X	.	.	.	.	.	.	X	
		710.50	216.56	.	X	.	X	.	X	.	.	.	.	X	
		720.00	219.46	X	.	X	.	.	.	.	.	.	.	X	
		723.00	220.37	.	.	.	.	.	.	.	.	.	.	X	
		726.40	221.41	X	.	X	X	.	.	.	.	.	X	X	
		729.00	222.20	X	.	X	X	.	.	.	.	.	X	X	P15
		732.20	223.18	.	.	.	X	.	.	.	.	.	.	X	
		735.10	224.06	X	X	X	.	X	.	.	.	.	.	.	
		737.96	224.93	.	X	.	X	.	X	.	.	.	.	.	
		741.00	225.86	.	.	.	.	.	.	.	.	.	.	.	
		743.90	226.74	X	X	X	.	X	.	.	.	.	X	.	
		747.00	227.69	X	X	X	.	.	.	.	.	.	.	.	
		750.00	228.60	.	.	.	.	.	.	.	.	.	X	.	
		753.00	229.51	.	.	.	.	.	.	.	.	.	.	.	
		756.10	230.46	X	X	X	.	.	.	.	.	.	X	.	
		759.30	231.44	X	.	.	.	.	.	.	.	.	.	.	
		762.00	232.26	.	X	.	.	.	.	.	.	.	X	.	
		764.95	233.16	.	.	.	X	.	.	.	.	.	.	.	
		768.10	234.12	X	X	.	.	.	.	.	.	X	X	.	
		770.70	234.91	X	X	X	.	.	.	.	.	X	X	.	
		772.60	235.49	X	X	.	.	.	.	.	.	X	X	.	
		772.90	235.58	X	.	.	.	.	.	.	.	X	.	.	
		773.05	235.63	X	.	.	.	.	.	.	.	X	.	.	

Figure H8. Occurrence chart showing the presence of key planktonic foraminifera and bolboformids in samples of the Chickahominiy Formation in the USGS-NASA Langley core. Zones are based on Berggren and others (1995). Symbols: X=present, .=not present.

Taxon	Chickahominy Formation		Drummonds Corner beds
	211.7 m (694.7 ft)	197.9 m (649.4 ft)	182.5 m (598.5–599.3 ft)
Sharks:			
Scyliorhinus gilberti....................	.	X	.
Squalus sp....................................	.	.	X
Rays:			
Dasyatis sp...................................	.	.	X
Bony fishes:			
Acanthocybium proosti..............	X	.	.
Diaphyodus wilsoni.....................	.	.	X
Trichiurides sagittidens..............	.	.	X

Figure H9. Occurrence chart showing the presence of teeth of sharks, rays, and bony fishes in samples of the Chickahominy Formation and the Drummonds Corner beds in the USGS-NASA Langley core. The teeth are shown in plate H9. Symbols: X=present, .=not observed.

tum (highest occurrence is in sample R6110 AN, 206.7 m= 677.9–678.3 ft), and *Thalassiphora reticulata* (highest occurrence is in sample R6110 AN). Species that are present but not in the lowest sample include *Membranophoridium aspinatum* (lowest occurrence is in sample R6110 AN) and *Dapsilidinium pseudocolligerum* (lowest occurrence is in sample R6110 AR, 222.7 m=730.3–730.7 ft).

Dinocysts from the Chickahominy Formation in the Langley core can be compared with dinocysts from the Eocene-Oligocene boundary stratotype at Massignano, Italy. The form that Brinkhuis (1994) called *Escharisphaeridia* sp. is clearly *Batiacasphaera compta*. The highest occurrence of this form makes a good proxy for the Eocene-Oligocene boundary at the boundary stratotype. Because this species ranges to the top of the Chickahominy, the entire Chickahominy is Eocene, although the presence of *Operculodinium divergens* (in sample R6110 AL) suggests that this sample (and higher samples) is near the boundary. The Chickahominy dinoflagellate samples show striking similarities with the dinoflagellates reported from the Bassevelde Sands of the Zelzate Formation in Belgium (De Coninck, 1986, 1995).

Mollusks.—Molluscan remains are relatively sparse in the Chickahominy Formation in the Langley core (fig. H6). Seven taxa are represented in the lower portion of the formation, from 232.3 to 205.6 m (762.2 to 674.4 ft) depth, including several species of pectens, *Astarte* sp., *Dentalium* sp., *Nucula* sp., and *Nuculana* sp. (pl. H6, figs. 4–6). From 205.6 to 183.3 m (674.4 to 601.3 ft), molluscan remains are rare to absent in each sample, and no recognizable forms are present.

Ostracodes.—Before discussing the ostracode assemblages from the Eocene-Oligocene interval in the Langley core, it is first necessary to discuss the limitations on assigning ages. First, the preservation in some samples is marginal in terms of the valves themselves (commonly broken) and the abundances are low, usually less than 10 specimens except at 221.7 m (727.2–727.6 ft), 186.7 m (612.4–612.7 ft), and 173.8 m (570.2–570.4 ft). Such preservation precludes detailed examination of populations and morphologic variability in potentially age-diagnostic species until additional samples and cores are analyzed.

The second factor is the absence of a formal ostracode biostratigraphic zonation for the mid-Atlantic region. In contrast to the Gulf of Mexico region, where detailed ostracode zonations exist (see Poag, 1974; Hazel and others, 1980), only a few isolated Eocene-Oligocene ostracode faunas from the Chesapeake Bay region have been described and illustrated in the published literature (for example, Swain, 1951; Deck, 1985). Therefore, we must proceed on the assumption, which may not be valid for some species, that their stratigraphic ranges are isochronous in the Gulf and mid-Atlantic coastal regions.

The third factor is the taxonomic status of species in several relatively important genera (*Actinocythereis*, *Cytheridea*, *Leguminocythereis*), which will require additional comparative study in the future. These factors mean that any age interpretation based on the ostracodes must be done in conjunction with biostratigraphic data from other fossil groups.

In spite of these limitations, the ostracodes from the Langley core provide some age indications. The assemblages from the Chickahominy Formation include the key species *Actinocythereis* cf. *A. dacyi*, *A.* cf. *A. stenzeli*, *Alatacythere ivani*, *Digmocythere russelli*, *Leguminocythereis* cf. *L. scarabaeus*, and *Trachyleberidea blanpiedi.* Together these species suggest a late Eocene to early Oligocene age. These species are common guide fossils for the Jacksonian and Vicksburgian provincial stages of the Gulf of Mexico Coast (Hazel and others, 1980) and also occur in the Santee Formation and Cooper Group of

South Carolina (Pooser, 1965; Hazel and others, 1977) and subsurface units in North Carolina (Swain, 1951). Distinctive ostracodes from the middle Claibornian to middle Jacksonian described by Deck (1985) from the middle Eocene Piney Point Formation have not been found in the Langley core.

Planktonic foraminifera and bolboformids.—The stratigraphic record of late Eocene planktonic foraminifera and bolboformids from the Chickahominy Formation inside the Chesapeake Bay crater has previously been established in the Kiptopeke and Exmore coreholes (Poag and Aubry, 1995; Poag and Commeau, 1995; Poag, 1997). Poag and Aubry (1995) demonstrated that these two Chickahominy sections are biostratigraphically correlative with an upper Eocene chalk section cored by the Deep Sea Drilling Project (DSDP) at Site 612 on the continental slope of New Jersey (Poag, Watts, and others, 1987).

The planktonic foraminiferal suite at these cored sites is a typical late Eocene association (Zones P15–P17 as defined by Berggren and others, 1995), composed of the following key species:

Cribrohantkenina inflata
Globigerina gortanii
Globigerina medizzai
Globigerina ouachitaensis
Globigerina praebulloides
Globigerina tripartita
Globigerinatheka index
Globigerinatheka semiinvoluta
Hantkenina alabamensis
Praetenuitella praegemma
Pseudohastigerina naguewichiensis
Testacarinata inconspicua
Turborotalia cerroazulensis cerroazulensis
Turborotalia cerroazulensis cocoaensis
Turborotalia cerroazulensis cunialensis
Turborotalia cerroazulensis pomeroli

It is difficult to recognize the P15-P16 and P16-P17 biozonal boundaries in the two previously studied Chickahominy sections because the requisite taxa (*Globigerinatheka semiinvoluta, Cribrohantkenina inflata*, and *Turborotalia cerroazulensis cunialensis*) are scarce and (or) sporadically present. Poag and Aubry (1995) found, however, that the highest occurrence of *Bolboforma spinosa* overlaps briefly the lowest occurrence of *Bolboforma latdorfensis* approximately at the P15-P16 boundary (lowest occurrence of *Turborotalia cerroazulensis cunialensis*) at DSDP Site 612. They, therefore, used this bolboformid overlap interval as a proxy for the P15-P16 boundary at their two Chickahominy sites.

At the USGS-NASA Langley corehole site, above the top of the Exmore beds, a succession of 59 samples, spaced approximately 1 m (about 3 ft) apart, reveals typical Chickahominy planktonic foraminiferal and bolboformid assemblages, nearly identical to those of the Kiptopeke and Exmore coreholes. The presence of the following key species indicates the late Eocene age of the Chickahominy Formation (fig. H8):

Cribrohantkenina inflata
Globigerinatheka index
Hantkenina alabamensis
Praetenuitella praegemma
Testacarinata inconspicua
Turborotalia cerroazulensis cocoaensis
Turborotalia cerroazulensis cunialensis
Turborotalia cerroazulensis pomeroli

As at the Kiptopeke and Exmore sites, the late Eocene planktonic foraminiferal biozonal boundaries cannot be recognized in the USGS-NASA Langley corehole. However, the position of the P15-P16 biochronozonal boundary can be approximated at 221.8 m (727.7 ft) by the *Bolboforma latdorfensis-Bolboforma spinosa* overlap interval (fig. H8). Berggren and others (1995) placed the P15-P16 boundary at 35.2 Ma.

Vertebrates.—A fragmentary tooth of *Acanthocybium proosti* (USNM 519553; pl. H9, fig. 5), an extinct species of wahoo (Weems, 1999), was recovered from the Chickahominy Formation at 211.7 m (694.7 ft) depth in the Langley core (fig. H9). The stout, roughly triangular shape of the tooth and the basal cross section that has one side nearly planar and the other strongly arched are characteristic of this species. Living wahoos typically are found in tropical waters and tend to prefer open ocean environments (Wheeler, 1975). Although wahoos generally are near-surface inhabitants, teeth of dead animals could readily have drifted downward through the crater water column and been buried at great depth far from the normal depths inhabited by this fish. *Acanthocybium proosti* is known from the lower Eocene Nanjemoy Formation (Weems, 1999), and so its presence in the upper Eocene Chickahominy Formation in the Langley core represents a range extension for this species. No wahoo remains have been reported yet from the middle Eocene Piney Point Formation.

A well-preserved tooth of *Scyliorhinus gilberti* (USNM 519554; pl. H9, fig. 4), an extinct species of catshark, was recovered from the Chickahominy Formation at 197.9 m (649.4 ft). This species is known in Europe from upper Eocene beds (Kent, 1999), and so its presence here is not unexpected. Many species of living catsharks prefer deep water (Kent, 1999), so it is most interesting that this is the only shark specimen to show up in the presumably deepwater depositional environment of this formation.

Paleoenvironmental information.—The benthic foraminiferal assemblage (Poag and Norris, this volume, chap. F) indicates a Chickahominy sea floor of about 300 m (984 ft) paleodepth (outer neritic to upper bathyal, 150–500 m), with restricted oxygen availability and high flux rates of organic carbon.

Although the emphasis of the dinoflagellate studies was biostratigraphic, it is interesting to note that specimens of the nearshore genus *Homotryblium* are present in only two of the samples in the middle of the Chickahominy (209.3–206.7 m= 686.4–678.3 ft) (fig. H5).

The numbers of molluscan specimens present are too low to determine anything definitive about the environment. However, the Nuculacea and *Dentalium* present are indicative of deep and (or) quiet water. The *Dentalium* are large (length greater than 5 centimeters (cm), or about 2 inches (in.)) and relatively well preserved for fossils having their fragile construction and aragonitic composition; the preservation implies little to no transport.

The ostracodes present suggest that the environment of deposition of the Chickahominy Formation was mainly outer neritic to upper bathyal; the record of the deepest water environment for the formation is at 221.7 m (727.2–727.6 ft), where *Krithe* and *Argilloecia* occur. These taxa may also reflect slope-to-shelf upwelling of cooler slope waters.

Of the two vertebrate teeth found at different levels in the Chickahominy, one species suggests a deepwater environment, whereas the other is nektonic and could readily have had its remains sink into a deepwater depositional basin from the overlying near-surface nektonic environment. Although these two occurrences are far too sparse to constitute proof of a deepwater environment for the Chickahominy Formation, they are fully compatible with such an interpretation.

Other paleontological information.—Both calcareous nannofossil samples and dinoflagellate samples throughout the Chickahominy Formation contain sporadic specimens reworked from older units. All dinoflagellate samples include rare specimens that appear to have been altered (for example, folded or partially melted, as described in Powars and Edwards, 2003; Frederiksen and others, this volume, chap. D).

Implications of sediment accumulation rates in the Chickahominy.—Two zone boundaries and the Eocene-Oligocene boundary were used to set limits on the sediment accumulation rate in the Chickahominy Formation based on the time scale of Berggren and others (1995). The P15/P16-P17 boundary at 35.2 Ma is placed at 221.8 m (727.7 ft) and the NP 19-20/NP 21 boundary at 34.2 Ma is placed between samples at 196.4 and 195.5 m (644.5 and 641.5 ft). Because the highest samples in the Chickahominy are still within the Eocene, the top of the Chickahominy at a depth of 183.3 m (601.3 ft) must be assigned an age of 33.7 Ma or older. By using these points, the possible lines that can be constructed are quite limited (fig. H10). Sediment accumulation rates must be in the range of 25–27 m/m.y. (82–89 ft/m.y.) The top of the Chickahominy is nearly coincident with the Eocene-Oligocene boundary. Using slightly different assumptions, but the same tie point at the P15/P16-P17 boundary, Poag and Norris (this volume, chap. F) arrive at almost the same sedimentation rates.

One can project the base of the Chickahominy at 235.65 m (773.12 ft) into the time scale of Berggren and others (1995), using these zone boundaries and sediment accumulation rates to yield a value of 35.7–35.8 Ma for the time of impact (fig. H10). This value is based ultimately on the geomagnetic reversal time scale of Cande and Kent (1995), which is calibrated to numeric ages at 33.7±0.4 and 46.8±0.5 Ma. Thus, 35.7–35.8 Ma does not differ significantly from ages of tektites given by Horton and Izett (this volume, chap. E).

Drummonds Corner Beds

The Drummonds Corner beds at 183.3–176.0 m (601.3–577.4 ft) depth in the Langley core were studied for calcareous nannofossils (fig. H4, in pocket), dinoflagellates (fig. H5), ostracodes (fig. H7), and vertebrates (fig. H9). Molluscan remains in the Drummonds Corner beds are highly weathered and not identifiable. Dinoflagellates indicate placement in the upper part of the lower Oligocene. Calcareous nannofossils indicate placement in Zone NP 24, which includes parts of both the lower and upper Oligocene. Together, these two fossil groups indicate calibration to 29.9–28.5 Ma (base of Zone NP 24 and top of lower Oligocene according to Berggren and others, 1995). Thus, this 7.3-m-thick (23.9-ft-thick) unit represents 1.4 m.y. or less of deposition.

Calcareous nannofossils and dinoflagellates show a sharp floral change, and ostracodes show a sharp faunal change, between the Drummonds Corner beds and the underlying Chickahominy Formation. Fossils representing the lower part of the lower Oligocene are not present. The Drummonds Corner beds appear to represent shallower water or more nearshore deposition than the underlying Chickahominy deposits. The inferred climate is subtropical.

Calcareous nannofossils.—Only three samples were examined for calcareous nannofossils from the Drummonds Corner beds in the Langley core; they are from depths of 182.6, 180.1, and 177.2 m (599.1, 591.0, and 581.5 ft). Calcareous nannofossils were abundant in all three samples and had moderate to good preservation. The unit is tentatively placed within Zone NP 24. *Reticulofenestra umbilicus* (LAD defines the top of Zone NP 22) is absent from these samples, placing the unit in Zone NP 23 or higher. *Helicosphaera recta* (first appears in Zone NP 24) is present in the lower two samples, as is *Sphenolithus predistentus* (LAD within Zone NP 24). The absence of these two species in the uppermost sample at 177.2 m (581.5 ft) may be due to the somewhat poorer preservation of this sample. The absence of *Sphenolithus distentus* (ranges from Zone NP 23 to Zone NP 24) and *Sphenolithus ciperoensis* (FAD defines the base of Zone NP 24) from this interval, which contains other sphenoliths, cannot be explained. Berggren and others (1995) calibrated the lower boundary of Zone NP 24 at 29.9 Ma and the upper boundary of this zone at 27.5 Ma (fig. H3).

Dinoflagellates and acritarchs.—Two samples were examined for dinocysts from the Drummonds Corner beds in the Langley core (fig. H5). The samples are from depths of 178.0 and 177.3 m (583.8–584.1 and 581.5–581.9 ft). Presevation ranges from fair to good.

The dinocysts indicate that the age of this unit is “mid” Oligocene (late Rupelian, the latter part of the early Oligocene). Dinoflagellate species that have their lowest occurrences in the Drummonds Corner beds include *Chiropteridium lobospinosum*, *Homotryblium vallum* (pl. H3, fig. 6), *Reticulatosphaera*

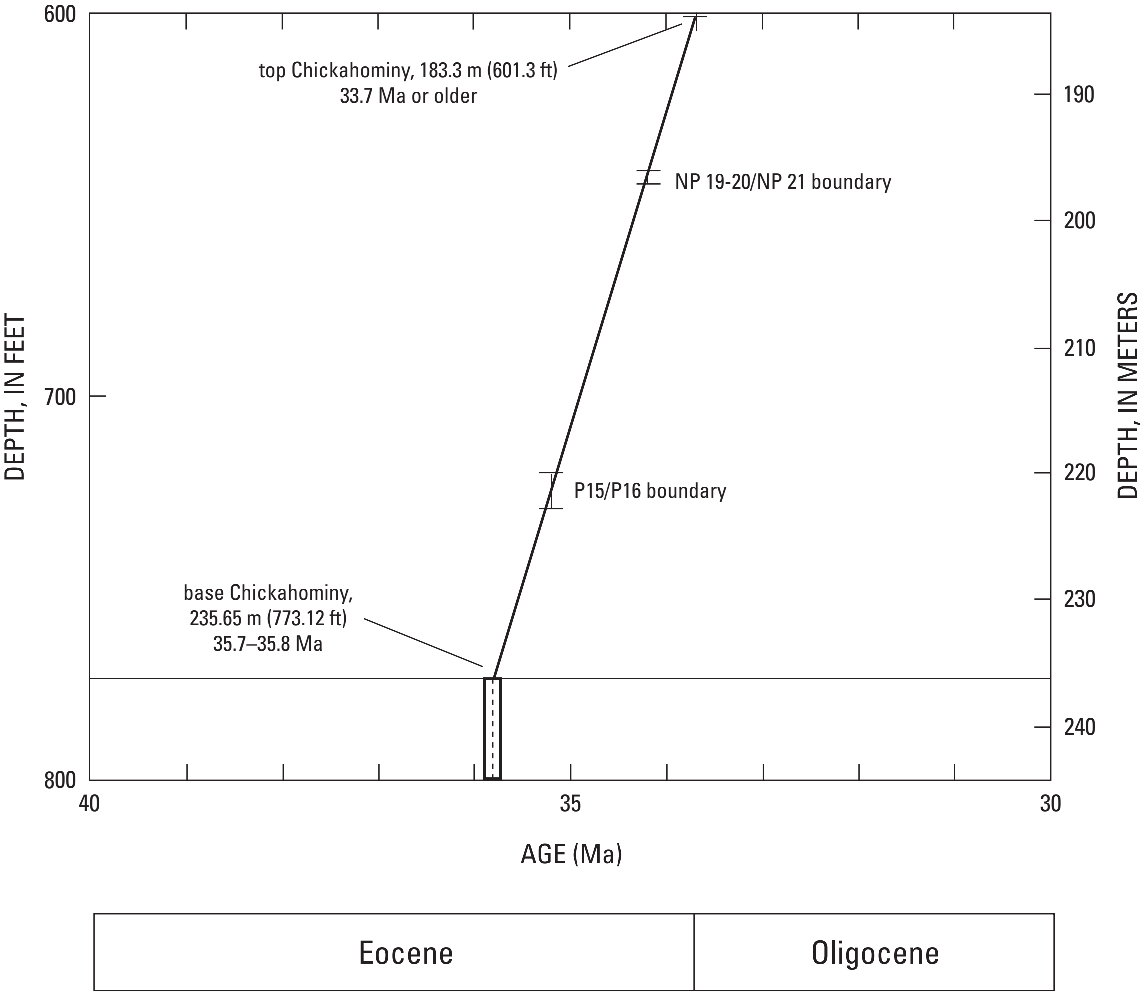

Figure H10. Age-depth plot for the Chickahominy Formation in the USGS-NASA Langley core. Time scale is from Berggren and others (1995).

actinocoronata (pl. H3, fig. 9), *Spiniferites mirabilis*, and *Wetzeliella symmetrica*. Both *Chiropteridium lobospinosum* and *Homotryblium vallum* have their lowest occurrences in the upper part of the lower Oligocene, within calcareous nannofossil Zone NP 23. *Achilleodinium biformoides* (p. H3, fig. 5) has its highest occurrence near the top of the lower Oligocene; it is present in both samples of the Drummonds Corner beds. Both samples lack *Tuberculodinium vancampoae*, which has its lowest occurrence in the upper part of the upper Oligocene and is present in the overlying Old Church Formation samples.

Ostracodes.—Ostracodes are extremely sparse and poorly preserved in the Drummonds Corner beds in the Langley core (fig. H7). The possible occurrence of a form resembling *Pterygocythereis americana* at 182.5 m (598.7–599.0 ft) in the Drummonds Corner beds is unusual in lower Oligocene sediments of this region (see discussion in Hazel, 1967), where it usually occurs in sediments of latest Oligocene or early Miocene age. Further work must confirm this identity and compare the Langley material with *P. howei*.

Vertebrates.—A sample of sediment from 182.5 m (598.5–599.3 ft) depth in the Drummonds Corner beds of the Langley core was sieved for vertebrate remains. Teeth from four species of fish were found (pl. H9), three of which suggest that the depositional environment was shallow coastal waters. The only mutual overlap in the climatic preference of the living representatives of these four species is in the modern subtropical climatic zone.

A tooth of *Squalus* sp. (USNM 519557; pl. H9, fig. 1*)* documents the presence of a dogfish shark in this unit. Dogfish sharks are typically deepwater species that frequently range into shallower water (Kent, 1999).

A male tooth referable to *Dasyatis* sp. (USNM 519558; pl. H9, fig. 2*)* documents the presence of whiptail stingrays in the lower Oligocene Drummonds Corner beds. The genus has been reported from beds as old as Cretaceous in North America (Cappetta, 1987), and so its presence is not surprising. Living *Dasyatis* prefer coastal subtropical to tropical waters.

A tooth of *Trichiurides sagittidens* (USNM 519556; pl. H9, fig. 3*)* documents the presence of a cutlassfish in this unit. Among fossil cutlassfishes, the presence of a deep, conical pulp cavity in the base of the tooth is characteristic of this genus. The tooth is not discernibly different from similar teeth noted from the Nanjemoy Formation (Weems, 1999) and from upper Eocene beds in Georgia (Dennis Parmley, Georgia College and State University, written commun., 2001). Modern trichiurids inhabit tropical to warm temperate seas and generally are found at shallow to moderate depths (Wheeler, 1975).

A small round and flattened tooth with a shallow and broadly open pulp cavity seems referable to an extinct drumfish. In the Eocene, *Diaphyodus wilsoni* is the only known representative of this group in eastern North America (Westgate, 1989), and so the present tooth (USNM 519555; pl. H9, fig. 6) is referred to this species in the absence of any features that would debar it. Presumably *Diaphyodus* gave rise to the living genus of drumfish, *Pogonias*. The timing of this evolutionary transition has not been documented, but specimens clearly referable to *Pogonias* are not known from beds older than Miocene at the present time. Living drumfishes are bottom dwellers that live in coastal waters and eat mollusks and crustaceans with their specialized crushing dentitions. They inhabit temperate to subtropical waters at the present time (Wheeler, 1975).

Paleoenvironmental information.—The presence of relatively nearshore dinoflagellate genera, such as *Homotryblium* and *Chiropteridium*, suggests that the Drummonds Corner beds represent shallower water deposition than the underlying Chickahominy Formation. The ostracodes suggest that the environment of deposition was most likely middle-outer neritic, where species of *Pterygocythereis* typically live today in the mid-Atlantic region. Fish teeth collectively suggest a subtropical climate.

Other paleontological information.—Lower Tertiary reworking is noticeable in the Drummonds Corner beds. The lowest dinoflagellate sample (R6110 AH, 178.0 m, 583.8–584.1 ft) shows a single specimen of *Hafniasphaera septata*. Reworked lower Tertiary calcareous nannofossils include specimens of *Chiasmolithus titus*, *Isthmolithus recurvus*, and *Markalius inversus*.

Old Church Formation

The Old Church Formation at 176.0–143.5 m (577.4–470.9 ft) depth in the Langley core was studied for calcareous nannofossils (fig. H4, in pocket), dinoflagellates (fig. H5), mollusks (fig. H6, in pocket), and ostracodes (fig. H7). Dinoflagellates indicate placement in the upper part of the upper Oligocene (to lowest Miocene), and calcareous nannofossils indicate placement in Zone NP 24. Although Zone NP 24 includes parts of both the lower and upper Oligocene, the Old Church sediments represent the upper part of the zone; the lower part of Zone NP 24 is found in the underlying Drummonds Corner beds. Because the presence of the dinoflagellate *Tuberculodinium vancampoae* sets a maximum age late in the late Oligocene, and because the placement of the uppermost sample in calcareous nannofossil Zone NP 24 is based on a single specimen, we allow the possibility that the Old Church includes both NP 24 and NP 25 (queried interval in fig. H3). According to Berggren and others (1995), the total time span of the upper Oligocene part of Zones NP 24 plus NP 25 is 28.5–23.9 Ma. This 32.5-m-thick (106.5-ft-thick) unit represents 4.6 m.y. or less of deposition. A paleoenvironment of middle-outer neritic, subtropical, is suggested.

Calcareous nannofossils. —Eleven samples were examined from the Old Church Formation from 175.3 to 145.4 m (575.0 to 477.1 ft). All of the samples contained abundant to common calcareous nannofossils with good to moderate preservation (fig. H4).

The entire interval can be placed within Zone NP 24 because of the presence of *Sphenolithus ciperoensis* (FAD defines the base of Zone NP 24) in the lowest sample at 175.3 m (575.0 ft) and *Sphenolithus distentus* (LAD defines the top of Zone NP 24) in the top sample at 145.4 m (477.1 ft). The presence of only one specimen of *S. distentus* at 151.0 and 145.4 m (495.4 and 447.1 ft) is not strong evidence for this material being placed in Zone NP 24 rather than Zone NP 25. However, *Helicosphaera compacta* (LAD in Zone NP 24) is still present at 167.5 m (549.6 ft), and *Transversopontis zigzag* (LAD also in Zone NP 24) is questionably present up to 164.0 m (538.1 ft). *Helicosphaera truempyi* (FAD in the uppermost part of Zone NP 24) first appears at 148.7 m (487.9 ft). Combining this evidence indicates that the Old Church Formation in the Langley core is most likely in Zone NP 24. Zone NP 24 spans the early-late Oligocene boundary (Berggren and others, 1995). The calcareous nannofossils cannot determine whether this material in the Langley core is of early or late Oligocene age, although late Oligocene is more likely because Zone NP 24 sediments are present in the underlying Drummonds Corner beds.

Dinoflagellates and acritarchs. —Four samples were examined for dinocysts from the Old Church Formation in the Langley core (fig. H5); selected specimens are shown in plates H3 and H4. The samples are from depths of 171.1 to 144.9 m (581.0 to 475.4 ft). The preservation in all but the lowest is poor.

The lower three samples are late Oligocene, as indicated by the overlapping ranges of *Tuberculodinium vancampoae* (lowest occurrence in the late Oligocene) and *Saturnodinium pansum* (highest occurrence in calcareous nannofossil Zone NP 25 according to de Verteuil and Norris, 1996). The highest sample (R6110 AA, 144.9 m=475.4–475.7 ft) does not contain *S. pansum*, and it contains no other species that restrict its possible age more precisely than late Oligocene or earliest Miocene.

Mollusks.—Calcitic molluscan remains are present from 169.5 to 148.7 m (556 to 488 ft) depth in the Old Church Formation of the Langley core, and most of the mollusks are concentrated in the segment from 159.7 to 153.9 m (524 to 505 ft) (fig. H6). The absence of aragonitic mollusks indicates extensive leaching, which is consistent with Ward's (1985, p. 51) description of the type Old Church. The calcitic remains include an *Anomia* sp., fragments of *Ecphora* sp., and five distinct species of pectens (pl. H6, figs. 1, 3). Several of the pectens may be undescribed, but two of the species (pectinid cf. *Chlamys brooksvillensis* Mansfield and pectinid cf. *Chlamys* aff. *C. vaun wythei* Hertlein Mansfield) bear a resemblance to specimens described by Mansfield (1937) from the lower Oligocene Suwannee Limestone of Florida (age refined by Brewster-Wingard and others, 1997). *Rebeccapecten berryae*, present in a single sample at 159.3–159.4 m (522.7–522.9 ft), was reported by Ward (1992) from zone M14, Oligocene to lowermost Miocene.

Ostracodes.—Ostracodes are extremely sparse and poorly preserved in the two samples obtained from the Old Church Formation in the Langley core (fig. H7). The lowest occurrences of *Hulingsina*, *Echinocythereis* (perhaps *E. clarkana* Ulrich and Bassler 1904), and *Cytheridea subovalis* in the Old Church Formation suggest a possible age equivalent to the upper part of the Cooper Group (now Ashley Formation), which Hazel and others (1977) correlated with the Chickasawhayan. These taxa typically first appear in the uppermost Oligocene and lower Miocene sediments of the Atlantic Coastal Plain.

Paleoenvironmental information.—The present-day environment of the dinoflagellate *Tuberculodinium vancampoae* is nearshore and subtropical to tropical. Its occurrence in the Old Church may suggest similar conditions. The ostracodes present suggest that the environment of deposition for the Old Church Formation was most likely middle-outer neritic, where species of *Echinocythereis* typically live today in the mid-Atlantic region. Because of the extensive leaching, the molluscan fauna cannot provide any paleoenvironmental information.

Other paleontological information.—Paleontology supports the presence of a considerable lag bed at the base of the Old Church Formation. The lowest dinoflagellate sample (R6110 AF, 171.1 m, 561.0–561.4 ft) shows a noteworthy component of reworked material from a variety of different ages, including late Eocene (time of impact), early Eocene or Paleocene, and Paleocene. Folding of specimens and curling of processes were noted on some Eocene specimens in which an impact origin is most likely. Dinoflagellate assemblages from higher in the Old Church include rare impact-related specimens. Reworked calcareous nannofossils (scattered specimens of *Isthmolithus recurvus*) are also recorded in the lower part of the Old Church.

Calvert Formation

The Calvert Formation at 143.5–123.6 m (470.9–405.5 ft) depth in the Langley core was divided into the lower Miocene Newport News beds (informal unit) and the middle Miocene Plum Point Member and Calvert Beach Member (fig. H3). The Fairhaven Member of the Calvert Formation, known from outcrops and subsurface studies in Virginia and Maryland, is not recognized in the Langley core.

Newport News Beds

The Newport News beds of the Calvert Formation at 143.5–140.5 (470.9–461.1 ft) depth in the Langley core were studied for calcareous nannofossils (fig. H4, in pocket) and dinoflagellates (fig. H11). Molluscan remains were not studied, as the Newport News beds in the core contain only scattered oyster shells and fragments (fig. H6, in pocket). No siliceous microfossils were found. Dinoflagellates and calcareous nannofossils indicate placement in the lower Miocene. Dinoflagellate biostratigraphy places this unit in the lower Miocene subzone DN2b, which de Verteuil (1997) calibrated at 19.4–20.0 Ma. Thus, this 3.0-m-thick (9.8-ft-thick) unit represents approximately 0.6 m.y. or less of deposition.

Calcareous nannofossils.—Only one calcareous nannofossil sample was examined from the Newport News beds, from 142.1 m (466.3 ft) depth in the Langley core (fig. H4). Nannofossils were common with good preservation. This sample was placed in the lower Miocene Zone NN 2–3 on the basis of the presence of *Helicosphaera ampliaperta* (FAD within Zone NN 2) and the absence of *Sphenolithus heteromorphus* (FAD in Zone NN 4), which does occur in the overlying sample at 139.3 m (457.0 ft). However, none of Martini's (1971) zone-defining species was found in the sample from the Newport News beds.

Dinoflagellates and acritarchs.—A single sample (R6110 Z, 142.2 m=466.3–466.5 ft depth in the Langley core) was examined for dinocysts from the Newport News beds of the Calvert Formation (fig. H11). Two specimens are shown in plate H4 (figs. 1 and 5). Preservation is good.

This sample is assigned to the lower Miocene Zone DN2 of de Verteuil and Norris (1996), and more specifically to subzone DN2b of de Verteuil (1997), on the basis of the co-occurrence of *Cordosphaeridium cantharellus* (highest occurrence defines top of subzone DN2b) and *Exochosphaeridium insigne* (lowest occurrence defines base of subzone DN2b). Specimens of *Chiropteridium* spp. and *Homotryblium plectilum* may be reworked, or their occurrences here may represent upward range extensions.

Paleoenvironmental information.—The high-diversity dinocyst assemblage suggests normal marine surface-water conditions; some nearshore species are present. The presence of *Tuberculodinium vancampoae* may indicate subtropical to tropical temperatures somewhat warmer than the present Chesapeake Bay.

Plum Point Member

The Plum Point Member of the Calvert Formation at 140.5–139.0 m (461.1–456.1 ft) depth in the Langley core was studied for calcareous nannofossils (fig. H4, in pocket) and dinoflagellates (fig. H11). Only indeterminate diatoms (fig. H12) and ostracodes (fig. H7) and highly weathered mollusks and pieces of *Isognomon* sp. are reported. Dinoflagellates and calcareous nannofossils indicate placement in the middle Miocene. According to the time scale of de Verteuil and Norris

(1996), the time represented by middle Miocene dinoflagellate Zone DN4 is 16.7–15.2 Ma. Thus, this 1.5-m-thick (5.0-ft-thick) unit represents approximately 1.5 m.y. or less of deposition.

Calcareous nannofossils.—Only one calcareous nannofossil sample was examined from the Plum Point Member, from 139.3 m (457.0 ft) depth in the Langley core (fig. H4). Calcareous nannofossils were abundant with moderate preservation. This sample is placed in the middle Miocene Zones NN 3–5 on the basis of the presence of *Sphenolithus heteromorphus* (LAD defines the top of Zone NN 5; FAD within Zone NN 3).

Dinoflagellates and acritarchs.—A single sample (R6110 Y, 139.4 m=457.4–457.6 ft depth in the Langley core) was examined for dinocysts from the Plum Point Member (fig. H11). Four specimens are shown in plate H4 (figs. 4, 7, 9, and 10). Preservation is fair.

The sample was determined to be latest early (Burdigalian) or early middle Miocene (Langhian). This sample is assigned to Zone DN4 of de Verteuil and Norris (1996) on the basis of the co-occurrence of *Distatodinium paradoxum* (highest occurrence defines the top of DN4) and *Labyrinthodinium truncatum* (lowest occurrence defines the base of DN4). A single specimen of *Habibacysta tectata* (lowest occurrence within DN5) may be a downhole contaminant. The early-middle Miocene boundary is near, but may not be coincident with, the base of Zone DN4. De Verteuil and Norris (1996) also placed the Plum Point Member of the Calvert Formation in Zone DN4.

Diatoms and silicoflagellates.—Two samples of the Plum Point Member in the Langley core were examined for siliceous microfossils (figs. H12, H13). No silicoflagellates were reported in these samples.

In the sample from 140.5 m (460.8–460.9 ft) depth, diatoms are rare and poorly preserved. *Paralia sulcata,* a robust diatom ranging from the Cretaceous to the present, is the only form identified. The sample from 139.4 m (457.3–457.4 ft) also contained poorly preserved diatoms, mostly *Paralia sulcata.* The lack of age-diagnostic diatoms in these two samples prevents their assignment to a diatom zone.

Mollusks.—The Plum Point Member in the Langley core has abundant evidence of highly weathered aragonitic mollusks and pieces of *Isognomon* sp. No samples of the member were collected for mollusk analysis.

Ostracodes.—Only indeterminate ostracodes are reported from the Plum Point Member in the Langley core (fig. H7).

Paleoenvironmental information.—The high-diversity dinocyst assemblage suggests normal marine surface-water conditions; some nearshore species are present. The presence of the dinoflagellate *Tuberculodinium vancampoae* may indicate subtropical to tropical temperatures somewhat warmer than the present Chesapeake Bay. The sparse molluscan fauna is unusual for the Calvert Formation and does not provide any paleoenvironmental information.

Calvert Beach Member

The Calvert Beach Member of the Calvert Formation at 139.0–123.6 m (456.1–405.5 ft) depth in the Langley core was studied for calcareous nannofossils (fig. H4, in pocket), dinoflagellates (fig. H11), diatoms (fig. H12), and silicoflagellates (fig. H13). No molluscan remains were observed in the Calvert Beach Member, and no samples were studied for ostracodes. Dinoflagellates, diatoms, and silicoflagellates indicate placement in the middle Miocene for material up to 128.0 m (419.9 ft) depth. Calcareous nannofossils include specimens of the genus *Catinaster*, which would suggest, in the absence of dinoflagellate, diatom, and silicoflagellate data, a slightly younger age (Zone NN 8 in the latest middle or early late Miocene). Fossils of all groups are sparse or absent in the upper part of this unit. The base of this 15.4-m-thick (50.6-ft-thick) unit is calibrated at 14.1 Ma or younger (base 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 DN 6 (12.7 Ma according to de Verteuil and Norris, 1996).

Calcareous nannofossils.—Four calcareous nannofossil samples were examined from the Calvert Beach Member in the Langley core (fig. H4). The two upper samples, from 131.4 and 127.9 m (431.2 and 419.5 ft), could not be dated because one was barren of calcareous nannofossils and the other sample contained only rare, nondiagnostic species.

The bottom two samples, from 136.6 and 134.4 m (448.0 and 440.9 ft), contained common calcareous nannofossils with good preservation. Each of these samples contained several specimens of at least two morphologies that are assigned to the genus *Catinaster*. Two of these specimens have been observed with the scanning-electron microscope (SEM); they are similar to *Catinaster coalitus* and *Catinaster mexicanus*, but they differ enough that they may represent one or more new species. Additional SEM searches for these *Catinaster* specimens are planned, and they may clarify these identifications. Although the earliest reported occurrence of the genus *Catinaster* (Peleo-Alampay and others, 1998) is *C. coalitus*, whose base defines the base of Zone NN 8, it cannot be assumed that these specimens must indicate a Zone NN 8 age, particularly when other fossil groups place this interval within the middle Miocene. The presence of *Discoaster exilis* (LAD in Zone NN 8) in these two samples indicates an age no younger than Zone NN 8 age.

Dinoflagellates and acritarchs.—Three samples were examined for dinocysts from the upper middle Miocene part of the Calvert Formation between depths of 134.5 and 125.0 m (441.4 and 409.9 ft) in the Langley core (fig. H11). Four specimens are shown in plates H4 (figs. 8, 11, and 12) and H5 (fig. 1). Preservation is fair to poor.

The two lower samples are assigned to the upper part of Zone DN5 of de Verteuil and Norris (1996) on the basis of the co-occurrence of *Habibacysta tectata* (lowest occurrence about midway within DN5) and *Cleistosphaeridium placacanthum* (highest occurrence defines the top of DN5). According to the correlation charts in de Verteuil and Norris (1996), these sam-

Formation	Calvert Formation					St. Marys Formation					Eastover Formation				Yorktown Formation			
Member	NN	PP	Calvert Beach															
Depth to midpoint (m)	142.2	139.4	134.5	129.6	125.0	120.4	114.5	102.2	86.9	72.2	66.1	59.9	52.4	24.8	21.9	16.0	9.6	7.3
Depth range (ft)	466.3–466.5	457.4–457.6	441.0–441.4	425.2–425.4	409.9–410.2	394.8–395.2	375.5–375.8	335.0–335.4	285.0–285.3	236.8–237.2	216.6–216.9	196.4–196.7	171.6–172.0	81.2–81.6	71.5–71.9	52.4–52.8	31.4–31.7	23.8–24.1
Sample number R6110	Z	Y	X	W	V	U	T	R	O	L	K	J	I	F	E	D	C	B
Taxon Zonation of de Verteuil and Norris (1996), de Verteuil (1997)	DN2b	DN4	DN5	DN5	DN6	DN8/9	DN9	DN9	DN9	DN9	DN9	DN9	DN10	DN10	post DN10			
Achomosphaera andalousiensis	.	.	.	.	.	X	X	X	.			X	X	X	.	.	.	.
Achomosphaera sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.
Amiculasphaera umbracula	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	X	?
Apteodinium spiridoides	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	1R	.	.
Apteodinium tectatum	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ataxiodinium confusum	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Barssidinium evangelineae (including *B. pliocenicum*)	.	.	.	.	.	X	X	X	.	.	.	X	X	X	.	X	.	X
Batiacasphaera sphaerica	X	X	.	.	X	.	.	.	.	.	X	.	.	.	.	.	.	.
Bitectatodinium tepikiense/Bitectatodinium raedwaldii	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	X	X	.
Brigantedinium cariacoense	.	.	X	.	.	.	.	.	.	.	.	.	X	.	X	.	.	.
Cerebrocysta poulsenii	X	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.
Cerebrocysta satchelliae	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Chiropteridium spp.	R?	.	.	.	.	.	? (R)	.	.	.	.	.	.	.	.	.	.	.
Cleistosphaeridium placacanthum	X	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cordosphaeridium cantharellus	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cousteaudinium aubryae	.	?	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cribroperidinium tenuitabulatum	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cyclopsiella lusatica	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Dapsilidinium pseudocolligerum	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Distatodinium paradoxum	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Erymnodinium delectabile	.	.	.	.	.	.	.	X	.	.	X	X	X	X	.	.	.	.
Exochosphaeridium insigne	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Filisphaera microornata	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.
Geonettia clineae	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Habibacysta tectata	.	C?	X	X	X	X	X	X	.	X	X	X	X	X	.	.	X	.
Heteraulacacysta sp.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Homotryblium plectilum	R?	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Hystrichokolpoma rigaudiae	X	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Hystrichosphaeropsis obscura	.	X	X	X	X	X	X	X	X	X	X	X	.	.	.	.	.	.
Impagdinium pallidum	.	.	.	.	.	?	.	.	.	.	.	.	.	.	.	.	.	.
Impagidinium antecarcerum	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.
Impagidinium maculatum of Santarelli (1997)	.	.	.	.	.	X	X	.	.	.	.	.	.	.	.	.	.	.
Impagidinium paradoxum	.	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Impagidinium sphaericum	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Impagidinium spp. (including *I.* sp. cf. *strialatum*)	X	X	.	X	.	.	.	X	X	X	X	X	.	.	.	.	.	X
Invertocysta lacrymosa	.	.	X	.	.	X	X	.	.	.	X	.	X	.	X	X	X	.
Invertocysta tabulata	.	.	?	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Invertocysta sp. indet.	?	X	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.
Labyrinthodinium truncatum subsp. *modicum*	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Labyrinthodinium truncatum subsp. *truncatum*	.	X	X	X	X	X	X	X	X	X	X	X	X	.	.	.	.	.
Lejeunecysta spp.	X	X	X	X	X	.	X	X	.	.	X	X	X	X	X	X	.	X
Lingulodinium machaerophorum	X	X	X	X	X	.	X	X	.	.	X	.	X	.	.	X	.	.
Melitasphaeridium choanophorum	.	X	X	X	X	.	X	X	.	.	X	.	.	X	.	.	.	.
Membranilarnaci? picena	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Nematosphaeropsis rigida	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.
Nematosphaeropsis sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.
Operculodinium centrocarpum	X	X	.	.	.	.	.	.	.	.	.	.	X	X	X	X	X	.
Operculodinium centrocarpum sensu Wall (1967)	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Operculodinium piaseckii	.	.	X	X	X	X	X	X	X	X	X	X	.	.	.	.	.	.
Operculodinium tegillatum	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	?
Operculodinium spp.	.	.	X	X	X	X	X	X	X	X	X	X	.	.	.	.	.	.
Palaeocystodinium golzowense	X	X	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.
Pentadinium sp. cf. *P. laticinctum granulatum*	X	X	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.
Pentadinium sp. I of Edwards (1986)	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Polysphaeridium zoharyi/Homotryblium vallum	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.
Pyxidiella? simplex	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.
Reticulatosphaera actinocoronata	X	X	X	X	X	X	X	X	.	.	.	X	X	X	.	.	.	.
Selenopemphix armageddonensis	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	.	.	.
Selenopemphix brevispinosa	.	X	.	X	X	.	.	.	.	.	X	.	.	X	.	X	.	.
Selenopemphix brevispinosa /S. dionaeacysta	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Selenopemphix dionaeacysta	.	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	.	.
Selenopemphix nephroides	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	.
Selenopemphix quanta	.	.	.	X	.	.	X	.	.	.	.	.	.	X	.	.	.	X
Spiniferites mirabilis	.	X	X	X	.	.	.	X	.	.	X	X	.	.	.	X	.	.
Spiniferites pseudofurcatus	X	X	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.
Spiniferites spp.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sumatradinium druggii	.	.	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.
Sumatradinium soucouyantiae	X	X	X	X	X	1R?	.	.	.	.	.	.	.	.	.	.	.	.
Sumatradinium? sp. (fragment)	.	.	.	.	.	.	.	.	.	?	.	.	.	.	.	.	.	.
Tectatodinium pellitum	X	X	X	.	X	.	X	.	.	X	.	.	X	X	X	X	X	X
Trinovantedinium ferugnomatum	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Trinovantedinium glorianum	.	.	.	.	X	.	.	X	.	.	.	.	.	X	.	.	.	.
Trinovantedinium harpagonium	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Trinovantedinium papula	.	.	.	.	X	.	.	.	.	.	X	.	X	.	.	.	.	.
Trinovantedinium spp.	.	.	.	.	.	.	X	.	.	.	.	.	X	.	.	.	.	.
Trinovantedinium? xylochoporum	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Tuberculodinium vancampoae	X	X	X	.	.	X	X	.	.	.	X	X	.	.	X	X	X	.
Unipontidinium aquaeductum	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
freshwater alga *Pediastrum*	.	.	.	.	.	.	X	X	X	X	X	.	.	.	.	X	.	X
Preservation	good	fair	fair	poor	poor	fair	good	fair	poor	poor	fair	good	good	good	fair	fair	good	good

Figure H11. Occurrence chart showing the presence of dinoflagellates and acritarchs in samples from the Calvert, St. Marys, Eastover, and Yorktown Formations in the USGS-NASA Langley core. The Calvert Formation contains the informal Newport News beds (NN), the Plum Point Member (PP), and the Calvert Beach Member. Selected specimens are shown in plates H4 and H5. Symbols: X= present, 1=single specimen, ?=questionably present, R=present but presumably reworked, R?=questionably reworked, ?(R)=questionably identified, reworked if identification is correct, C?=questionably a contaminant, .=not present.

Zone	**?**		***Delphineis penelliptica* Zone (middle Miocene)**								**?**
Unit	**PP**		**Calvert Beach Member**								
Taxon / **Depth (ft)** / **Depth (m)**	140.5 m (460.8–460.9 ft)	139.4 m (457.3–457.4 ft)	138.4 m (454.0–454.1 ft)	136.9 m (449.0–449.2 ft)	135.3 m (443.7–443.9 ft)	133.8 m (439.0–439.1 ft)	131.9 m (432.8–433.0 ft)	130.8 m (429.1–429.3 ft)	129.6 m (425.2–425.4 ft)	128.0 m (419.9–420.0 ft)	125.9 m (413.1–413.3 ft)
Abundance	VR	R	C	A	A	A	A	A	A	C	VR
Preservation	P	P	M	M	G	G	G	G	G	M	M
Actinocyclus ellipticus	.	.	.	.	.	.	.	.	.	R	.
Actinocyclus ingens	.	.	R	F	F	F	R	R	R	F	VR
Actinocyclus octonarius	.	.	F	F	F	R	R	R	F	F	.
Actinoptychus senarius	.	R	.	R	F	R	R	F	R	R	.
Actinoptychus thumii	.	.	.	.	.	.	.	.	R	.	.
Actinoptychus virginicus	.	.	.	R	R	R	.	R	.	.	.
Annellus californicus	.	.	R	.	.	.	R	.	.	.	.
Azpeitia vetustissimus	.	.	R	R	R	R	R	R	R	R	.
Cavitatus miocenicus	.	.	.	.	.	R	R	R	.	.	.
Cladogramma dubium	.	.	.	R	.	R	.	.	.	.	.
Coscinodiscus apiculatus	.	.	R	F	R	R	R	R	R	F	.
Coscinodiscus curvatulus	.	.	.	R	.	.	.	R		R	.
Coscinodiscus lewisianus	.	.	.	.	R	.	.	R	.	.	.
Coscinodiscus marginatus	.	.	F	R	R	R	R	R	R	R	.
Coscinodiscus oculus-iridis	.	R	.	.	.	R	R	R	R	R	.
Coscinodiscus radiatus	.	.	R	R	R	R	R	R	R	R	.
Coscinodiscus rothii	.	.	.	.	.	R	.	R	R	.	.
Cosmiodiscus elegans	.	.	.	.	.	.	.	R	.	.	.
Craspedodiscus coscinodiscus	.	R	R	.	.	.	F	R	.	.	.
Cymatogonia amplyoceras	.	.	.	R	R	.	.	.	.	.	.
Delphineis angustata	.	.	.	.	.	.	.	.	R	.	VR
Delphineis biseriata	.	.	.	R	R	R	F	F	R	.	.
Delphineis novaecesarea	.	.	.	.	R	.	F	R	R	.	.
Delphineis penelliptica	.	.	.	R	F	F	F	F	F	R	VR
Denticulopsis simonsenii	.	.	.	R	.	R	R	R	R	R	.
Goniothecium rogersii	.	.	.	.	.	.	.	.	.	R	.
Melosira westii	.	.	F	F	F	R	F	F	C	C	.
Navicula pennata	.	.	.	.	.	.	R	R	.	.	.
Paralia complexa	.	.	F	F	R	R	.	R	.	R	.
Paralia sulcata	R	F	C	A	A	C	A	A	C	C	VR
Pleurosigma affine var. *marylandica*	.	.	.	.	.	R	R	R	R	R	.
Pyxidicula cruciata	.	.	R	R	R	R	R	F	R	R	.
Rhaphoneis gemmifera	.	.	.	R	R	R	.	.	R	R	.
Rhaphoneis lancelettula	.	.	.	.	.	.	.	.	R	R	.
Stellarima sp.	.	.	.	.	.	.	R	.	.	.	.
Stephanopyxis corona	.	.	R	.	R	.	.	.	R	.	.
Stephanopyxis grunowii	.	.	R	.	R	R	R	.	R	.	.
Stephanopyxis turris	.	.	R	.	.	R	R	R	R	R	.
Stephanopyxis sp. cf. *S. lineata*	.	.	R	.	.	.	.	R	R	.	.
Thalassionema nitzschioides	.	.	F	F	F	R	F	F	F	R	VR
Thalassiosira leptopus	.	.	.	.	.	.	R	.	.	.	.
Thalassiosira praeyabei	.	.	.	.	.	.	R	.	.	.	.
Thalassiothrix longissima	.	.	.	.	.	R	R	R	R	R	VR
Triceratium condecorum	.	.	.	R	R	.	R	.	R	.	.
Xanthiopyxis spp.	.	.	R	R	F	R	F	F	F	R	.
TABULAR GLASSY MINERALS	A	A	.	.	.	.	.	.	.	.	.

Figure H12. Occurrence chart showing the presence of diatoms in samples from the Miocene Plum Point Member (PP) and Calvert Beach Member of the Calvert Formation in the USGS-NASA Langley core. The diatom zone is from Abbott (1980). Abundance definitions: A=abundant (more than one specimen per field of view); C=common (at least one specimen per three fields of view); F=few (at least one specimen per vertical traverse having a length of 22 mm); R=rare (fewer occurrences than few but more than two specimens per slide); VR=very rare (only one or two specimens per slide); .=not present. Preservation abbreviations: P=poor, M=moderate, G=good.

Unit	Depth (ft)	Depth (m)	Specimens	Ts	Taxon																				Subzones of the middle Miocene *Corbisema triacantha* Zone
					Bachmannocena circulus	*Bachmannocena elliptica elliptica*	*Bachmannocena elliptica miniformis*	*Bachmannocena triangula*	*Caryocha* sp.	*Corbisema triacantha*	*Dictyocha brevispina ausonia*	*Dictyocha brevispina brevispina*	*Dictyocha fibula* (large)	*Dictyocha fibula* (small)	*Dictyocha pulchella*	*Distephanus crux crux*	*Distephanus crux parvus*	*Distephanus crux scutulatus*	*Distephanus longispinus*	*Distephanus speculum speculum*	*Distephanus speculum triommata*	*Distephanus stauracanthus*	*Distephanus stradneri*	*Distephanus* sp. aff. *D. schauinslandii*	
CB	407.4–407.6	124.2	0		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
CB	413.1–413.3	125.9	0		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
CB	419.9–420.0	128.0	50	51	2	.	.	4	2	4	.	8	.	2	6	40	10	.	12	4	.	6	.	.	*D. stauracanthus*
CB	425.2–425.4	129.6	100	52	.	.	.	.	1	1	1	.	4	.	.	56	26	4	.	.	1	1	3	2	*D. stauracanthus*
CB	429.1–429.3	130.8	200	55	.	2	.	.	1	1	2	2	3	.	1	41	23	12	12	1	.	.	3	.	*D. schulzii*
CB	432.8–433.0	131.9	260	45	.	.	7	.	1	1	3	.	3	.	.	37	34	3	4	8	1	.	1	.	*D. schulzii*
CB	439.0–439.1	133.8	100	56	.	1	.	.	1	2	2	.	13	.	.	48	18	1	3	3	.	.	7	.	*D. schulzii*
CB	443.7–443.9	135.3	100	56	.	.	.	.	2	1	.	.	13	.	.	42	28	.	3	1	.	.	10	.	*D. schulzii*
CB	449.0–449.2	136.9	30		.	.	.	x	.	.	x	.	.	.	.	X	x	.	x	.	.	.	.	.	
CB	454.0–454.1	138.4	0		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
PP	457.3–457.4	139.4	0		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
PP	460.8–460.9	140.5	0		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
NN	467.0–467.1	142.4	0		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	

Figure H13. Occurrence chart showing the presence of silicoflagellates from the Miocene Calvert Formation in the USGS-NASA Langley core. Units of the Calvert Formation that were sampled are the Newport News beds (NN), Plum Point Member (PP), and Calvert Beach Member (CB). All the silicoflagellate-bearing samples are in the middle Miocene *Corbisema triacantha* Zone. Ts values are relative values; higher values represent relatively warmer temperatures. The specimen count for each sample is listed; species abundances are given as percentages. Any sub-50 sample count is shown as a species checklist (small x) with the one most numerous species indicated by a large X.

ples should be equivalent biostratigraphically to the Calvert Beach Member of the Calvert Formation.

The highest sample (R6110 V) is assigned to Zone DN6 of de Verteuil and Norris (1996) on the basis of the absence of *Cleistosphaeridium placacanthum* (highest occurrence defines the top of DN5). The sample contains *Pentadinium* sp. (highest occurrence within DN7, but rare above DN6) and a single specimen of *Trinovantedinium glorianum* (lowest occurrence within DN6). Although this sample is technically above the highest occurrence of *C. placacanthum*, its flora is otherwise quite similar to that in the sample below. In de Verteuil and Norris' (1996) original publication, their highest middle Miocene sample (Calvert Formation) in the Exmore core was also lacking *C. placacanthum*.

Diatom biostratigraphy.—Samples of the Calvert Beach Member in the Langley core were studied for siliceous microfossils (figs. H12, H13). The presence of *Delphineis penelliptica*, *Denticulopsis simonsenii* (=*D. hustedtii*), and *Coscinodiscus lewisianus*, along with the absence of *Thalassiosira grunowii* (=*Coscinodiscus plicatus*) and *Delphineis ovata*, in the diatom assemblages of samples from 136.9 m (449.0–449.2 ft) through 128.0 m (419.9–420.0 ft) places them in the *Delphineis penelliptica* Partial Range Zone (IV) of Abbott (1978) (Abbott, 1980). It is presumed that the more poorly preserved interval represented by the sample from 138.4 m (454.0–454.1 ft) also correlates with the *D. penelliptica* Zone, because the background diatom assemblage is the same.

Abbott's (1980) *Delphineis penelliptica* Zone is documented in offshore cores from Atlantic Margin Coring Project (AMCOR) Sites 6022 (lat 31°08.75' N., long 80°31.05' W., water depth 32 m (105 ft)) and 6011 (lat 39°43.5' N., long 73°58.6' W., water depth 22.3 m (73 ft)) and therefore would seem to have wide application along the U.S. East Coast. Abbott (1984) emphasized the importance of the first occurrence of *T. grunowii* in both onshore and offshore sections along the U.S. Atlantic margin and stated that it falls within strata assigned to planktonic foraminiferal Zone N11. This taxon was not found in the samples studied from the Langley core.

According to Abbott (1984), the first occurrence of *Denticulopsis simonsenii* coincides with the base of Zone N11 along the U.S. East Coast, whereas the last occurrence of *C. lewisianus* occurs within the lower half of Zone N12. The first occurrence of *D. simonsenii*, a cool-water species, is dated at about 14.2 Ma in California and in the Southern Ocean, so presumably this age would be a maximum age for the diatom-bearing section studied from the Langley core. The last occurrence of the warm-water diatom *C. lewisianus* in the equatorial Pacific is dated at 12.93 Ma, establishing a minimum age for the section studied. Although Burckle (1996) favored a somewhat younger age (about 12.1 Ma) for the last occurrence of *C. lewisianus* in the equatorial Pacific, Burckle may have confused some specimens of *C. lewisianus* with *Actinocyclus ellipticus* var. *spiralis*, a morphologically similar taxon that ranges above the true last occurrence of *C. lewisianus* (Barron, 1985). The entire interval (14.1–12.93 Ma) represented by samples from 138.4 to 128.0 m (454.0–454.1 to 419.9–420.0 ft) is correlated with planktonic foraminiferal Zone N10 and is correlated with the uppermost part of calcareous nannofossil Zone CN4 and the lowermost part of CN5a according to Berggren and others (1995).

The diatom assemblage appears to correlate entirely with the *Coscinodiscus lewisianus* Zone of Burckle (1996). However, if the last occurrence of *C. lewisianus* in the sample from 130.8 m (429.1–429.3 ft) represents a true last occurrence datum level, then samples from 129.6 m (425.2–425.4 ft) and 128.0 m (419.9–420.0 ft) would be assignable to the overlying *Rhizosolenia barboi/Delphineis penelliptica* Zone of Burckle (1996).

The diatom assemblage would also appear to correlate with the middle to upper part of Andrews' (1988) East Coast Diatom Zone (ECDZ) 5, the *Delphineis novaecesarea* Partial Range Zone because of the presence of *Actinoptychus virginicus*, *Delphineis penelliptica,* and *D. novaecesarea* and the absence of *Rhaphoneis magnapunctata, R. clavata,* and *Thalassiosira grunowii*. As such, it is an assemblage that coincides with that of Shattuck's (1904) bed "14" to lower "15" of the Calvert Formation in the Scientist Cliffs area of Calvert County, Md. (Andrews, 1988). Such a correlation is in agreement with de Verteuil and Norris (1996), who correlated ECDZ 5 with dinoflagellate zone DN5.

Diatom correlation with other East Coast sections.—The diatom assemblage in the Calvert Beach Member of the Calvert Formation in the Langley core resembles those of other reports on the U.S. East Coast. It is very similar to that of the Coosawhatchie Clay Member of the Hawthorn Formation of South Carolina as described by Ernissee and others (1977); however, the absence of *Thalassiosira grunowii* (=*C. plicatus*) in the Langley core material suggests that it is slightly older than the Coosawhatchie Clay. Similarly, the diatom assemblage closely resembles the diatom assemblage of the Choptank Formation from Calvert County, Md., described by Andrews (1976), but it lacks *Rhaphoneis diamantella*, a marker taxon for Andrews' (1988) East Coast Diatom Zone 7 and, therefore, it appears to be older.

Andrews and Abbott (1985) also documented a similar diatom assemblage from the Hawthorn Formation of Thomas County, Ga.; however, the lack of *Denticulopsis simonsenii* in the Hawthorn suggests that that assemblage was slightly older than that studied from the Langley core, a conclusion that is also supported by the presence of *Rhaphoneis magnapunctata* in the former and its absence from the latter (Andrews, 1988).

Silicoflagellates.—The first occurrence of *Distephanus stauracanthus* in the sample from 129.6 m (425.2–425.4 ft) depth in the Langley core (fig. H13) is correlated with the lowermost part of calcareous nannofossil Subzone CN5a in the equatorial Pacific according to Barron and others (1985), a correlation slightly younger than that of Perch-Nielsen (1985) and Ernissee and others (1977), who placed this silicoflagellate datum at the CN4-CN5 zonal boundary. Either way, it appears that the equivalent of the CN4-CN5 boundary, dated at 13.6 Ma by Berggren and others (1995), would fall in the upper part of the section studied.

Langley core silicoflagellate floras of the *Corbisema triacantha* Zone are dominated (50 to 82 percent) by *Distephanus crux crux* and *D. crux parvus* and contain sparse (2 to 12 percent) *Bachmannocena*, *Caryocha*, and *Corbisema*. Silicoflagellates are abundant in only one sample, from 131.9 m (432.8–433.0 ft), where *B. elliptica miniformis* and *D. speculum speculum* indicate strongest nutrient upwelling. The silicoflagellate section in the Langley core extends from 136.9 to 128.0 m (449.0–449.2 to 419.9–420.0 ft); the zonal guide species in this short, 9-m-thick (29-ft-thick) Langley section, *C. triacantha* and *D. stauracanthus*, have been reported together with mid-Miocene coccoliths of Subzone CN5a in a 27-m (90-ft) section at DSDP Site 470 in the Pacific off northern Mexico (Bukry, 1981). The silicoflagellate relative paleotemperature values (Ts column in fig. H13) for the Langley samples are moderate and show slight cooling upwards.

Nearly identical *Distephanus stauracanthus* Subzone floras have been described from cores of mid-Miocene strata from southern New Jersey (Bukry, 1990). There, well ACOW 1 (lat 39°19'52" N., long 74°25'89" W.), south of Atlantic City, contains a 71-m (234-ft) interval assigned to the subzone by the presence of *C. triacantha* and *D. stauracanthus*. The floras are also dominated by the *D. crux* group. Sample 658, near the bottom of the subzone in ACOW 1, has the overlap of *D. stauracanthus* with diatom guide *Coscinodiscus lewisianus*. This overlap might occur in the unsampled interval between 129.6 and 128.0 m (425.3 and 420.0 ft) in the Langley core, if the last *C. lewisianus* in the sample from 130.8 m (429.1–429.3 ft) represents a true last occurrence datum (fig. H12).

In noting the co-occurrence of *D. stauracanthus* and *C. lewisianus* in the Coosawhatchie Clay Member of the Hawthorn Formation in South Carolina and its equivalent in Georgia, Ernissee and others (1977) emphasized that the overlap of these two taxa is substantial in the equatorial Pacific, a conclusion that is also supported at DSDP Site 470 in the Pacific off northern Mexico (Barron, 1981a; Bukry, 1981). Ernissee and others (1977) indicated that the first *Distephanus stauracanthus* occurs below the first occurrence of the diatom *T. grunowii* (= *Coscinodiscus plicatus*) in an interval correlated with the lowermost part of calcareous nannofossil Zone NN 6 (=CN5a). In contrast to the correlations of Abbott (1978, 1984), Ernissee and others (1977) showed that *Thalassiosira grunowii* first occurs near the middle of NN 6 (=CN5a), a correlation supported in the equatorial Pacific (Barron, 1981b). It would, therefore, appear that the top of the biosiliceous section studied in the sample from 128 m (419.9–420.0 ft) correlates with the lower portion of calcareous nannofossil Subzone CN5a (=NN 6) and that the last occurrence of *C. lewisianus* in the sample from 130.8 m (429.1–429.3 ft) does not represent a true last occurrence datum.

Paleoenvironmental information.—Strong nutrient upwelling is indicated for the sample at 131.9 m (432.8–433.0 ft) because of the presence of *Bachmannocena elliptica miniformis* and *Distephanus speculum speculum*. The silicoflagellate relative paleotemperature Ts values for the Langley samples are moderate and show slight cooling upwards (fig. H13).

Middle Miocene correlation of the Calvert Beach Member of the Calvert Formation.—Dinoflagellate, diatom, and silicoflagellate biostratigraphy all indicate placement of the Calvert Beach Member of the Calvert Formation in the middle Miocene. Dinoflagellate placement is in the upper half of Zone DN5 and in Zone DN6 of de Verteuil and Norris (1996). Diatoms indicate the *Delphineis penelliptica* Partial Range Zone (IV) of Abbott 1978 (Abbott, 1980) and *Coscinodiscus lewisianus* Zone of Burckle (1996). Silicoflagellates indicate placement in the *Distephanus schulzii* and *Distephanus stauracanthus* Subzones of the *Corbisema triacantha* Zone.

In the absence of dinoflagellate, diatom, and silicoflagellate data to the contrary, the presence of specimens of the calcareous nannofossil genus *Catinaster* would have indicated a latest middle or early late Miocene age. A similar anomalous occurrence of *Catinaster* was noted by the shipboard scientific party for Ocean Drilling Program (ODP) Leg 150, Site 905, offshore New Jersey (Mountain, Miller, Blum, and others, 1994, p. 277). Aubry (1996, p. 436) attributed the Leg 150 occurrence to core contamination. The number of occurrences of *Catinaster* in the Langley core suggests that contamination is not the cause; rather, the lowest occurrence of genus *Catinaster* may be within the middle Miocene, possibly at 13–14 Ma.

St. Marys Formation

The St. Marys Formation at 123.6–68.4 m (405.5–224.5 ft) depth in the Langley core was studied for dinoflagellates (fig. H11), mollusks (fig. H6, in pocket), and ostracodes (fig. H7). Although 13 samples were examined for calcareous nannofossils from this formation, most of the samples were barren of calcareous nannofossils, and the rest contained no age-diagnostic species. Dinoflagellates place the unit in Zone DN9, although the lowest sample is possibly in DN8. Both zones are upper Miocene. The unit is 55.2 m (181.0 ft) thick and represents less than 1.3 m.y of deposition. The base of this unit is calibrated at the base of Zone DN9 (8.7 Ma according to de Verteuil and Norris, 1996). The top of the St. Marys is still within DN9 (and thus older than 7.4 Ma according to de Verteuil and Norris, 1996). As discussed below, both mollusks and ostracodes indicate intervals representing episodes of upwelling within the St. Marys Formation.

Dinoflagellates and acritarchs.—Five samples were examined for dinocysts from the St. Marys Formation in the Langley core (fig. H11). The sample depths range from 120.4 to 72.2 m (395.2 to 236.8 ft). Three specimens are shown in plate H5 (figs. 2, 3, and 7). Preservation ranges from good to poor.

These five samples are placed in the upper Miocene (Tortonian) Zone DN9 on the basis of the presence of *Barssidinium evangelineae* (lowest occurrence at or near the base of DN9) and *Hystrichosphaeropsis obscura* (highest occurrence defines the top of DN9). The lowest St. Marys sample (R6110 U) contains a single, poorly preserved specimen of *Sumatradinium soucouyantiae* (highest occurrence defines the top of DN8), and thus it alternatively could be placed in uppermost Zone DN8. The absence of *Palaeocystodinium golzowense* (highest occurrence at the top of DN8) favors the interpretation of *S. soucouyantiae* as reworked.

Mollusks.—The St. Marys Formation at 123.6–68.4 m (405.5–224.5 ft) depth within the Langley core contains 15 recognizable molluscan taxa (fig. H6) scattered throughout the unit. The dominant taxa are *Turritella plebeia plebeia*, *T. plebeia carinata*, and *T. subvariabilis,* and these are concentrated in zones around 95.1–94.5 m (312–310 ft) and 92.3–90.1 m (303–295.5 ft). The preservation of *Turritella subvariabilis* within the Langley core does not allow separation of this species into subspecies. Ward (1992) listed the stratigraphic ranges of these species of *Turritella* as shown in table H2.

The presence of *Turritella plebeia plebeia* and *Turritella subvariabilis* in the St. Marys is in agreement with Ward (1992); however, the occurrence of *T. plebeia carinata* is outside the published range. *Turritella plebeia carinata* is distinctive (see specimen from Eastover Formation on pl. H7, figs. 11, 12, for representative form), well preserved, and relatively abundant in the St. Marys in the Langley core, and so the most likely explanation is that the subsurface St. Marys contains species not seen in outcrop and, therefore, extends the stratigraphic range of *T. plebeia carinata*.

Ostracodes.—Although the ostracodes from the classic Miocene Calvert Cliffs of Maryland were described by Ulrich and Bassler (1904) and their taxonomy was updated by Forester (1980), the detailed stratigraphic distribution of species is still only generally known. Nonetheless, the Langley core samples between 120.2 m (394.2–394.6 ft) and 71.3 m (233.9–234.1 ft) contain typical St. Marys assemblages that include *Actinocythereis exanthemata*, *Muellerina lienenklausi*, *Murrayina barclayi*, and *Murrayina macleani* (fig. H7). It should be noted that an apparently undescribed species of *Cytheridea* occurs in this interval and that the specimens of *A. exanthemata* are more reticulated than is typical of this species. The lowest occurrence of *Pseudocytheretta burnsi* in the upper St. Marys at 88.1 m (289.1–289.3 ft) may prove to be a noteworthy marker for the transition between the St. Marys and the overlying Eastover Formation.

Paleoenvironmental information.—Both mollusks and ostracodes indicate intervals of upwelling within the St. Marys Formation.

The abundance of *Turritella* in the St. Marys Formation indicates favorable conditions for this group during the time of deposition. Allmon (1988), in a summary of living turritelline

Table H2. Stratigraphic ranges and mollusk zones of selected *Turritella* species reported by Ward (1992) from the U.S. middle Atlantic Coastal Plain.

Taxon	Formation	Age	Mollusk zone
Turritella plebeia plebeia	Eastover Formation St. Marys Formation Choptank Formation Calvert Formation	Lower middle Miocene to upper Miocene	M7–M13
Turritella plebeia carinata	Eastover Formation (Claremont Manor Member)	Upper Miocene	M8
Turritella subvariabilis subvariabilis	St. Marys Formation (Windmill Point beds)	Lower upper Miocene	M9
Turritella subvariabilis bohaski	St. Marys Formation (Little Cove Point beds)	Lower upper Miocene	M10
Turritella subvariabilis dianae	Choptank Formation (Drumcliff Member)	Middle middle Miocene	M12

ecology, concluded that they are most commonly found at depths of less than 100 m (330 ft) and in fully marine water, although some species can tolerate salinities less than 35 parts per thousand (ppt). Typically they are found in waters between 15°C and 20°C, although they can range from 2°C to 27°C. Living *Turritella* frequently occur in areas of coastal upwelling, and most high-density populations of *Turritella* are found landward of these upwelling zones (Allmon, 1988). The dense zones of *Turritella* within the St. Marys may be indicative of coastal upwelling. The other molluscan species in the St. Marys indicate marine shelf conditions but do not provide any further details on depositional environment.

Ostracodes indicate that the depositional environment for the St. Marys Formation (120.2 –71.3 m; 394.6–233.9 ft) was inner-middle neritic, although the consistent occurrence, often in abundance, of *Cytherella* may signify outer neritic conditions, upwelling cooler water, or both. Seasonality in temperatures was relatively small.

Other paleontological information.—Rare dinoflagellate specimens that appear to have been altered by the impact (curled processes as described in Frederiksen and others, this volume, chap. D) were found in the St. Marys Formation (R6110 T, 114.5 m=375.5–375.8 ft) and thus are possibly, but not necessarily, reworked.

Eastover Formation

The Eastover Formation at 68.4–23.3 m (224.5–76.3 ft) depth in the Langley core was studied for dinoflagellates (fig. H11), mollusks (fig. H6, in pocket), and ostracodes (fig. H7). All calcareous nannofossil samples but one were either barren or very questionably datable. The single clearly datable nannofossil sample at 56.9 m (186.6 ft) is in Zone NN 11 (fig. H4). Dinoflagellates place the unit in Zones DN9 and DN10. Both zones are upper Miocene. The boundary between DN9 and DN10 is bracketed by samples at 52.4 and 59.9 m (171.6–172.0 and 196.4–196.7 ft). The DN9-DN10 boundary is calibrated at 7.4 Ma, and the top of DN10 is at 5.9 Ma (de Verteuil and Norris, 1996). The unit is 45.1 m (148.2 ft) thick.

Calcareous nannofossils.—Twelve samples from 67.3 to 23.8 m (220.8 to 78.2 ft) depth in the Langley core were examined for calcareous nannofossils from the Eastover Formation. Most of the samples were barren or contained only rare calcareous nannofossils. However, a sample from 56.9 m (186.6 ft) contained frequent calcareous nannofossils, and the presence of *Discoaster berggrenii* (FAD and LAD within Zone NN 11) restricts this sample to the late Miocene Zone NN 11.

The sample from 31.4 m (103.0 ft) contains a questionable occurrence of *Discoaster intercalaris* (Zones NN 11–12 in range). If it is this species, then the samples from 50.6 to 31.4 m (166.1 to 103.0 ft) can be no older than Zone NN 11 because they overlie samples of this zone, and no younger than Zone NN 12 because *D. intercalaris* does not occur above Zone NN 12. If the specimen is not *D. intercalaris,* then the upper part of the Eastover cannot be dated any closer than Zones NN 11–15 on the basis of calcareous nannofossils.

Dinoflagellates and acritarchs.—Four samples from the Eastover Formation were examined for dinocysts. The sample depths range from 66.1 to 24.8 m (216.9 to 812 ft) in the Langley core. All are upper Miocene. Selected specimens are shown in plate H5 (figs. 4–6, 8–11). Preservation ranges from fair to good.

The lower two samples are assigned to Zone DN9 on the basis of the presence of *Hystrichosphaeropsis obscura*, the highest occurrence of which defines the top of DN9. The two higher samples are assigned to the upper upper Miocene Zone DN10 on the basis of the presence of *Selenopemphix armageddonensis* (lowest occurrence at or near the base of DN10) and *Erymnodinium delectabile* (highest occurrence defines the top of DN10) and the absence of *Hystrichosphaeropsis obscura* (highest occurrence defines the top of DN9). The presence of *Labyrinthodinium truncatum* (lowest occurrence at or near the top of DN9) in sample R6110 I (52.4 m=171.6–172.0 ft depth) suggests that this sample should fall near the DN9-DN10 boundary, as this species is not known to range very far into DN10. The uppermost sample also contains *Filisphaera microornata* (lowest occurrence at or near the base of DN10).

Mollusks.—The molluscan assemblages within the Eastover Formation in the Langley core are relatively diverse, containing 46 recognizable molluscan taxa (fig. H6, pl. H7). The dominant forms are *Anomia* sp., *Lirophora vredenburgi*, *Nucula proxima*, *Isognomon* sp., *Turritella* spp., and pectens. Two segments within the Eastover portion of the core contain more concentrated and diverse molluscan remains: 61.2–56.8 m (200.7–186.2 ft) and 41.6–34.4 m (136.5–113 ft).

Ward (1992) designated molluscan interval zones M7 and M8 (upper part of the upper Miocene) within the Eastover Formation, which correlate with the Cobham Bay and Claremont Manor Members of the Eastover. *Ecphora gardnerae whiteoakensis*, present in the sample from 66.8 m (219 ft), is restricted to M8 (Ward, 1992). The segment of the core from 58.8 to 37.2 m (193 to 122 ft) contains a mixture of specimens from zones M7 and M8 (Ward, 1992): *Turritella plebeia carinata* (M8), *Chesapecten middlesexensis* (M7–M8), *Anadara carolinensis* (M7–M8), *Spisula rappahannockenis* (M7–M8), and *Lirophora vredenburgi* (M7). The co-occurrence of *Turritella plebeia carinata* and *Lirophora vredenburgi* indicates either that the ranges of one or both species need to be revised or that the Langley core preserves Eastover beds that lie stratigraphically between the Cobham Bay and the Claremont Manor Members as they are known in outcrop. In addition, *Turritella subvariabilis*, typical of zones M9–M12 in the St. Marys Formation (see discussion above), is present from 44.0 to 38.6 m (144.5 to 126.5 ft). The very worn and weathered condition of *Turritella subvariabilis* implies that reworking may have occurred in this segment of the Eastover. From 37.1 m (121.6 ft) to the top of the Eastover at 23.3 m (76.3 ft), the sediments contain two species of mollusks restricted to the M7 zone of Ward (1992)—*Carolinapecten urbannaensis* and *Lirophora vredenburgi*.

Fragments of *Isognomon* sp. occur throughout the Eastover sediments in the Langley core but are densely concentrated from 62.5 to 59.7 m (205 to 196 ft) and from 42.7 to 41.8 m (140.1 to 137.0 ft). Ward (1992) described *Isognomon* as being abundant in the Eastover Formation, occurring in thin beds in the Claremont Manor Member and in thick beds (up to 1.8 m (6 ft) thick) in the Cobham Bay Member.

Ostracodes.—The lower Eastover Formation in the Langley core is marked by the first occurrence of the ostracodes *Loxoconcha florencensis* and *Hulingsina calvertensis* and the genus *Bensonocythere*. *Microcytherura shattucki* is a distinctive species that seems to be a useful indicator of the upper Miocene of the region, though it occurs only rarely. *Pterygocythereis inexpectata* first occurs in the lower Eastover; additional work is needed on the stratigraphic ranges of intermediate forms between *P. americana* and *P. inexpectata* (see Forester, 1980).

Paleoenvironmental information.—The molluscan pelecypod genera present in the Eastover Formation in the Langley core are similar to an assemblage from a modern subtropical to warm-temperate, relatively shallow, marine shelf having diverse substrates, analogous to the modern Gulf Coast of Florida (Brewster-Wingard and others, 2001; for modern environmental information, see the U.S. Geological Survey's (2004) South Florida Information Access databases at http://sofia.usgs.gov/flaecohist/). The absence of a diverse gastropod assemblage implies that the waters were cooler than the modern Florida coast or that there was an absence of subaquatic vegetation or both. The sample from 32.5 m (106.5–106.6 ft) contains a single specimen of *Truncatella*, which belongs to a group that lives just above high tide and is typically found in nearshore deposits (Emerson and Jacobson, 1976). Ostracodes suggest that the depositional environment for the Eastover Formation was inner-middle neritic.

Other paleontological information.—As in other Virginia cores, the dinocyst DN9-DN10 boundary in the Langley core does not exactly coincide with the St. Marys-Eastover contact. In the Langley core, this boundary is placed well up into the Eastover Formation (bracketed by samples at 52.4 and 59.9 m (171.6–172.0 and 196.4–196.7 ft). Sedimentation appears to have been essentially continuous.

Yorktown Formation

The Yorktown Formation at 23.3–2.2 m (76.3–7.2 ft) depth in the Langley core was studied for calcareous nannofossils (fig. H4, in pocket), dinoflagellates (fig. H11), mollusks (fig. H6, in pocket), and ostracodes (fig. H7). Fossils place the Yorktown in the Pliocene, both lower Pliocene and lower part of the upper Pliocene. Neither the mollusks nor the ostracodes record the presence of the oldest Yorktown known from other localities. Mollusks from zone M6 and ostracodes corresponding to the Sunken Meadow Member (Zone 1 of Mansfield, 1943) were not found. The Yorktown Formation in the Langley core is 21.1 m (69.1 ft) thick. We have used calibration points of 3.0 and 4.0 Ma for the upper and lower boundaries of the Yorktown, respectively, following Dowsett and Wiggs (1992). This calibration is based on the presence of the foraminifera *Dentoglobigerina altispira*, *Sphaeroidinellopsis*, and *Globorotalia puncticulata,* not in the Langley core, but in outcrops they studied nearby in southeastern Virginia.

Calcareous nannofossils.—Seven samples from 21.3 to 6.0 m (70.0 to 19.7 ft) depth in the Langley core were examined for calcareous nannofossils from the Yorktown Formation (fig. H4). These samples had abundant to common calcareous nannofossils with good to poor preservation. However, these samples were very difficult to date because, although the samples contained many specimens, the diversity was low, and there were few age-diagnostic species.

The lowest two samples, from 21.3 and 20.5 m (70.0 and 67.2 ft), are placed questionably in Zone NN 15 because they contain *Sphenolithus abies* (LAD near the top of Zone NN 15) and the Yorktown elsewhere has never been found older than Zone NN 15. *Reticulofenestra pseudoumbilicus* (LAD defines the top of Zone NN 15) is present only in the lowest sample at

21.3 m (70.0 ft), which also supports a NN 15 call for only the lowest part of the Yorktown in the Langley core. The absence of this species from the sample at 20.5 m (67.2 ft), which contains *S. abies,* is unexplained.

Although the samples in the interval from 18.2 to 16.5 m (59.8 to 54.2 ft) do not have any *Sphenolithus abies* or *Pseudoemiliania lacunosa*, it is more likely that they are in Zones NN 16–17 because *S. abies* is clearly present in the two underlying samples at 20.5 and 21.3 m (67.2 and 70.0 ft), and because its absence in the interval from 18.2 m (59.8 ft) and above is considered to be more diagnostic than the absence of *P. lacunosa*.

The upper three samples from 9.6 to 6.0 m (31.4 to 19.7 ft) are placed in Zones NN 16–17 because they do not have any sphenoliths, and they do contain *Pseudoemiliania lacunosa* (FAD in upper part of Zone NN 15) and *Discoaster asymmetricus* (LAD in Zone NN 17).

Dinoflagellates and acritarchs.—Four samples from 21.9 to 7.3 m (71.9 to 24.1 ft) depth in the Langley core were examined for dinoflagellates from the Yorktown Formation. Dinoflagellate samples from the Yorktown are most likely Pliocene. Two specimens are shown in plate H5 (figs. 12–15). Preservation ranges from fair to good.

The lowest dinoflagellate sample from the Yorktown Formation is similar to those of the underlying Eastover Formation, with the significant exception of the absence of *Erymnodinium delectabile,* the highest occurrence of which defines the top of Zone DN10. The top of DN10 is just below the top of the Miocene. The lowest Yorktown sample (R6110 E) additionally contains *Selenopemphix armageddonensis*, which is typically a late Miocene form but is known to range into the Pliocene.

The presence of *Ataxiodinium confusum* in sample R6110 C (9.6 m=31.4–31.7 ft depth) is diagnostic. The reported range of this species is approximately Zones NN 12–16 (lower Pliocene and lower part of the upper Pliocene). *Invertocysta lacrymosa*, also present in this sample, has its highest occurrence in the upper Pliocene. The highest Yorktown sample is most likely Pliocene as it contains *Barssidinium evangelineae* (or *Barssidinium pliocenicum*), which does not range into the Pleistocene or may range only slightly into it. Sample R6110 D (16.0 m=52.4–52.8 ft depth) has material reworked from the Oligocene or Miocene.

Mollusks.—The Yorktown Formation in the Langley core contains 52 identifiable molluscan taxa identified from the sediments examined (fig. H6; pl. H6, fig. 2; pl. H8). The dominant species are *Turritella alticostata*, *Yoldia laevis*, *Nuculana acuta*, *Pitar sayana*, *Nucula proxima*, and *Crepidula fornicata*. *Tectonatica pusilla* and *Parvilucina crenulata*, two minute species, are abundant in some samples. Molluscan remains are scattered throughout the unit, but concentrations are increased in the segments at 19.7–16.8 m (64.5–55 ft), 13.1–12.5 m (43–41 ft), and about 6.7 m (22 ft).

No molluscan species representative of mollusk zone M6 (lower Pliocene) from the lower part of the Yorktown were identified in the Langley core. *Chesapecten madisonius, Turritella alticostata, Striarca centenaria*, and *Astarte undulata* of M5 (lower Pliocene to mid-upper Pliocene) (Blackwelder, 1981) were present in the sediments. A number of molluscan species identified by Harris (Harris *in* Ward, 1993) from the type Yorktown sections are present in the core: *Acteocina candei, Astarte concentrica, Chesapecten madisonius, Crepidula fornicata, Cyclocardia granulata, Nucula proxima, Nuculana acuta, Pitar sayana, Striarca centenaria, Turritella alticostata,* and *Yoldia laevis*.

Ostracodes.—The lowest Yorktown Formation ostracode sample in the Langley core (22.8 m (74.7–74.9 ft) depth) cannot be assigned to an ostracode zone. The next higher sample at 20.3 m (66.5–66.7 ft) contains ostracode species that place it within the middle part of the Pliocene but do not restrict it to either of the *Pterygocythereis inexpectata* or *Orionina vaughani* Zones of Hazel (1971). Ostracodes corresponding to the Sunken Meadow Member (Zone 1 of Mansfield, 1943) were not found.

The Yorktown Formation samples between 16.1 m (52.8–53.1 ft) and 5.6 m (18.4–18.6 ft) contain the most abundant and diverse ostracode assemblages in the core. These faunas typically contain age-diagnostic Pliocene species described in detail in Hazel (1977, 1983), Cronin and Hazel (1980), and Cronin (1990), whose taxonomy and biostratigraphy of Yorktown ostracodes supersede those of earlier workers (Malkin, 1953; Swain, 1974). The Yorktown beds above 16.1 m in the Langley core represent the *Orionina vaughani* ostracode assemblage zone, and they include several age-diagnostic Pliocene species such as *Orionina vaughani* and several species of *Muellerina* and *Bensonocythere*. Elsewhere in Virginia, the *Orionina vaughani* Zone is represented by the Rushmere, Morgarts Beach, and Moorehouse Members of the Yorktown of Ward and Blackwelder (1980).

The Yorktown ostracode assemblages indicate a pattern of progressively warmer water temperatures and (or) shallower water during this mid-Pliocene transgression that has been well documented in previous studies in Virginia and in the age-equivalent Raysor and Duplin Formations in South Carolina (Hazel, 1971; Cronin, 1988). This transition is exemplified by the shift from assemblages dominated by cool-mild temperate taxa (such as *Actinocythereis dawsoni*, *Thaerocythere*, *Cytheromorpha warneri*, and *Cytherura howei*) to those dominated by warm temperate and marginally subtropical conditions. The progressive appearances of the following warmer water taxa are noteworthy: *O. vaughani*, *Proteoconcha tuberculata, Paracytheridea altila,* and *Hulingsina* spp., at 16.1 m (52.8–53.1 ft), *Loxoconcha reticularis* at 15.4 m (50.5–50.7 ft), *Neonesidea laevicula* and *Paracytheridea* cf. *P. mucra* at 10.8 m (35.4–35.6 ft), and *Puriana rugipunctata* and *P. carolinensis* at 9.7 m (31.7–32.0 ft).

Paleoenvironmental information.—The abundant Nuculacea and *Crepidula* within the Yorktown sediments in the Langley core indicate a shallow, quiet-water environment, possibly back barrier or bay. Many of the other molluscan taxa (Lucinidae, Arcidae, *Astarte* spp., *Tellina* spp., *Chione cancellata*) require near-normal marine salinities but could be found in an open bay system or shallow shelf. The *Turritella* typically suggest marine conditions and possible upwelling (Allmon, 1988; see discussion above under "St. Marys Formation").

The ostracodes indicate a nearly complete record of the *Orionina vaughani* Zone of the Yorktown in the Langley core; during depositon of this zone, paleoceanographic changes led to large-scale faunal changes and useful age-diagnostic stratigraphic ranges. The progressive warming during the late Miocene through middle Pliocene, indicated by the northward migration of subtropical ostracode taxa and the corresponding decrease in temperate taxa, has been discussed as a manifestation of the growing influence of the Gulf Stream-North Atlantic drift system, which probably intensified as the Central American Isthmus formed (Cronin and Dowsett, 1996). The broader significance of the middle Pliocene warmth indicated by the Yorktown ostracodes is discussed in Cronin (1991).

The presence of the dinoflagellate *Tuberculodinium vancampoae* may indicate temperatures somewhat warmer than the present Chesapeake Bay. Low numbers of offshore genera, such as *Invertocysta* and *Impagidinium,* are present.

Tabb Formation

The upper 2.2 m (7.2 ft) of the Langley core is assigned to the Lynnhaven Member of the Tabb Formation (Powars and others, this volume, chap. G). The unit consists of oxidized, muddy and sandy gravel that grades upward to oxidized muddy sand. No fossils were recovered from this unit in the Langley core.

Discussion

The combination of the various fossil data allows the construction of a depth-age plot for the Langley core (fig. H14). Minimum sediment accumulation rates are shown here, as only zone boundaries are plotted even where a unit may not span an entire zone. The steep slope on the plot clearly shows an initial rapid sedimentation throughout the deposition of the Chickahominy Formation, reflecting the filling or partial filling of the crater. Sediment accumulation rates slowed in the Oligocene and early and middle Miocene, where sea-level changes caused unconformities that punctuate the record. Deposition of the St. Marys and Eastover Formations reflects a second episode of rapid sedimentation. Gaps in the plot below the Yorktown and Tabb Formations also reflect unconformities punctuating the record.

The Miocene lithostratigraphic units discussed in this chapter have been divided into members in the classic outcrops in Virginia and Maryland (Shattuck, 1904; Dryden and Overbeck, 1948; Gernant, 1970; Ward and Blackwelder, 1980; Ward, 1984; see de Verteuil and Norris, 1996, for further discussion); the members are listed in table H3. In the USGS-NASA Langley core, these members reflect the sedimentary history of the crater-fill. For the lower and middle Calvert Formation, three of the four formal and informal members are recognized here. None are very thick in the Langley core. The upper middle Miocene Choptank Formation is not present in the Langley core. As figure H14 shows, the lower and middle Miocene sediment record at the Langley corehole is dominated by large gaps in the recovered record. In contrast, the upper Miocene St. Marys and Eastover Formations show rapid accumulation of a thick sedimentary record. We do not distinguish individual members of these formations at the Langley corehole, because they show nearly continuous sediment accumulation and thus reveal a more complete record than sections in which the members were defined.

Reworking of microfossils is a notable feature of many of the samples from the Langley core. For the Chickahominy Formation, all dinoflagellate samples studied thus far contain rare specimens that have been folded, partially melted, or otherwise altered by the impact, as described by Frederiksen and others (this volume, chap. D). Altered dinoflagellates were also recognized in the Old Church and St. Marys Formation. The finding of these specimens in postimpact sediments as young as the late Miocene supports the idea of continued exhumation of impact-generated sediments, especially around the buried rim of the Chesapeake Bay impact structure (Johnson and others, 1998).

Summary and Conclusions

The USGS-NASA Langley core provides an exceptional opportunity to describe the paleontology of upper Eocene, lower Oligocene, and upper Oligocene sediments of the Chickahominy Formation, the Drummonds Corner beds, and the Old Church Formation. These units are unknown to poorly known in outcrop. The Chickahominy Formation in the Langley core is a 52-m-thick (172-ft-thick) unit that represents approximately 2 m.y. of depositional accumulation in outer neritic to upper bathyal marine environments during the late Eocene.

The Drummonds Corner beds are newly recognized in the Langley core. This 7.3-m-thick (23.9-ft-thick) unit represents 1.4 m.y. or less of deposition. Paleontology indicates an age in the later part of the early Oligocene, with a sharp floral and faunal break between the Drummonds Corner beds and the underlying Chickahominy Formation. The Drummonds Corner beds appear to represent shallower water or more nearshore deposition than the underlying Chickahominy deposits.

The Old Church Formation is 32.5 m (106.5 ft) thick in the Langley core and represents 4.6 m.y. or less of deposition. It contains a more complete upper Oligocene record than is known from outcrops or shallow cores. A paleoenvironment of middle-outer neritic, subtropical, is suggested.

In contrast to the underlying units, the Miocene, Pliocene, and Pleistocene units have been recognized and studied extensively in outcrops in Virginia, Maryland, and Delaware. The Langley core provides the opportunity to relate some of these classic stratigraphic units to microfossil and megafossil studies of the core. Other regional stratigraphic units are not present at this site.

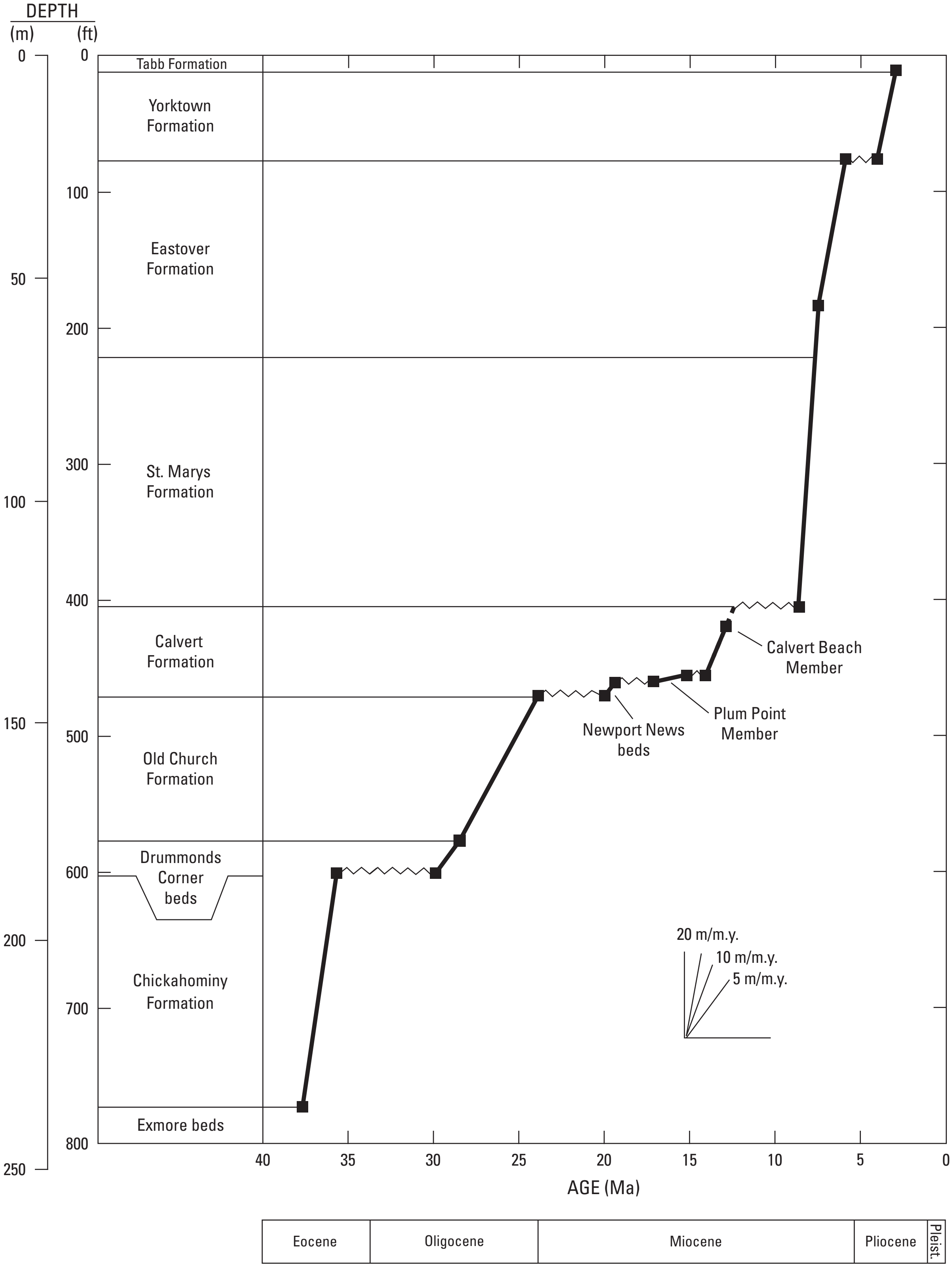

Figure H14. Age-depth plot for the postimpact sediments in the USGS-NASA Langley core. Time scale is from Berggren and others (1995). Calibration points are discussed in text. Sediment accumulation rates represent minimum values.

Table H3. Miocene lithostratigraphic units in the classic outcrops in Virginia and Maryland and in the USGS-NASA Langley core, Hampton, Va.

Formation	Member or informal subunit in outcrops	Member or informal subunit in Langley core	Thickness in Langley core (m)	Thickness in Langley core (ft)	Comment
Eastover			45.1	148.2	The Eastover Formation is undivided in the Langley core and contains a more complete record than outcrops where the members were established
	Cobham Bay Member	Not differentiated	–	–	
	Claremont Manor Member	Not differentiated	–	–	
St. Marys			55.2	181.0	The St. Marys Formation is undivided in the Langley core and contains a more complete record than outcrops where the members were established
	Windmill Point beds	Not differentiated	–	–	
	Little Cove Point beds	Not differentiated	–	–	
Choptank			–	–	The Choptank Formation is absent from the Langley core
	Conoy Member[1]	Absent	–	–	
	Boston Cliffs Member	Absent	–	–	
	Drumcliff Member	Absent	–	–	
	St. Leonard Member	Absent	–	–	
Calvert			–	–	
	Calvert Beach Member	Calvert Beach Member	15.4	50.6	
	Plum Point Member	Plum Point Member	1.5	5.0	
	Fairhaven Member	Absent	–	–	
	Popes Creek Sand Member[2]	Newport News beds[2]	3.0	9.8	

[1] Placement of the Conoy Member in the Choptank Formation follows the usage of de Verteuil and Norris (1996).

[2] We follow Powars and Bruce (1999) in placing the lower part of the Calvert Formation in the Langley core in the informal Newport News beds. This unit may not be precisely correlative with the lowest named member of the Calvert Formation (Popes Creek Sand Member) in Maryland.

The Calvert Formation in the Langley core is represented by the lower Miocene Newport News beds and the middle Miocene Plum Point and Calvert Beach Members. Each member is bounded above and below by unconformities.

The St. Marys Formation represents 55.2 m (181.0 ft) and the Eastover Formation represents 45.1 m (148.2 ft) of late Miocene sedimentation. The unconformity-bounded members of these two formations cannot be distinguished florally or faunally in the Langley core because this core represents a more complete, and probably more continuous, section than is found in the areas where their members were described.

The Yorktown Formation is 21.1 m (69.1 ft) thick, and its fossils provide a record of a warm interval in the middle of the Pliocene. The Pleistocene Tabb Formation was not studied paleontologically.

The biostratigraphic study of the Langley core includes calcareous nannofossils, dinoflagellates and acritarchs, diatoms and silicoflagellates, mollusks, ostracodes, planktonic foraminifera and bolboformids, and vertebrate remains. This core will likely prove to be a benchmark for correlations among the various fossil groups in the upper Eocene, Oligocene, Miocene, and Pliocene sediments in southeastern Virginia.

Patterns in the rate of sediment accumulation indicate at least two episodes of rapid filling at the site of the Langley core: late Eocene and late Miocene. In contrast, the record of early and middle Miocene deposition at the site is punctuated by unconformities.

Reworking of microfossils, especially dinoflagellates, is a notable feature of many samples from the upper Oligocene to Pliocene units in the USGS-NASA Langley core. Some of the reworked specimens show impact-related damage, as described by Edwards and Powars (2003) and Frederiksen and others (this volume, chap. D). Other reworked specimens clearly postdate the impact. Continued exhumation along faults may have enhanced the contributions of older material into the various units filling the Chesapeake Bay impact crater (see also discussions in Powars and others, this volume, chap. G, and Catchings and others, this volume, chap. I).

Acknowledgments

U.S. Geological Survey (USGS) investigations of the Chesapeake Bay impact structure are conducted in cooperation with the Hampton Roads Planning District Commission, the Virginia Department of Environmental Quality, and the National Aeronautics and Space Administration (NASA) Langley Research Center. The Hampton Roads Planning District Commission and the USGS provided funds for the drilling of the USGS-NASA Langley corehole. The NASA Langley Research Center provided extensive operational and logistical support for the drilling operation. The Virginia Department of Environmental Quality and the Department of Geology of the College of William and Mary provided extensive operational support at the drill site.

We especially thank the USGS drilling crew of Manuel Canabal Lopez, Arthur C. Clark, Eugene F. Cobbs, Eugene F. Cobbs, III, Orren C. Doss, Jeffery D. Eman, Stephen J. Grant, Robert Hovland, Donald G. Queen, and Michael E. Williams for spectacular core recovery. Stephen E. Curtin (USGS) and Richard E. Hodges (USGS) provided the geophysical logs of the Langley corehole.

We thank Nancy Durika and Colleen McCartan (USGS) for processing dinoflagellate samples. Colleen McCartan also prepared dinoflagellate plates. James Murray (USGS) assisted in sample collection, processed all molluscan samples, and prepared the plates of mollusks. Carleigh Trappe (USGS) assisted in the preparation of the digital images of mollusks. Barron and Bukry thank Scott Starratt (USGS) for processing of siliceous microfossils. Christopher J. Nytch (USGS) processed material for ostracodes. We thank Emily Denham (USGS) for processing of foraminifera. Rob Stamm and Ellen Seefelt (both USGS) assisted with scanning-electron microscope work. Norman O. Frederiksen and Jean M. Self-Trail (both USGS) reviewed an earlier version of the manuscript and aided in difficult interpretations.

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Appendix H1. Full Taxonomic Citations for Taxa Mentioned in Chapter H

Selected samples from postimpact sediments in the USGS-NASA Langley core were studied for calcareous nannofossils (Bybell), dinoflagellates (Edwards), diatoms (Barron), silicoflagellates (Bukry), mollusks (Wingard), ostracodes (Cronin), planktonic foraminifera and bolboformids (Poag; see also Poag and Norris, this volume, chap. F, for information on benthic foraminifera), and vertebrate remains (Weems). For the purpose of formal names of species and genera, calcareous nannofossils, dinoflagellates, diatoms, silicoflagellates, and bolboformids are classified as plants. Mollusks, ostracodes, foraminifera, and vertebrates are classified as animals. Complete taxonomic names are given below.

Calcareous Nannofossils

Amaurolithus tricorniculatus (Gartner 1967) Gartner & Bukry 1975

Blackites spinosus (Deflandre & Fert 1954) Hay & Towe 1962
Blackites tenuis (Bramlette & Sullivan 1961) Sherwood 1974
Blackites Hay & Towe 1962 spp.
Braarudosphaera bigelowii (Gran & Braarud 1935) Deflandre 1947

Calcidiscus leptoporus (Murray & Blackman 1898) Loeblich & Tappan 1978
Calcidiscus macintyrei (Bukry & Bramlette 1969) Loeblich & Tappan 1978
Catinaster coalitus Martini & Bramlette 1963
Catinaster mexicanus Bukry 1971
Catinaster Martini & Bramlette 1963 spp.
Cepekiella lumina (Sullivan 1965) Bybell 1975
Ceratolithus rugosus Bukry & Bramlette 1968
Chiasmolithus altus Bukry & Percival 1971
Chiasmolithus bidens (Bramlette & Sullivan 1961) Hay & Mohler 1967
Chiasmolithus oamaruensis (Deflandre *in* Deflandre and Fert, 1954) Hay et al. 1966
Chiasmolithus titus Gartner 1970
Chiasmolithus Hay et al. 1966 spp.
Coccolithus eopelagicus (Bramlette & Riedel 1954) Bramlette & Sullivan 1961
Coccolithus pelagicus (Wallich 1877) Schiller 1930
Coronocyclus nitescens (Kamptner 1963) Bramlette & Wilcoxon 1967
Cribrocentrum reticulatum (Gartner & Smith 1967) Perch-Nielsen 1971
Cruciplacolithus Hay & Mohler, *in* Hay and others 1967 spp.
Cyclococcolithus formosus Kamptner 1963
Cyclococcolithus Kamptner 1954 spp.

Dictyococcites antarcticus Haq 1976
Dictyococcites bisectus (Hay et al. 1966) Bukry & Percival 1971
Dictyococcites scrippsae Bukry & Percival 1971
Discoaster asymmetricus Gartner 1969
Discoaster barbadiensis Tan Sin Hok 1927
Discoaster berggrenii Bukry 1971
Discoaster brouweri Tan Sin Hok 1927
Discoaster deflandrei Bramlette & Riedel 1954
Discoaster distinctus Martini 1958
Discoaster druggii Bramlette & Wilcoxon 1967
Discoaster exilis Martini & Bramlette 1963
Discoaster hamatus Martini & Bramlette 1963
Discoaster intercalaris Bukry 1971
Discoaster kugleri Martini & Bramlette 1963
Discoaster musicus Stradner 1959
Discoaster nodifer (Bramlette & Riedel 1954) Bukry 1973
Discoaster pentaradiatus Tan Sin Hok 1927
Discoaster quinqueramus Gartner 1969
Discoaster saipanensis Bramlette & Riedel 1954
Discoaster signus Bukry 1971
Discoaster surculus Martini & Bramlette 1963
Discoaster tanii Bramlette & Riedel 1954
Discoaster variabilis Martini & Bramlette 1963
Discoaster woodringii Bramlette & Riedel 1954
Discoaster Tan Sin Hok 1927 spp.

Ellipsolithus macellus (Bramlette & Sullivan 1961) Sullivan 1964
Ericsonia fenestrata (Deflandre & Fert 1954) Stradner *in* Stradner and Edwards, 1968
Ericsonia obruta Perch-Nielsen 1971

Gephyrocapsa Kamptner 1943 spp.
Goniolithus fluckigeri Deflandre 1957

Helicosphaera ampliaperta Bramlette & Wilcoxon 1967
Helicosphaera bramlettei (Müller 1970) Jafar & Martini 1975
Helicosphaera carteri (Wallich 1877) Kamptner 1954
Helicosphaera compacta Bramlette & Wilcoxon 1967
Helicosphaera euphratis Haq 1966
Helicosphaera intermedia Martini 1965
Helicosphaera minuta Müller 1981
Helicosphaera obliqua Bramlette & Wilcoxon 1967
Helicosphaera paleocarteri Theodoridis 1984
Helicosphaera recta (Haq 1966) Jafar & Martini 1975
Helicosphaera reticulata Bramlette & Wilcoxon 1967
Helicosphaera sellii (Bukry & Bramlette 1969) Jafar & Martini 1975
Helicosphaera seminulum Bramlette & Sullivan 1961
Helicosphaera truempyi Biolzi & Perch-Nielsen 1982

Helicosphaera wilcoxonii (Gartner 1971) Jafar & Martini 1975
Helicosphaera Kampter 1954 spp.

Isthmolithus recurvus Deflandre *in* Deflandre and Fert, 1954

Lithostromation operosum (Deflandre *in* Deflandre and Fert, 1954) Bybell 1975
Lithostromation perdurum Deflandre 1942
Lithostromation simplex (Klumpp 1953) Bybell 1975
Lithostromation Deflandre 1942 spp.

Markalius inversus Bramlette & Martini 1964

Neochiastozygus concinnus (Martini 1961) Perch-Nielsen 1971
Neococcolithes Sujkowski 1931 spp.

Pedinocyclus larvalis Bukry & Bramlette 1971
placoliths
Pontosphaera alta Roth 1970
Pontosphaera enormis (Locker 1967) Perch-Nielsen 1984
Pontosphaera multipora (Kamptner *ex* Deflandre 1959) Roth 1970
Pontosphaera pygmaea (Locker 1967) Bystrická & Lehotayova 1974
Pontosphaera segmenta (Bramlette & Percival 1971) Knuttel 1986
Pontosphaera wechesensis (Bukry & Percival 1971) Aubry 1986
Pontosphaera Lohmann 1902 spp.
Pseudoemiliania lacunosa (Kamptner 1963) Gartner 1969
Pseudotriquetrorhabdulus inversus (Bukry & Bramlette 1969) Wise *in* Wise and Constans, 1976

Reticulofenestra abisecta (Müller 1970) Roth & Thierstein 1972
Reticulofenestra daviesii (Haq 1968) Haq 1971
Reticulofenestra dorinocoides (Black & Barnes 1961) Kothe 1986
Reticulofenestra floridana (Roth & Hay *in* Hay and others, 1967) Theodoridis 1984
Reticulofenestra lockeri Müller 1970
Reticulofenestra pseudolockeri Juráková 1974
Reticulofenestra pseudoumbilicus (Gartner 1967) Gartner 1969
Reticulofenestra umbilicus (Levin 1965) Martini & Ritzkowski 1968
Reticulofenestra Hay et al. 1966 spp.
Rhabdosphaera vitrea (Deflandre *in* Deflandre and Fert, 1954) Bramlette & Sullivan 1961
Rhabdosphaera Haeckel 1894 spp.
Rhomboaster bramlettei (Brönnimann & Stradner 1960) Bybell & Self-Trail 1995

Scyphosphaera Lohmann 1902 spp.
Sphenolithus abies Deflandre *in* Deflandre and Fert, 1954
Sphenolithus belemnos Bramlette & Wilcoxon 1967
Sphenolithus ciperoensis Bramlette & Wilcoxon 1967
Sphenolithus distentus (Martini 1965) Bramlette & Wilcoxon 1967
Sphenolithus heteromorphus Deflandre 1953
Sphenolithus moriformis (Brönnimann & Stradner 1960) Bramlette & Wilcoxon 1967
Sphenolithus neoabies Bukry & Bramlette 1969
Sphenolithus predistentus Bramlette & Wilcoxon 1967
Sphenolithus pseudoradians Bramlette & Wilcoxon 1967
Sphenolithus Deflandre 1952 spp.
Syracosphaera clathrata Roth & Hay *in* Hay and others, 1967

Transversopontis pulcher (Deflandre *in* Deflandre and Fert, 1954) Perch-Nielsen 1967
Transversopontis pulcheroides (Sullivan 1964) Báldi-Beke 1971
Transversopontis zigzag Roth & Hay *in* Hay and others, 1967
Triquetrorhabdulus carinatus Martini 1965

Zygrhablithus bijugatus (Deflandre *in* Deflandre and Fert, 1954) Deflandre 1959

Dinoflagellates and Acritarchs

Achilleodinium biformoides (Eisenack 1954) Eaton 1976
Achomosphaera andalousiensis Jan du Chêne 1977
Achomosphaera Evitt 1963 sp.
Amiculasphaera umbracula Harland 1979
Apteodinium spiridoides Benedek 1972
Apteodinium tectatum Piasecki 1980
Areosphaeridium diktyoplokus (Klumpp 1953) Eaton 1971
Ataxiodinium confusum Versteegh & Zevenboom 1995

Barssidinium evangelineae Lentin et al. 1994 [may include *Barssidinium pliocenicum* (Head 1993) Head 1994]
Batiacasphaera baculata Drugg 1970
Batiacasphaera compta Drugg 1970
Batiacasphaera hirsuta Stover 1977
Batiacasphaera sphaerica Stover 1977
Bitectatodinium tepikiense Wilson 1973/*Bitectatodinium raedwaldii* Head 1997
Brigantedinium cariacoense (Wall 1967) Lentin & Williams 1993

Cerebrocysta poulsenii de Verteuil & Norris 1996
Cerebrocysta satchelliae de Verteuil & Norris 1996
Charlesdowniea coleothrypta (Williams & Downie 1966) Lentin & Vozzhennikova 1989
Charlesdowniea variabilis (Bujak 1980) Lentin & Vozzhennikova 1989
Chatangiella Vozzhennikova 1967
Chiropteridium galea (Maier 1959) Sarjeant 1983
Chiropteridium lobospinosum Gocht 1960
Chiropteridium Gocht 1960 spp.
Cleistosphaeridium placacanthum (Deflandre & Cookson 1955) Eaton et al. 2001
Cordosphaeridium cantharellus (Brosius 1963) Gocht 1969

Cordosphaeridium fibrospinosum Davey & Williams 1966
Cordosphaeridium funiculatum Morgenroth 1966
Cordosphaeridium gracile (Eisenack 1954) Davey & Williams 1966
Corrudinium incompositum (Drugg 1970) Stover & Evitt 1978
Corrudinium Stover & Evitt 1978 sp.
Cousteaudinium aubryae de Verteuil & Norris 1996
Cribroperidinium tenuitabulatum (Gerlach 1961) Helenes 1984
Cribroperidinium Neale & Sarjeant 1962 spp.
Cyclopsiella lusatica (Krutzsch 1970) Strauss & Lund 1992
Cyclopsiella vieta Drugg & Loeblich 1967
Cyclopsiella Drugg & Loeblich 1967 sp.

Damassadinium californicum (Drugg 1967) Fensome et al. 1993
Dapsilidinium pseudocolligerum (Stover 1977) Bujak et al. 1980
Deflandrea phosphoritica and forms intermediate with *D. heterophlycta*
Deflandrea phosphoritica Eisenack 1938 [including *D. phosphoritica* var. *spinulosa*]
Deflandrea Eisenack 1938 sp.
Dinopterygium cladoides sensu Morgenroth (1966)
Diphyes colligerum (Deflandre & Cookson 1955) Cookson 1965
Distatodinium ellipticum (Cookson 1965) Eaton 1976
Distatodinium paradoxum (Brosius 1963) Eaton 1976
Distatodinium Eaton 1976 spp.
Dracodinium varielongitudum (Williams & Downie 1966) Costa & Downie 1979

Ennaedocysta Stover & Williams 1995 sp. or spp.
Eocladopyxis peniculata Morgenroth 1966
Erymnodinium delectabile (de Verteuil & Norris 1992) Lentin et al. 1994
Escharisphaeridia Erkmen & Sarjeant 1980 sp.
Exochosphaeridium insigne de Verteuil & Norris 1996
Exochosphaeridium Davey et al. 1966? sp.

Filisphaera microornata (Head et al. 1989) Head 1994

Geonettia clineae de Verteuil & Norris 1996
Glaphyrocysta semitecta (Bujak 1980) Lentin & Williams 1981 [grouped as miscellaneous areoligeracean forms (*Glaphyrocysta* spp.) in figure H5]
Glaphyrocysta Stover & Evitt 1978 spp.

Habibacysta tectata Head et al. 1989
Hafniasphaera septata (Cookson & Eisenack 1967) Hansen 1977
Heteraulacacysta porosa Bujak 1980
Heteraulacacysta Drugg & Loeblich 1967 sp.
Histiocysta sp. of Stover and Hardenbol (1993)
Homotryblium aculeatum Williams 1978
Homotryblium plectilum Drugg & Loeblich 1967
Homotryblium vallum Stover 1977
Hystrichokolpoma cinctum Klumpp 1953
Hystrichokolpoma rigaudiae Deflandre & Cookson 1955
Hystrichosphaeropsis obscura Habib 1972
Hystrichostrogylon aff. *coninckii* of De Coninck (1995)

Impagdinium pallidum Bujak 1984
Impagidinium antecarcerum de Verteuil & Norris 1996
Impagidinium maculatum (Cookson & Eisenack 1961) Stover & Evitt 1978 sensu Santarelli (1997)
Impagidinium paradoxum (Wall 1967) Stover & Evitt 1978
Impagidinium sphaericum (Wall 1967) Lentin & Williams 1981
Impagidinium Stover & Evitt 1978 spp. [including cf. *I. strialatum* (Wall 1967) Stover & Evitt 1978]
Invertocysta lacrymosa Edwards 1984
Invertocysta tabulata Edwards 1984
Invertocysta Edwards 1984 spp.
Isabelidinium Lentin & Williams 1977 sp.

Kallosphaeridium capulatum Stover 1977

Labyrinthodinium truncatum Piasecki 1980 subsp. *modicum* de Verteuil & Norris 1996
Labyrinthodinium truncatum Piasecki 1980 subsp. *truncatum*
Lejeunecysta hyalina (Gerlach 1961) Artzner & Dörhöfer 1978
Lejeunecysta Artzner & Dörhöfer 1978 spp.
Lentinia serrata Bujak 1980
Lingulodinium machaerophorum (Deflandre & Cookson 1955) Wall 1967 [including *Lingulodinium siculum*]
Lophocysta? sp. indet. of De Coninck (1986)

Melitasphaeridium choanophorum (Deflandre & Cookson 1955) Harland & Hill 1979
Membranilarnacia? *picena* Biffi & Manum 1988
Membranophoridium aspinatum Gerlach 1961

Nematosphaeropsis pusulosa (Morgenroth 1966) Stover & Evitt 1978
Nematosphaeropsis rigida Wrenn 1988
Nematosphaeropsis Deflandre & Cookson 1955 sp.
new genus?, new species [apical archeopyle, areoligeracean group, with ectophragm]

Operculodinium? *placitum* Drugg & Loeblich 1967
Operculodinium centrocarpum (Deflandre & Cookson 1955) Wall 1967
Operculodinium centrocarpum sensu Wall (1967)
Operculodinium divergens (Eisenack 1954) Stover & Evitt 1978
Operculodinium piaseckii Strauss & Lund 1992
Operculodinium tegillatum Head 1997
Operculodinium Wall 1967 spp.

Palaeocystodinium golzowense Alberti 1961
Pentadinium imaginatum (Benedek 1972) Stover & Hardenbol 1993

Pentadinium laticinctum Gerlach 1961 [grano-vermiculate forms]
Pentadinium laticinctum Gerlach 1961 subsp. *laticinctum*
Pentadinium membranaceum (Eisenack 1965) Stover & Evitt 1978
Pentadinium Gerlach 1961 sp.
Pentadinium sp. cf. *P. laticinctum granulatum* Gocht 1969
Pentadinium sp. I of Edwards (1986)
Phthanoperidinium comatum (Morgenroth 1966) Eisenack & Kjellstrom 1971
Polysphaeridium zoharyi (Rossignol 1962) Bujak et al. 1980/ *Homotryblium vallum* Stover 1977
Pyxidiella? *simplex* Harland 1979

Reticulatosphaera actinocoronata (Benedek 1972) Bujak & Matsuoka 1986
Rhombodinium perforatum (Jan du Chêne & Châteauneuf 1975) Lentin & Williams 1977
Rottnestia borussica (Eisenack 1954) Cookson & Eisenack 1961

Samlandia chlamydophora Eisenack 1954
Samlandia chlamydophora sensu Stover and Hardenbol (1993)
Saturnodinium pansum (Stover 1977) Brinkhuis et al. 1992
Saturnodinium Brinkhuis et al. 1992 sp.
Selenopemphix armageddonensis de Verteuil & Norris 1992
Selenopemphix brevispinosa Head et al. 1989
Selenopemphix brevispinosa Head et al. 1989 subsp. *brevispinosa*
Selenopemphix brevispinosa/*S. dionaeacysta* Head et al. 1989
Selenopemphix dionaeacysta de Verteuil & Norris 1992
Selenopemphix nephroides Benedek 1972
Selenopemphix quanta (Bradford 1975) Matsuoka 1985
Selenopemphix Benedek 1972 sp.
Spiniferites mirabilis (Rossignol 1964) Sarjeant 1970
Spiniferites pseudofurcatus (Klumpp 1953) Sarjeant 1970
Spiniferites Mantell 1850 spp.
Sumatradinium druggii Lentin et al. 1994
Sumatradinium soucouyantiae de Verteuil & Norris 1996
Sumatradinium Lentin & Williams 1976 sp.? [fragment]

Tectatodinium pellitum Wall 1967
Thalassiphora delicata Williams & Downie 1966
Thalassiphora pelagica (Eisenack 1954) Eisenack & Gocht 1960
Thalassiphora reticulata Morgenroth 1966
Trigonopyxidia fiscellata De Coninck 1986
Trinovantedinium ferugnomatum de Verteuil & Norris 1992
Trinovantedinium glorianum (Head et al. 1989) de Verteuil & Norris 1992
Trinovantedinium harpagonium de Verteuil & Norris 1992
Trinovantedinium papula de Verteuil & Norris 1992
Trinovantedinium Reid 1977 spp.
Trinovantedinium? *xylochoporum* de Verteuil & Norris 1992
Tuberculodinium vancampoae (Rossignol 1962) Wall 1967
Turbiosphaera Archangelsky 1969 sp.

Unipontidinium aquaeductum (Piasecki 1980) Wrenn 1988

Wetzeliella gochtii Costa & Downie 1976
Wetzeliella symmetrica Weiler 1956
Wetzeliella Eisenack 1938 sp.

miscellaneous areoligeracean forms
miscellaneous peridiniacean forms
freshwater alga *Pediastrum* Meyen 1829

Diatoms

Actinocyclus ellipticus Grunow
Actinocyclus ellipticus var. *spiralis* Barron
Actinocyclus ingens Rattray
Actinocyclus octonarius Ehrenberg
Actinoptychus senarius (Ehrenberg) Ehrenberg
Actinoptychus thumii (Schmidt) Hanna
Actinoptychus virginicus (Grunow) Andrews
Annellus californicus Tempère
Azpeitia vetustissima (Pantocsek) P.A. Sims

Cavitatus miocenicus (Schrader) Akiba et Yanagisawa
Cladogramma dubium Lohman
Coscinodiscus apiculatus Ehrenberg
Coscinodiscus curvatulus Grunow
Coscinodiscus lewisianus Greville
Coscinodiscus marginatus Ehrenberg
Coscinodiscus oculus-iridis Ehrenberg
Coscinodiscus plicatus Grunow
Coscinodiscus radiatus Ehrenberg
Coscinodiscus rothii (Ehrenberg) Grunow
Cosmiodiscus elegans Greville
Craspedodiscus coscinodiscus Ehrenberg
Cymatogonia amplyoceras (Ehrenberg) Hanna

Delphineis angustata (Pantocsek) Andrews
Delphineis biseriata (Grunow) Andrews
Delphineis novaecesarea (Kain et Schulze) Andrews
Delphineis ovata Andrews
Delphineis penelliptica Andrews
Denticulopsis hustedtii (Simonsen et Kanaya) Simonsen
Denticulopsis simonsenii (Mertz) Akiba

Goniothecium rogersii Ehrenberg

Melosira westii W. Smith

Navicula pennata Schmidt

Paralia complexa (Lohman) Andrews
Paralia sulcata (Ehrenberg) Cleve
Pleurosigma affine var. *marylandica* Grunow
Pyxidicula cruciata Ehrenberg

Rhaphoneis clavata Andrews
Rhaphoneis diamantella Andrews
Rhaphoneis gemmifera Ehrenberg
Rhaphoneis lancelettula Grunow
Rhaphoneis magnapunctata Andrews

Stellarima sp.
Stephanopyxis corona (Ehrenberg) Grunow
Stephanopyxis grunowii Grove et Sturt
Stephanopyxis turris (Greville) Ralfs
Stephanopyxis sp. cf. *S. lineata* (Ehrenberg) Forti

Thalassionema nitzschioides Grunow
Thalassiosira grunowii Akiba et Yanagisawa
Thalassiosira leptopus (Grunow) Hasle et Fryxell
Thalassiosira praeyabei (Schrader) Akiba et Yanagisawa
Thalassiothrix longissima Cleve et Grunow
Triceratium condecorum Ehrenberg

Xanthiopyxis spp.

Silicoflagellates

Bachmannocena circulus (Ehrenberg) Locker
Bachmannocena elliptica elliptica (Ehrenberg) Bukry
Bachmannocena elliptica miniformis (Bachmann et Papp) Bukry
Bachmannocena triangula (Ehrenberg) Locker

Caryocha sp. Bukry et Monechi
Corbisema triacantha (Ehrenberg) Hanna

Dictyocha brevispina ausonia (Deflandre) Bukry
Dictyocha brevispina brevispina (Lemmermann) Bukry
Dictyocha fibula Ehrenberg
Dictyocha pulchella Bukry
Distephanus crux crux (Ehrenberg) Haeckel
Distephanus crux parvus (Bachmann) Bukry
Distephanus crux scutulatus Bukry
Distephanus longispinus (Schulz) Bukry et Foster
Distephanus schulzii (Deflandre *in* Bachmann et Ichikawa) Ciesielski et al.
Distephanus speculum speculum (Ehrenberg) Haeckel
Distephanus speculum triommata (Ehrenberg) Bukry
Distephanus stauracanthus (Ehrenberg) Haeckel
Distephanus stradneri (Jerkovic) Bukry
Distephanus sp. aff. *D. schauinslandii* Lemmermann

Mollusks

Pelecypoda

Amiantis? sp.
Anadara carolinensis (juv.) (Dall, 1895)?
Anisodonta? sp.
Anomia sp.
Astarte concentrica Conrad 1834
Astarte exalta Conrad, 1841
Astarte undulata Say 1824
Astarte spp. (worn)

Brachidontes sp.

carditid fragments
Carolinapecten urbannaensis (Mansfield 1929)
Chama sp.
Chesapecten madisonius (Say 1824)
Chesapecten middlesexensis (Mansfield 1936)
Chesapecten sp.
Chione cancellata (Linne 1767)
Clinocardium laqueatum (Conrad 1830)
Clinocardium sp.
corbulid fragments
Crassinella lunulata (Conrad 1834)
Crassinella sp.
Crassostrea sp.
Cyclocardia granulata (Say 1824)

Dosinia sp.

Eucrassatella sp. (juv.)

Glycymeris pectinata (Gmelin 1791)

Isognomon sp.

Leptomactra delumbis (Conrad 1832)
Leptonacea
Lirophora vredenburgi Ward 1992
Lirophora sp.
Lucina floridana Conrad 1833
Lucinisca cribraria (Say 1824)
Lucinoma contracta (Say 1824)

Macrocallista sp.
Mercenaria sp.
Musculus lateralis (Say 1822)? [?=*M. virginicus* Conrad 1867]
Mya wilsoni Ward 1992?

Nucula proxima Say 1822
Nucula sp.
Nuculana acuta (Conrad 1832)
Nuculana sp.

ostreid fragments and juv.

Pandora sp. cf. *P. dalli* Gardner
Panopea sp.
Parvilucina crenulata (Conrad 1840)
pectinid cf. “*Pecten*” *choctavensis* Aldrich 1895
pectinid cf. *Chlamys brooksvillensis* Mansfield 1937

pectinid cf. *Chlamys* aff. *C. vaun wythei* Hertlein Mansfield 1937
pectinid cf. *Placopecten* sp. (juv.)
pectinid fragments
Pitar sayana (Conrad 1833)
Placopecten sp.
Pleuromeris sp.

Raisa arata (Say 1824)
Rebeccapecten berryae Ward 1992

Solen sp.
Spisula rappahannockensis Gardner 1944
Spondylus sp.
Striarca centenaria (Say 1824)

Tellina spp.

Yoldia laevis (Say 1824)

Scaphopoda

Dentalium sp.

Gastropoda

Acteocina candei (d'Orbigny 1842)

Cadulus sp.
Calliostoma sp.
Cochliolepsis sp.
Crepidula fornicata (Linne 1758)
Crepidula plana Say 1822

Diodora sp. cf. *D. auroraensis* Ward and Blackwelder 1987

Ecphora gardnerae whiteoakensis Ward and Gilinsky 1988
Ecphora sp. (fragments)
Epitonium junceum Gardner 1948
Epitonium sp.
Eulima dalli (Gardner and Aldrich 1919)
Eupleura caudata (Say 1822)

Lunatia heros (Say 1822)
Lunatia sp.

Mitrella communis (Conrad 1862)

Nassarius marylandica (Martin 1904)
Nassarius peralta (Conrad 1868)
Nassarius spp.

Odostomia sp.
Olivella sp.

pyramidellids

"*Scalaspira*" *strumosa* (Conrad 1832)

Tectonatica pusilla (Say 1822)
Teinostoma tectispira Pilsbry 1953
Teinostoma sp.
Terebra? sp.
Truncatella sp.
Turbonilla sp.
Turritella alticostata Conrad 1834
Turritella plebeia Say 1824
Turritella plebeia carinata Gardner 1948
Turritella plebeia plebeia Say 1824
Turritella subvariabilis d'Orbigny 1852
Turritella subvariabilis bohaski Ward 1992
Turritella subvariabilis dianae Ward 1992
Turritella subvariabilis subvariabilis d'Orbigny 1852
Turritella sp.

Ostracodes

Acanthocythereis sp.
Actinocythereis captionis Hazel 1983
Actinocythereis dawsoni (Brady 1870)
Actinocythereis exanthemata (Ulrich and Bassler 1904)
Actinocythereis thompsoni Howe and Law 1936
Actinocythereis cf. *A. dacyi* (Howe and Law 1936)
Actinocythereis cf. *A. stenzeli* (Stephenson 1946)
Actinocythereis sp.
Alatacythere ivani Howe 1951
Argilloecia sp.
Aurila laevicula Edwards 1944

Bensonocythere americana Hazel 1967
Bensonocythere blackwelderi Hazel 1983
Bensonocythere bradyi Hazel 1983
Bensonocythere calverti (Ulrich and Bassler 1904)
Bensonocythere ricespitensis Hazel 1983
Bensonocythere rugosa Hazel 1983
Bensonocythere trapezoidalis (Swain 1974)
Bensonocythere spp.
Buntonia sp.

Campylocythere laeva Edwards 1944
Cytherella spp.
Cytheridea subovalis (Ulrich and Bassler 1904)
Cytheridea virginiensis (Malkin 1953)
Cytheridea n. sp.
Cytheromorpha macroincisa Hazel 1983
Cytheromorpha warneri Howe and Spurgeon 1935
Cytheropteron talquinensis Puri 1954
Cytheropteron yorktownensis (Malkin 1953)
Cytheropteron sp.
Cytherura coryelli Malkin 1953
Cytherura howei (Puri 1954)
Cytherura reticulata Edwards 1944

Digmocythere russelli Howe and Lea 1936

Echinocythereis clarkana Ulrich and Bassler 1904
Echinocythereis miniscula (Ulrich and Bassler 1904)
Echinocythereis sp.
Eucythere gibba Edwards 1944

Haplocytheridea n. sp.
Hemicytheridea cf. *H. montgomeryensis* Howe and Chambers 1935
Henryhowella evax (Ulrich and Bassler 1904)
Hulingsina americana (Cushman 1906)
Hulingsina calvertensis Forester 1980
Hulingsina rugipustulosa (Edwards 1944)
Hulingsina spp.

Krithe sp.

Leguminocythereis cf. *L. scarabaeus* Howe and Law 1936
Leguminocythereis sp.
Loxoconcha florencensis Cronin 1990
Loxoconcha reticularis Edwards 1944
Loxoconcha aff. *L. granulata* Sars 1865
Loxoconcha sp.

Malzella conradi (Howe and McGuirt 1953)
Malzella evexa Hazel 1985
Microcytherura choctawhatcheensis (Puri 1954)
Microcytherura shattucki (Ulrich and Bassler 1904)
Microcytherura similis (Malkin 1953)
Muellerina blowi Hazel 1983
Muellerina lienenklausi (Ulrich and Bassler 1904)
Muellerina micula (Ulrich and Bassler 1904)
Muellerina ohmerti Hazel 1983
Muellerina wardi Hazel 1983
Munseyella sp.
Murrayina barclayi Mclean 1957
Murrayina macleani Swain 1974
Murrayina radiata (Malkin 1953)

Neonesidea laevicula (Edwards 1944)

Orionina vaughani (Ulrich and Bassler 1904)

Paracytheridea altila Edwards 1944
Paracytheridea rugosa Edwards 1944
Paracytheridea aff. *P. mucra* Edwards 1944
Paradoxostoma sp.
Proteoconcha gigantea Plusquelec and Sandberg 1969
Proteoconcha tuberculata Puri 1960
Pseudocytheretta burnsi (Ulrich and Bassler 1904)
Pseudocytheretta plebeia (Ulrich and Bassler 1904)
Pterygocythereis americana (Ulrich and Bassler 1904)
Pterygocythereis howei (Hill 1954)
Pterygocythereis inexpectata (Blake 1929)
Puriana carolinensis Hazel 1983
Puriana rugipunctata (Ulrich and Bassler 1904)

Sahnia sp.

Thaerocythere schmidtae (Malkin 1953)
Trachyleberidea blanpiedi Howe and Law 1936

Planktonic Foraminifera

Cribrohantkenina inflata (Howe 1928)

Globigerina gortanii (Borsetti 1959)
Globigerina medizzai Toumarkine and Bolli 1975
Globigerina ouachitaensis Howe and Wallace 1932
Globigerina praebulloides Blow 1959
Globigerina tripartita Koch 1926
Globigerinatheka index (Finlay 1939)
Globigerinatheka semiinvoluta (Keijzer 1945)

Hantkenina alabamensis Cushman 1925

Praetenuitella praegemma Li 1987
Pseudohastigerina naguewichiensis Myatliuk 1950

Testacarinata inconspicua (Howe 1939)
Turborotalia cerroazulensis cerroazulensis (Cole 1928)
Turborotalia cerroazulensis cocoaensis (Cushman 1928)
Turborotalia cerroazulensis cunialensis (Toumarkine and Bolli 1970)
Turborotalia cerroazulensis pomeroli (Toumarkine and Bolli 1970)

Bolboformids

Bolboforma latdorfensis Spiegler 1991
Bolboforma spinosa Daniels and Spiegler 1974

Vertebrates

Acanthocybium proosti (Storms 1897)

Dasyatis Rafinesque 1810 sp.
Diaphyodus wilsoni Westgate 1989

Scyliorhinus gilberti Casier 1946
Squalus Linnaeus 1758 sp.

Trichiurides sagittidens Winkler 1874

Appendix H2. Useful Cenozoic Calcareous Nannofossil Datums

The following calcareous nannofossil species can be used to date sediments of late Eocene to late Pliocene age. Many, but not all, of these species are present in the USGS-NASA Langley core. FAD is a first appearance datum, and LAD is a last appearance datum. Zonal markers for the NP and NN zones of Martini (1971) are indicated with an asterisk (*). Bybell has found the remaining species to be biostratigraphically useful in the U.S. Gulf of Mexico and Atlantic Coastal Plains.

LAD **Discoaster brouweri*—top of Zone NN 18, late Pliocene

LAD **Discoaster pentaradiatus*—top of Zone NN 17, late Pliocene
LAD *Discoaster asymmetricus*—within Zone NN 17, late Pliocene

LAD **Discoaster surculus*—top of Zone NN 16, late Pliocene

LAD **Reticulofenestra pseudoumbilicus*—top of Zone NN 15, early Pliocene
FAD *Pseudoemiliania lacunosa*—within upper part of Zone NN 15, early Pliocene

LAD **Amaurolithus tricorniculatus*—top of Zone NN 14, early Pliocene
FAD **Discoaster asymmetricus*—base of Zone NN 14, early Pliocene

FAD **Ceratolithus rugosus*—base of Zone NN 13, early Pliocene

LAD **Discoaster quinqueramus*—top of Zone NN 11, late Miocene
LAD *Discoaster berggrenii*—within Zone NN 11, late Miocene
FAD *Discoaster berggrenii*—near base of Zone NN 11, late Miocene
FAD **Discoaster quinqueramus*—base of Zone NN 11, late Miocene

LAD **Discoaster hamatus*—top of Zone NN 9, late Miocene
FAD **Discoaster hamatus*—base of Zone NN 9, late Miocene

LAD *Discoaster exilis*—within Zone NN 8; middle or late Miocene
FAD **Catinaster coalitus*—base of Zone NN 8; middle or late Miocene

FAD **Discoaster kugleri*—base of Zone NN 7, middle Miocene

LAD **Sphenolithus heteromorphus*—top of Zone NN 5, middle Miocene

LAD **Helicosphaera ampliaperta*—top of Zone NN 4, middle Miocene
FAD *Discoaster variabilis*—near base of Zone NN 4; may occur sporadically within Zone NN 3, early Miocene

LAD **Sphenolithus belemnos*—top of Zone NN 3, early Miocene
FAD *Sphenolithus heteromorphus*—within Zone NN 3, early Miocene
FAD **Sphenolithus belemnos*—base of Zone NN 3, early Miocene

LAD **Triquetrorhabdulus carinatus*—top of Zone NN 2, early Miocene
FAD *Helicosphaera ampliaperta*—within Zone NN 2, early Miocene
FAD **Discoaster druggii*—base of Zone NN 2, early Miocene

LAD *Zygrhablithus bijugatus*—near bottom of Zone NN 1, early Miocene
LAD *Dictyococcites bisectus*—near bottom of Zone NN 1, early Miocene

LAD **Helicosphaera recta*—top of Zone NP 25, late Oligocene
LAD *Sphenolithus ciperoensis*—near top of Zone NP 25, late Oligocene
LAD *Chiasmolithus altus*—within Zone NP 25, late Oligocene

LAD **Sphenolithus distentus*—top of Zone NP 24, late Oligocene
LAD *Transversopontis zigzag*—within Zone NP 24, late Oligocene
LAD *Helicosphaera compacta*—within Zone NP 24, late Oligocene
FAD *Helicosphaera recta*—lower Zone NP 24, early Oligocene
FAD **Sphenolithus ciperoensis*—base of Zone NP 24, early Oligocene

FAD *Sphenolithus distentus*—within Zone NP 23, early Oligocene

LAD **Reticulofenestra umbilicus*—top of Zone NP 22, early Oligocene
LAD *Chiasmolithus oamaruensis*—within Zone NP 22, early Oligocene
FAD *Chiasmolithus altus*—within Zone NP 22, early Oligocene

LAD **Cyclococcolithus formosus*—top of Zone NP 21, early Oligocene
LAD *Isthmolithus recurvus*—within Zone NP 21, early Oligocene

LAD **Discoaster saipanensis*—top of Zone NP 19/20, late Eocene
LAD *Discoaster barbadiensis*—near top of Zone NP 19/20, late Eocene
LAD *Cribrocentrum reticulatum*—very near top of Zone NP 19/20, late Eocene
FAD **Isthmolithus recurvus*—base of Zone NP 19/20, late Eocene

Plates H1–H9

Plate H1

Dinoflagellate Cysts from the Chickahominy Formation in the USGS-NASA Langley Core, Hampton, Va.

[Scale bar shown applies to all photomicrographs. Sample depths and assemblages are shown in figure H5]

Figure 1. *Areosphaeridium diktyoplokus* (Klumpp 1953) Eaton 1971, Chickahominy Formation (sample R6110 AN), possible ventral view, upper focus.

2. *Batiacasphaera baculata* Drugg 1970, Chickahominy Formation (sample R6110 AO), orientation uncertain, upper focus.

3. *Batiacasphaera compta* Drugg 1970, Chickahominy Formation (sample R6110 AR), orientation uncertain, upper focus.

4. *Cordosphaeridium funiculatum* Morgenroth 1966, Chickahominy Formation (sample R6110 AR), orientation uncertain, upper focus.

5, 6. *Histiocysta* sp. of Stover and Hardenbol (1993 [1994]), Chickahominy Formation (sample R6110 AN), ventral views; 5, upper focus; 6, lower focus.

7. *Glaphyrocysta semitecta* (Bujak 1980) Lentin & Williams 1981 [grouped as miscellaneous areoligeracean forms (*Glaphyrocysta* spp.) in figure H5], Chickahominy Formation (sample R6110 AR), ventral view, intermediate focus.

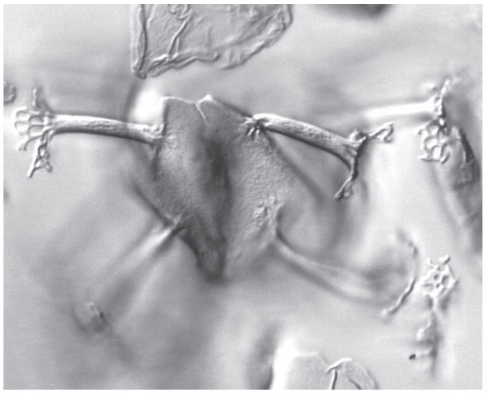
8. *Dapsilidinium pseudocolligerum* (Stover 1977) Bujak et al. 1980, Chickahominy Formation (sample R6110 AL), orientation uncertain, upper focus.

9, 10. *Saturnodinium* Brinkhuis et al. 1992 sp., Chickahominy Formation (sample R6110 AO), possible antapical view; 9, upper focus; 10, intermediate focus.

11. *Trigonopyxidia fiscellata* De Coninck 1986, Chickahominy Formation (sample R6110 AR), dorsal view, dorsal surface.

12. *Rhombodinium perforatum* (Jan du Chêne & Châteauneuf 1975) Lentin & Williams 1977, Chickahominy Formation (sample R6110 AN), ventral view, intermediate focus.

13. *Operculodinium divergens* (Eisenack 1954) Stover & Evitt 1978, Chickahominy Formation (sample R6110 AL), possible right-lateral view, upper focus.



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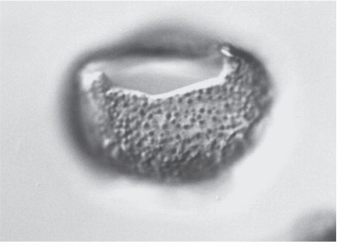

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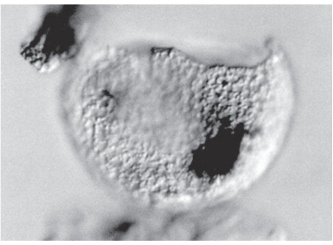

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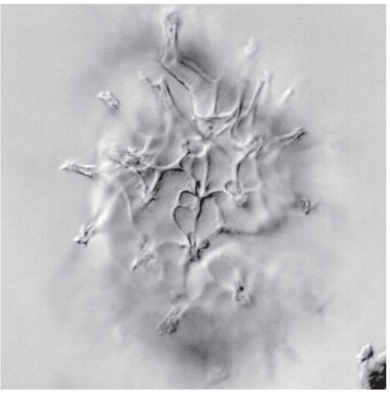

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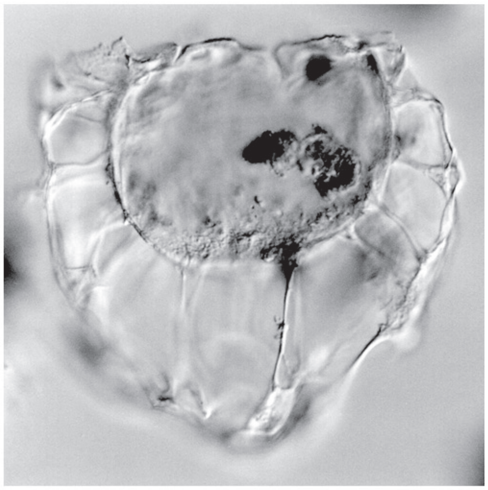

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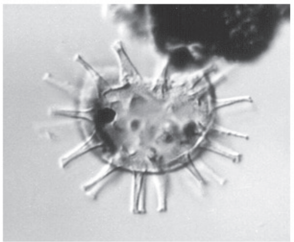

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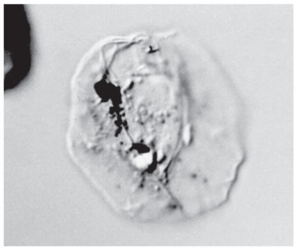

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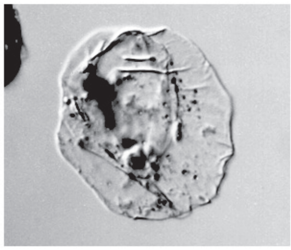

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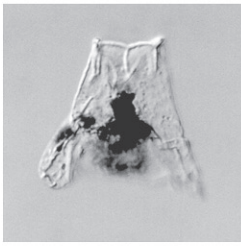

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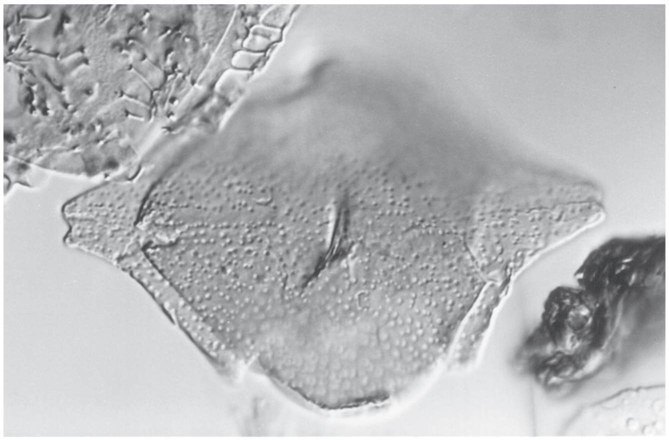

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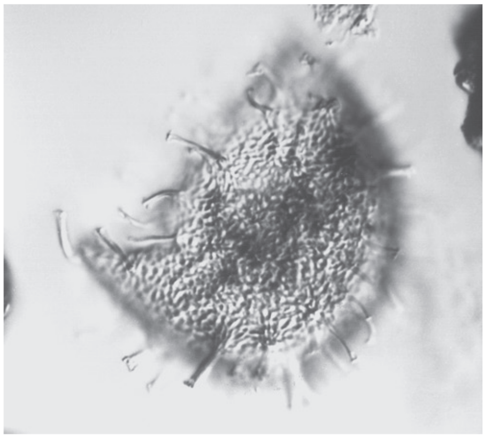

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Dinoflagellate Cysts from the Chickahominy Formation in the USGS-NASA Langley Core, Hampton, Va.

Plate H2

Dinoflagellate Cysts from the Chickahominy Formation in the USGS-NASA Langley Core, Hampton, Va.

[Scale bar shown applies to all photomicrographs. Sample depths and assemblages are shown in figure H5]

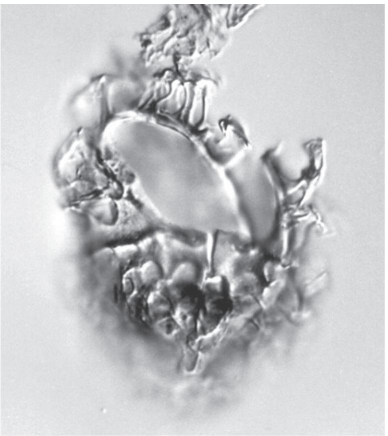
Figure 1, 2. S*amlandia chlamydophora* sensu Stover and Hardenbol (1993 [1994]), Chickahominy Formation (sample R6110 AL), dorso-left-lateral views; 1, upper focus; 2, intermediate focus.

3. Miscellaneous areoligeracean form (*Glaphyrocysta* Stover & Evitt 1978 sp.), showing curling of processes around the central body, Chickahominy Formation (sample R6110 DA), presumably reworked from impact, possible dorsal view, intermediate focus.

4, 5. *Thalassiphora reticulata* Morgenroth 1966, Chickahominy Formation (sample R6110 AN), ventral views; 4, ventral surface; 5, dorsal surface.

6. Miscellaneous chorate form, *Exochosphaeridium* Davey et al. 1966? sp., showing curling of processes around the central body, Chickahominy Formation (R6110 AK), presumably reworked from impact, dorso-right-lateral view, intermediate focus.

7, 8. *Turbiosphaera* Archangelsky 1969 sp., Chickahominy Formation (sample R6110 AR), reworked, dorso-left-lateral views; 7, upper focus; 8, intermediate focus.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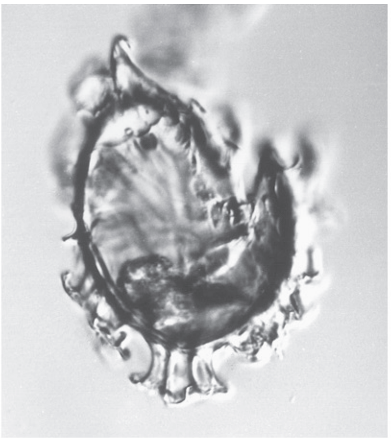
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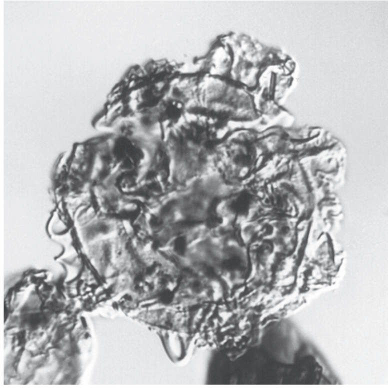
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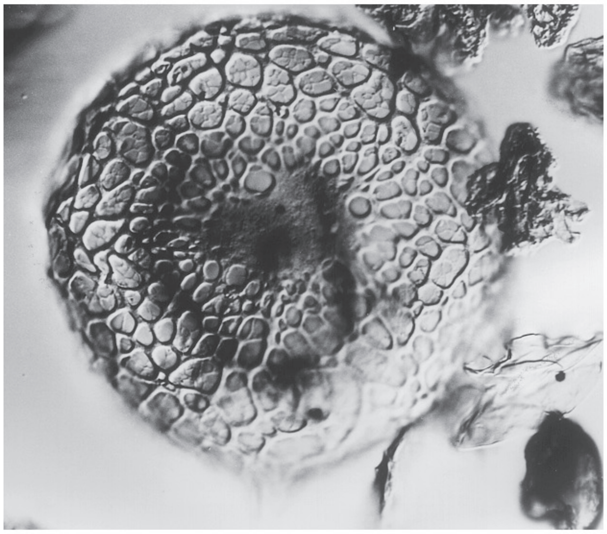
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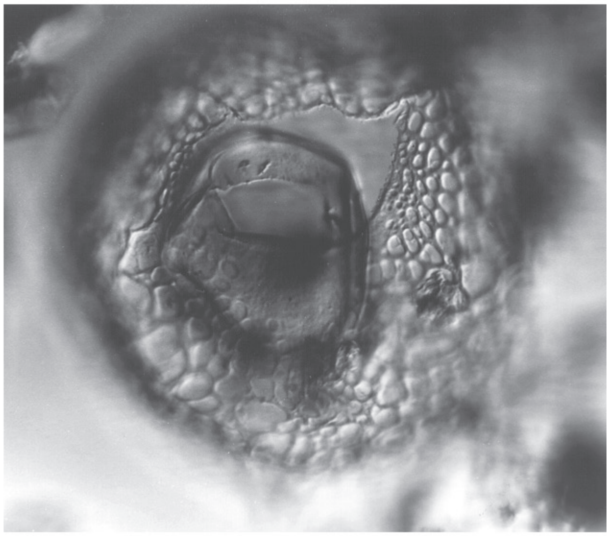
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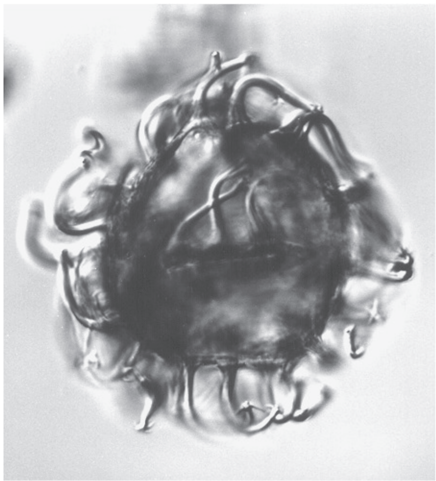
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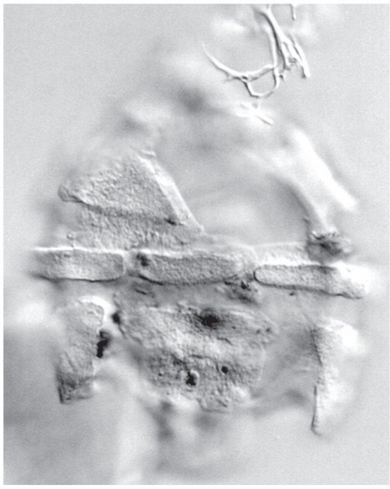
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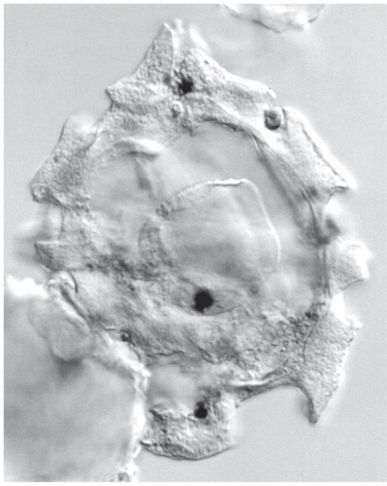
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Dinoflagellate Cysts from the Chickahominy Formation in the USGS-NASA Langley Core, Hampton, Va.

Plate H3

Dinoflagellate Cysts from the Chickahominy Formation, Drummonds Corner Beds, and Old Church Formation in the USGS-NASA Langley Core, Hampton, Va.

[Scale bar shown applies to all photomicrographs. Sample depths and assemblages are shown in figure H5]

Figure 1. *Deflandrea* Eisenack 1938 sp., Chickahominy Formation (sample R6110 AN), presumably reworked from impact, dorsal view, dorsal surface.

2. *Cordosphaeridium gracile* (Eisenack 1954) Davey & Williams 1966, Chickahominy Formation (sample R6110 AN), presumably reworked from impact, fragment showing bent processes, upper focus.

3. *Chatangiella* Vozzhennikova 1967 or *Isabelidinium* Lentin & Williams 1977, Chickahominy Formation (sample R6110 DB), presumably reworked from impact, folded specimen, dorsal view, dorsal surface.

4. *Chiropteridium lobospinosum* Gocht 1960, Old Church Formation (sample R6110 AD), dorsal view, dorsal surface.

5. *Achilleodinium biformoides* (Eisenack 1954) Eaton 1976, Drummonds Corner beds (sample R6110 AH), dorsal view, dorsal surface.

6. *Homotryblium vallum* Stover 1977, Drummonds Corner beds (sample R6110 AH), oblique interior view of antapex.

7. *Chiropteridium galea* (Maier 1959) Sarjeant 1983, Old Church Formation (sample R6110 AD), dorsal view, intermediate focus.

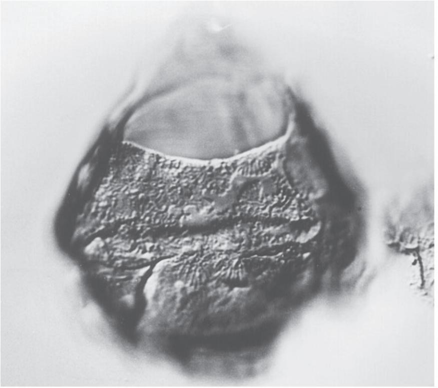
8. *Membranophoridium aspinatum* Gerlach 1961, Old Church Formation (sample R6110 AF), ventral view, ventral surface.

9. *Reticulatosphaera actinocoronata* (Benedek 1972) Bujak & Matsuoka 1986, Drummonds Corner beds (sample R6110 AH), orientation uncertain, upper focus.

10, 14. *Trigonopyxidia fiscellata* De Coninck 1986, Old Church Formation (sample R6110 AF), presumably reworked from impact, folded specimen, left-lateral views; 10, upper focus; 14, lower focus.

11. *Tuberculodinium vancampoae* (Rossignol 1962) Wall 1967, Old Church Formation (sample R6110 AF), orientation uncertain, upper focus.

12, 13. *Saturnodinium pansum* (Stover 1977) Brinkhuis et al. 1992, Old Church Formation, possible antapical views; 12, (sample R6110 AD) upper focus; 13, (sample R6110 AB) detail of margin.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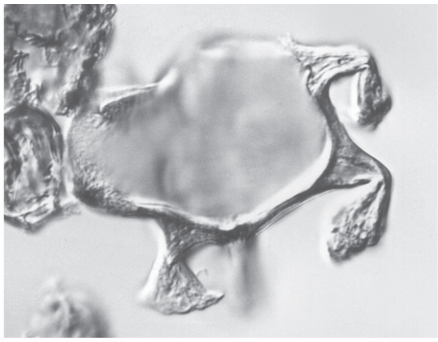
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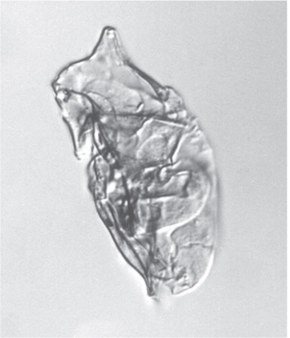
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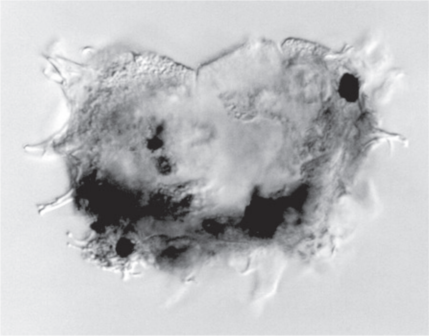
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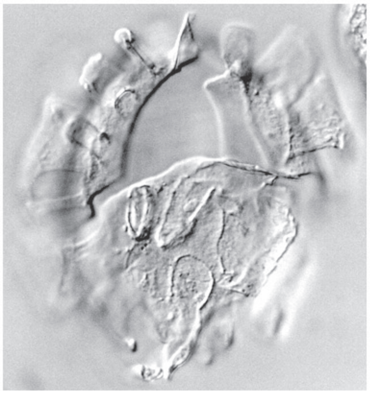
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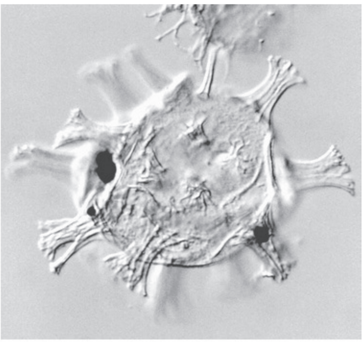
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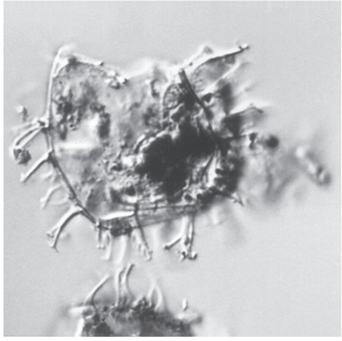
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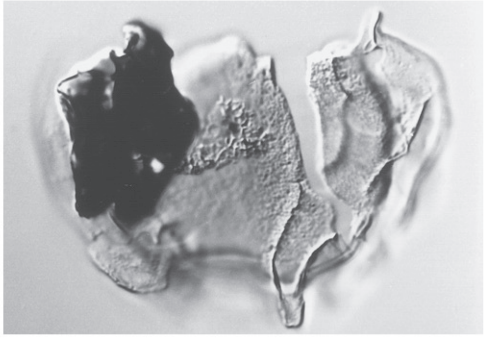
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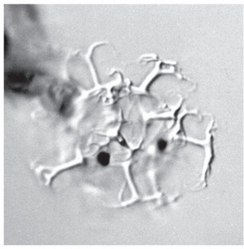
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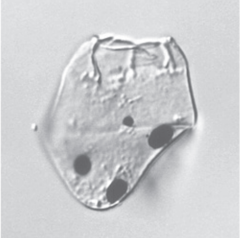
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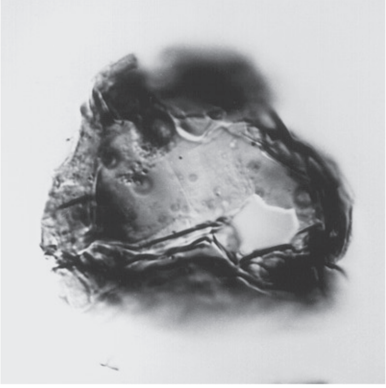
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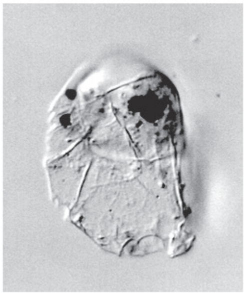
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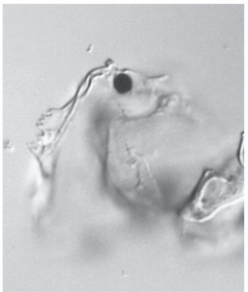
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14

Dinoflagellate Cysts from the Chickahominy Formation, Drummonds Corner Beds, and Old Church Formation in the USGS-NASA Langley Core, Hampton, Va.

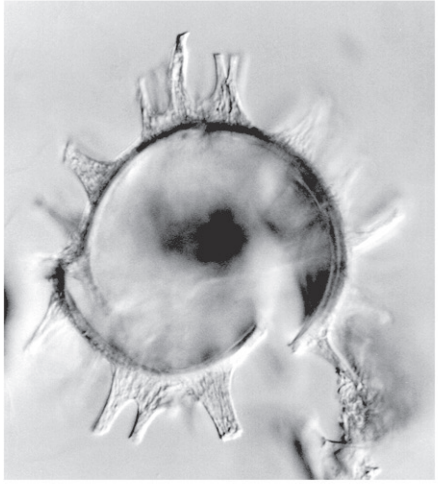
Plate H4

Dinoflagellate Cysts from the Old Church and Calvert Formations in the USGS-NASA Langley Core, Hampton, Va.

[Scale bar shown applies to all photomicrographs. Sample depths and assemblages are shown in figures H5 and H11]

Figure

1. *Exochosphaeridium insigne* de Verteuil & Norris 1996, Newport News beds of the Calvert Formation (sample R6110 Z), ventral view, intermediate focus.
2. New genus?, new species (apical archeopyle), Old Church Formation (sample R6110 AA), ventral view, ventral focus.
3. *Damassadinium californicum* (Drugg 1967) Fensome et al. 1993 operculum, Old Church Formation (sample R6110 AF), reworked, apical view, upper focus.
4. *Labyrinthodinium truncatum* Piasecki 1980 subsp. *modicum* de Verteuil & Norris 1996, Plum Point Member of the Calvert Formation (sample R6110 Y), apical view, intermediate focus.
5. *Apteodinium spiridoides* Benedek 1972, Newport News beds of the Calvert Formation (sample R6110 Z), dorsal view, dorsal surface.
6. *Wetzeliella gochtii* Costa & Downie 1976, Old Church Formation (sample R6110 AF), dorsal view, dorsal surface.
7. *Distatodinium paradoxum* (Brosius 1963) Eaton 1976, Plum Point Member of the Calvert Formation (sample R6110 Y), orientation uncertain, upper focus.
8. *Habibacysta tectata* Head et al. 1989, Calvert Beach Member of the Calvert Formation (sample R6110 W), dorso-left-lateral view, upper focus.
9. *Sumatradinium soucouyantiae* de Verteuil & Norris 1996, Plum Point Member of the Calvert Formation (sample R6110 Y), orientation uncertain, intermediate focus.
10. *Apteodinium spiridoides* Benedek 1972, Plum Point Member of the Calvert Formation (sample R6110 Y), oblique ventral view, upper focus. Many of the specimens of *A. spiridoides* in this sample have the distinctive, somewhat circular ornament shown in this specimen that is atypical for the species.
11. *Pentadinium* sp. cf. *P. laticinctum granulatum* Gocht 1969, Calvert Beach Member of the Calvert Formation (sample R6110 V), ventral view, ventral surface.
12. *Cleistosphaeridium placacanthum* (Deflandre & Cookson 1955) Eaton et al. 2001, Calvert Beach Member of the Calvert Formation (sample R6110 W), oblique ventral view, upper focus.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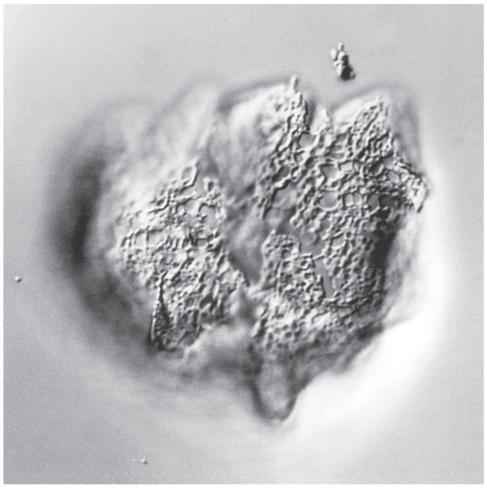
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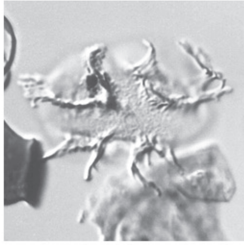
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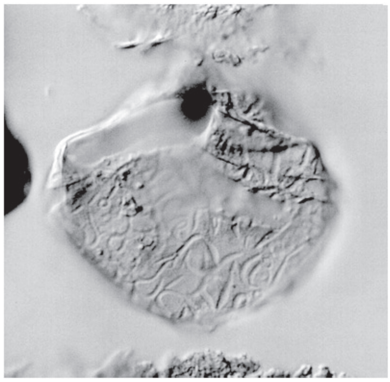
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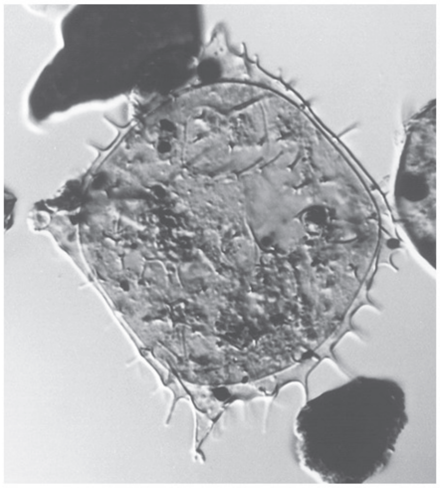
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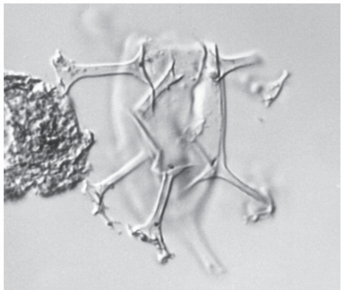
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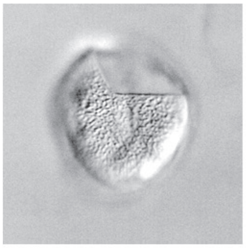
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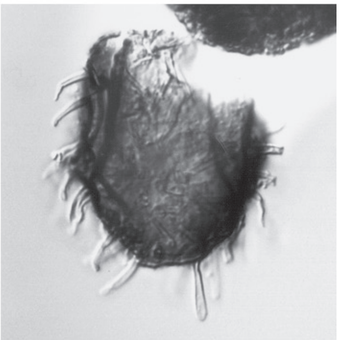
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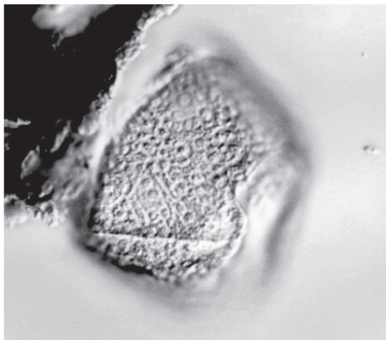
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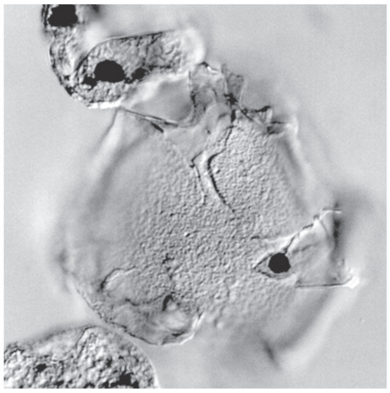
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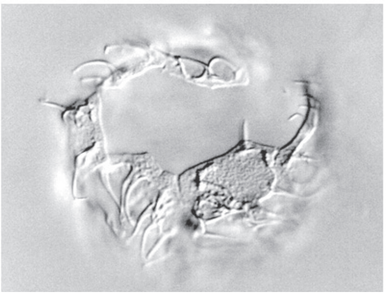
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Dinoflagellate Cysts from the Old Church and Calvert Formations in the USGS-NASA Langley Core, Hampton, Va.

Plate H5

Dinoflagellate Cysts from the Calvert, St. Marys, Eastover, and Yorktown Formations in the USGS-NASA Langley Core, Hampton, Va.

[Scale bar shown applies to all photomicrographs. Sample depths and assemblages are shown in figure H11]

Figure 1. *Trinovantedinium harpagonium* de Verteuil & Norris 1992, Calvert Beach Member of the Calvert Formation (sample R6110 X), dorsal view, dorsal surface.

2. *Geonettia clineae* de Verteuil & Norris 1996, St. Marys Formation (sample R6110 R), orientation uncertain, upper focus.

3. *Hystrichosphaeropsis obscura* Habib 1972, St. Marys Formation (sample R6110 L), right-lateral view, upper focus.

4. *Erymnodinium delectabile* (de Verteuil & Norris 1992) Lentin et al. 1994, Eastover Formation (sample R6110 I), dorsal view, dorsal surface.

5. *Barssidinium evangelineae* Lentin et al. 1994, Eastover Formation (sample R6110 F), ventral view, ventral surface.

6. *Achomosphaera andalousiensis* Jan du Chêne 1977, Eastover Formation (sample R6110 I), orientation uncertain, upper focus.

7. Miscellaneous chorate form (*Spiniferites* Mantell 1850? sp.), showing curling of processes around the central body, St. Marys Formation (sample R6110 T), possibly reworked from impact, orientation uncertain, intermediate focus.

8. *Invertocysta lacrymosa* Edwards 1984, Eastover Formation (sample R6110 K), possible ventral view, intermediate focus.

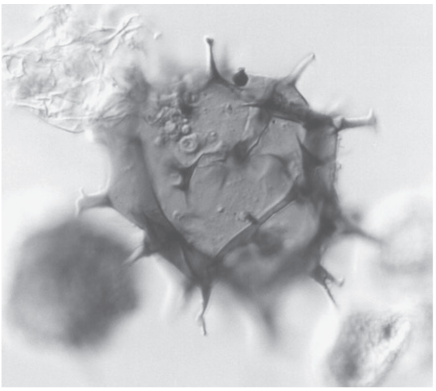
9. *Labyrinthodinium truncatum* Piasecki 1980 subsp. *truncatum,* Eastover Formation (sample R6110 K), orientation uncertain, intermediate focus.

10. *Selenopemphix armageddonensis* de Verteuil & Norris 1992, Eastover Formation (sample R6110 F), possible apical view, intermediate focus.

11. *Filisphaera microornata* (Head et al. 1989) Head 1994, Eastover Formation (sample R6110 F), dorsal view, dorsal surface.

12–14. *Ataxiodinium confusum* Versteegh & Zevenboom 1995, Yorktown Formation (sample R6110 C), dorsal views; 12, dorsal surface; 13, intermediate focus; 14, ventral surface.

15. *Bitectatodinium tepikiense* Wilson 1973, Yorktown Formation (sample R6110 D), ventral view, dorsal surface.



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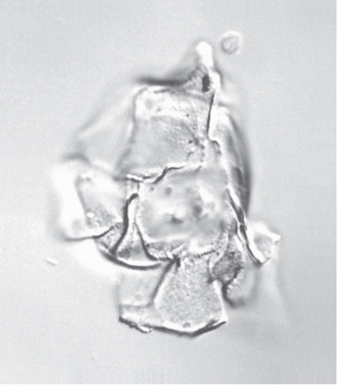

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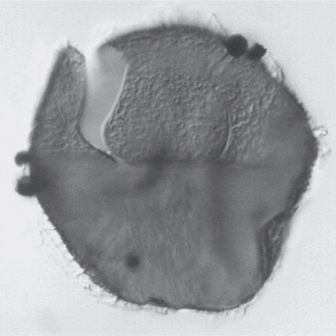

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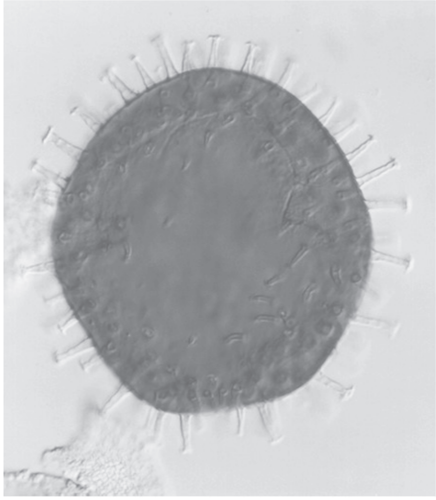

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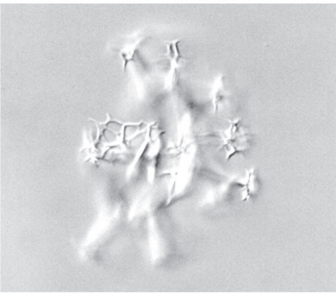

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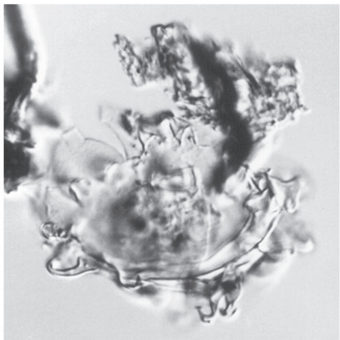

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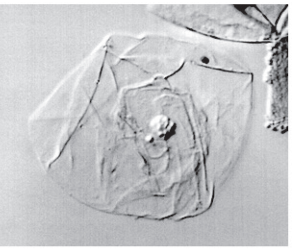
50 µm



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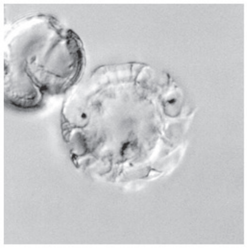

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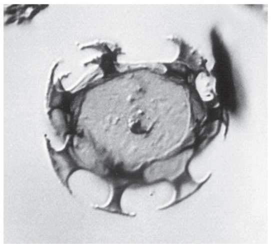

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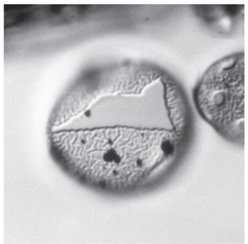

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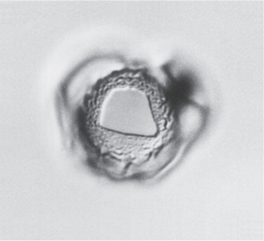

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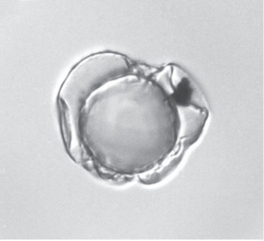

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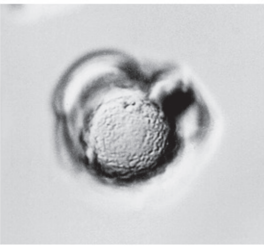

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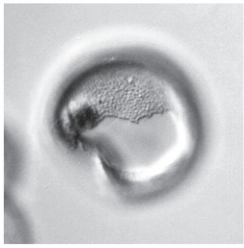

15

Dinoflagellate Cysts from the Calvert, St. Marys, Eastover, and Yorktown Formations in the USGS-NASA Langley Core, Hampton, Va.

Plate H6

Representative Mollusca from the Chickahominy, Old Church, and Yorktown Formations in the USGS-NASA Langley Core, Hampton, Va.

[Scale bars are 1 cm. Assemblage data are in figure H6, in pocket]

Figure 1. Pectinid cf. *Chlamys brooksvillensis* Mansfield 1937, 155.5 m (510.1–510.2 ft), Old Church Formation, exterior view.

2. *Cyclocardia granulata* (Say 1824), 19.5–19.6 m (64.0–64.2 ft), Yorktown Formation, exterior view.

3. Pectinid cf. "*Pecten*" *choctavensis* Aldrich 1895, 151.1 m (495.6–495.7 ft), Old Church Formation, exterior view.

4. *Dentalium* sp., 211.8–211.9 m (695.0–695.1 ft), Chickahominy Formation, shell is compressed and surrounding matrix was retained.

5. *Nuculana* sp., 205.6 m (674.5 ft), Chickahominy Formation, aragonitic "ghost" of shell in surrounding matrix.

6. *Rebeccapecten berryae* Ward 1992?, 212.08 m (695.8 ft), Chickahominy Formation, exterior view of aragonitic "ghost" of shell in surrounding matrix.

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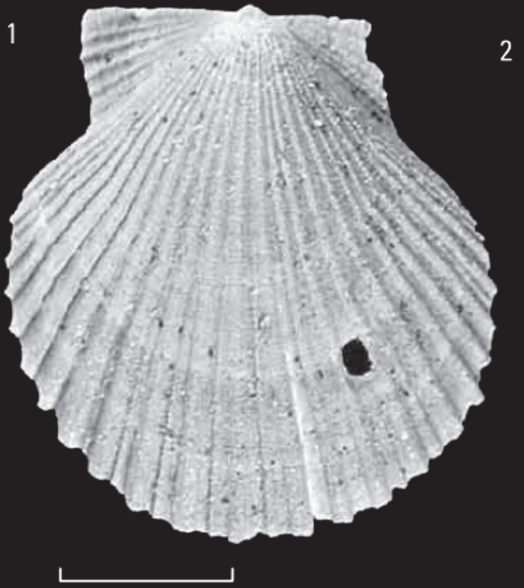

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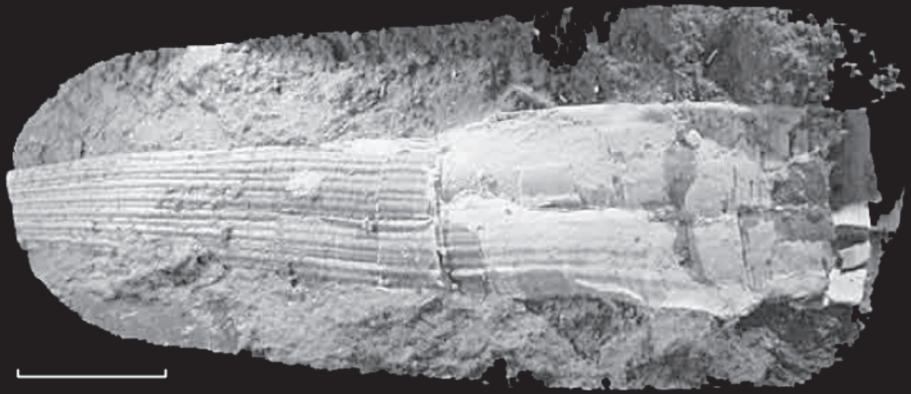

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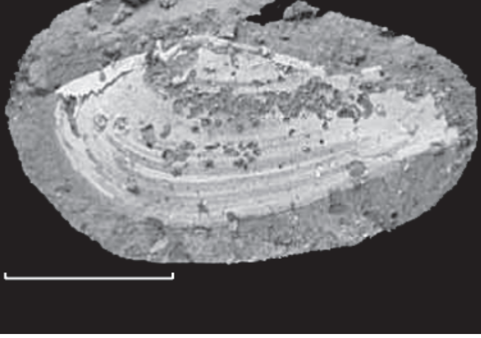


6

Representative Mollusca from the Chickahominy, Old Church, and Yorktown Formations in the USGS-NASA Langley Core, Hampton, Va.

Plate H7

Representative Mollusca from the Eastover and St. Marys Formations in the USGS-NASA Langley Core, Hampton, Va.

[Scale bars are 1 cm unless otherwise noted. Assemblage data are in figure H6, in pocket]

Figures 1, 3. *Lirophora vredenburgi* Ward 1992, Eastover Formation; 1, 54.9 m (180.1–180.2 ft), exterior view of right valve, scale bar is 1 cm; 3, 37.1 m (121.6–121.7 ft), interior view of left valve, scale bar is 1 mm.

2, 4. *Nucula proxima* Say 1822, 66.8 m (219.1–219.3 ft), Eastover Formation, right valve; 2, interior view; 4, exterior view. Scale bars are 1 mm.

5, 6. *Mitrella communis* (Conrad 1862), 66.8 m (219.1–219.3 ft), Eastover Formation; 5, back view; 6, apertural view. Scale bars are 1 mm.

7. *Ecphora gardnerae whiteoakensis* Ward and Gilinsky 1988, 66.8 m (219.1–219.3 ft), Eastover Formation, apical whorls of broken specimen.

8. *Nassarius peralta* (Conrad 1868), 66.8 m (219.1–219.3 ft), Eastover Formation, back view, scale bar is 1 mm.

9. *Nassarius* sp., 66.8 m (219.1–219.3 ft), Eastover Formation, apertural view, scale bar is 1 mm.

10. *Turbonilla* sp., 66.8 m (219.1–219.3 ft), Eastover Formation, apertural view, scale bar is 1 mm.

11, 12. *Turritella plebeia carinata* Gardner 1948, 38.3–38.4 m (125.8–126.0 ft), Eastover Formation, apertural views, scale bars are 1 mm.

13. *Lunatia heros* (Say 1822)?, 66.8 m (219.1–219.3 ft), Eastover Formation, back view of specimen with broken body whorl and encrusting bryozoan.

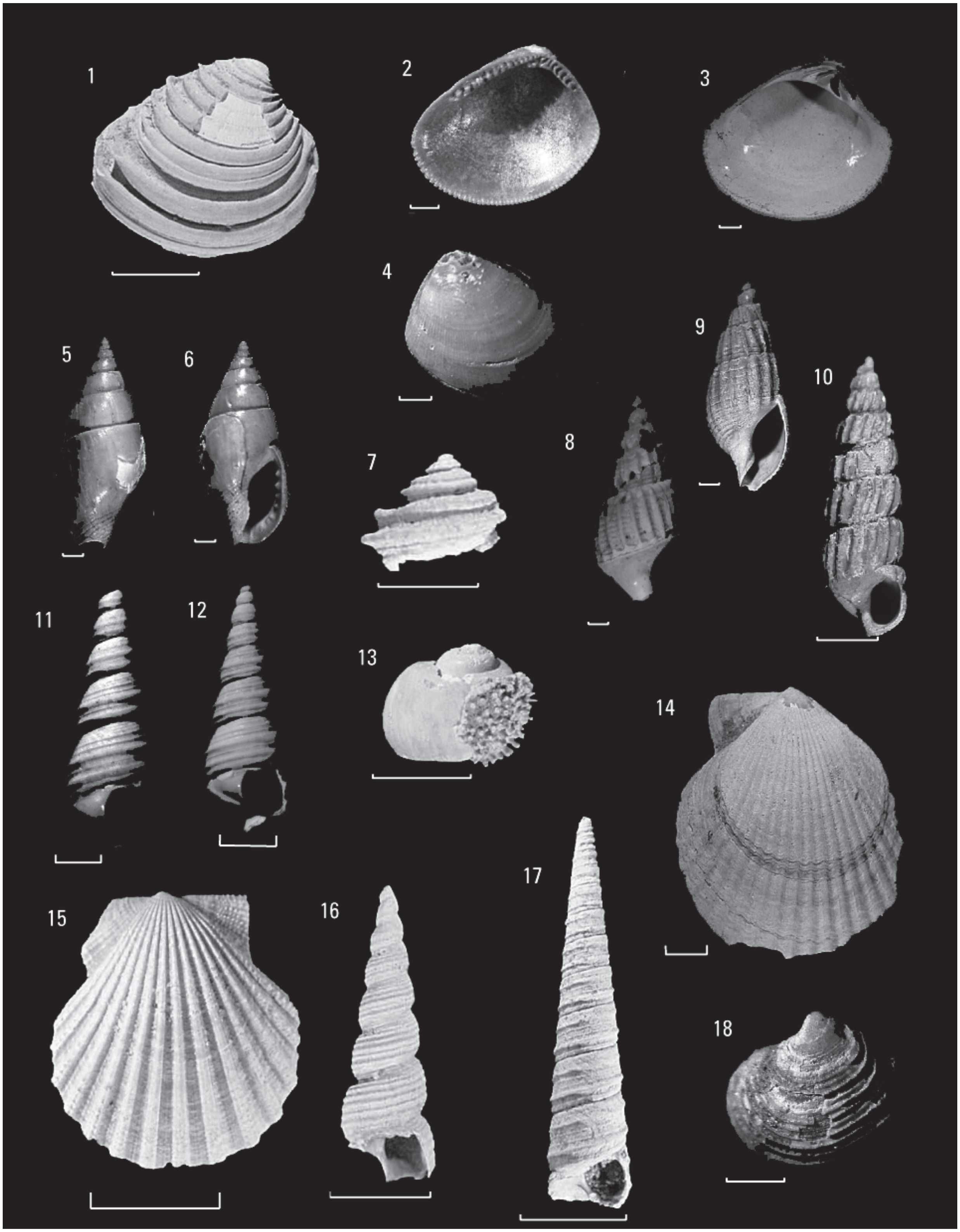
14. *Carolinapecten urbannaensis* (Mansfield 1929), 28.3 m (92.7–93.0 ft), Eastover Formation, exterior view of specimen with damaged ventral margin.

15. *Chesapecten middlesexensis* (Mansfield 1936), 38.3–38.4 m (125.8–126.0 ft), Eastover Formation, exterior view of juvenile specimen.

16. *Turritella plebeia plebeia* Say 1824, 74.5 m (244.4–244.5 ft), St. Marys Formation, apertural view.

17. *Turritella subvariabilis* d'Orbigny 1852, 43.3 m (142.0–142.1 ft), Eastover Formation, apertural view. Worn and pitted condition of shell may indicate that the specimen is reworked.

18. *Parvilucina crenulata* (Conrad 1840), 66.8 m (219.1–219.3 ft), Eastover Formation, exterior view of left valve, scale bar is 1 mm.



Representative Mollusca from the Eastover and St. Marys Formations in the USGS-NASA Langley Core, Hampton, Va.

Plate H8

Representative Mollusca from the Yorktown Formation in the USGS-NASA Langley Core, Hampton, Va.

[Scale bars are 1 mm unless otherwise noted. Assemblage data are in figure H6, in pocket]

Figures 1, 2. *Nuculana acuta* (Conrad 1832), 6.5 m (21.3–21.5 ft), right valve; 1, interior view; 2, exterior view.

3. *Epitonium junceum* Gardner 1948, 8.6–8.7 m (28.3–28.4 ft), apertural view, scale bar is 5 mm.

4. *Cadulus* sp., 6.5 m (21.3–21.5 ft).

5. *Eulima dalli* (Gardner and Aldrich 1919), 6.5 m (21.3–21.5 ft), apertural view.

6, 7. *Tectonatica pusilla* (Say 1822), 6.5 m (21.3–21.5 ft); 6, back view; 7, apertural view.

8. *Crassinella lunulata* (Conrad 1834), 6.5 m (21.3–21.5 ft), exterior of right valve.

9. *Acteocina candei* (d’Orbigny 1842), 6.5 m (21.3–21.5 ft), apertural view.

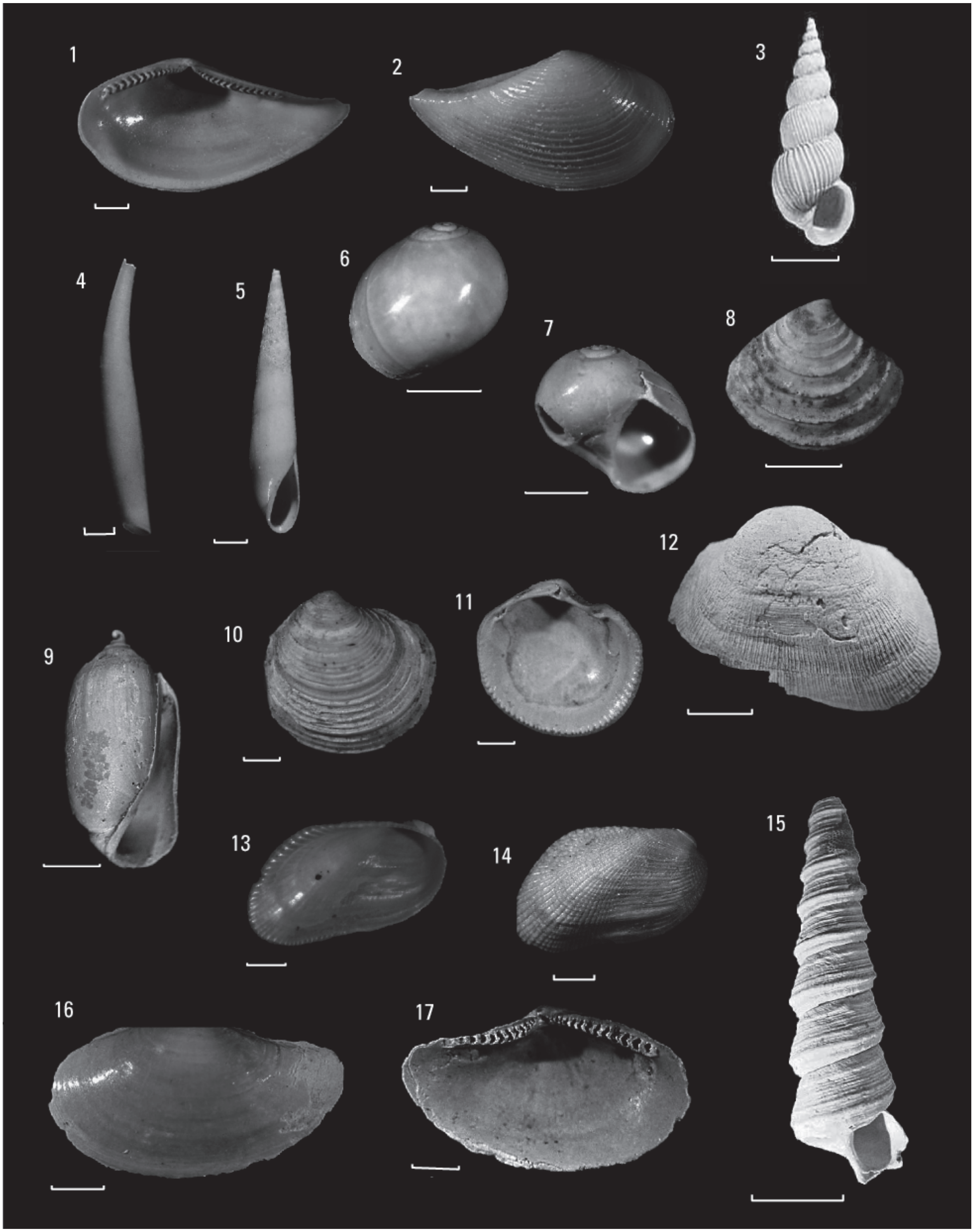
10, 11. *Parvilucina crenulata* (Conrad 1840), 6.5 m (21.3–21.5 ft); 10, exterior view of right valve; 11, interior view of left valve.

12. *Striarca centenaria* (Say 1824), 19.5–19.6 m (64.0–64.2 ft), exterior view of left valve with broken ventral margin, scale bar is 1 cm.

13, 14. *Musculus lateralis* (Say 1822)? [possibly synonymous with *M. virginicus* Conrad 1867], 17.3 m (56.6–56.7 ft); 13, interior view of left valve; 14, exterior view of right valve.

15. *Turritella alticostata* Conrad 1834, 6.5 m (21.3–21.5 ft), apertural view, scale bar is 1 cm.

16, 17. *Yoldia laevis* (Say 1824), 6.5 m (21.3–21.5 ft), left valve; 16, exterior view; 17, interior view.



Representative Mollusca from the Yorktown Formation in the USGS-NASA Langley Core, Hampton, Va.

Plate H9

Late Eocene and Early Oligocene Fish Teeth from the USGS-NASA Langley Core, Hampton, Va.

[USNM, U.S. National Museum of Natural History, Washington, D.C. Scale bars are 1 mm. Sample depths are in figure H9]

Figure 1. *Squalus* Linnaeus 1758 sp. (USNM 519557), Drummonds Corner beds, lower Oligocene.
2. *Dasyatis* Rafinesque 1810 sp. (USNM 519558), Drummonds Corner beds, lower Oligocene.
3. *Trichiurides sagittidens* Winkler 1874 (USNM 519556), Drummonds Corner beds, lower Oligocene.
4. *Scyliorhinus gilberti* Casier 1946 (USNM 519554), Chickahominy Formation, upper Eocene.
5. *Acanthocybium proosti* (Storms 1897) (USNM 519553), Chickahominy Formation, upper Eocene.
6. *Diaphyodus wilsoni* Westgate 1989 (USNM 519555), Drummonds Corner beds, lower Oligocene.

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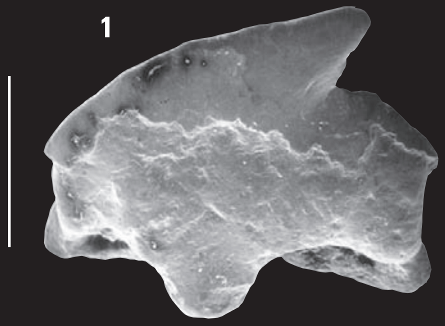

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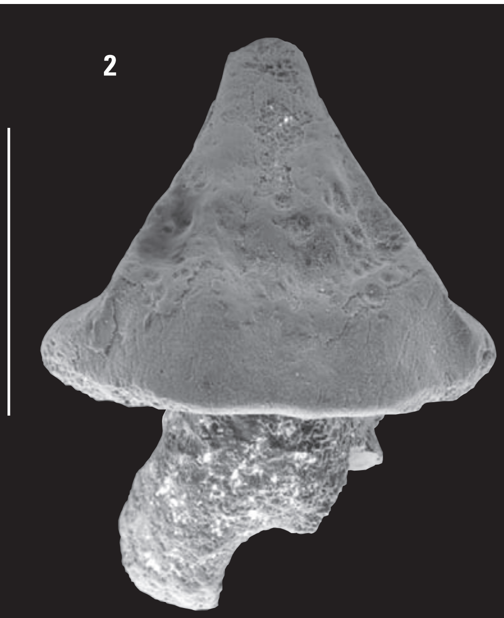

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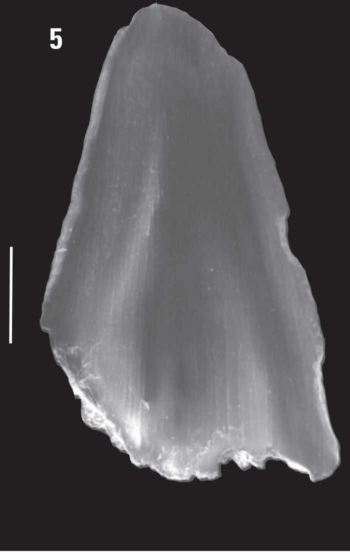

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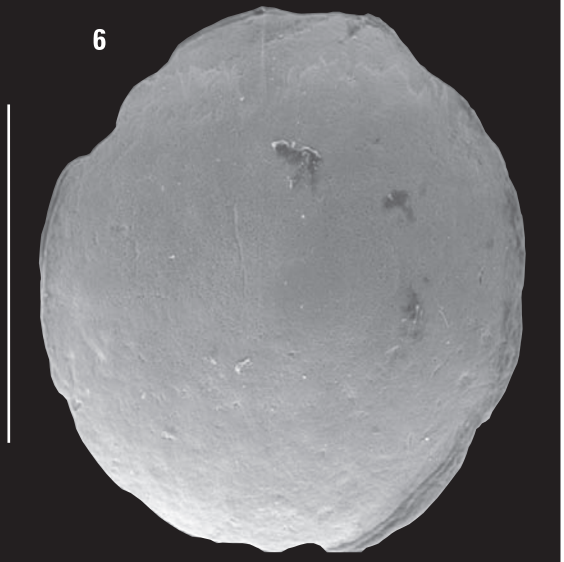

Late Eocene and Early Oligocene Fish Teeth from the USGS-NASA Langley Core, Hampton, Va.