Paleontology of the Impact-Modified and Impact-Generated Sediments in the USGS-NASA Langley Core, Hampton, Virginia

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Chapter D of

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

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Paleontology of the Impact-Modified and Impact-Generated Sediments in the USGS-NASA Langley Core, Hampton, Virginia

By Norman O. Frederiksen,[1] Lucy E. Edwards,[1] Jean M. Self-Trail,[1] Laurel M. Bybell,[1] and Thomas M. Cronin[1]

Abstract

Spores and pollen, dinoflagellate cysts, calcareous nannofossils, and marine ostracodes provide important information about the ages and conditions of deposition of the strata, clasts, and matrix materials that compose the impact-modified and impact-generated sediments in the USGS-NASA Langley corehole, which was drilled into the Chesapeake Bay impact crater in Hampton, Va. These sediments are divided into three parts: crater unit A (626.3 to 442.5 meters (m); 2,054.7 to 1,451.7 feet (ft)), crater unit B (442.5 to 269.4 m; 1,451.7 to 884.0 ft), and the Exmore beds (269.4 to 235.65 m; 884.0 to 773.12 ft). Crater unit A consists of relatively undisrupted strata of the Potomac Formation. One spore-pollen sample from near the top of this unit yielded a middle Albian to early Cenomanian age. All other samples from this unit were barren of spores and pollen grains.

Crater unit B is a clast-supported diamicton. Seven productive spore-pollen samples of Aptian to Cenomanian age in this unit were derived from Potomac Formation clasts. Several of the samples had mixed ages, indicating that these clasts had been contaminated by slurry sediment that penetrated the clasts during the violent movements of the material following the comet or asteroid impact or possibly during drilling. Some other clasts that contained dinocysts and nannofossils, from this unit and from the Exmore beds, were similarly contaminated. One dinocyst and one nannofossil sample from the matrix within the upper part of crater unit B were productive, and both had a mixture of Paleocene and Eocene specimens.

The Exmore beds form the matrix-supported part of the diamicton and contain the full variety of fossil types studied by the present authors—pollen, dinocysts, nannofossils, and ostracodes. Clasts within the Exmore range from Early Cretaceous to late Eocene in age. Most interesting were dinocyst, nannofossil, and ostracode species known only from the lower part of the middle Eocene, which must have been derived from previously undocumented sediments younger than the Nanjemoy Formation and older than the Piney Point Formation, and species known only from the uppermost middle Eocene and lowermost upper Eocene, which must have been derived from sediments younger than the Piney Point Formation but older than the Chickahominy Formation (the Chickahominy overlies the diamicton in the core). Units of these intermediate ages apparently were once present in the Virginia Coastal Plain but have since been eroded away or have not yet been recovered in the subsurface.

Most Potomac Formation clasts within the Exmore beds came from the upper part of the formation (Cenomanian in age). Samples from the matrix material that makes up the bulk of the Exmore beds are of mixed Late Cretaceous, Paleocene, and Eocene ages.

Many dinocyst specimens from the Exmore beds and injection zones of exotic matrix in the underlying crater unit B are fragmented, curled up, or otherwise degraded in a highly unusual manner; the degradation was probably caused by a combination of heat, pressure, and abrasion resulting from the impact. Similarly, some specimens of *Discoaster*, a genus of calcareous nannofossils, are fragmented and broken, probably from the same cause.

Introduction

This chapter documents the paleontology and biostratigraphy of part of the USGS-NASA Langley corehole, which was drilled into the Chesapeake Bay impact crater in Hampton, Va. (figs. D1, D2). The crater formed in the late Eocene, when a comet or asteroid struck the Atlantic continental shelf near the present town of Cape Charles, Va. (fig. D1; Poag and others, 1994).

The Langley corehole is approximately 8 kilometers (km; 5 miles (mi)) inside the outer margin of the buried crater and approximately 35 km (22 mi) from the center of the crater (Poag, 1997; Powars and Bruce, 1999). The corehole was drilled between July 22 and October 13, 2000, by the U.S. Geological Survey (USGS) and its partners (see “Acknowledgments”). The drill site is on the York-James Peninsula at the National Aeronautics and Space Administration (NASA) Langley Research Center in Hampton (fig. D2). The location is in the northeast quarter of the Newport News North 7.5-minute quadrangle (USGS, 1986), at lat 37°05'44.28" N., long 76°23'08.96"

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

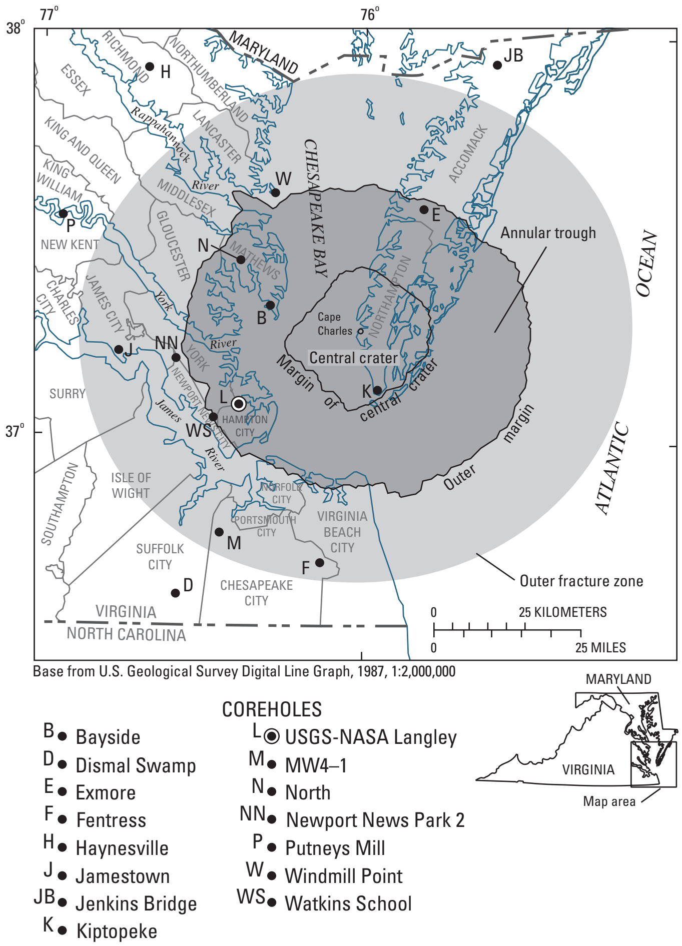

Figure D1. Regional map showing the location of the Chesapeake Bay impact structure, the USGS-NASA Langley corehole at Hampton, Va., and some other coreholes in southeastern Virginia. Locations of the central crater and outer margin are from Powars and Bruce (1999). The extent of the outer fracture zone (light gray) is based on Powars (2000) and Johnson and others (2001); the eastern part is speculative. Illustration modified from Powars, Johnson, and others (2002) and Edwards and Powars (2003).

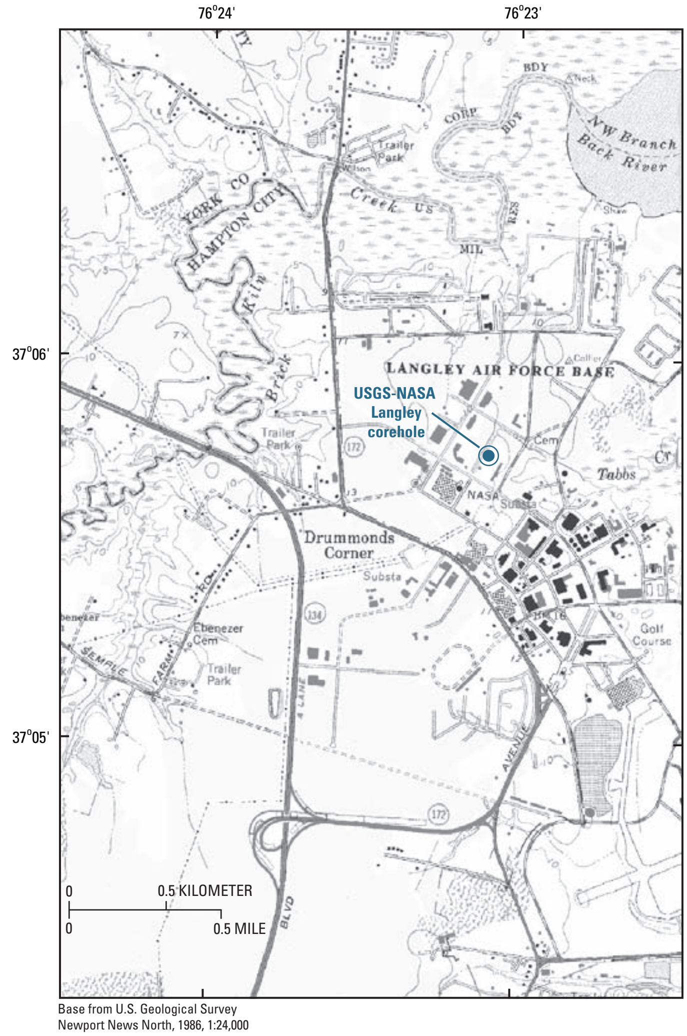

Figure D2. Detailed map showing the location of the USGS-NASA Langley corehole, Hampton, Va.

W. (North American Datum of 1927), and at a ground altitude of 2.4 meters (m; 7.9 feet (ft)) above the North American Vertical Datum of 1988.

The USGS-NASA Langley core can be divided into a number of impact-modified, impact-generated, and postimpact stratigraphic units. This chapter is concerned only with the impact-modified and impact-generated strata that form part of the crater fill. These strata are composed, in ascending order, of crater units A and B and the Exmore beds (fig. D3). These units extend from 626.3 to 235.65 m (2,054.7 to 773.12 ft) depth in the corehole. They contain strata and clasts derived from various preimpact sediments (table D1) and crystalline rocks in the region; they also contain matrix material that is composed of sands, silts, and clays.

The objectives of this study were threefold:

1. To examine various fossil groups in the impact-modified and impact-generated strata of the Langley core
2. To use the fossil data to determine the ages, provenance, and depositional environments of the strata, clasts, and matrix materials
3. To understand the dynamics involved in an impact in a shallow-marine setting

Fossils studied include palynomorphs (pollen and spores; dinoflagellate cysts, called dinocysts), calcareous nannofossils, and ostracodes. Pollen and spores are generally the only fossils found in the Lower to lower Upper Cretaceous Potomac Formation, a mainly or entirely terrigenous deposit that was affected by the impact. Dinocysts, calcareous nannofossils, foraminifera, diatoms, and ostracodes, among other marine microfossils, are present in the post-Potomac Formation, preimpact Upper Cretaceous to upper Eocene sediments of the Chesapeake Bay region.

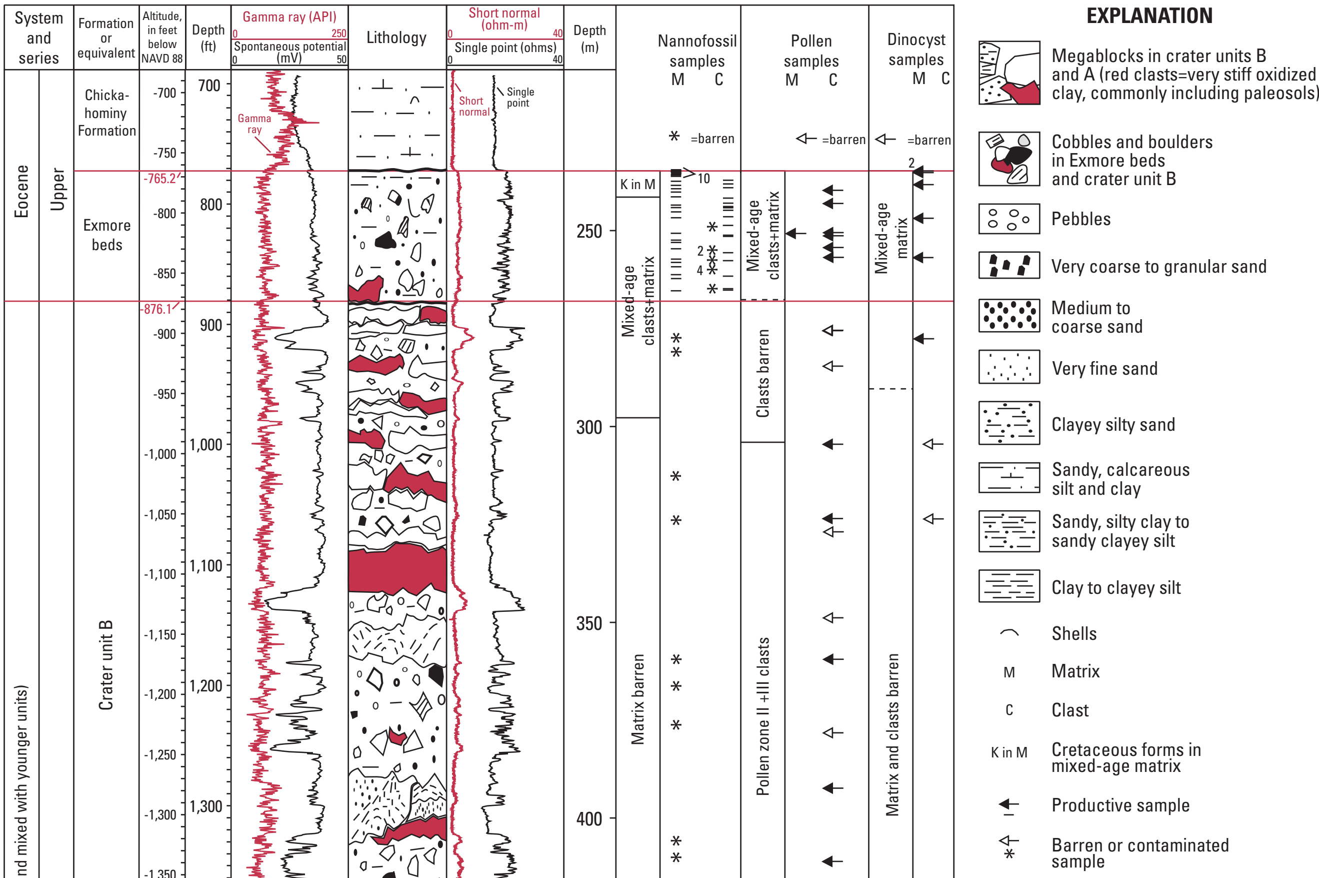

Figure D3. Generalized lithostratigraphic column, selected geophysical logs, and a summary of the biostratigraphy of samples from crater units A and B and the Exmore beds in the USGS-NASA Langley core. Definitions: API, API units; ft, feet; m, meters; mV, millivolts; NAVD 88, North American Vertical Datum of 1988; ohm-m, ohm-meters.

Table D1. Cretaceous to middle Eocene (preimpact) stratigraphic units in Virginia.

[Units are from Teifke (1973), Meng and Harsh (1988), Olsson and others (1988), Mixon and others (1989), and Powars and Bruce (1999). These units are expected to be represented by the clasts and matrix materials in the diamicton part of the USGS-NASA Langley core, Hampton, Va.]

Unit	Age	Lithology
Piney Point Formation	Middle Eocene	Olive-gray, shelly, glauconitic sand.
Nanjemoy Formation	Early Eocene	Olive- to greenish-gray, shelly, glauconitic clay and sand.
Marlboro Clay	Latest Paleocene to earliest Eocene	Gray to reddish clay, silt, and very fine sand.
Aquia Formation	Late Paleocene	Greenish-gray, shelly, glauconitic sand.
Brightseat Formation	Early Paleocene	Olive-gray to black, partly glauconitic, clayey and silty sand.
Various names[1]	Post-Potomac Late Cretaceous	Clay and sand, partly glauconitic, and red beds.
Potomac Formation or Group (fig. D6)	Barremian(?) to early Cenomanian	Gray, pink to red, and greenish sand, silt, and clay.

[1] In Virginia, Upper Cretaceous strata are now present only in the subsurface and are more or less deeply buried (Mixon and others, 1989), but they would have been at or nearer to the surface at the time of the comet or asteroid impact. Some names attached to these Upper Cretaceous strata in Virginia include the following:
– Lower part of the Mattaponi Formation (Teifke, 1973)
– [Upper Cretaceous] undifferentiated sediments (Meng and Harsh, 1988)
– Units A, B, and C of an unnamed formation (Olsson and others, 1988)
– Upper Cretaceous deposits, undivided (Mixon and others, 1989)
– Unnamed Upper Cretaceous deposits (Powars and Bruce, 1999)

This chapter includes data from 15 productive clast and matrix samples examined for spores and pollen, 6 productive matrix samples examined for dinocysts, 47 productive clast and matrix samples examined for calcareous nannofossils, and 2 matrix samples examined for ostracodes. Depths of sampling intervals for dinocysts and spores and pollen are given in full in table D2 and figure D4, but, for expediency, generally only the midpoint of the sampling interval is stated in the text. Nannofossil samples are so small that their locations in the core are given by only single depths. Lists of spore-pollen, dinocyst, and calcareous nannofossil taxa mentioned in this chapter are given in figure D4, figure D5, and appendix D1, respectively. Photographs of selected fossils are shown in plates D1–D5.

Previous Work

The spore-pollen zonation of the Cretaceous Potomac Formation in the Middle Atlantic States was defined by Brenner (1963), Doyle and Hickey (1976), and Doyle and Robbins (1977). This zonation is tied both to lithostratigraphy and to the standard Cretaceous chronostratigraphy of Gradstein and others (1995) (fig. D6). Many articles have been published on Paleocene and Eocene pollen and dinocysts from the Middle Atlantic and Southern Atlantic States. Among those that describe the stratigraphic distributions of palynomorphs from Virginia are papers by Edwards (1984, 1989, 1996), Edwards and others (1991), and Frederiksen (1979, 1984, 1991).

Calcareous nannofossil biostratigraphy is based on the lowest and highest occurrences of species; FAD indicates a first appearance datum, and LAD indicates a last appearance datum. Ages of Cretaceous nannofossils are based on the zonation of Sissingh (1977) as modified by Perch-Nielsen (1985) and Burnett (1998). Dating of Cenozoic calcareous nannofossils is based primarily on the zonation of Martini (1971) and secondarily on the zonation of Bukry (1973) and Okada and Bukry (1980). Details about the distribution of nannofossil species in lower Tertiary formations of Virginia were provided by DiMarzio (1984) and Bybell and Gibson (1991, 1994).

Detailed information about lower Tertiary pollen, dinocysts, calcareous nannofossils, and ostracodes from the Oak Grove core in northern Virginia was given by Gibson and others (1980). Data on the lower Tertiary ostracode biostratigraphy of the Gulf and Atlantic Coastal Plains appear in Swain (1952), Pooser (1965), Hazel and others (1977, 1980), and Deck (1984).

Previous biostratigraphic studies from equivalent lithic units (impact-modified and impact-generated units) in other coreholes in the Chesapeake Bay crater have been published by Poag and Aubry (1995), Poag and Commeau (1995), and Poag (1997, 2002).

Sample Processing

Materials sampled for fossils consisted mainly of poorly sorted, partly glauconitic gray clay, silt, and very fine to coarse sand occurring in the form of matrix material, clasts, and, in the lower part of the core, marginally rotated and slumped strata and megablocks.

The early phase of processing samples for palynomorphs began in the same way for both pollen and dinocysts. One-quarter round, one-half round, or a whole piece of core was sampled over a depth interval of 3–9 centimeters (cm; 1.2–3.5 inches (in.)) and scraped thoroughly. In the laboratory, 45–65 grams (g) of raw material was weighed and disaggregated. Each sample was treated with hydrochloric acid followed by hydrofluoric acid. Samples were then treated with nitric acid and ammonia and washed in a series of soap floats under short centrifugation.

There is an important difference in processing samples for angiosperm pollen from the Lower Cretaceous to lower Upper Cretaceous Potomac Formation as opposed to samples from younger stratigraphic units. This difference arises because angiosperm pollen grains from the Potomac Formation are generally very small, so that some of the grains will pass through even a 10-micrometer (µm) screen. In addition, Potomac Formation sediments contain large amounts of charcoal fragments. Therefore, Potomac Formation samples processed for angiosperm pollen were not sieved; following soap washes, they were separated from inorganic matter and charcoal by using a zinc chloride solution having a light specific gravity of 1.45 and designed particularly to drop out the charcoal. In contrast, zinc chloride solutions having a specific gravity of 2.0 were used for pollen samples from younger sediments, as well as for dinocyst samples. Pollen samples from younger sediments were then sieved, and the material between 10 and 200 µm was saved; dinocyst samples were sieved, and the material between 20 and 200 µm was saved. All palynomorph residues were stained with Bismark brown. Material was mounted in glycerin jelly on a glass slide with coverslip and was examined with the light microscope.

Forty nannofossil samples from the matrix portion of crater unit B and the Exmore beds and 26 nannofossil samples from clasts within the matrix were examined from the Langley core (fig. D3). For each matrix sample, a small amount of material was extracted from the central portion of a freshly broken core segment. Individual clasts were first scraped clean of drilling mud; then a small portion was removed from the center of the clast. The samples were dried in a convection oven to remove residual water, and the resultant sediments were stored in plastic vials.

To make slides, a small amount of sediment was placed in a beaker with 20 milliliters (mL) of water, stirred, and allowed to settle through the water column. An initial settling time of 1 minute (min) was used to remove the sand-sized fraction, and a second settling time of 10 min was used to concentrate the silt-sized material. Smear slides were made from the resultant slurry, and slides were affixed by using Norland Optical Adhesive 61 (NOA–61). Samples were primarily examined by using a Zeiss Photomicroscope III. Samples having exceptional preservation and abundance were further examined by using a JEOL JSM–6400 scanning-electron microscope (SEM). All palynological and nannofossil slides are stored at the U.S. Geological Survey, Reston, Va.

For ostracodes, approximately 50 g of sediment was processed by soaking the sediment overnight in tap water and washing on 63-µm sieves. Ostracodes were picked with a fine brush from the fraction >150 µm. Because so few individuals were present, all ostracodes were picked, including fragments.

Table D2. Depth of each dinocyst sample in the USGS-NASA Langley core.

[ft, feet; m, meters]

Sample	Top (ft)	Bottom (ft)	Midpoint (ft)	Midpoint (m)	Stratigraphic unit
R6110 DC	773.8	773.9	773.8	235.9	Exmore beds
R6110 DD	774.4	774.7	774.6	236.1	Exmore beds
R6110 DE	784.3	784.6	784.5	239.1	Exmore beds
R6110 DF	812.6	812.9	812.8	247.7	Exmore beds
R6110 DG	845.1	845.4	845.3	257.6	Exmore beds
R6110 DH	913.3	913.4	913.4	278.4	Crater unit B

Counting Methods for Dinocysts

One slide for each sample was examined completely for dinoflagellates and other palynomorphs. Then one or more slides were examined and counted until either 300 whole or partial specimens were noted (samples R6110 DH, DG, DF, DD, DC in table D3) or no additional slides and specimens remained (R6110 DE). All fragments that could be recognized as having dinoflagellate affinity were counted. Whole or nearly whole and fragmented specimens were placed into identifiable species, genera, or generic groups. Specimens that were not attributable to generic groups because of poor preservation were counted as "not identified to group."

Individual species could be identified in the case of some, but not all, of the whole or nearly whole specimens; most fragments could be identified only to genus level. The areoligeracean group is perhaps problematic. For whole or nearly whole specimens, most are attributable to the genus *Glaphyrocysta*. For fragmented specimens, this counting group includes chorate specimens that have solid processes but are not obviously members of the genus *Spiniferites* (pl. D2, fig. 8).

Spore-Pollen Biostratigraphy of Crater Unit A

Crater unit A extends from 626.3 to 442.5 m (2,054.7 to 1,451.7 ft) depth in the Langley core and consists of Potomac Formation strata that were disrupted very little by the impact (fig. D3). There are no matrix zones, although some fluidization of sands and fracturing of clays occurred in the upper part of the unit. There are no obvious contacts between blocks within this unit; if blocks occur in crater unit A, they are hundreds of meters in size (Gohn and others, this volume, chap. C). Potomac Formation strata in crater unit A are composed mainly of medium to very coarse sands that are barren or nearly barren of organic matter. The sands contain small numbers of clay clasts, interpreted to be primary clasts within the sand bodies, and subordinate primary clay-silt beds.

Stratigraphic unit	Crater unit A	Crater unit B							Exmore beds						
Depth (m)	446.4–446.5	426.8–426.8	425.5–425.6	411.0–411.0	392.3–392.3	359.6–359.7	323.5–323.6	304.7–304.7	268.7–268.8	257.4	255.0–255.0	251.9–252.0	251.0–251.1	243.6–243.6	240.3–240.4
Depth (ft)	1,464.5–1,464.8	1,400.1–1,400.4	1,396.1–1,396.4	1,348.3–1,348.5	1,287.0–1,287.2	1,179.8–1,180.0	1,061.5–1,061.7	999.6–999.8	881.6–881.8	844.6	836.5–836.7	826.5–826.7	823.5–823.7	799.1–799.3	788.5–788.6
Sample	R6110CB	R6110EC	R6110CA	R6110BJ	R6110BI	R6110BG	R6110BB	R6110BA	R6110AX	R6110AV	R6110AU	R6110EB	R6110AT	R6110EA	R6110AS
Matrix or clast	Clast	Clast	Clast	Clast	Clast	Clast	Clast	Clast	Clast	Clast	Clast	Matrix	Clast	Clast	Clast
Lithology	Greenish-black, lignitic, silty clay	Black, massive, noncalcareous clay	Olive-black, silty clay	Brownish-black, noncalcareous, silty clay	Very dark gray, noncalcareous, silty clay	Olive-gray, micaceous, lignitic, noncalcareous, fine sand	Olive-black, noncalcareous, silty clay	Black, noncalcareous, silty clay	Brownish-black, noncalcareous, silty clay	Brownish-black silty clay	Medium-gray to very light gray silt and very fine sand	Dark-greenish-gray, micaceous, calcareous, silty clay	Dark-olive-gray, micaceous, clayey silt	Calcareous very clayey silt	Medium-gray, micaceous, noncalcareous silty clay
Early Tertiary taxa															
Bombacacidites paulus Frederiksen 1989	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Carya <29 µm of Frederiksen and Christopher (1978)	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.
Favitricolporites baculoferus (Pflug in Thomson & Pflug 1953) Srivastava 1972	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Insulapollenites rugulatus Leffingwell 1970	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Interpollis microsupplingensis Krutzsch 1961	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.
Intratriporopollenites pseudinstructus group of Frederiksen (1988)	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.
Kyandopollenites anneratus Stover in Stover et al. 1966	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Labrapollis globosus (Pflug in Thomson & Pflug 1953) Krutzsch 1968	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Momipites coryloides Wodehouse 1933	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Momipites microfoveolatus (Stanley 1965) Nichols 1973	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.
Nudopollis terminalis (Pflug & Thomson in Thomson & Pflug 1953) Elsik 1968	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.
Nyssa sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Platycaryapollenites swasticoidus (Elsik 1974) Frederiksen & Christopher 1978	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Rhoipites angustus Frederiksen 1980	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.
Symplocos? *virginiensis* group of Frederiksen (1988)	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Thomsonipollis magnificus (Pflug in Thomson & Pflug 1953) Krutzsch 1960	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.
Ulmipollenites krempii (Anderson 1960) Frederiksen 1979	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Late Early and early Late Cretaceous taxa															
Ajatipollis sp. A of Doyle and Robbins (1977)	.	X	X	X	.	.	.	.	.	.	.	.	X	.	.
Aff. *Ajatipollis* sp. A of Doyle and Robbins (1977)	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.
Appendicisporites segmentus Brenner 1963	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Asteropollis sp. A of Doyle and Robbins (1977)	.	.	.	X	.	.	.	.	.	.	X	.	.	.	X
Cercidiphyllum type	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Aff. *Clavatipollenites minutus* Brenner 1963 of Doyle and Robbins (1977)	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ephedripites virginiaensis Brenner 1963	.	.	.	.	P	.	.	.	.	.	.	.	.	.	.
"*Foveotricolpites*" *concinnus* Singh 1971	.	.	.	.	.	.	.	.	.	S	.	.	.	.	.
"*Foveotricolporites*" *rhombohedralis* Pierce 1961	.	.	X	.	.	.	.	.	.	.	.	.	.	.	X
Liliacidites sp. B of Doyle and Robbins (1977)	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Liliacidites sp. D of Doyle and Robbins (1977)	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.
Liliacidites sp. E of Doyle and Robbins (1977)	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Liliacidites sp. F of Doyle and Robbins (1977)	X	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Peromonolites reticulatus Brenner 1963	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.
Reticulatisporites arcuatus Brenner 1963	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.
"*Retitricolpites*" *geranioides* (Couper 1960) sensu Brenner 1963	.	.	.	.	.	X	.	S	.	X	.	.	.	.	.
Cf. "*Retitricolpites*" *magnificus* Habib 1970 of Doyle and Robbins (1977)	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.
"*Retitricolpites*" *prosimilis* Norris 1967	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.
"*Retitricolpites*" *vermimurus* Brenner 1963	.	.	.	.	.	.	.	S	.	.	.	.	.	.	.
"*Retitricolpites*" *virgeus* (Groot et al. 1961) Brenner 1963	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.
Rugubivesiculites reductus Pierce 1961	.	.	.	.	.	.	X	X	.	.	.	.	.	.	.
Stephanocolpites tectorius Hedlund 1966	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.
Tricolpites albiensis Kemp 1968	.	.	.	.	S	S	.	.	.	S	.	.	.	.	.
Cf. *Tricolpites albiensis* Kemp 1968 of Doyle and Robbins (1977)	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.
Aff. *Tricolpites albiensis* Kemp 1968 of Doyle and Robbins (1977)	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.
Tricolpites crassimurus (Groot & Penny 1960) Singh 1971	.	.	.	.	S	S	.	.	.	S	.	.	.	.	.
Tricolpites georgensis (Brenner 1963) Burger 1970	.	.	.	.	S	X	.	X	.	S	.	.	.	.	.
Tricolpites micromunus (Groot & Penny 1960) Burger 1970	X	.	X	.	.	X	.	.	.	.	.	.	.	.	.
Cf. *Tricolpites micromunus* (Groot & Penny 1960) Burger 1970 of Doyle and Robbins (1977)	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Tricolpites nemejci Pacltová 1971	.	.	.	.	.	.	.	S	.	.	.	.	.	.	.
Tricolpites sp. A of Doyle and Robbins (1977)	.	.	.	.	P	.	.	.	.	X	.	.	.	.	.
Tricolporoidites bohemicus Pacltová 1971	.	.	.	S	.	.	.	.	.	.	.	.	.	.	.
Tricolporoidites sp. A of Doyle and Robbins (1977)	.	S	X	.	.	.	.	.	.	.	.	.	.	.	.
Aff. *Tricolporoidites* sp. A of Doyle and Robbins (1977)	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.
"*Tricolporopollenites*" *distinctus* Groot & Penny 1960	.	.	.	S	.	.	.	.	.	.	.	.	.	.	.
Tricolporopollenites sp. A of Wolfe and others (1975)	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.
Verrumonocolpites conspicuous Pierce 1961	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.

Figure D4. Occurrence chart showing the presence of spore and pollen taxa in each productive sample from crater units A and B and the Exmore beds in the USGS-NASA Langley core. Sample positions are plotted in figure D3. Symbols: X, present; ., not present; P, probably a specimen of this species; S, similar to the species but not exactly the same.

Unit	Crater unit B	Exmore beds				
Depth (m)	278.4	257.6	247.7	239.1	236.1	235.9
Depth (ft)	913.4	845.3	812.8	784.5	774.6	773.8
Sample R6110	DH	DG	DF	DE	DD	DC
Taxon						
Achilleodinium biformoides (Eisenack 1954) Eaton 1976	.	.	X	.	.	.
Andalusiella Riegel 1974 sp. (pl. D1, fig. 20)	.	.	.	.	.	X
Apectodinium parvum (Alberti 1961) Lentin & Williams 1977 (pl. D1, figs. 17, 18)	X	.	.	.	.	.
Batiacasphaera baculata Drugg 1970 (pl. D1, fig. 2)	X	.	.	.	.	.
Carpatella cornuta Grigorovich 1969 (pl. D1, fig. 19)	.	.	.	.	X	.
Charlesdowniea coleothrypta (Williams & Downie 1966) Lentin & Vozzhennikova 1989	X	.	.	X	.	X
Cordosphaeridium funiculatum Morgenroth 1966 (pl. D1, fig. 1)	X	X	X	.	X	X
Cordosphaeridium gracile (Eisenack 1954) Davey & Williams 1966	X	.	.	.	.	X
Cordosphaeridium inodes (Klumpp 1953) Eisenack 1963	.	.	.	.	X	.
Cribroperidinium Neale & Sarjeant 1962 sp.	X	X	.	.	.	.
Deflandrea oebisfeldensis Alberti 1959	.	.	?	.	.	.
Deflandrea phosphoritica Eisenack 1938 and closely related forms (pl. D2, figs. 7, 14)	X	X	X	X	X	X
Diphyes colligerum (Deflandre & Cookson 1955) Cookson 1965	X	.	.	.	.	.
Dracodinium varielongitudum (Williams & Downie 1966) Costa & Downie 1979 (p. D1, fig. 10; pl. D2, figs. 4, 5, 6; pl. D3, figs. 1, 2, 10, 11)	X	X	X	X	X	X
Emmetrocysta Stover 1975 sp.	X	.	.	.	.	.
Eocladopyxis n. sp. A of Edwards (2001) (pl. D1, fig. 12)	X	.	.	.	.	.
Exochosphaeridium Davey et al. 1966 sp. (pl. D2, fig. 1)	.	.	X	.	.	.
Exochosphaeridium or *Operculodinium* group	X	X	.	.	.	.
Fibradinium annetorpense Morgenroth 1968 (pl. D1, figs. 7–9)	.	.	.	.	X	.
Hafniasphaera Hansen 1977 spp.	.	.	.	.	.	X
Histiocysta sp. of Stover and Hardenbol (1993) (pl. D1, figs. 3, 4)	X	X	X	X	.	.
Homotryblium tasmaniense Cookson & Eisenack 1967 (pl. D1, fig. 11)	X	.	.	.	.	.
Homotryblium tenuispinosum Cookson & Eisenack 1967	.	?	.	.	.	.
Hystrichokolpoma rigaudiae Deflandre & Cookson 1955	X	.	.	.	.	.
Hystrichokolpoma Klumpp 1953 sp.	.	X	.	.	.	.
Hystrichosphaeridium tubiferum or *Homotryblium tenuispinosum*	X	.	.	.	.	.
Impagidinium Stover & Evitt 1978 sp.	.	.	.	.	.	X
Lingulodinium machaerophorum (Deflandre & Cookson 1955) Wall 1967	X	.	.	.	.	.
Pentadinium goniferum Edwards 1982	.	.	X	.	X	X
Pentadinium laticinctum Gerlach 1961 subsp. *laticinctum* (pl. D1, fig. 16)	.	X	.	.	X	X
Pentadinium membranaceum (Eisenack 1965) Stover & Evitt 1978 (pl. D1, figs. 5, 6; pl. D2, fig. 13)	X	X	X	X	X	X
Pentadinium Gerlach 1961 spp., undifferentiated (pl. D2, figs. 9–12)	X	X	X	X	X	X
Phthanoperidinium brooksii Edwards & Bebout 1981 (pl. D1, fig. 15)	X	X	.	.	.	.
Samlandia chlamydophora Eisenack 1954	.	.	.	.	.	X
Spinidinium Cookson & Eisenack 1962 spp.	.	X	.	.	.	.
Spiniferites pseudofurcatus (Klumpp 1953) Sarjeant 1970	.	.	.	.	.	X
Spiniferites Mantell 1850 sp. (pl. D3, figs. 8, 9)	X	X	.	X	X	X
Spiniferites and *Impagidinium* group	X	X	.	.	X	.
Tectatodinium pellitum Wall 1967	X	.	.	.	.	.
Turbiosphaera or *Thalassiphora* group	X	X	X	.	X	X
Wetzeliella complex spp.	X	X	X	X	X	X
Wetzeliella hampdenensis Wilson 1967 (pl. D1, fig. 13)	.	X	.	.	.	.
Wilsonidium Lentin & Williams 1976 sp.	.	?	.	.	.	.
miscellaneous areoligeracean forms (predominantly *Glaphyrocysta* Stover & Evitt 1978 spp.) but also including miscellaneous chorate fragments (pl. D3, figs. 12–14; pl. D2, fig. 8)	X	X	X	X	X	X
miscellaneous cladopyxidiacean forms	X	X	X	.	X	.
small peridiniacean forms (pl. D1, fig. 14)	X	X	X	X	X	X

Figure D5. Occurrence chart showing the presence of dinocyst taxa in each productive matrix sample from crater unit B and the Exmore beds in the USGS-NASA Langley core. Sample positions are plotted in figure D3. Depth ranges sampled are listed in table D2; depths shown here are midpoints of the ranges. Symbols: X, present; ., not present; ?, questionably present.

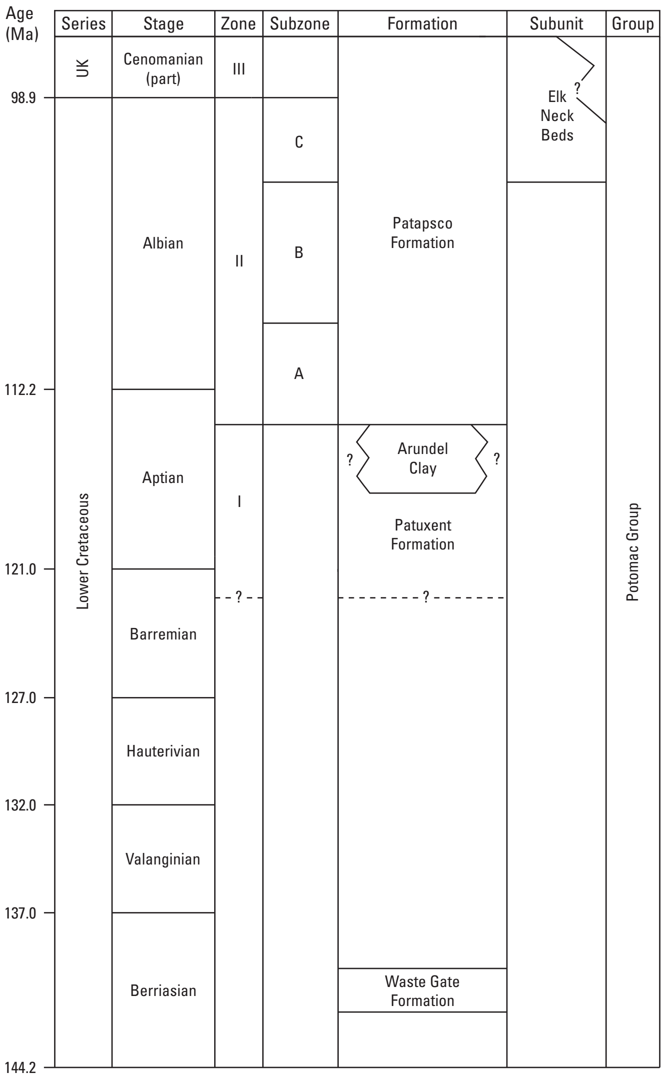

Figure D6. Correlation diagram showing stratigraphic units and palynological zones of the Potomac Group in the Middle Atlantic States. The Potomac Formation in Virginia as used in this report is equivalent to the Potomac Group in Maryland, which includes the Patapsco and Patuxent Formations and Arundel Clay, as shown above. Zonation is from Brenner (1963), Doyle and Hickey (1976), and Doyle and Robbins (1977); no zonal designation has been proposed for the spore-pollen assemblages (Doyle, 1983) of the Waste Gate Formation on the Delmarva Peninsula, east of the Chesapeake Bay. Ages of stage boundaries are from Gradstein and others (1995). UK, Upper Cretaceous.

Twelve samples of clay, silt, and sand were taken between 620.1 and 446.4 m (2,034.5 and 1,464.7 ft) in crater unit A (fig. D4; table D4); however, all samples but one were barren or nearly barren of organic matter including pollen and spores. Although the darkest strata available were sampled, all but two samples were greenish gray (the exceptions were dark red); the lack of organic matter (including pollen and spores) in these barren samples is undoubtedly due to the flood-plain strata originally having been oxidized during times of low ground-water level and then reduced during later times of high ground-water level, producing green colors of the iron minerals. However, it is assumed that all sedimentary materials within crater unit A are assignable to the Potomac Formation because no clasts or matrix materials were observed that appeared likely, on the basis of lithology, to be of post-Potomac Formation age (Gohn and others, this volume, chap. C).

The only sample from crater unit A that contained pollen and spores was the uppermost sample collected from this unit, from 446.4 m (1,464.7 ft; fig. D4). This sample was from lignitic beds; the sample was greenish black. The pollen assemblage is from Subzone IIB to Zone III, middle Albian to early Cenomanian in age. This sample was examined for dinocysts, but none were found, confirming the nonmarine origin of the sample. No palynomorph-bearing samples were obtained from the lowermost 179.8 m (589.7 ft) of crater unit A in the core, and these strata could be as old as early Aptian (fig. D6).

Biostratigraphy of Crater Unit B

Crater unit B extends from 442.5 to 269.4 m (1,451.7 to 884.0 ft; fig. D3) depth in the Langley core. Crater unit B is a sedimentary-clast diamicton in which the clast sizes vary greatly, from less than 1 cm (0.4 in.) to more than 20 m (66 ft) in diameter (Gohn and others, this volume, chap. C). This part of the diamicton is clast supported; the amount of matrix material between clasts constitutes a minor proportion of the total sediment. Clasts consist mainly of a variety of clays and sands. Zones of exotic matrix that penetrated this unit consist of muddy, fine to very coarse quartz-glauconite sand and granules. The lithology and the general absence of calcareous marine microfossils indicated at the time of drilling that most of the clasts were from the Potomac Formation.

Spores and Pollen

Thirteen samples from between 442.4 and 275.9 m (1,451.6 and 905.3 ft) in crater unit B were processed for spores and pollen (figs. D3, D4; table D4). Six of these samples were barren of palynomorphs (table D4), and these were greenish gray. Therefore, as seen also in crater unit A, prospects for obtaining spores and pollen grains from greenish samples of the Potomac Formation are rather poor. Higher in the section, abundant palynomorphs were recovered from greenish Tertiary matrix and clast samples in which the color comes from glauconite. The seven productive samples from the Potomac Formation in crater unit B were black, brownish black, or dark gray to olive black or olive gray (fig. D4).

Details about the spore-pollen assemblages found in samples from crater unit B are given in figure D4, and the ages of the assemblages are given in table D5. The seven productive clast samples from crater unit B all represented sediments derived from the Potomac Formation. The uppermost two samples could not be well dated. Among the remaining five sam-

Table D3. Quantitative composition of the dinocyst assemblage in each matrix sample from crater unit B and the Exmore beds in the USGS-NASA Langley core.

[m, meters; %, percent; W, whole; F, fragment]

Stratigraphic unit	Sample	Depth (m)	Count	% Whole or nearly whole	% Frag-ments	*Penta-dinium* spp.		Areoliger-acean group		*Deflandrea phosphorit-ica*		*Dracodinium varielongitu-dum*		Other *Wetzeli-ella* group		Misc. small peridini-aceans		Other identi-fiable forms		Not identified to group	
						W	F	W	F	W	F	W	F	W	F	W	F	W	F	W	F
Exmore beds	R6110 DC	235.9	300	22.3	77.7	16	105	11	76	11	18	20	0	4	2	1	0	3	6	1	26
Exmore beds	R6110 DD	236.1	300	6.3	93.7	5	140	2	74	0	9	5	0	2	0	1	0	4	17	0	41
Exmore beds	R6110 DE	239.1	203	22.7	77.3	5	89	0	5	19	31	8	3	9	2	2	0	1	0	2	27
Exmore beds	R6110 DF	247.7	300	15.0	85.0	14	99	3	107	6	10	4	0	12	7	1	0	5	12	0	20
Exmore beds	R6110 DG	257.6	300	21.0	79.0	8	74	6	106	6	8	3	1	14	12	12	0	12	20	2	16
Crater unit B	R6110 DH	278.4	300	23.3	76.7	3	28	12	140	4	2	5	0	10	9	16	2	19	35	1	14

ples, four or five of them contain at least some Aptian-Albian material and three contain some Cenomanian material. At least two and perhaps three of the samples contain mixed assemblages, indicating that these clasts had been contaminated by slurry sediment that penetrated the clasts during the violent movements of the material following the impact, or possibly during the drilling operation.

Dinocysts

Six samples from crater unit B were examined for the presence of dinocysts (fig. D3). Four of the samples were barren of these fossils. A fifth sample, of a clast from 426.8 m (1,400.3 ft), contained a few dinocyst specimens or fragments. However, these specimens most probably came from drilling-mud contamination, although infiltration of the sample with Tertiary material as a result of the impact event is also a possibility.

The sixth sample from crater unit B that was examined for the presence of dinocysts was a matrix sample from 278.4 m (913.4 ft; fig. D5); this sample, from near the top of crater unit B, consisted of a muddy, calcareous, quartz-glauconite sand. As in the samples from the matrix of the Exmore beds, dinocysts from 278.4 m represent a mixture of ages and show a variety of distinctive taphonomic effects. Because the matrix in the clast-supported crater unit B is genetically and lithologically continuous with the matrix in the Exmore beds, the dinocysts in the matrix from 278.4 m are discussed under "Biostratigraphy of the Exmore Beds."

Calcareous Nannofossils

Eleven matrix samples were examined from crater unit B for calcareous nannofossils, but most of these were barren (fig. D7). Only the sample from 298.5 m (979.3 ft) contained nannofossils, and the mixed assemblage in this sample consisted of species whose first occurrences (range bases) were in the early and late Paleocene and in the early, middle, and late Eocene; however, no Cretaceous species were observed.

Biostratigraphy of the Exmore Beds

The Exmore beds extend from 269.4 to 235.65 m (884.0 to 773.12 ft; fig. D3) depth in the Langley core. This unit is a matrix-supported, sedimentary-clast diamicton. Clasts in the Exmore beds generally are smaller than those in crater unit B and rarely exceed 1.0 m (3.3 ft) in diameter (Gohn and others, this volume, chap. C). Lithologically, the Exmore clasts are distinctly more heterogeneous than those in crater unit B, indicating a much larger variety of clast ages. The matrix consists mainly of muddy, calcareous, quartz-glauconite sand. Mixed sediments in the Exmore beds consist mainly of subaqueous resurge and (or) tsunami washback deposits that contain small amounts of reworked ejecta (Gohn and others, this volume, chap. C; Horton and Izett, this volume, chap. E).

Clasts appear to be of three origins (Poag, 1997; Gohn and others, this volume, chap. C):

1. Subaqueous resurge caused by the flow of seawater toward the center of the crater when the sea floor was exposed by the impact; the resurge carried with it blocks of sediment eroded from the crater rim
2. Tsunami washback derived from the return flow of huge tsunamis generated by the impact
3. Sparse fallback ejecta, consisting of blocks and unlithified sediments from the crater site that were blasted into the air, then fell back down over the region

Spores and Pollen

One matrix and six clast samples from between 268.7 and 240.4 m (881.7 and 788.6 ft) in the Exmore beds were processed for spores and pollen. All seven contained assemblages that could be dated (fig. D4). An overview of the ages of these samples is given in figure D8. The pollen assemblage from the matrix sample is compatible with an early Eocene age; however, some of the taxa have long stratigraphic ranges, and so the

Text continues on page D20.

Table D4. Depth and lithology of samples from the USGS-NASA Langley core that were collected for spore-pollen analysis but were barren of these fossils.

[m, meters; ft, feet]

Depth (m)	Depth (ft)	Sample number	Clast or matrix	Lithology
		Crater unit B		
275.9	905.2–905.3	R6110AZ	Clast	Mottled grayish-olive-green, muddy, fine to very coarse sand.
285.0–285.1	935.1–935.3	R6110BD	Clast	Light-olive-gray silty clay.
327.2–327.3	1,073.60–1,073.85	R6110BC	Clast	Greenish-gray, muddy, noncalcareous, very fine to fine sand.
349.0–349.1	1,145.00–1,145.25	R6110BE	Clast	Mottled (burrowed?) dark-greenish-gray to greenish-gray clayey sand.
378.3	1,241.0–1,241.2	R6110BH	Clast	Olive-gray noncalcareous clayey sand.
442.4–442.5	1,451.5–1,451.7	R6110ED	Matrix	Dark-greenish-gray, glauconitic, very coarse to very fine sand.
		Crater unit A		
503.4–503.5	1,651.7–1,652.0	R6110CC	Clast	Light-olive-gray, very coarse to fine, pebbly, noncalcareous sand.
504.1–504.2	1,654.0–1,654.3	R6110BK	Clast	Olive-gray, micaceous, noncalcareous, massive silty clay.
512.2	1,680.3–1,680.5	R6110EE	Clast	Greenish-black, noncalcareous silty clay.
523.7–523.8	1,718.2–1,718.4	R6110EF	Clast	Greenish-gray clay.
542.9–543.0	1,781.3–1,781.6	R6110EG	Clast	Dusky-yellowish-green, noncalcareous clayey silt.
570.9–571.0	1,872.9–1,873.2	R6110EH	Clast	Dark-greenish-gray, waxy clay.
598.3–598.4	1,963.0–1,963.2	R6110EI	Clast	Dark-greenish-gray clay.
613.7	2,013.3–2,013.6	R6110EJ	Clast	Very-dusky-red, noncalcareous silty clay.
614.6	2,016.3–2,016.5	R6110GA	Clast	Very-dusky-red, noncalcareous silty clay.
617.2	2,024.85–2,025.00	R6110EK	Clast	Dark-greenish-gray silty clay.
620.0–620.1	2,034.2–2,034.5	R6110EL	Clast	Dark-greenish-gray and dark-bluish-gray sandy clay.

Table D5. Spore-pollen ages of clast samples from crater units A and B in the USGS-NASA Langley core.

[The clasts all represent sediments derived from the Potomac Formation. Spore and pollen taxa in each clast are given in figure D4. m, meters; ft, feet]

Apparent diameter of clast		Depth		Age
(m)	(ft)	(m)	(ft)	
Crater unit B				
0.3	1	304.7	999.7	This sample contains relatively few species, which are probably long ranging; therefore, it is difficult to determine whether the assemblage is of mixed ages.
.3	1	323.6	1,061.6	Zone IIB or higher; middle Albian or younger. This sample contains only one significant species, which is long ranging. Therefore, it cannot be determined whether the assemblage includes pollen of mixed ages.
15	50	359.6	1,179.9	Probably Subzone IIB, middle Albian.
20.5	68	392.3	1,287.1	Probably Subzone IIA or IIB, probably late Aptian to middle Albian.
.5	1.5	411.0	1,348.4	This sample contains six significant species, three of them limited to Zone III, two of them apparently limited to Zone II, and one of them ranging from the upper part of Zone II to Zone III. Thus, the assemblage appears to indicate mixed ages.
2.2	6.2	425.6	1,396.2	This sample contains six significant species, two of them limited to Zone III, two species apparently limited to Zone II, and two species ranging from Zone II to Zone III. Thus, the assemblage appears to indicate mixed ages.
.15	.5	426.8	1,400.2	This sample contains only four significant species, two of them limited to Zone III, one species limited to the upper part of Zone II, and one species ranging from Zone II to Zone III. Thus, this assemblage may indicate mixed ages or may indicate a single age near the Zone II-Zone III boundary.
Crater unit A				
0.8	2.5	446.4	1,464.6	Subzone IIB to Zone III, middle Albian to early Cenomanian.

Stratigraphic unit	Depth (m)	Depth (ft)	BARREN	*Bomolithus conicus*	*Chiasmolithus consuetus*	*Chiasmolithus danicus*	*Coccolithus pelagicus*	*Cruciplacolithus asymmetricus*	*Cruciplacolithus edwardsii*	*Cruciplacolithus frequens*	*Cruciplacolithus inseadus*	*Cruciplacolithus primus*	*Cruciplacolithus tenuis*	*Cyclagelosphaera prima*	*Cyclagelosphaera reinhardtii*	*Ellipsolithus distichus*	*Ellipsolithus macellus*	*Ericsonia cava*	*Ericsonia subpertusa*	*Fasciculithus ulii*	*Hornibrookina arca*	*Markalius apertus*	*Neobiscutum parvulum*	*Prinsius bisulcus*	*Prinsius dimorphosus*	*Sphenolithus primus*	*Thoracosphaera* spp.	*Toweius pertusus*
			First occurrence in early Paleocene																									
Exmore beds	235.7	773.5	.	.	.	.	X	.	.	.	.	.	.	.	.	X	.	.	.	.	X	.	.	.	.	.	.	.
	235.8	773.8	.	.	.	.	X	.	.	.	.	.	.	X	.	.	.	.	.	X	.	.	.	.	.	.	X	.
	235.9	774.2	.	.	X	.	X	.	.	.	.	.	.	X	.	.	X	.	.	.	X	.	.	.	.	.	.	.
	236.0	774.4	.	.	X	.	X	.	.	.	.	X	.	.	.	X	X	.	X	.	X	.	.	.	.	X	.	X
	236.1	774.6	.	.	.	.	X	.	.	.	.	X	.	.	.	X	.	X	X	.	X	X	.	X	.	X	.	X
	236.12	774.7	.	.	.	.	X	X	.	.	.	X	X	.	.	X	.	.	X	.	X	X	.	.	.	.	.	X
	236.3	775.2	.	.	X	.	X	.	X	.	.	X	.	.	.	.	X	X	X	.	X	.	.	.	.	.	.	X
	236.5	775.9	.	.	X	.	X	X	X	.	.	X	.	.	.	.	X	X	X	.	X	.	.	X	.	X	.	.
	236.7	776.5	.	.	X	.	X	.	.	.	.	X	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X
	236.9	777.4	.	.	X	.	X	.	.	X	.	.	.	.	.	X	.	.	X	.	X	.	X	.	.	X	.	X
	238.1	781.3	.	.	.	.	X	X	X	.	.	.	.	.	.	.	.	.	X	.	X	.	.	X	.	.	.	X
	239.3	785.0	.	.	X	.	X	.	.	.	.	X	.	.	X	.	X	.	X	.	X	.	.	X	.	X	X	X
	240.0	787.3	.	.	X	.	X	.	.	.	.	X	.	.	.	X	X	.	X	.	X	.	.	X	X	X	.	X
	241.0	790.8	.	.	.	.	X	.	X	.	.	X	X	.	X	X	.	.	.	.	X	.	X	X	.	X	X	X
	242.2	794.7	.	.	X	.	X	.	.	.	.	X	X	.	.	X	.	.	X	.	X	.	X	.	.	X	.	X
	244.3	801.5	.	.	X	.	X	.	X	.	.	X	.	.	.	X	.	.	X	.	X	.	.	X	.	X	.	X
	245.0	803.8	.	.	.	.	X	X	.	.	.	.	.	.	.	.	.	X	X	.	X	.	.	X	.	.	.	X
	246.0	807.0	.	.	X	.	X	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	.	X	.	X	.	X
	247.6	812.4	.	X	X	.	X	.	.	.	.	.	X	.	.	X	.	X	X	.	X	.	.	X	.	.	.	X
	251.5	825.2	.	.	.	.	X	X	.	.	.	X	.	X	.	X	.	.	X	.	X	.	.	X	.	.	.	X
	253.3	831.2	.	.	.	X	X	.	.	.	.	X	.	.	.	X	.	.	.	.	X	.	.	.	.	.	.	X
	254.0	833.2	.	.	.	.	X	.	.	.	.	.	.	.	.	X	X	.	X	.	X	.	.	X	.	X	.	X
	255.3	837.5	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	.	X	.	X
	258.0	846.4	.	.	.	.	X	.	.	.	.	.	.	X	.	X	X	.	X	.	X	.	X	.	.	X	.	X
	258.8	849.0	.	.	.	.	X	.	.	.	.	.	.	.	.	.	X	.	X	.	X	.	X	.	.	X	.	X
	260.0	853.0	.	.	X	.	X	.	.	.	.	.	.	X	X	X	.	X	X	.	X	.	.	X	.	X	.	X
	262.0	859.5	.	.	.	.	X	.	.	.	X	.	.	X	.	X	X	X	X	.	X	.	.	X	.	X	.	X
	263.0	863.0	.	.	X	.	X	.	.	.	.	.	.	.	.	X	.	.	X	.	X	.	.	.	.	.	.	X
	266.2	873.2	.	.	.	.	X	.	.	.	.	X	.	X	.	X	.	.	X	.	X	.	.	X	.	X	.	X
Crater unit B	278.4	913.4	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	281.3	923.1	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	298.5	979.3	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.
	313.7	1,029.3	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	324.1	1,063.3	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	360.2	1,181.9	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	366.6	1,202.9	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	376.9	1,236.7	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	406.1	1,332.5	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	410.7	1,347.3	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	442.4	1,451.5	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Figure D7. Occurrence chart showing the presence of calcareous nannofossil taxa in each matrix sample from crater unit B and the Exmore beds in the USGS-NASA Langley core. Abundance and preservation data are shown on the sixth page. Symbols: X, present; ., not present; 1, a single specimen. The only productive matrix sample from crater unit B is from a thin matrix section at the top of a coring run. As such, it was susceptible to drilling-mud contamination during core recovery and handling. However, its mixed early Tertiary assemblage could be due to sediment mixing during the impact.

Stratigraphic unit	Depth (m)	Depth (ft)	First occurrence in late Paleocene																																							
			Bomolithus elegans	*Camplyosphaera dela*	*Chiasmolithus bidens*	*Discoaster anartios*	*Discoaster diastypus*	*Discoaster falcatus*	*Discoaster lenticularis*	*Discoaster mahmoudii*	*Discoaster mediosus*	*Discoaster mohleri*	*Discoaster multiradiatus*	*Discoaster salisburgensis*	*Discoaster splendidus*	*Fasciculithus billii*	*Fasciculithus involutus*	*Fasciculithus sidereus*	*Fasciculithus thomasii*	*Fasciculithus tympaniformis*	*Heliolithus cantabriae*	*Heliolithus riedelii*	*Lophodolithus nascens*	*Neochiastozygus concinnus*	*Neochiastozygus denticulatus*	*Neochiastozygus distentus*	*Neochiastozygus junctus*	*Neococcolithes protenus*	*Neocrepidolithus biskayae*	*Neocrepidolithus bukryi*	*Pontosphaera plana*	*Rhomboaster spineus*	*Scapholithus apertus*	*Sphenolithus anarrhopus*	*Toweius callosus*	*Toweius eminens* var. *eminens*	*Toweius eminens* var. *tovae*	*Toweius occultatus*	*Toweius serotinus*	*Transversopontis pulcher*	*Zygodiscus herlynii*	*Zygrhablithus bijugatus*
Exmore beds	235.7	773.5	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X
	235.8	773.8	.	X	X	.	.	.	.	.	.	.	X	X	.	.	.	.	.	.	.	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	X
	235.9	774.2	.	X	X	.	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	.	X	.	.	.	X	X	.	.	.	.	.	.	.	.	.	.	X	X	X	X
	236.0	774.4	.	.	X	.	.	.	X	X	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	X	X	.	.	.	.	X	X	.	X	X	.	X	X	X	X
	236.1	774.6	.	X	X	X	.	X	.	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X	X	X	X	X	X	X	.	X
	236.12	774.7	.	X	X	.	.	X	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X	.	X	X	X	X	X	X	X	X
	236.3	775.2	X	X	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	X	.	.	X	X	.	X	X	X	.	X
	236.5	775.9	.	.	X	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	X	X	.	.	.	.	X	.	X	X	X	X	X	X	.	X
	236.7	776.5	X	X	X	.	.	X	X	.	.	X	X	X	.	.	.	X	.	.	.	.	.	.	.	.	X	X	.	.	X	.	X	.	X	X	X	.	X	X	X	X
	236.9	777.4	.	.	X	X	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	X	X	.	X	X	X	.	.	.	.	X	.	X	.	.	X	X	X	X	X
	238.1	781.3	X	.	X	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	X	X	X	X	.	.	X	X	.	.	.	.	X	.	X	.	.	X	X	X	X	X
	239.3	785.0	.	X	X	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	X	.	X	.	.	X	X	.	.	.	.	X	X	X	.	.	X	X	X	X	X
	240.0	787.3	.	X	X	.	.	.	.	.	.	X	X	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	X	.	X	X	X	X	X	X
	241.0	790.8	.	.	X	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X	.	X	X	X	X	X	X
	242.2	794.7	.	X	X	.	.	.	.	.	.	X	X	.	.	.	.	.	.	X	.	.	.	.	.	.	X	.	.	.	.	.	X	.	X	.	X	X	X	X	X	X
	244.3	801.5	.	X	X	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.	.	X	.	X	.	X	X	X	X	X	X
	245.0	803.8	.	.	X	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.	.	.	.	X	.	.	X	.	X	X	X
	246.0	807.0	.	X	X	.	.	X	.	X	.	X	X	.	.	.	.	.	.	.	.	X	X	X	.	.	.	.	.	.	.	.	X	.	X	.	X	X	X	X	X	X
	247.6	812.4	.	.	X	X	X	.	X	.	.	X	X	.	.	.	X	.	.	X	.	.	.	.	.	.	X	X	.	.	.	.	.	.	X	X	X	X	X	X	X	X
	251.5	825.2	.	.	X	.	.	X	X	.	.	X	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	X	X	X	X	X	X	X	X
	253.3	831.2	.	.	X	.	.	X	X	.	.	X	X	X	.	.	X	.	.	.	.	.	X	.	.	.	X	X	.	.	X	.	X	.	X	.	X	X	X	X	X	X
	254.0	833.2	X	X	X	.	.	X	.	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	X	.	X	X	X	X	X	X	.	X
	255.3	837.5	.	.	X	.	.	.	X	.	.	X	X	.	.	.	X	.	.	.	.	.	.	X	.	.	X	.	.	.	X	.	.	.	X	X	X	X	X	X	.	X
	258.0	846.4	.	X	X	.	.	X	X	.	.	.	X	X	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	X	.	X	X	X	X	X	X
	258.8	849.0	.	X	X	.	.	X	.	.	.	X	X	X	.	.	X	.	.	.	.	.	.	X	.	.	X	X	.	.	.	.	X	.	X	X	X	X	X	X	X	X
	260.0	853.0	X	X	X	.	.	.	X	.	.	X	X	.	.	X	.	.	X	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	X	X	X	X	X	X	X	X
	262.0	859.5	X	X	X	.	.	.	X	.	.	X	X	X	.	.	.	.	.	X	.	.	.	.	X	.	X	X	.	.	.	.	.	.	X	.	X	X	X	X	X	.
	263.0	863.0	.	.	X	.	.	.	X	.	.	X	X	X	.	X	.	.	X	.	.	.	.	X	.	.	X	.	.	.	.	.	X	.	X	X	X	X	X	X	.	X
	266.2	873.2	X	X	X	.	.	.	.	.	.	X	X	.	.	.	X	.	.	X	.	.	.	.	.	.	X	.	X	X	.	.	X	.	X	.	X	X	X	X	X	X
Crater unit B	278.4	913.4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	281.3	923.1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	298.5	979.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.
	313.7	1,029.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	324.1	1,063.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	360.2	1,181.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	366.6	1,202.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	376.9	1,236.7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	406.1	1,332.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	410.7	1,347.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	442.4	1,451.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Figure D7. Continued.

Stratigraphic unit	Depth (m)	Depth (ft)	*Chiasmolithus eograndis*	*Chiasmolithus expansus*	*Coronocyclus prionion*	*Discoaster barbadiensis*	*Discoaster deflandrei*	*Discoaster gemmifer*	*Discoaster kuepperi*	*Discoaster lodoensis*	*Discoaster septemradiatus*	*Discoaster sublodoensis*	*Ericsonia formosa*	*Helicosphaera lophota*	*Helicosphaera papillata*	*Helicosphaera seminulum*	*Holodiscolithus solidus*	*Neococcolithes dubius*	*Neococcolithes minutus*	*Pontosphaera ocellata*	*Pseudotriquetrorhabdulus inversus*	*Reticulofenestra dictyoda*	*Rhabdosphaera creber*	*Rhabdosphaera perlongus*	*Rhabdosphaera pinguis*	*Rhabdosphaera truncata*	*Rhomboaster bramlettei*	*Rhomboaster contortus*	*Rhomboaster orthostylus*	*Sphenolithus editus*	*Sphenolithus moriformis*	*Sphenolithus radians*	*Toweius? magnicrassus*	*Transversopontis obliquipons*	*Transversopontis pulcheroides*
			First occurrence in early Eocene																																
Exmore beds	235.7	773.5	.	.	.	X	.	.	.	.	.	.	X	X	.	X	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.
	235.8	773.8	.	.	.	.	.	.	X	X	.	.	X	.	.	X	.	X	.	.	.	.	X	.	.	.	.	.	X	.	.	.	.	.	X
	235.9	774.2	.	.	.	X	.	.	.	.	.	.	X	.	.	X	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X
	236.0	774.4	X	X	X	.	.	X	X	.	.	.	.	X	.	.	.	X	X	.	X	X	.	.	.	X	.	.	X	.	.	.	X	.	.
	236.1	774.6	.	.	.	X	X	.	.	.	.	.	.	X	.	.	.	.	X	.	X	X	.	.	.	.	.	.	.	.	X	X	.	.	.
	236.12	774.7	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	X	.	X	X	.	.	.	.	X	.	.	.	.	.	.	.	.
	236.3	775.2	.	.	X	X	.	X	.	.	.	.	.	.	X	.	.	X	X	.	X	X	.	.	.	X	.	.	X	X	.	.	.	.	.
	236.5	775.9	.	.	X	.	.	.	.	.	.	X	.	.	.	X	.	.	X	X	X	X	.	.	.	X	.	.	X	.	.	.	.	.	.
	236.7	776.5	.	.	.	.	.	.	.	.	.	X	.	X	.	X	.	.	X	.	X	X	.	.	.	.	.	.	.	.	X	.	.	.	.
	236.9	777.4	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	X	X	X	.	.	.	X	.	.	X	.	.	.	.	.	.
	238.1	781.3	.	.	.	X	X	.	.	.	.	.	.	X	.	.	.	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.
	239.3	785.0	.	.	X	.	.	.	.	.	.	.	.	.	X	X	.	.	X	.	X	X	.	.	.	.	X	.	.	.	.	X	.	.	.
	240.0	787.3	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	X	X	.	X	X	.	.	.	.	.	.	.	.	.	X	.	X	.
	241.0	790.8	.	X	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	.
	242.2	794.7	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	.
	244.3	801.5	.	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	.
	245.0	803.8	.	.	.	X	.	.	.	.	X	.	.	.	.	X	.	X	X	.	X	X	.	.	.	X	.	.	X	.	.	.	.	X	.
	246.0	807.0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	.	.	X	.	.	.	X	.	.	.	.	X	.
	247.6	812.4	.	.	X	.	.	.	.	.	.	.	X	.	.	.	.	.	X	.	X	X	X	X	.	.	.	.	.	X	.	.	X	X	.
	251.5	825.2	.	.	X	.	.	.	.	.	.	.	X	.	.	.	.	.	X	.	X	X	X	.	.	.	.	.	.	.	.	.	.	X	.
	253.3	831.2	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X	.	X	X	.	.	.	X	.	.	.	.	.	.	.	X	.
	254.0	833.2	.	X	.	.	X	.	.	.	.	.	X	.	.	X	X	.	X	.	.	X	.	.	.	.	X	.	X	.	.	X	.	X	.
	255.3	837.5	.	X	.	.	.	.	.	.	.	.	X	.	.	.	.	X	X	.	X	X	.	.	.	X	.	.	.	.	.	.	.	X	.
	258.0	846.4	.	X	X	.	.	.	.	.	.	.	X	.	.	X	.	X	X	.	X	X	.	.	.	.	X	.	X	.	.	.	.	X	.
	258.8	849.0	.	X	.	.	X	.	X	.	.	.	X	.	.	.	.	X	.	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	.
	260.0	853.0	.	.	.	.	X	.	X	X	.	.	X	.	.	X	.	.	X	.	X	X	.	.	.	X	.	.	.	.	.	.	.	X	.
	262.0	859.5	.	.	X	X	.	.	X	.	.	.	X	.	.	X	.	X	X	.	X	X	.	.	.	X	.	.	X	.	.	.	.	X	.
	263.0	863.0	.	X	X	.	X	.	.	.	.	.	X	.	.	.	.	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	.
	266.2	873.2	.	X	.	.	.	.	X	.	.	.	X	X	.	X	.	X	X	.	X	X	.	.	.	.	.	.	.	X	.	.	.	X	.
Crater unit B	278.4	913.4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	281.3	923.1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	298.5	979.3	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	X	.	.	.	X	.	X	.	.	X	.	.	X	.
	313.7	1,029.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	324.1	1,063.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	360.2	1,181.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	366.6	1,202.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	376.9	1,236.7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	406.1	1,332.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	410.7	1,347.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	442.4	1,451.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Figure D7. Continued.

Stratigraphic unit	Depth (m)	Depth (ft)	First occurrence in middle Eocene																																											
			Blackites spinosus	*Blackites tenuis*	*Chiasmolithus gigas*	*Chiasmolithus modestus*	*Chiasmolithus titus*	*Coronocyclus nitescens*	*Cribrocentrum reticulatum*	*Cruciplacolithus vanheckae*	*Cyclicargolithus luminis*	*Daktylethra punctulata*	*Dictyococcites bisectus*	*Dictyococcites callidus*	*Dictyococcites daviesii*	*Dictyococcites scrippsae*	*Discoaster martinii*	*Discoaster nodifer*	*Discoaster saipanensis*	*Discoaster tanii*	*Ericsonia* aff. *E. fenestrata*	*Ericsonia obruta*	*Helicosphaera bramlettei*	*Helicosphaera compacta*	*Helicosphaera intermedia*	*Lanternithus minutus*	*Lithostromation operosum*	*Lithostromation simplex*	*Lophodolithus acutus*	*Micrantholithus altus*	*Micrantholithus angulosus*	*Micrantholithus mirabilis*	*Micrantholithus vesper*	*Pedinocyclus larvalis*	*Pemma basquense*	*Pemma rotundum*	*Pemma serratum*	*Pemma stradneri*	*Pontosphaera multipora*	*Pontosphaera wechesensis*	*Reticulofenestra floridana*	*Reticulofenestra umbilica*	*Sphenolithus intercalaris*	*Sphenolithus pseudoradians*	*Sphenolithus spinenger*	*Transversopontis zigzag*
Exmore beds	235.7	773.5	.	.	.	.	.	.	X	.	X	.	X	.	X	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	X	.	.	X	.	.	X	.	.	.	X
	235.8	773.8	.	.	.	.	X	.	X	.	X	X	X	.	X	.	.	.	X	.	.	.	X	.	X	.	X	.	.	.	.	.	X	.	X	X	.	X	X	X	X	X	.	.	.	X
	235.9	774.2	.	X	.	.	.	.	X	.	X	.	X	.	X	.	.	.	X	.	.	.	X	X	.	.	.	.	.	.	.	.	X	.	X	.	.	X	X	.	.	X	.	.	.	X
	236.0	774.4	.	.	.	.	.	X	X	.	.	.	X	.	.	X	X	.	X	.	.	X	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X
	236.1	774.6	.	.	.	.	.	X	X	.	.	.	X	.	.	.	.	.	X	.	.	X	.	.	.	X	.	.	.	.	.	X	.	.	X	.	.	.	X	.	.	X	.	.	X	X
	236.12	774.7	.	.	.	.	X	X	X	X	.	.	X	.	.	X	.	.	X	.	.	.	X	.	.	.	.	X	.	X	.	X	.	.	X	.	.	.	X	.	.	X	.	.	.	X
	236.3	775.2	.	.	.	.	.	X	X	.	.	.	X	X	.	.	.	.	X	.	.	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X
	236.5	775.9	.	.	.	.	.	X	X	.	X	.	X	X	.	.	.	.	X	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	X	.	.	X	.	.	.	X
	236.7	776.5	.	.	X	.	.	X	X	.	X	.	X	X	.	.	.	.	X	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	.	X
	236.9	777.4	.	.	.	.	.	X	X	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	.	X
	238.1	781.3	X	.	.	.	.	X	X	.	X	.	X	X	.	.	.	.	X	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	.	X
	239.3	785.0	X	.	.	.	.	X	X	.	X	.	X	X	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	X	X	.	.	X	.	.	.	X
	240.0	787.3	.	.	.	.	.	X	X	.	.	.	X	X	.	.	.	.	X	.	.	X	.	.	.	X	.	.	.	.	X	.	.	.	X	.	.	X	X	.	.	X	.	.	.	X
	241.0	790.8	.	X	.	.	.	X	X	.	.	.	X	X	.	.	.	.	X	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	.	.
	242.2	794.7	.	.	.	.	.	X	X	.	X	.	X	X	.	.	.	.	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	X	.	X	.	.	X	.	.	.	.
	244.3	801.5	X	.	.	.	X	X	X	.	X	.	X	X	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	X	.
	245.0	803.8	.	.	.	.	.	X	X	.	X	.	X	X	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	X	.	.	X	.	.	X	.
	246.0	807.0	.	.	.	X	.	X	X	.	.	.	X	X	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	.	X	.	.	.	.
	247.6	812.4	.	.	.	.	.	X	X	.	X	.	X	X	.	X	.	X	X	.	.	X	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	.
	251.5	825.2	.	.	.	.	X	X	X	.	.	.	X	X	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	.	X
	253.3	831.2	.	.	.	.	.	X	X	.	X	.	X	X	.	.	.	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	X	X	X	X
	254.0	833.2	.	.	.	.	.	X	X	.	X	.	X	X	.	X	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	X	X	.	.	.	X	.	.	X	.	.	.	X
	255.3	837.5	.	.	.	.	.	X	X	.	X	.	X	X	.	X	.	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	X	X
	258.0	846.4	.	.	.	.	.	.	X	.	X	.	X	X	.	X	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X	.	.	X	.	.	.	X
	258.8	849.0	.	X	.	.	.	.	X	.	X	.	X	X	.	X	.	X	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	.	X
	260.0	853.0	.	.	.	.	.	X	X	.	.	.	X	X	.	X	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	X	X
	262.0	859.5	.	.	.	.	.	X	X	.	.	.	X	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	X	.	.	.	.
	263.0	863.0	.	.	.	.	.	.	X	.	X	.	X	X	.	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X
	266.2	873.2	X	X	.	.	.	X	X	.	.	.	X	X	.	X	.	X	X	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X
Crater unit B	278.4	913.4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	281.3	923.1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	298.5	979.3	.	.	.	.	.	.	X	.	.	.	X	X	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	.
	313.7	1,029.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	324.1	1,063.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	360.2	1,181.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	366.6	1,202.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	376.9	1,236.7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	406.1	1,332.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	410.7	1,347.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	442.4	1,451.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Figure D7. Continued.

Stratigraphic unit	Depth (m)	Depth (ft)	First occurrence (FO) in late Eocene								Survivor species						Unknown FOs					
			Chiasmolithus oamaruensis	*Cyclicargolithus floridanus*	*Ericsonia subdisticha*	*Helicosphaera euphratis*	*Helicosphaera reticulata*	*Helicosphaera wilcoxonii*	*Isthmolithus recurvus*	*Reticulofenestra oamaruensis*	*Biscutum constans*	*Braarudosphaera bigelowii*	*Cyclagelosphaera reinhardtii*	*Goniolithus fluckigeri*	*Markalius inversus*	*Placozygus sigmoides*	*Biscutum* spp.	*Discoaster* spp.	*Fasciculithus* spp.	*Micrantholithus* spp.	*Naninfula* spp.	*Pontosphaera* spp.
Exmore beds	235.7	773.5	X	X	.	.	.	.	X	.	.	X	.	.	.	X	.	X	.	.	.	X
	235.8	773.8	X	.	.	.	.	.	X	.	.	X	.	.	X	X	.	.	.	.	.	.
	235.9	774.2	X	X	.	.	.	.	X	.	.	X	.	.	X	.	.	.	.	.	.	.
	236.0	774.4	X	X	.	.	.	X	X	X	.	X	.	X	X	.	.	.	.	.	X	X
	236.1	774.6	.	.	.	.	.	.	X	.	X	X	.	.	X	.	.	.	.	.	.	.
	236.12	774.7	X	.	.	.	.	.	X	.	.	X	.	.	X	.	.	.	.	.	.	.
	236.3	775.2	X	.	.	.	.	.	X	.	.	X	X	.	X	.	.	.	.	.	.	X
	236.5	775.9	.	.	.	.	X	.	X	.	X	X	X	.	X	.	.	.	.	.	.	X
	236.7	776.5	X	.	.	.	.	.	X	.	X	X	.	.	X	X	.	.	.	.	.	.
	236.9	777.4	X	.	.	.	.	.	X	.	X	X	.	.	X	.	.	.	X	.	.	X
	238.1	781.3	.	.	.	.	.	.	X	.	X	X	.	.	X	.	.	.	.	.	.	X
	239.3	785.0	X	.	.	.	.	.	X	.	.	X	.	.	X	.	.	.	.	.	.	.
	240.0	787.3	X	.	.	.	.	.	X	.	.	X	.	.	X	.	.	X	X	.	.	.
	241.0	790.8	X	.	X	.	.	.	X	.	X	X	.	.	X	X	.	.	.	.	.	X
	242.2	794.7	.	.	.	.	.	.	X	.	.	X	.	.	X	.	.	.	.	.	.	.
	244.3	801.5	X	.	.	.	.	.	X	.	X	X	.	X	X	.	.	.	X	.	.	X
	245.0	803.8	X	.	.	.	.	.	X	.	.	X	.	.	.	.	.	X	.	.	.	X
	246.0	807.0	X	.	X	.	.	.	X	.	.	X	X	.	X	X	.	.	X	.	.	X
	247.6	812.4	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	X	.	.	X
	251.5	825.2	.	.	.	.	.	.	X	.	.	.	.	.	X	.	X	.	X	.	.	.
	253.3	831.2	X	.	.	.	.	.	X	.	.	X	.	.	X	.	X	.	X	.	.	X
	254.0	833.2	.	.	.	X	.	.	X	.	X	X	.	.	X	X	.	X	.	X	.	.
	255.3	837.5	.	X	.	.	.	.	X	.	.	X	.	.	X	.	.	.	X	.	.	.
	258.0	846.4	X	.	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	X
	258.8	849.0	X	.	.	.	.	.	X	.	.	X	X	.	X	.	.	.	.	.	.	X
	260.0	853.0	X	.	.	.	.	.	X	.	.	X	.	.	.	.	.	.	.	.	.	X
	262.0	859.5	X	.	X	.	.	.	X	.	.	.	.	.	X	.	.	X	.	.	.	
	263.0	863.0	.	.	.	.	.	.	X	.	.	X	.	.	X	X	.	.	X	.	.	X
	266.2	873.2	.	.	.	.	.	.	X	.	X	.	.	.	X	.	.	.	.	.	.	.
Crater unit B	278.4	913.4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	281.3	923.1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	298.5	979.3	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.
	313.7	1,029.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	324.1	1,063.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	360.2	1,181.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	366.6	1,202.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	376.9	1,236.7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	406.1	1,332.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	410.7	1,347.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	442.4	1,451.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Figure D7. Continued.

Stratigraphic unit	Depth (m)	Depth (ft)	First occurrence in Late Cretaceous																																Abundance[a]	Preservation[b]
			Ahmuellerina octoradiata	*Arkhangelskiella cymbiformis*	*Broinsonia dentata*	*Calculites obscurus*	*Calculites ovalis*	*Corollithion signum*	*Cretarhabdus conicus*	*Cribrosphaerella ehrenbergii*	*Cylindralithus crassus*	*Discorhabdus ignotus*	*Eiffellithus eximius*	*Eiffellithus turriseiffelii*	*Eprolithus floralis*	*Flabellites oblonga*	*Garnerago obliquum*	*Glaukolithus diplogrammis*	*Helicolithus trabeculatus*	*Lithastrinus grillii*	*Microrhabdulus attenuatus*	*Micula decussata*	*Prediscosphaera cretacea*	*Prediscosphaera spinosa*	*Reinhardtites anthophorus*	*Repagulum parvidentatum*	*Retemediaformis* sp.	*Sollasites barringtonensis*	*Staurolithites imbricatus*	*Stovarius asymmetricus*	*Tranolithus minimus*	*Vekshinella aachena*	*Vekshinella stradneri*	*Watznaueria barnesae*		
Exmore beds	235.7	773.5	.	.	.	.	.	.	.	X	.	.	.	X	.	.	.	X	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	A	G
	235.8	773.8	.	.	.	.	.	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	A	M
	235.9	774.2	.	.	.	.	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	A	G
	236.0	774.4	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	.	.	.	C	G
	236.1	774.6	X	X	X	.	.	.	.	X	.	.	.	X	.	X	.	.	.	X	.	X	.	.	.	.	X	.	X	.	.	X	.	.	C	G
	236.12	774.7	.	.	.	.	.	.	.	.	X	X	.	.	.	.	.	.	.	.	.	X	X	.	.	.	.	.	.	.	X	.	.	.	C	G
	236.3	775.2	.	.	.	.	.	X	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	C	G
	236.5	775.9	.	.	.	X	X	.	X	.	.	.	.	X	.	.	X	X	.	.	.	X	X	.	.	.	X	.	.	.	.	.	.	.	C	G
	236.7	776.5	.	.	.	.	.	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	X	.	X	X	.	.	.	X	.	.	.	.	C	G
	236.9	777.4	.	.	.	.	.	.	.	X	.	.	.	X	X	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	C	G
	238.1	781.3	.	.	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	X	.	C	G
	239.3	785.0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	C	G
	240.0	787.3	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	241.0	790.8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	F+	G
	242.2	794.7	.	.	.	.	.	.	.	X	.	X	.	X	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	244.3	801.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	245.0	803.8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	246.0	807.0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	247.6	812.4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	A	G
	251.5	825.2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	253.3	831.2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	254.0	833.2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	C	G
	255.3	837.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	258.0	846.4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	258.8	849.0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	260.0	853.0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	262.0	859.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	M
	263.0	863.0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
	266.2	873.2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	G
Crater unit B	278.4	913.4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	281.3	923.1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	298.5	979.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	F	M
	313.7	1,029.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	324.1	1,063.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	360.2	1,181.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	366.6	1,202.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	376.9	1,236.7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	406.1	1,332.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	410.7	1,347.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
	442.4	1,451.5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		

[a]Abundance: A, abundant (≥10 specimens per field of view); C, common (1–9 specimens per field of view); F, frequent (1 specimen per 1–10 fields of view).
[b]Preservation: G, good; M, moderate.

Figure D7. Continued.

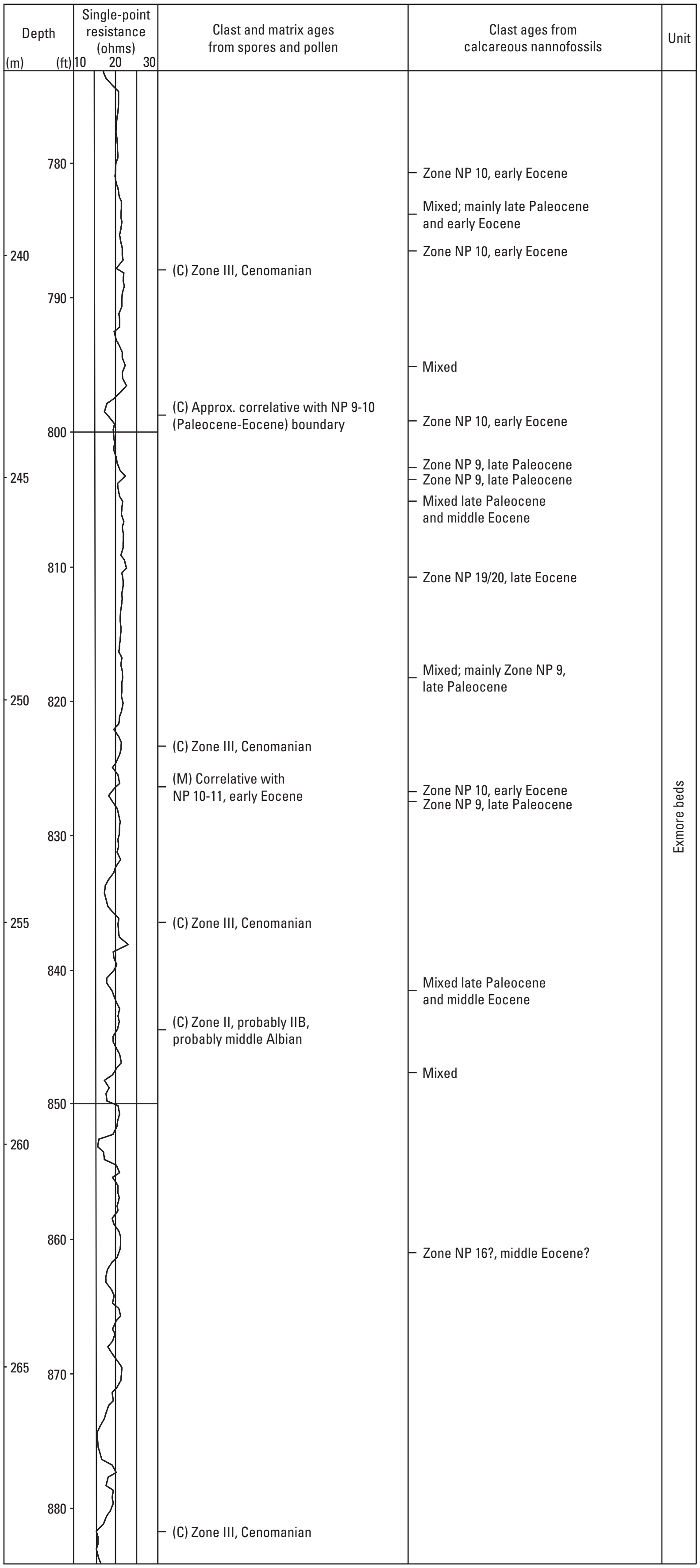

Figure D8. Single-point resistance log of the Exmore beds in the USGS-NASA Langley core, with a summary of spore-pollen ages of clast (C) and matrix (M) samples and calcareous nannofossil ages of clast samples.

assemblage might well include material of mixed ages. One of the clasts examined for pollen and spores from the Exmore beds is from near the Paleocene-Eocene boundary. The remaining five clast samples are from the Potomac Formation; one is probably from the middle Albian and four are from the lower Cenomanian. There is no evidence of any particular stratigraphic ordering of these clasts by age.

Dinocysts

Five samples from the matrix material of the Exmore beds were studied for dinoflagellate cysts (table D2; fig. D5). The four lower samples, from 257.6 to 236.1 m (845.3 to 774.6 ft), are from muddy, calcareous, quartz-glauconite sand. The uppermost sample is near the top of the Exmore and consists of massive, sandy, clayey, calcareous quartz silt. The sample from 278.4 m (913.4 ft) in the upper part of crater unit B is included in the discussion below.

Two aspects of the dinocyst assemblages need emphasis: (1) the fossils that are found represent a suite of ages, some known from typical Virginia Coastal Plain assemblages and some not previously reported from Virginia, and (2) the preservation is unusual.

Forty-six species, genera, and genera groups were identified in the matrix samples from the upper part of crater unit B and the Exmore beds (fig. D5). Most of these forms have been found in more than one of the coastal plain units that are the sources for the matrix. Biostratigraphically important forms include *Batiacasphaera baculata* (pl. D1, fig. 2), *Carpatella cornuta* (pl. D1, fig. 19), *Cordosphaeridium funiculatum* (pl. D1, fig. 1), *Dracodinium varielongitudum* (pl. D1, fig. 10; pl. D2, figs. 4–6; pl. D3, figs. 2, 10, 11), *Eocladopyxis* n. sp. A of Edwards (2001) (pl. D1, fig. 12), *Homotryblium tasmaniense* (pl. D1, fig. 11), *Pentadinium goniferum*, and *Pentadinium membranaceum* (pl. D1, figs. 5, 6; pl. D2, fig. 13).

A single, poorly preserved specimen (*Andalusiella* sp., pl. D1, fig. 20) is the only dinocyst evidence thus far of a contribution by Cretaceous units. This specimen was noted in the uppermost matrix sample from the Exmore beds (R6110 DC). Another Cretaceous specimen (*Chatangiella* sp.) was found in the overlying Chickahominy Formation of the Langley core (Edwards and others, this volume, chap. H).

Carpatella cornuta is restricted to the early Paleocene and hence has its source in the Brightseat Formation (table D1). Although no forms specifically restricted to the Aquia Formation were identified, many of the forms encountered are common in the Aquia. *Apectodinium parvum* (pl. D1, figs. 17, 18), which has previously been recorded from the Marlboro Clay (Edwards, 1996), is present in sample R6110 DH. *Dracodinium varielongitudum* and *Homotryblium tasmaniense* are early Eocene species and are common in the Nanjemoy Formation (Edwards, 1996). *Pentadinium goniferum* has a range restricted to the late part of the middle Eocene and is common in the Piney Point Formation (Edwards, 1989). *Batiacasphaera baculata* and *Cordosphaeridium funiculatum* are common in upper Eocene deposits. In summary, many of the dinocysts in the matrix material of the Exmore beds consist of late Eocene taxa that are indistinguishable from those of the Chickahominy Formation; both units have major contributions of dinocysts from the Nanjemoy Formation (lower Eocene) and Piney Point Formation (middle Eocene).

Eocladopyxis n. sp. A of Edwards (2001) has previously been reported only in Alabama and Georgia, in sediments representing the lower part of the middle Eocene (Edwards, 2001). These sediments would be younger than the Nanjemoy Formation and older than the Piney Point. A unit of this intermediate age may once have been present in the Virginia Coastal Plain but has since been eroded away or has not yet been recovered in the subsurface of the coastal plain.

Similarly, *Pentadinium membranaceum* has been reported from the uppermost middle Eocene and lowermost upper Eocene deposits in the Gulf of Mexico Coast (Edwards, 1982). The presence of this species appears to indicate the former existence of a unit younger than the Piney Point Formation but older than the Chickahominy because *P. membranaceum* has not been found in the Chickahominy. Sediments of latest middle Eocene/earliest late Eocene age contributed heavily to the tsunami washback matrix, especially near the top of the Exmore beds, as indicated by the relative abundance of *P. membranaceum* in those strata.

Phthanoperidinium brooksii (pl. D1, fig. 15) has previously been reported from offshore (Edwards and Bebout, 1981). Its presence in the Exmore beds may indicate a contribution from offshore sediments.

It is difficult to describe the dinoflagellates recovered from the Exmore matrix because the overall preservation of palynomorphs is poor. One can recognize material of dinoflagellate origin but sometimes cannot identify it to species or even to genus or family level. Fragments are much more common than whole or nearly whole specimens (table D2). Whole specimens may be folded, corroded, “curled up,” “smoothed,” or well preserved (Edwards and Powars, 2003). On further examination, many seemingly well preserved specimens are seen to be broken. Breakage is commonly sharp and crosses both tabulation and wall layers (pl. D2, figs. 10, 11).

In all samples, much of the organic material occurs in clumps (pl. D2, figs. 2, 3), and the clumps are distinctive in having many degrees of preservation, including opaque debris, misshapen fragments of miscellaneous plant debris, misshapen fragments of dinoflagellates, and whole, well-preserved dinoflagellate specimens. In the present study, clump size is determined by the sieve sizes used in the preparation of the slides (20–200 μm).

Many specimens have surfaces that are pitted, cratered (features that appear like broken blisters; pl. D3, figs. 4–7), or pockmarked (having distinctive radial features that have been related by previous authors (for example, Elsik, 1966, but see also Edwards and Powars, 2003) to fungal degradation; pl. D3, fig. 10). Species known to have originally smooth surfaces have been heavily corroded (pl. D2, fig. 7). Individual processes (especially in the *Wetzeliella* group) may be broken off or may be intact but severely pitted or pocked (pl. D3, fig. 2).

Clumped specimens are often seen in unusual orientations. Clumps appear to consist of material that is welded together, although individual pieces sometimes can be teased apart with heat and a paper clip. With less heat, the individual pieces can be moved around slightly in the glycerin jelly mounting medium, but they remain loosely attached at points of contact. Under the scanning electron microscope, points of fusion can be seen (pl. D2, fig. 4). Whole or nearly whole specimens are likely to be either small, as in the *Microdinium* group (pl. D1, figs. 3, 4) and small peridiniacean group (pl. D1, fig. 14), or large and robust, such as *Deflandrea phosphoritica* (pl. D2, fig. 14) and *Dracodinium varielongitudum* (pl. D1, fig. 10).

Fragments are commonly barely recognizable as having dinoflagellate affinity. Most miscellaneous chorate fragments are of the *Glaphyrocysta* group, but a few are of the *Cordosphaeridium* group. These fragments seldom absorb the stain. Delicate meshwork is preserved in many specimens, even where processes are jaggedly broken. Processes may appear shortened (pl. D3, fig. 14).

Fragments belonging to the various species of *Pentadinium*, especially the grano-vermiculate (g/v) ones—*P. goniferum*, *P. laticinctum* (g/v forms), and *P. membranaceum* (pl. D2, figs. 9, 13)—are easy to recognize. Surface texture of these is commonly moderately to slightly subdued (pl. D2, figs. 10–12). Some have almost lost the sculpture, except in the areas that were once below the pericoel. In optical section, the sculpture appears to have been melted or fused. Specimens may be folded (pl. D2, fig. 13; pl. D3, figs. 4–7) but not compressed.

A summary of the counts made is given in table D3 and shown graphically in figures D9 and D10. The percentage of whole or nearly whole specimens (table D3; fig. D10) hovers around 15–25 percent with the notable exception of the highest sand sample (R6110 DD, second sample from the top in figure D10), in which whole specimens are 6.3 percent. The percentage of specimens not identifiable to group (the worst preservation; table D3; fig. D10) is lowest in the lowest sample and increases upward. This concentration of poorly preserved dinocysts may represent specimens from seawater that was subject to the most violent forces of impact, ejection, resurge, or tsunamis. The highest sample studied here, the uppermost Exmore silt (R6110 DC), has fewer unidentifiable specimens (better preservation) than the sand samples below it. This is the same silt that has been described as a fallout layer containing pyrite lattices (Poag, 2002; Poag and Norris, this volume, chap. F).

The matrix sample from the upper part of crater unit B and those from the lower part of the Exmore beds show higher diversity in terms of more recognizable species (fig. D5) than are in the upper part of the Exmore beds. Samples near the top of the Exmore are dominated by species of *Pentadinium* as well as *Dracodinium* and other *Wetzeliella* group forms (Eocene forms; fig. D9). These are the most robust and easy to recognize forms. Stratigraphically lower samples have more small peridiniaceans; these forms, while most are not age diagnostic, are more common in Aquia Formation (Paleocene) sediments than in other units in the coastal plain.

Sample R6110 DE (the third sample from the top in figure D9) merits mention because of its high concentration of *Deflandrea phosphoritica*. In this sample, *D. phosphoritica* makes up 24.6 percent of the specimens counted (fig. D9; table D3), which were mainly poorly preserved. This dinocyst assemblage shows that the slurry of sediments that formed exotic matrix in the upper part of crater unit B and the Exmore beds was heterogeneous. The mixture apparently resulted from differences among sediments originating as ejecta, subaqueous resurge, or tsunami washback and from differences in source beds, variable fluidization, and localized sorting of the sediments. In sample R6110 DE, preservation of the fossils may be important because *D. phosphoritica* is a rather robust species. One preservational effect that does not appear in the counts is that fewer distinct clumps of dinocysts were observed in the stratigraphically lower samples, and these clumps are smaller (pl. D2, figs. 2, 3) than clumps in the higher samples.

Calcareous Nannofossils

Samples of Matrix

Overall, preservation of calcareous nannofossils in the matrix of the Exmore beds in the Langley core is moderate to good. Unlike the dinocysts, the calcareous nannofossils do not exhibit extensive pitting or fracturing. Individual nannofossils are typically whole or have only minor fractures consistent with normal dissolution or diagenesis.

The only exception to this rule is the preservational state of rosette forms of the genus *Discoaster*. Rosette forms such as *D. multiradiatus, D. salisburgensis, D. lenticularis,* and *D. saipanensis* (pl. D4, figs. 2, 16, 17; pl. D5, fig. 12) are normally round and have between 17 and 30 rays (Wei, 1992). Overgrowth causes thickening of the rays, and dissolution causes shortening of the rays, but normally the specimens retain their round shape. However, specimens in the Exmore beds from the Langley core show distinct fracture patterns not common in rosette discoasters; the patterns result in specimens that are square or pentagonal (Self-Trail, 2003). This phenomenon was illustrated by Poag and Aubry (1995, their fig. 13) in a specimen from the Exmore beds in the Exmore core (fig. D1) that has the same distinct pentagonal appearance, although these authors did not connect the fracturing with the impact. Bybell and Self-Trail (1994) did not document this phenomenon in samples from the New Jersey Coastal Plain.

Commonly, the species present in the Exmore matrix are robust forms like *Dictyococcites bisectus*, *Isthmolithus recurvus*, and *Reticulofenestra umbilica* (pl. D5, figs. 2, 5, 7, 10, 11). These forms dominate the assemblage and commonly exhibit calcite overgrowth, although not enough to impede species identification. Forms prone to dissolution, such as *Sphenolithus* and *Fasciculithus*, are uncommon in the Exmore beds.

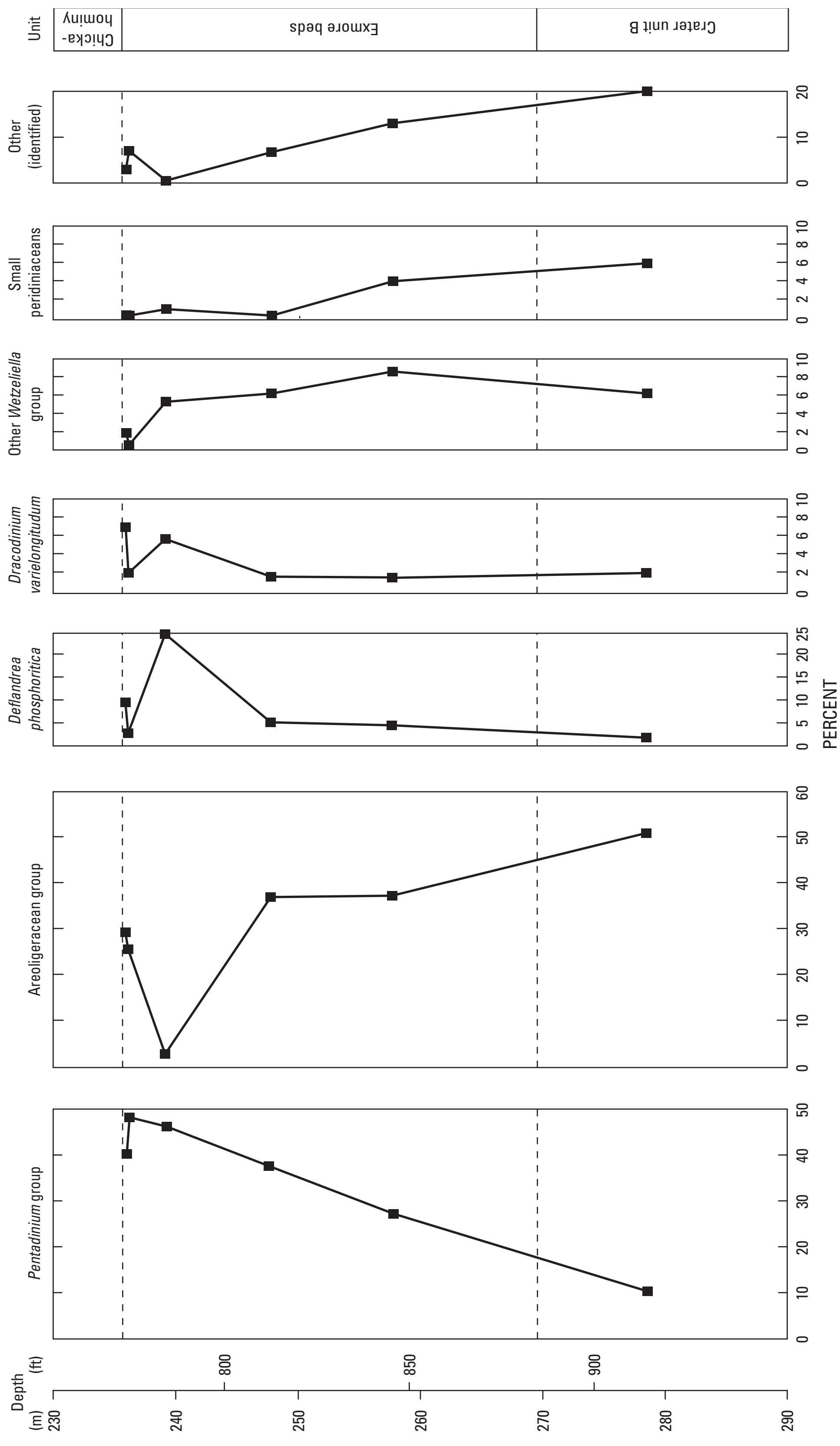

Figure D9. Graphical representation of percentages of the main dinocyst taxa in samples from crater unit B and the Exmore beds in the USGS-NASA Langley core.

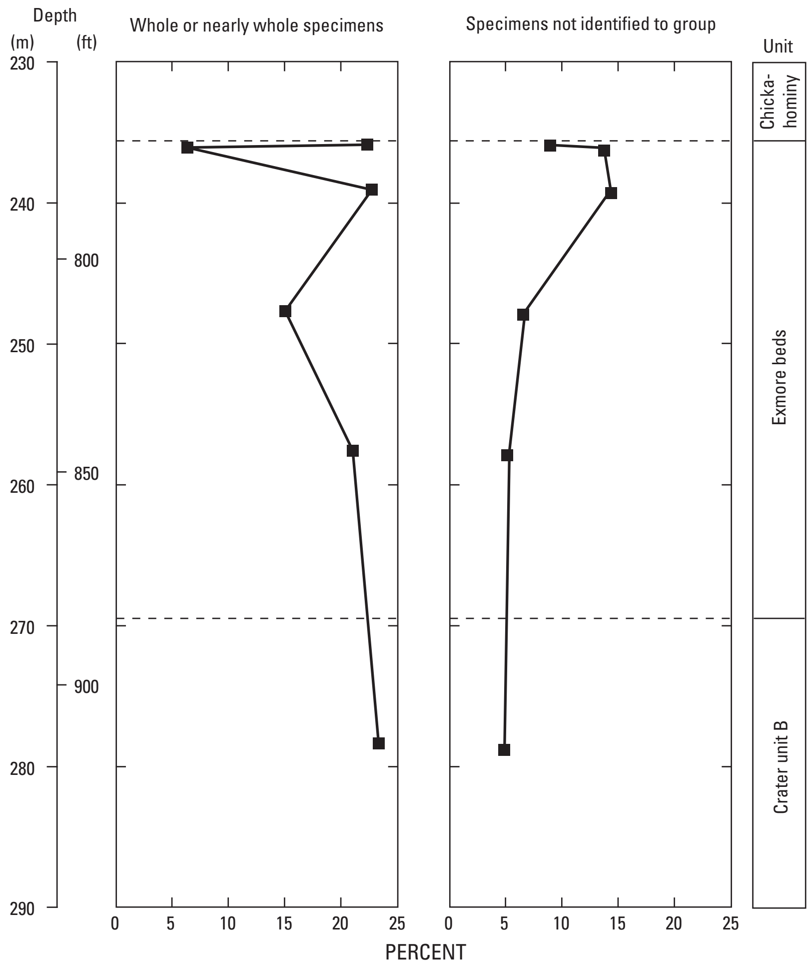

Figure D10. Graphical representation of percentages of whole dinocyst specimens and specimens not identified to group level in samples from crater unit B and the Exmore beds in the USGS-NASA Langley core. "Specimens not identified to group" includes both whole specimens and fragments.

In this study, 165 Tertiary and 32 Late Cretaceous species and genera were identified in the 30 productive matrix samples from crater unit B and the Exmore beds (fig. D7). Biostratigraphically important Tertiary forms include *Cruciplacolithus asymmetricus*, *Prinsius dimorphosus*, *Neobiscutum parvulum*, *Fasciculithus billii*, *Heliolithus riedelii*, *Heliolithus cantabriae*, *Rhomboaster contortus*, *Rhomboaster orthostylus*, *Rhomboaster bramlettei*, *Pemma basquense*, *Pemma serratum*, *Chiasmolithus gigas*, and *Isthmolithus recurvus* (pl. D5, figs. 1, 2, 3, 7). These species are present in situ in the Brightseat, Aquia, Nanjemoy, and Piney Point Formations, the Marlboro Clay, and several unnamed units in the Virginia Coastal Plain.

Cruciplacolithus asymmetricus, P. dimorphosus, and *N. parvulum* are restricted to lower Paleocene sediments and thus represent the Brightseat Formation. *Fasciculithus billii*, *Heliolithus cantabriae*, and *H. riedelii* are common in the upper Paleocene Aquia Formation.

Although no forms specifically restricted to the upper Paleocene-lower Eocene Marlboro Clay were identified, many of the species found span the Paleocene-Eocene boundary. Clasts lithologically similar to the Marlboro Clay are common in the matrix material; therefore, it seems likely that fossils from this formation are included in the Exmore beds.

Lower Eocene sediments are also represented by the Nanjemoy Formation. The calcareous nannofossil species *Rhomboaster contortus* and *R. orthostylus* are restricted to the Nanjemoy Formation, and *Rhomboaster bramlettei* is a common constituent of the Nanjemoy assemblages. The middle Eocene Piney Point Formation is represented by common occurrences of *P. basquense* (pl. D5, fig. 1) and *P. serratum* and by rare occurrences of *C. gigas*.

The Exmore beds are no older than Zone NP 19/20 because they contain *Isthmolithus recurvus* (pl. D5, figs. 2, 7), a nannofossil whose first appearance defines the base of this zone. The overlying Chickahominy Formation belongs to Zone NP 19/20 as indicated by the joint occurrences of *I. recurvus* and *Discoaster saipanensis*; the last appearance of the latter species defines the top of Zone NP 19/20. Therefore, the Exmore beds must also belong to Zone NP 19/20, and the impact must have occurred during the early part of the time represented by this zone or approximately at 35.7–35.8 Ma (million years ago). Some of the material composing the Exmore beds was derived from a preimpact formation belonging to Zone NP 19/20 that apparently was once present in the Virginia Coastal Plain but has since been eroded away or has remained undetected in the subsurface. There is no recorded in situ Zone NP 19/20 material from nearby outcrops or other coreholes that is *not* Chickahominy Formation.

Biostratigraphically important Late Cretaceous forms include *Eiffellithus eximius, Eprolithus floralis*, *Reinhardtites anthophorus*, *Stovarius asymmetricus*, *Flabellites oblonga*, and *Lithastrinus grillii.* These species indicate that sediments of Santonian and Campanian age compose part of the Exmore beds in the Langley core. Age-equivalent sediments from North and South Carolina include the Pleasant Creek Formation (Santonian), the Shepherd Grove Formation (Santonian), the Bladen Formation (Campanian), and the Donoho Creek Formation (Campanian) (Gohn, 1992; Self-Trail and others, 2004). Calcareous nannofossils restricted to the Maastrichtian were not identified from the Exmore beds, and therefore it cannot be stated with any certainty that sediment of late Maastrichtian age (such as the Severn Formation of Maryland) contributed to the matrix material. Sediments of Late Cretaceous age are described from the Dismal Swamp, Fentress, and MW4–1 cores (fig. D1; Powars and others, 1992; Powars and Bruce, 1999; Powars, 2000) to the south of the impact crater, and these strata are most likely the sediment source for the Cretaceous calcareous nannofossil assemblages found in the Exmore beds.

Samples of Clasts

Twenty-six clasts were examined for calcareous nannofossil content from the Exmore beds in the Langley core (table D6; fig. D11). These came from a variety of formations, and the dated clasts are from late Paleocene to late Eocene in age (fig. D8). Nine of the clasts are barren and most likely of Potomac Formation lithology. Six clasts have nannofossil assemblages of more than one age and it was therefore impossible to identify the formation of origin.

Two clasts from the Aquia Formation are identified on the basis of lithology and the calcareous nannofossil assemblage. These clasts contain both *Discoaster multiradiatus* (pl. D4, figs. 2, 16) and *Transversopontis pulcher* but do not contain *Rhomboaster bramlettei* or *Rhomboaster orthostylus*. It is interesting to note that both Aquia clasts are from Zone NP 9, even though the Aquia Formation includes Zones NP 5–9. One clay clast dated as late Paleocene (Zone NP 9) is thought to be from the Marlboro Clay because of its lack of glauconite and high percentage of clay.

Clayey clasts containing a calcareous nannofossil assemblage indicative of the lower Eocene Nanjemoy Formation (Zone NP 10) are the most common (table D6). Gibson and Bybell (1994) documented the age of the Nanjemoy Formation as early Eocene (NP 10 through NP 13). However, clasts of Nanjemoy sediments recovered in the Langley core contain *Rhomboaster bramlettei* (pl. D4, fig. 15) and *Discoaster multiradiatus* (pl. D4, figs. 2, 16) but lack younger indicators such as *Rhomboaster orthostylus*, *Rhomboaster contortus*, and *Discoaster lodoensis*, suggesting a Zone NP 10 assignment for these clasts.

Only one clast of possible middle Eocene age (NP 16) is identified from the Langley core. This possible age is based on the co-occurrence of *Chiasmolithus solitus* (LAD at top of NP 16) and *Cribrocentrum reticulatum* (FAD in middle NP 16). However, because of poor preservation and low diversity of calcareous nannofossil species in this clast, the possibility of a mixed assemblage should not be discounted.

One clast of late Eocene age was identified from the Langley core. This clast contained *Isthmolithus recurvus* (FAD at 36 Ma) along with *Chiasmolithus oamaruensis* (FAD at 37.0 Ma) and *Cribrocentrum reticulatum* (LAD at 35 Ma). The co-occurrence of these three species places this clast within the lowermost part of Zone NP 19/20. This clast is important because it provides strong evidence for the existence of an upper Eocene, preimpact formation in the subsurface of southeastern Virginia that is heretofore unidentified from either outcrop or corehole. Additionally, the co-occurrence of *I. recurvus* and *C. reticulatum* in this sample independently restricts the time of impact to between 36 and 35 Ma.

Preservation and diversity of nannofossils in clasts within the Exmore beds vary considerably from poor to good without any apparent relation to sediment type. For example, clasts of what appear to be sediments from the Aquia or Nanjemoy Formations have nannofossil assemblages that are moderately to well preserved. Species richness is greatest in Aquia and Nanjemoy clasts and decreases in Marlboro and middle Eocene clasts. Most clasts are noncalcareous, are barren of calcareous nannofossils, and represent either a noncalcareous Marlboro Clay lithology or Cretaceous Potomac Formation clasts.

Ostracodes

Two samples from the Exmore beds in the Langley core were examined for ostracodes (not shown in fig. D3). The matrix sample from 240.8–240.9 m (790.1–790.3 ft) contains *Digmocythere russelli* (Howe and Lea 1936). This species (late Eocene and perhaps early Oligocene) is typical of the Chickahominy Formation; because the Chickahominy itself was deposited after the impact, the presence of *D. russelli* supports dinocyst and nannofossil evidence that upper Eocene pre-Chickahominy deposits existed in the region prior to the impact and perhaps still exist there.

Ostracodes from the matrix sample from 235.9 m (773.9–774.0 ft) included bairdiids, *Clithrocytheridea* sp., *Loxoconcha* sp., and *Trachyleberis* cf. *pauca* (Schmidt 1948). This is an anomalous assemblage in terms of genus-level ecology and, therefore, the ostracodes represent a mixed assemblage.

Table D6. Lithologic descriptions and diagnostic calcareous nannofossil species for each calcareous clast examined from the Exmore beds of the USGS-NASA Langley core.

[m, meters; cm, centimeter; in., inch. Some color terms are used from Goddard and others (1948)]

Depth (m)	Lithologic description	Age	Diagnostic calcareous nannofossil species (fig. D11)
238.0	Silt, clayey, micaceous, medium-gray; strong acid fizz.	Early Eocene	*Rhomboaster bramlettei* present; *R. orthostylus* absent.
238.9	Glauconite sand, medium to coarse, muddy, with matrix dike that is 3.04 cm (1.2 in.) long and 0.304 cm (0.12 in.) wide; sharp clast boundaries, full core width.	Mixed	*Discoaster multiradiatus* present with *Coronocyclus nitescens.*
239.7	Silt, clayey, micaceous, medium-gray; strong acid fizz.	Early Eocene	*Rhomboaster bramlettei* present; *R. orthostylus* absent.
242.5	Silt, clayey; clast small.	Mixed	*Toweius occultatus, Cribrocentrum reticulatum,* and *Isthmolithus recurvus* all present.
243.7	Silt, very clayey, calcareous, slightly micaceous, knobby exterior, possible microfossils; full core width; moderate acid fizz.	Early Eocene	*Rhomboaster bramlettei* present; *R. orthostylus* absent.
244.6	Clay, silty, calcareous; clast small.	Late Paleocene	*Discoaster multiradiatus, Prinsius bisulcus,* and *Transversopontis pulcher* present; *Rhomboaster bramlettei* and *R. orthostylus* absent.
245.1	Clay, silty, calcareous; clast small.	Late Paleocene	*Discoaster multiradiatus, Prinsius bisulcus,* and *Transversopontis pulcher* present; *Rhomboaster bramlettei* and *R. orthostylus* absent.
245.6	Clay, silty, dry, dark-greenish-gray (5*GY* 4/1); clast large.	Mixed	*Discoaster multiradiatus, Cribrocentrum reticulatum,* and *Reticulofenestra umbilica* all present.
247.1	Clay, silty, dark-brown; large clast.	Late Eocene	*Isthmolithus recurvus* and *Cribrocentrum reticulatum* present.
249.4	Clay, silty, waxy, dark-yellowish-brown (10*YR* 4/2); contorted.	Mixed	*Transversopontis pulcher, Cribrocentrum reticulatum,* and *Reticulofenestra umbilica* all present.
252.0	Clay, silty, micaceous, calcareous, dark-greenish-gray (5*GY* 4/1); whole core width.	Early Eocene	*Rhomboaster bramlettei* present; *R. orthostylus* absent.
252.2	Clay, silty, micaceous, calcareous, dark-greenish-gray (5*GY* 4/1); whole core width.	Late Paleocene	*Discoaster multiradiatus, Prinsius bisulcus*, and *Transversopontis pulcher* present; *Rhomboaster bramlettei* and *R. orthostylus* absent.
256.5	Sand, very fine to medium, glauconite quartz, calcite-cemented, "salt-and-pepper," light-olive-gray (5*Y* 6/1); whole core width.	Mixed	*Discoaster multiradiatus, Cribrocentrum reticulatum,* and *Pemma stradneri* all present.
258.4	Clay, silty and sandy (5 percent very fine); exterior oxidizes quickly to brown; knobby exterior; interior is greenish black (5*GY* 2/1)**;** full core width.	Mixed	*Discoaster multiradiatus, Cribrocentrum reticulatum,* and *Dictyococcites scrippsae* all present.
262.4	Clay, silty, finely micaceous, dark-greenish-gray (5*GY* 4/1); whole core width.	Middle Eocene	*Cribrocentrum reticulatum* and *Chiasmolithus solitus* both present.

Sample	N10279	N10278	N10277	N10276	N10275	N10274	N10273	N10272	N10271	N10270	N10269	N10268	N10267	N10159
Depth (m)	266.0	265.8	265.2	262.4	261.7	261.2	260.7	259.7	258.4	257.0	256.5	255.8	254.8	252.2
Depth (ft)	872.8	872.0	870.1	861.0	858.5	857.0	855.4	852.0	847.7	843.1	841.5	839.4	835.9	827.4
Nannofossil preservation	Poor	Poor		Poor					Moderate		Moderate			Moderate
Nannofossil abundance	Rare	Rare	Barren	Frequent/Rare	Barren	Barren	Barren	Barren	Frequent	Barren	Frequent	Barren	Barren	Common
Age/zone from which the specimens were derived	Unknown	Unknown		Middle Eocene? (NP 16?)					Mixed		Mixed			Late Paleocene (NP 9)
Possible formation from which the specimens were derived	?	?	?	Unnamed	?	?	?	?	?	?	?	?	?	Marlboro Clay
Tertiary taxa														
Biscutum constans	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Braarudosphaera bigelowii	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Braarudosphaera spp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Camplyosphaera dela	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Chiasmolithus bidens	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Chiasmolithus consuetus	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Chiasmolithus oamaruensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Chiasmolithus solitus	.	.	.	X	.	.	.	.	.	.	.	.	.	.
Coccolithus pelagicus	.	.	.	.	.	.	.	.	X	.	X	.	.	X
Coronocyclus nitescens	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Coronocyclus spp.	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Cribrocentrum reticulatum	.	.	.	X	.	.	.	.	X	.	X	.	.	.
Cruciplacolithus primus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cyclagelosphaera reinhardtii	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Dictyococcites bisectus	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Dictyococcites callidus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Dictyococcites daviesii	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Dictyococcites scrippsae	.	.	.	.	.	.	.	.	X	.	.	.	.	.
Discoaster anartios	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Discoaster araneus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Discoaster falcatus	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Discoaster kuepperi	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Discoaster lenticularis	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Discoaster mediosus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Discoaster megastypus	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Discoaster mohleri	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Discoaster multiradiatus	.	.	.	.	.	.	.	.	X	.	X	.	.	X
Discoaster saipanensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ellipsolithus distichus	.	.	.	.	.	.	.	.	.	.	X	.	.	X
Ellipsolithus macellus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ellipsolithus spp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ericsonia cava	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ericsonia aff. *E. fenestra*	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ericsonia formosa	.	.	.	.	.	.	.	.	.	.	X	.	.	X
Ericsonia robusta	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Ericsonia subpertusa	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Fasciculithus aubertae	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Fasciculithus involutus	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Fasciculithus sidereus	.	.	.	.	.	.	.	.	.	.	X	.	.	X
Fasciculithus thomasii	.	.	.	.	.	.	.	.	.	.	X	.	.	X
Fasciculithus tympaniformis	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Fasciculithus spp.	.	.	.	.	.	.	.	.	X	.	.	.	.	.

Figure D11. Occurrence chart showing the presence of the calcareous nannofossil taxa, age(s), and probable formations of origin for each calcareous clast sample from the Exmore beds of the USGS-NASA Langley core. Symbols: X, present, ., not present. Abundance terms are defined as follows: rare, 1 specimen per 11–50 fields of view; frequent, 1 specimen per 1–10 fields of view; common, 1–9 specimens per field of view; abundant, 10 or more specimens per field of view.

N10158	N10266	N10265	N10264	N10263	N10157	N10262	N10155	N10261	N10154	N10152	N10151
252.0	251.1	249.4	247.1	245.6	245.1	244.6	243.7	242.5	239.7	238.9	238.0
826.7	823.9	818.2	810.7	805.9	804.0	802.6	799.7	795.5	786.5	783.7	780.7
Good		Moderate	Good	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Good	Poor
Abundant	Barren	Frequent	Common	Frequent	Common	Common	Common	Frequent	Common	Abundant	Frequent
Early Eocene (NP 10)		Mixed	Late Eocene (NP 19/20)	Mixed	Late Paleocene (NP 9)	Late Paleocene (NP 9)	Early Eocene (NP 10)	Mixed	Early Eocene (NP 10)	Mixed	Early Eocene (NP 10)
Nanjemoy Formation	?	?	Unnamed	?	Aquia Formation	Aquia Formation	Nanjemoy Formation	?	Nanjemoy Formation	?	Nanjemoy Formation
.	.	.	.	.	.	X	X	.	.	X	.
.	.	.	.	.	.	.	.	X	.	.	.
X	.	.	.	.	.	.	.	.	.	.	.
X	.	.	.	.	X	X	X	.	X	X	.
.	.	X	.	X	X	X	X	X	X	X	.
X	.	.	.	.	X	X	.	.	.	X	.
.	.	.	X	.	.	.	.	.	.	.	.
.	.	.	.	X	.	.	.	.	.	.	.
X	.	X	X	X	X	X	X	X	X	X	X
.	.	.	X	.	.	X	.	.	.	X	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	X	X	X	.	.	.	X	.	.	.
.	.	.	.	.	X	X	.	X	.	X	.
.	.	.	.	.	X	.	.	.	.	.	.
.	.	X	X	X	.	.	.	.	.	.	.
.	.	X	X	.	.	.	.	X	.	.	.
.	.	.	.	.	.	.	.	X	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
X	.	.	.	.	.	.	.	.	.	.	.
X	.	.	.	.	X	.	.	.	X	.	.
.	.	.	.	X	.	.	.	.	.	.	.
X	.	.	.	.	X	X	X	.	X	.	.
X	.	.	.	.	.	.	.	.	X	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	X	.	.	.	X	.
X	.	.	.	X	X	X	X	.	X	X	X
.	.	.	.	X	.	.	.	.	.	.	.
X	.	.	.	.	X	X	X	.	X	X	.
.	.	.	.	X	.	.	X	.	.	X	.
.	.	.	.	.	.	.	.	.	.	X	.
.	.	.	.	.	.	X	X	.	.	.	.
.	.	.	.	X	.	.	.	.	.	.	.
.	.	.	X	.	.	.	.	X	.	.	.
.	.	.	.	.	.	.	.	.	.	X	.
.	.	.	.	.	X	.	X	.	X	.	.
X	.	.	.	.	.	.	.	.	.	.	.
X	.	.	.	.	.	X	X	.	X	.	X
.	.	.	.	.	.	.	.	.	.	.	X
X	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	X	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	X	.

Figure D11. Continued.

Sample	N10279	N10278	N10277	N10276	N10275	N10274	N10273	N10272	N10271	N10270	N10269	N10268	N10267	N10159
Depth (m)	266.0	265.8	265.2	262.4	261.7	261.2	260.7	259.7	258.4	257.0	256.5	255.8	254.8	252.2
Depth (ft)	872.8	872.0	870.1	861.0	858.5	857.0	855.4	852.0	847.7	843.1	841.5	839.4	835.9	827.4
Nannofossil preservation	Poor	Poor		Poor					Moderate		Moderate			Moderate
Nannofossil abundance	Rare	Rare	Barren	Frequent/Rare	Barren	Barren	Barren	Barren	Frequent	Barren	Frequent	Barren	Barren	Common
Age/zone from which the specimens were derived	Unknown	Unknown		Middle Eocene? (NP 16?)					Mixed		Mixed			Late Paleocene (NP 9)
Possible formation from which the specimens were derived	?	?	?	Unnamed	?	?	?	?	?	?	?	?	?	Marlboro Clay
Helicosphaera seminulum	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Hornibrookina arca	.	.	.	.	.	.	.	.	X	.	X	.	.	X
Isthmolithus recurvus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Lophodolithus nascens	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Markalius inversus	.	.	.	.	.	.	.	.	.	.	X	.	.	X
Neochiastozygus concinnus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Neochiastozygus junctus	.	.	.	.	.	.	.	.	X	.	X	.	.	X
Neococcolithes dubius	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Neococcolithes minutus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Neococcolithes protenus	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Neocrepidolithus biskayae	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Neocrepidolithus bukryi	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Pemma stradneri	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Pontosphaera multipora	.	.	.	X	.	.	.	.	.	.	X	.	.	.
Pontosphaera spp.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Prinsius bisulcus	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Pseudotriquetrorhabdulus inversus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Reticulofenestra daviesii	.	.	.	.	.	.	.	.	X	.	.	.	.	.
Reticulofenestra dictyoda	.	.	.	X	.	.	.	.	X	.	X	.	.	.
Reticulofenestra umbilica	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Rhomboaster bramlettei	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Rhomboaster calcitrapa	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Rhomboaster digitalis	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Scapholithus apertus	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Sphenolithus anarrhopus	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Sphenolithus moriformis	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Sphenolithus primus	.	.	.	.	.	.	.	.	X	.	X	.	.	X
Thoracosphaera spp.	.	.	.	.	.	.	.	.	.	.	.	.	.	X
Toweius callosus	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Toweius eminens var. *eminens*	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Toweius eminens var. *tovae*	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Toweius occultatus	.	.	.	.	.	.	.	.	.	.	X	.	.	X
Toweius pertusus	.	.	.	.	.	.	.	.	X	.	X	.	.	X
Toweius serotinus	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Transversopontis obliquipons	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Transversopontis pulcher	.	.	.	.	.	.	.	.	X	.	X	.	.	X
Transversopontis zigzag	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Zygodiscus herlynii	.	.	.	.	.	.	.	.	.	.	X	.	.	.
Zygrhablithus bijugatus	.	.	.	.	.	.	.	.	.	.	X	.	.	.
placoliths	X	X	.	.	.	.	.	.	.	.	.	.	.	.
Cretaceous taxon														
Microrhabdulus attenuatus	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Figure D11. Continued.

N10158	N10266	N10265	N10264	N10263	N10157	N10262	N10155	N10261	N10154	N10152	N10151
252.0	251.1	249.4	247.1	245.6	245.1	244.6	243.7	242.5	239.7	238.9	238.0
826.7	823.9	818.2	810.7	805.9	804.0	802.6	799.7	795.5	786.5	783.7	780.7
Good		Moderate	Good	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Good	Poor
Abundant	Barren	Frequent	Common	Frequent	Common	Common	Common	Frequent	Common	Abundant	Frequent
Early Eocene (NP 10)		Mixed	Late Eocene (NP 19/20)	Mixed	Late Paleocene (NP 9)	Late Paleocene (NP 9)	Early Eocene (NP 10)	Mixed	Early Eocene (NP 10)	Mixed	Early Eocene (NP 10)
Nanjemoy Formation	?	?	Unnamed	?	Aquia Formation	Aquia Formation	Nanjemoy Formation	?	Nanjemoy Formation	?	Nanjemoy Formation
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	X	X	.	X	.	.	.
.	.	.	X	.	.	.	.	X	.	.	.
.	.	.	.	.	X	.	.	.	.	X	.
X	.	.	.	.	.	.	X	.	X	X	X
X	.	.	.	.	.	X	X	.	.	.	.
.	.	X	.	X	X	X	X	X	X	X	X
.	.	.	.	.	.	X	.	.	.	.	.
.	.	.	.	X	.	.	.	X	.	X	.
X	.	.	.	.	X	X	X	.	X	.	.
.	.	.	.	X	.	.	.	.	.	.	.
.	.	.	.	.	X	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	X	X	X	.	.	.	.	.	.	.
.	.	.	.	.	X	.	.	.	.	X	.
.	.	.	.	.	X	X	.	.	.	X	.
.	.	.	X	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	X	X	X	.	.	.	X	.	.	.
.	.	X	X	X	.	.	.	X	.	.	.
X	.	.	.	.	.	.	X	.	X	.	X
.	.	.	.	.	.	.	X	.	.	.	.
.	.	.	.	.	.	.	.	.	.	X	.
.	.	.	.	.	.	.	.	X	.	.	.
.	.	.	.	.	X	.	.	.	.	X	.
.	.	.	.	X	.	.	.	.	.	.	.
.	.	.	.	.	X	X	X	X	X	X	X
.	.	.	.	.	X	.	.	.	.	.	.
.	.	X	.	.	X	X	.	.	.	X	.
.	.	.	.	.	.	X	X	.	.	.	.
.	.	X	.	.	.	X	X	.	X	.	X
.	.	.	.	.	X	X	X	X	X	.	.
X	.	X	.	X	X	X	X	X	X	X	X
X	.	.	.	.	.	X	.	X	X	.	X
.	.	.	X	.	.	.	.	.	.	.	.
X	.	X	.	X	X	X	X	X	X	X	.
.	.	.	.	.	.	.	.	X	.	.	.
X	.	X	.	.	X	X	.	.	X	X	.
.	.	.	.	X	X	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
	.										
.	.	.	.	.	.	.	X	.	.	.	.

Figure D11. Continued.

Discussion and Conclusions

Biostratigraphy of Crater Unit A

The only fossils obtained from the Potomac Formation in crater unit A in the Langley core were spores and pollen grains from a lignitic sample near the top of this unit. The pollen assemblage is from Subzone IIB to Zone III, middle Albian to early Cenomanian in age.

Biostratigraphy of Crater Unit B

Five clast samples from the Potomac Formation in crater unit B in the Langley core could be fairly well dated on the basis of spores and pollen grains. Most or all of the five samples contain at least some Aptian-Albian material, and three contain some Cenomanian material. Several of the samples contain mixed assemblages, indicating that slurry sediment may have penetrated the clasts following the impact.

Six matrix samples from crater unit B were examined for the presence of dinocysts. Only one, from near the top of this unit, appears to contain indigenous dinocysts, and these specimens represent a mixture of ages.

Only one matrix sample from crater unit B, from the upper part of that unit, contained calcareous nannofossils. The mixed assemblage in this sample consists of species having first occurrences (range bases) in various parts of the Paleocene and Eocene; however, no Cretaceous species were found.

Biostratigraphy of the Exmore Beds

The Exmore beds in the Langley core provided spores and pollen grains, dinocysts, calcareous nannofossils, and ostracodes, as well as foraminifers (Poag and Norris, this volume, chap. F). Matrix samples from this interval are generally of mixed ages, but, taken as a group, the matrix and clast samples include fossils of late Aptian to Albian, early Cenomanian, Santonian, Campanian, early Paleocene, late Paleocene, early Eocene, and late middle Eocene ages; that is, they include material derived from the Potomac Formation, the "unnamed Upper Cretaceous deposits" of Powars and Bruce (1999), the Brightseat and Aquia Formations, the Marlboro Clay, and the Nanjemoy and Piney Point Formations (table D1).

Among the dinocyst, nannofossil, and ostracode taxa in the uppermost part of crater unit B and the Exmore beds are several that are of early middle Eocene and of latest middle Eocene to earliest late Eocene ages; these ages indicate that, at the time of impact, strata existed that were younger than the Nanjemoy Formation but older than the Piney Point Formation, and younger than the Piney Point Formation but older than the Chickahominy Formation. Therefore, two stratigraphic units were present prior to the impact that are not now known to exist on the Virginia Coastal Plain. In particular, sediments younger than the Piney Point Formation but older than the Chickahominy Formation contributed heavily to the matrix of the Exmore beds. Therefore, these samples from the Langley core are very important because they provide a more detailed account than was previously available of the full array of Eocene formations in Virginia, especially those that previously existed near the surface but which now may exist only in the subsurface.

Some evidence exists for age stratification of dinocysts and calcareous nannofossils in the matrix of the upper part of crater unit B and the Exmore beds, but the evidence is somewhat contradictory. Dinocysts derived mainly from younger preimpact deposits are more common in the upper part of the Exmore beds, whereas specimens derived mainly from older Tertiary deposits are more common in the lower part of the Exmore and the uppermost part of crater unit B. Therefore, it appears that older sediments on the average were washed back into the crater before the younger sediments. Late Cretaceous nannofossils are present in the Exmore beds down to a depth of 242.1 m (794.4 ft), but they are more common near the top of the unit and decrease in abundance and diversity downsection (fig. D7); no Late Cretaceous nannofossils were found in the single nannofossil-bearing sample from crater unit B. This nannofossil distribution implies that Upper Cretaceous sediments are slightly finer grained (and therefore were slower to sink in the ocean) or perhaps came from a different source area than the Tertiary sediments.

Effects of the Comet or Asteroid Impact on the Preservation of Microfossils

Dinocysts

Dinoflagellate cysts are composed of a waxlike hydrocarbon called dinosporin. The effects of heat on palynomorphs (including dinoflagellate cysts) have been studied extensively by the petroleum industry. At temperatures between 65°C and 170°C, gas and oil are generated; above about 200°C, most organic material is carbonized (Batten, 1996, and references therein).

Dinocysts at the center of the impact would have been vaporized. Dinocysts in resurge and tsunami deposits must have been subjected to varying amounts of heat, pressure, and turbulence from the impact. Dinocysts may have been ejected into the atmosphere by the impact and settled back down over a short interval of time. One can speculate that the causes of fragmentation include both direct shock and pummeling of the dinocysts by large and small grains and clasts in the extremely turbulent synimpact depositional regime.

Foreshortened processes on some dinocyst specimens give the appearance of partial melting, not enough to destroy the shape, but sufficient to fuse fibrous areas and turn long, slender processes into shorter, squatty ones. The partial melting may have occurred in air or water or both. Folded specimens must have been heated in order to bend. Partial melting is also the most likely explanation for the muted texture of formerly intricately sculptured surfaces. Where this sculpture is preserved below a protective outer layer, one can speculate that the outer layer offered some protection. The wall structure of many dinocysts allows pockets called pericoels. The gas or water in these pericoels must have expanded to cause the bubbles observed (pl. D3, figs. 8, 9).

Some dinocysts and other debris must have been boiled or toasted, as their shape is barely recognizable, and bubbles and craters occur without any relation to wall structure (pl. D3, figs. 4–7). Processes on some specimens appear to have been "blown off" by the force of the impact, commonly leaving pits or scars. One of the more fascinating impact-induced features is the curling of processes around a central body (pl. D3, fig. 13). The bending of the processes suggests aerodynamic or hydrodynamic shaping.

Higher in the Exmore beds, organic material appears more fragmental, but possibly more heat welded into clumps, than it does lower in the Exmore. Local differences occur among individual matrix samples, suggesting differing contributions from the various sources of the matrix material.

For all the features of dinocyst preservation described here, the most likely explanations are direct effects of the comet or asteroid that struck at approximately 35.7–35.8 Ma. Most are the product of a complex interplay of heat, shock, and abrasion. Some of these features shown may prove to be unique to impact-generated sediments. Dinocyst preservation may thus become an important tool for recognizing impact-related deposits elsewhere.

Calcareous Nannofossils

Because of the high temperatures generated by the impact, all calcareous nannofossils at ground zero, like the dinocysts, would have been vaporized. However, calcareous nannofossils in resurge and tsunami deposits would have been subjected to extreme amounts of heat and varying amounts of pressure due to the impact events. Therefore, it is interesting to note that calcareous nannofossil plates in the samples examined show little or no damage due to heat or shock. Unlike many of the dinoflagellates, which were fragmented by shock and pummeling by larger clasts, the calcareous nannofossil assemblage shows only minor fragmentation consistent with normal diagenetic processes. Only one morphotype, rosette discoasters, shows fragmentation, not common in this group, that apparently is due to the impact event.

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Appendix D1. List of Late Cretaceous and Tertiary Calcareous Nannofossil Species Present in Matrix and Clast Samples from Crater Unit B and the Exmore Beds in the USGS-NASA Langley Core, Hampton, Va.

Ahmuellerina octoradiata (Gorka 1957) Reinhardt 1964
Arkhangelskiella cymbiformis Vekshina 1959

Biscutum constans (Gorka 1957) Black *in* Black and Barnes (1959)
Blackites spinosus (Deflandre & Fert 1954) Hay & Towe 1962
Blackites tenuis (Bramlette & Sullivan 1961) Sherwood 1974
Bomolithus conicus (Perch-Nielsen 1971) Perch-Nielsen 1984
Bomolithus elegans Roth 1973
Braarudosphaera bigelowii (Gran & Braarud 1935) Deflandre 1947
Broinsonia dentata Bukry 1969

Calculites obscurus (Deflandre 1959) Prins & Sissingh *in* Sissingh (1977)
Calculites ovalis (Stradner 1963) Prins & Sissingh *in* Sissingh (1977)
Camplyosphaera dela (Bramlette & Sullivan 1961) Hay & Mohler 1967
Chiasmolithus bidens (Bramlette & Sullivan 1961) Hay & Mohler 1967
Chiasmolithus consuetus (Bramlette & Sullivan 1961) Hay & Mohler 1967
Chiasmolithus danicus (Brotzen 1969) Hay & Mohler 1967
Chiasmolithus eograndis Perch-Nielsen 1971
Chiasmolithus expansus (Bramlette & Sullivan 1961) Gartner 1970
Chiasmolithus gigas (Bramlette & Sullivan 1961) Radomski 1968
Chiasmolithus modestus Perch-Nielsen 1971
Chiasmolithus oamaruensis (Deflandre *in* Deflandre and Fert, 1954) Hay, Mohler, & Wade 1966
Chiasmolithus solitus (Bramlette & Sullivan 1961) Locker 1968
Chiasmolithus titus Gartner 1970
Coccolithus pelagicus (Wallich 1877) Schiller 1930
Corollithion signum Stradner 1963
Coronocyclus nitescens (Kamptner 1963) Bramlette & Wilcoxon 1967
Coronocyclus prionion (Deflandre & Fert 1954) Stradner *in* Stradner and Edwards (1968)
Cretarhabdus conicus Bramlette & Martini 1964
Cribrocentrum reticulatum (Gartner & Smith 1967) Perch-Nielsen 1971
Cribrosphaerella ehrenbergii (Arkhangelsky 1912) Deflandre *in* Piveteau (1952)
Cruciplacolithus asymmetricus van Heck & Prins 1987
Cruciplacolithus edwardsii Romein 1979
Cruciplacolithus frequens (Perch-Nielsen 1977) Romein 1979
Cruciplacolithus inseadus Perch-Nielsen 1969
Cruciplacolithus primus Perch-Nielsen 1977
Cruciplacolithus tenuis (Stradner 1961) Hay & Mohler *in* Hay and others (1967)
Cruciplacolithus vanheckae Perch-Nielsen 1984
Cyclagelosphaera prima (Bukry 1969) Bybell & Self-Trail 1995
Cyclagelosphaera reinhardtii (Perch-Nielsen 1968) Romein 1977
Cyclicargolithus floridanus (Roth & Hay *in* Hay and others (1967)) Bukry 1971
Cyclicargolithus luminis (Sullivan 1965) Bukry 1971
Cylindralithus crassus Stover 1966

Daktylethra punctulata Gartner *in* Gartner and Bukry (1969)
Dictyococcites bisectus (Hay & others 1966) Bukry & Percival 1971
Dictyococcites callidus Perch-Nielsen 1971
Dictyococcites daviesii (Haq 1968) Perch-Nielsen 1971
Dictyococcites scrippsae Bukry & Percival 1971
Discoaster anartios Bybell & Self-Trail 1995
Discoaster araneus Bukry 1971
Discoaster barbadiensis Tan 1927
Discoaster deflandrei Bramlette & Riedel 1954
Discoaster diastypus Bramlette & Sullivan 1961
Discoaster falcatus Bramlette & Sullivan 1961
Discoaster gemmifer Stradner 1961
Discoaster kuepperi Stradner 1959
Discoaster lenticularis Bramlette & Sullivan 1961
Discoaster lodoensis Bramlette & Sullivan 1961
Discoaster mahmoudii Perch-Nielsen 1981
Discoaster martinii Stradner 1959
Discoaster mediosus Bramlette & Sullivan 1961
Discoaster megastypus (Bramlette & Sullivan 1961) Perch-Nielsen 1984
Discoaster mohleri Bukry & Percival 1971
Discoaster multiradiatus Bramlette & Reidel 1954
Discoaster nodifer (Bramlette & Reidel 1954) Bukry 1973
Discoaster saipanensis Bramlette & Reidel 1954
Discoaster salisburgensis Stradner 1961
Discoaster septemradiatus (Klumpp 1953) Martini 1958
Discoaster splendidus Martini 1960
Discoaster sublodoensis Bramlette & Sullivan 1961

Discoaster tanii Bramlette & Riedel 1954
Discorhabdus ignotus (Gorka 1957) Perch-Nielsen 1968

Eiffellithus eximius (Stover 1966) Perch-Nielsen 1968
Eiffellithus turriseiffelii (Deflandre *in* Deflandre and Fert (1954)) Reinhardt 1965
Ellipsolithus distichus (Bramlette & Sullivan 1961) Sullivan 1964
Ellipsolithus macellus (Bramlette & Sullivan 1961) Sullivan 1964
Eprolithus floralis (Stradner 1962) Stover 1966
Ericsonia cava (Hay & Mohler 1967) Perch-Nielsen 1969
Ericsonia formosa (Kamptner 1963) Haq 1971
Ericsonia obruta Perch-Nielsen 1971
Ericsonia robusta (Bramlette & Sullivan 1961) Edwards & Perch-Nielsen 1975
Ericsonia subdisticha (Roth & Hay *in* Hay and others (1967)) Roth *in* Baumann and Roth (1969)
Ericsonia subpertusa Hay & Mohler 1967

Fasciculithus aubertae Haq & Aubry 1981
Fasciculithus billii Perch-Nielsen 1971
Fasciculithus involutus Bramlette & Sullivan 1961
Fasciculithus sidereus Bybell & Self-Trail 1995
Fasciculithus thomasii Perch-Nielsen 1971
Fascicultihus tympaniformis Hay & Mohler *in* Hay and others (1967)
Fasciculithus ulii Perch-Nielsen 1971
Flabellites oblonga (Bukry 1969) Crux *in* Crux and others (1982)

Gartnerago obliquum (Stradner 1963) Noel 1970
Glaukolithus diplogrammis (Deflandre *in* Deflandre and Fert (1954)) Reinhardt 1964
Goniolithus fluckigeri Deflandre 1957

Helicolithus trabeculatus (Gorka 1957) Verbeek 1977
Helicosphaera bramlettei (Müller 1970) Jafar & Martini 1975
Helicosphaera compacta Bramlette & Wilcoxon 1967
Helicosphaera euphratis Haq 1966
Helicosphaera intermedia Martini 1965
Helicosphaera lophota Bramlette & Sullivan 1961
Helicosphaera papillata Bukry & Bramlette 1969
Helicosphaera reticulata Bramlette & Wilcoxon 1967
Helicosphaera seminulum Bramlette & Sullivan 1961
*Helicosphaera wilcoxonii (*Gartner 1971) Jafar & Martini 1975
Heliolithus cantabriae Perch-Nielsen 1971
Heliolithus riedelii Bramlette & Sullivan 1961
Holodiscolithus solidus (Deflandre *in* Deflandre and Fert (1954)) Roth 1970
Hornibrookina arca Bybell & Self-Trail 1995

Isthmolithus recurvus Deflandre *in* Deflandre and Fert (1954)

Lanternithus minutus Stradner 1962
Lithastrinus grillii Stradner 1962
Lithostromation operosum (Deflandre *in* Deflandre and Fert (1954)) Bybell 1975
Lithostromation simplex (Klumpp 1953) Bybell 1975
Lophodolithus acutus Bukry & Percival 1971
Lophodolithus nascens Bramlette & Sullivan 1971

Markalius apertus Perch-Nielsen 1979
Markalius inversus (Deflandre *in* Deflandre and Fert (1954)) Bramlette & Martini 1964
Micrantholithus altus Bybell & Gartner 1972
Micrantholithus angulosus Stradner 1961
Micrantholithus mirabilis Locker 1965
Micrantholithus vesper Deflandre *in* Deflandre and Fert (1954)
Microrhabdulus attenuatus (Deflandre 1959) Deflandre 1963
Micula decussata Vekshina 1959

Neobiscutum parvulum (Romein 1979) Varol 1989
Neochiastozygus concinnus (Martini 1961) Perch-Nielsen 1971
Neochiastozygus denticulatus (Perch-Nielsen 1969) Perch-Nielsen 1971
Neochiastozygus distentus (Bramlette & Sullivan 1961) Perch-Nielsen 1971
Neochiastozygus junctus (Bramlette & Sullivan 1961) Perch-Nielsen 1971
Neococcolithes dubius (Deflandre 1954) Black 1967
Neococcolithes minutus (Perch-Nielsen 1967) Perch-Nielsen 1971
Neococcolithes protenus (Bramlette & Sullivan 1961) Black 1967
Neocrepidolithus biskayae Perch-Nielsen 1981
Neocrepidolithus bukryi Perch-Nielsen 1981

Pedinocyclus larvalis (Bukry & Bramlette 1969, 1971) Loeblich & Tappan 1973
Pemma basquense (Martini 1959) Bybell & Gartner 1972
Pemma rotundum Klumpp 1953

Pemma serratum (Chang 1969) Bybell & Gartner 1972
Pemma stradneri (Chang 1969) Bybell & Gartner 1972
Placozygus sigmoides (Bramlette & Sullivan 1961) Romein 1979
Pontosphaera multipora (Kamptner 1948) Roth 1970
Pontosphaera ocellata (Bramlette & Sullivan 1961) Perch-Nielsen 1984
Pontosphaera plana (Bramlette & Sullivan 1961) Haq 1971
Pontosphaera wechesensis (Bukry & Percival 1971) Aubry 1986
Prediscosphaera cretacea (Arkhangelsky 1912) Gartner 1968
Prediscosphaera spinosa (Bramlette & Martini 1964) Gartner 1968
Prinsius bisulcus (Stradner 1963) Hay & Mohler 1967
Prinsius dimorphosus (Perch-Nielsen 1969) Perch-Nielsen 1977
Pseudotriquetrorhabdulus inversus (Bukry & Bramlette 1969) Wise *in* Wise and Constans (1976)

Reinhardtites anthophorus (Deflandre 1959) Perch-Nielsen 1968
Repagulum parvidentatum (Deflandre & Fert 1954) Forchhimer 1972
Reticulofenestra daviesii (Haq 1968) Haq 1971
Reticulofenestra dictyoda (Deflandre *in* Deflandre and Fert (1954)) Stradner *in* Stradner and Edwards (1968)
Reticulofenestra floridana (Roth & Hay *in* Hay and others (1967)) Theodoridis 1984
Reticulofenestra oamaruensis (Deflandre *in* Deflandre and Fert (1954)) Stradner *in* Haq (1968)
Reticulofenestra umbilica (Levin 1965) Martini & Ritzkowski 1968
Rhabdosphaera creber Deflandre *in* Deflandre and Fert (1954)
Rhabdosphaera perlongus (Deflandre *in* Grassé (1952)) Bramlette & Sullivan 1961
Rhabdosphaera pinguis Deflandre *in* Deflandre and Fert (1954)
Rhabdosphaera truncata Bramlette & Sullivan 1961
Rhomboaster bramlettei (Brönnimann & Stradner 1960) Bybell & Self-Trail 1995
Rhomboaster calcitrapa Gartner 1971
Rhomboaster contortus (Stradner 1958) Bybell & Self-Trail 1995
Rhomboaster digitalis (Aubry 1996) Bybell & Self-Trail 1997
Rhomboaster orthostylus (Shamrai 1963) Bybell & Self-Trail 1995
Rhomboaster spineus (Shafik & Stradner 1971) Perch-Nielsen 1984

Scapholithus apertus Hay & Mohler 1967
Sollasites barringtonensis Black 1967
Sphenolithus anarrhopus Bukry & Bramlette 1969
Sphenolithus editus Perch-Nielsen *in* Perch-Nielsen and others (1978)
Sphenolithus intercalaris Martini 1976
Sphenolithus moriformis (Brönnimann & Stradner 1960) Bramlette & Wilcoxon 1967
Sphenolithus primus Perch-Nielsen 1971
Sphenolithus pseudoradians Bramlette & Wilcoxon 1967
Sphenolithus radians Deflandre *in* Grassé (1952)
Sphenolithus spinenger Bukry 1971
Staurolithites imbricatus (Gartner 1968) Burnett 1998
Stovarius asymmetricus (Bukry 1969) Perch-Nielsen 1984

Toweius callosus Perch-Nielsen 1971
Toweius eminens var. *eminens* (Bramlette & Sullivan 1961) Gartner 1971
Toweius eminens var. *tovae* (Bramlette & Sullivan 1961) Perch-Nielsen 1971
Toweius? *magnicrassus* (Bukry 1971) Romein 1979
Toweius occultatus (Locker 1967) Perch-Nielsen 1971
Toweius pertusus (Sullivan 1965) Romein 1979
Toweius serotinus Bybell & Self-Trail 1995
Tranolithus minimus (Bukry 1969) Perch-Nielsen 1984
Transversopontis obliquipons (Deflandre *in* Deflandre and Fert (1954)) Hay & others 1966
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)

Vekshinella aachena Bukry 1969
Vekshinella stradneri Rood & others 1971

Watznaueria barnesae (Black *in* Black and Barnes (1959)) Perch-Nielsen 1968

Zygodiscus herlynii Sullivan 1964
Zygrhablithus bijugatus (Deflandre *in* Deflandre and Fert (1954)) Deflandre 1959

Plates D1–D5

Plate D1

Dinoflagellate Cysts from the Impact-Modified and Impact-Generated Deposits, USGS-NASA Langley Core, Hampton, Va.

[Scale bar shown applies to all photomicrographs. Sample depths and assemblages are shown in figure D5]

Figure 1. *Cordosphaeridium funiculatum* Morgenroth 1966, fragment, Exmore beds (sample R6110 DD), internal view, lower focus.

2. *Batiacasphaera baculata* Drugg 1970, fragment, crater unit B (sample R6110 DH), internal view, lower focus.

3, 4. *Histiocysta* sp. of Stover and Hardenbol (1993), crater unit B (sample R6110 DH), orientation uncertain; 3, upper focus; 4, intermediate focus.

5, 6. *Pentadinium membranaceum* (Eisenack 1965) Stover & Evitt 1978, fragment, Exmore beds (sample R6110 DC), exterior views; 5, upper focus; 6, intermediate focus.

7–9. *Fibradinium annetorpense* Morgenroth 1968, Exmore beds (sample R6110 DD), dorsal views; 7, dorsal focus; 8, intermediate focus; 9, ventral focus.

10. *Dracodinium varielongitudum* (Williams & Downie 1966) Costa & Downie 1979, crater unit B (sample R6110 DH), dorsal view, upper focus.

11. *Homotryblium tasmaniense* Cookson & Eisenack 1967, crater unit B (sample R6110 DH), antapical view, intermediate focus.

12. *Eocladopyxis* n. sp. A of Edwards (2001), fragment, crater unit B (sample R6110 DH), interior view, intermediate focus.

13. *Wetzeliella hampdenensis* Wilson 1967, Exmore beds (sample R6110 DG), ventral view, dorsal focus.

14. Miscellaneous small peridiniacean form, crater unit B (sample R6110 DH), ventral view, intermediate focus.

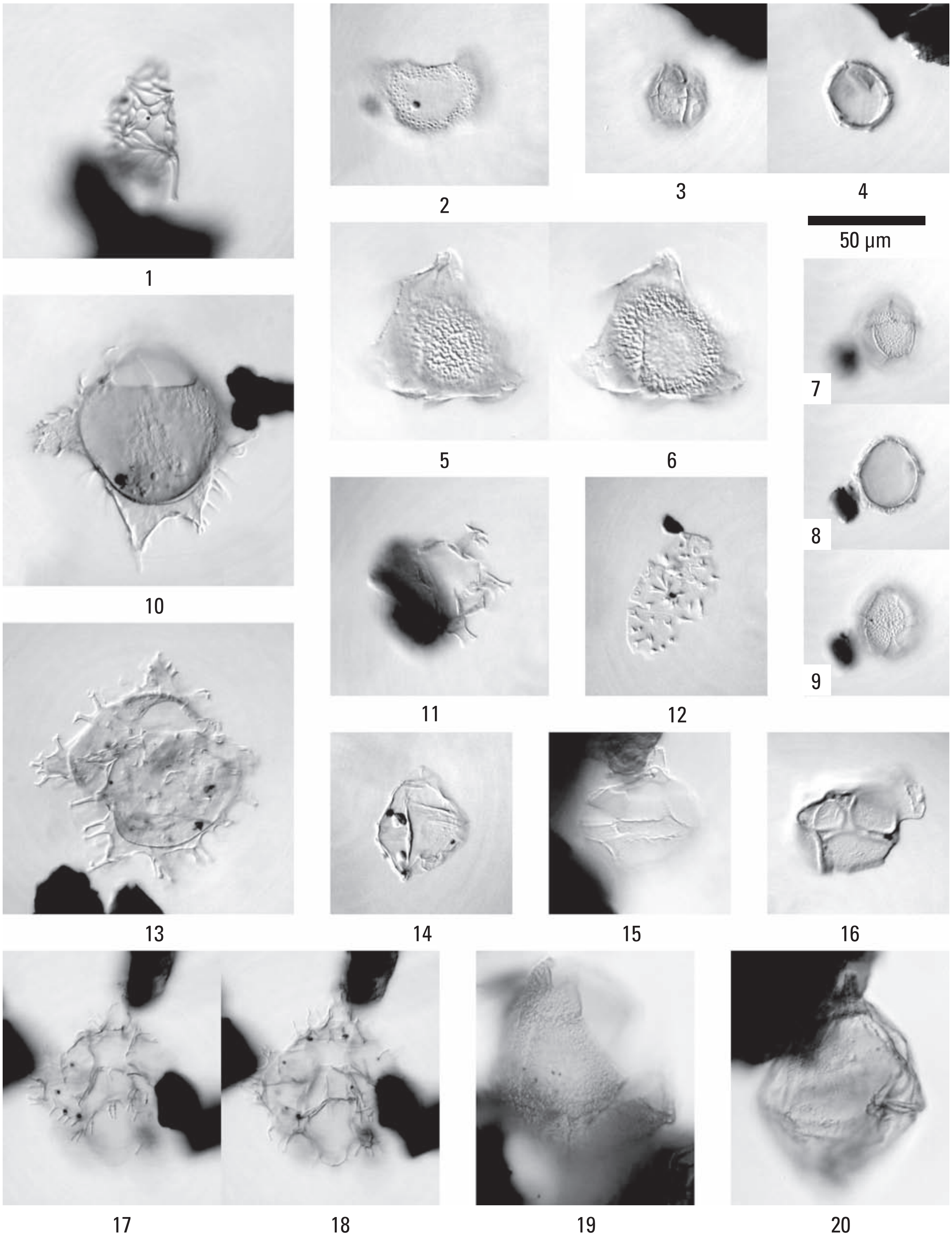
15. *Phthanoperidinium brooksii* Edwards & Bebout 1981, crater unit B (sample R6110 DH), dorsal view, upper focus.

16. *Pentadinium laticinctum* Gerlach 1961 subsp. *laticinctum*, fragment, Exmore beds (sample R6110 DD), external view, upper focus.

17, 18. *Apectodinium parvum* (Alberti 1961) Lentin & Williams 1977, crater unit B (sample R6110 DH), dorsal views; 17, dorsal surface; 18, intermediate focus.

19. *Carpatella cornuta* Grigorovich 1969, Exmore beds (sample R6110 DD), left-lateral view, upper focus.

20. *Andalusiella* Riegel 1974 sp., Exmore beds (sample R6110 DC), ventral view, upper focus.



Dinoflagellate Cysts from the Impact-Modified and Impact-Generated Deposits, USGS-NASA Langley Core, Hampton, Va.

Plate D2

Dinoflagellate Cysts from the Impact-Modified and Impact-Generated Deposits, USGS-NASA Langley Core, Hampton, Va.

[Scale bar shown is 6 µm for figures 5 and 6; 30 µm for figures 4, 9, 10, and 13; 40 µm for figures 1, 7, 8, 11, 12, and 14; 150 µm for figures 2 and 3. Sample depths and assemblages are shown in figure D5]

Figure 1. *Exochosphaeridium* Davey et al. 1966 sp., Exmore beds (sample R6110 DF), oblique right-lateral view, upper focus.

2. Clump of loosely welded, acid-resistant debris, highest Exmore beds (sample R6110 DC).

3. Clump of loosely welded, acid-resistant debris, high in crater unit B (sample R6110 DH).

4–6. *Dracodinium varielongitudum* (Williams & Downie 1966) Costa & Downie 1979, Exmore beds (sample R6110 DC), scanning-electron micrographs, ventral surface; 4, entire specimen, welded to debris; 5, detail of fused processes; 6, detail of inflated (bubbled) process.

7. *Deflandrea phosphoritica* Eisenack 1938, fragment showing degraded areas and welded debris, Exmore beds (sample R6110 DF), exterior view, dorsal focus.

8. Chorate dinoflagellate fragment, an example of what was included with the areoligeracean group, Exmore beds (sample R6110 DF), exterior view, upper focus.

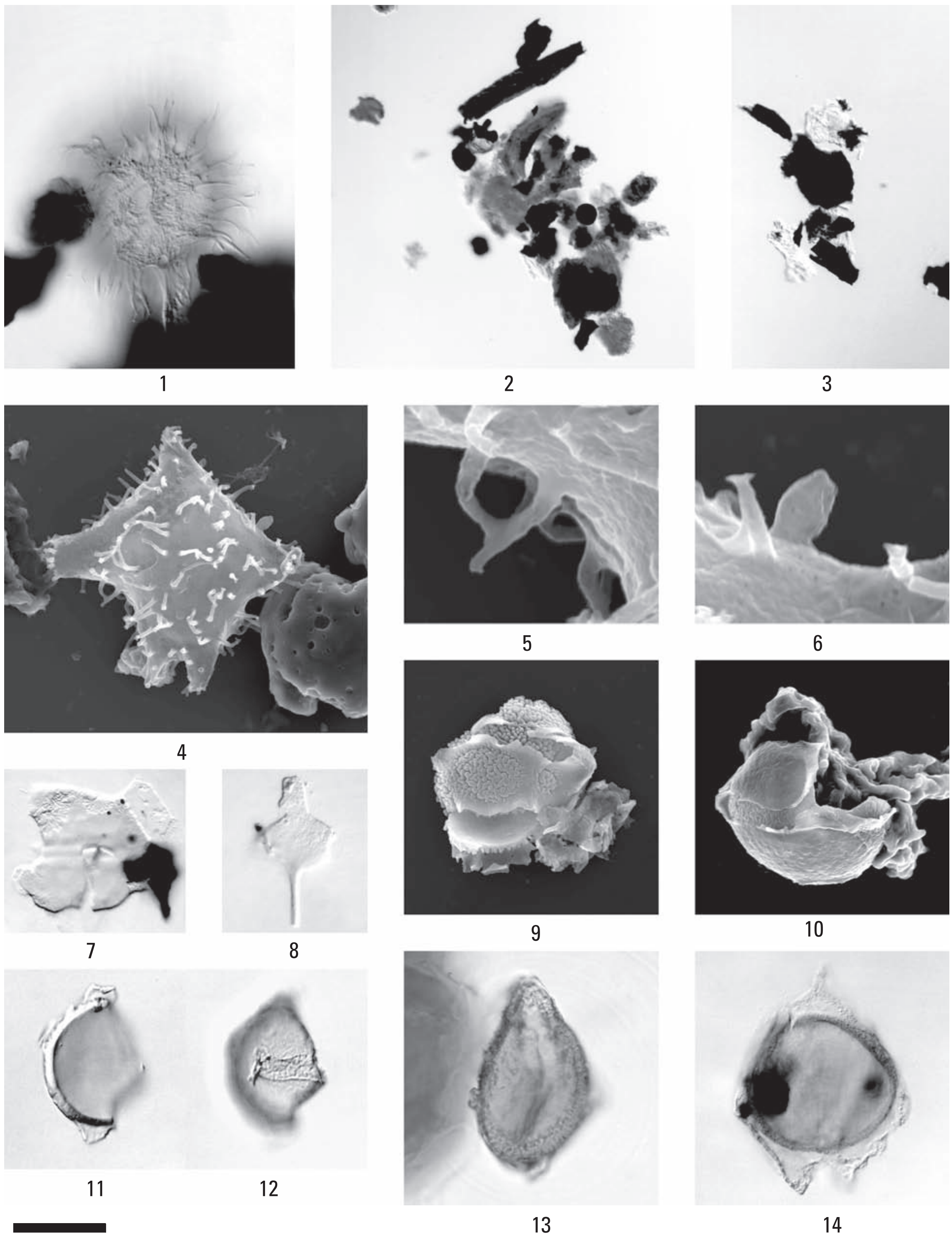
9. *Pentadinium* Gerlach 1961 sp., specimen showing sculptured surface, breakage, welded debris, Exmore beds (sample R6110 DC), scanning-electron micrograph, orientation uncertain.

10. *Pentadinium* Gerlach 1961 sp., specimen showing sculptured surface (highly subdued; original surface probably resembled that shown in figure 9), welded debris, Exmore beds (sample R6110 DC), scanning-electron micrograph, left-lateral view.

11, 12. *Pentadinium* Gerlach 1961 sp., fragment showing sculptured surface (highly subdued; original surface probably resembled that shown in figure 9) and optically dense endocyst, Exmore beds (sample R6110 DD), interior views; 11, high focus; 12, lower focus.

13. *Pentadinium membranaceum* (Eisenack 1965) Stover & Evitt 1978, Exmore beds (sample R6110 DC), ventral view, intermediate focus.

14. *Deflandrea* sp., probably *D. phosphoritica* Eisenack 1938, degraded specimen, Exmore beds (sample R6110 DC), ventral view, intermediate focus.



Dinoflagellate Cysts from the Impact-Modified and Impact-Generated Deposits, USGS-NASA Langley Core, Hampton, Va.

Plate D3

Dinoflagellate Cysts from the Impact-Modified and Impact-Generated Deposits, USGS-NASA Langley Core, Hampton, Va., and One Specimen from Outside the Crater, Nanjemoy Formation, Haynesville 1 Core, Richmond County, Va.

[Scale bar shown applies to all photomicrographs. Sample depths and assemblages are shown in figure D5]

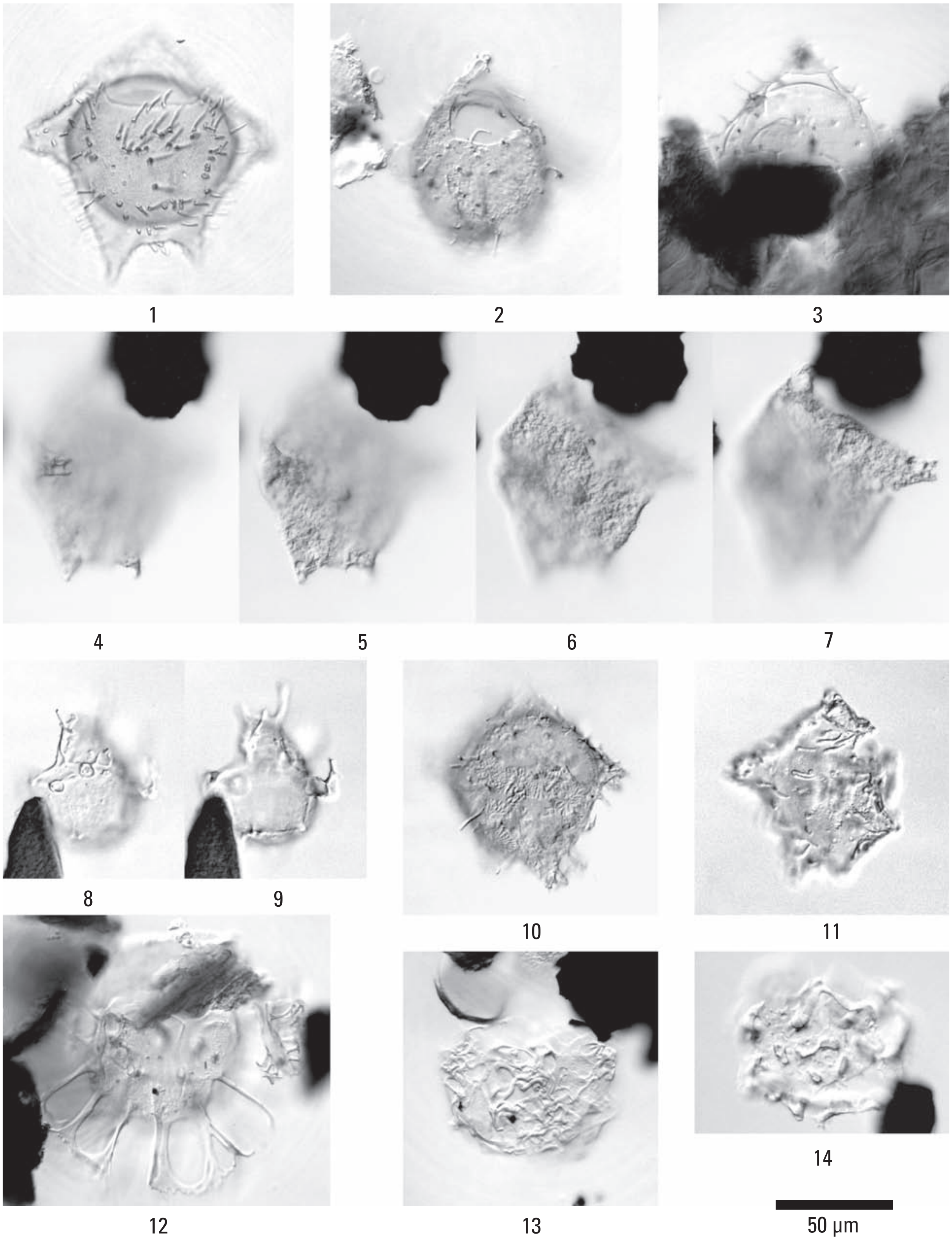
Figure

1. *Dracodinium varielongitudum* (Williams & Downie 1966) Costa & Downie 1979, typical, well-preserved specimen from outside the crater, Nanjemoy Formation, Haynesville 1 core (sample R3341 A), Richmond County, Va., dorsal view, upper focus.
2. *Dracodinium varielongitudum* (Williams & Downie 1966) Costa & Downie 1979, poorly preserved specimen, crater unit B (sample R6110 DH), dorsal view, upper focus.
3. Clump of loosely welded, acid-resistant debris with *Dracodinium* or *Wetzeliella* sp., Exmore beds (sample R6110 DD), specimen in ventral view, lower focus.

4–7. *Dracodinium* Gocht 1955 or *Wetzeliella* Eisenack 1938 sp., showing folding and bubbling, Exmore beds (sample R6110 DC), probably ventral views; 4, high focus; 5, high-intermediate focus; 6, low-intermediate focus; 7, low focus. Note that only portions of the specimen are in focus in any photograph because of folding.

8, 9. *Spiniferites* Mantell 1850 sp., fragment showing inflated bases of processes (bubbles), crater unit B (sample R6110 DH); 8, high focus; 9, intermediate focus.

10. *Dracodinium varielongitudum* (Williams & Downie 1966) Costa & Downie 1979, Exmore beds (sample R6110 DG), ventral view of ventral surface. Note star-burst scars where processes once were.
11. *Dracodinium varielongitudum* (Williams & Downie 1966) Costa & Downie 1979?, degraded specimen missing endocyst, Exmore beds (sample R6110 DG), dorsal view, upper focus.
12. Miscellaneous areoligeracean form in a clump of welded debris, crater unit B (sample R6110 DH), dorsal view?, upper focus.
13. Miscellaneous areoligeracean form with curled processes, Exmore beds (sample R6110 DG), ventral view, upper focus.
14. Miscellaneous areoligeracean fragment with curled and partially melted processes, Exmore beds (sample R6110 DG), interior view, lower focus.



Dinoflagellate Cysts from the Impact-Modified and Impact-Generated Deposits, USGS-NASA Langley Core, Hampton, Va., and One Specimen from Outside the Crater, Nanjemoy Formation, Haynesville 1 Core, Richmond County, Va.

Plate D4

Calcareous Nannofossils from Clasts in the Exmore Beds, USGS-NASA Langley Core, Hampton, Va.

[Sample depths are given in meters (feet) below land surface. XP, cross-polarized light; PC, phase contrast; T, transmitted light; SEM, scanning-electron micrograph]

Figure

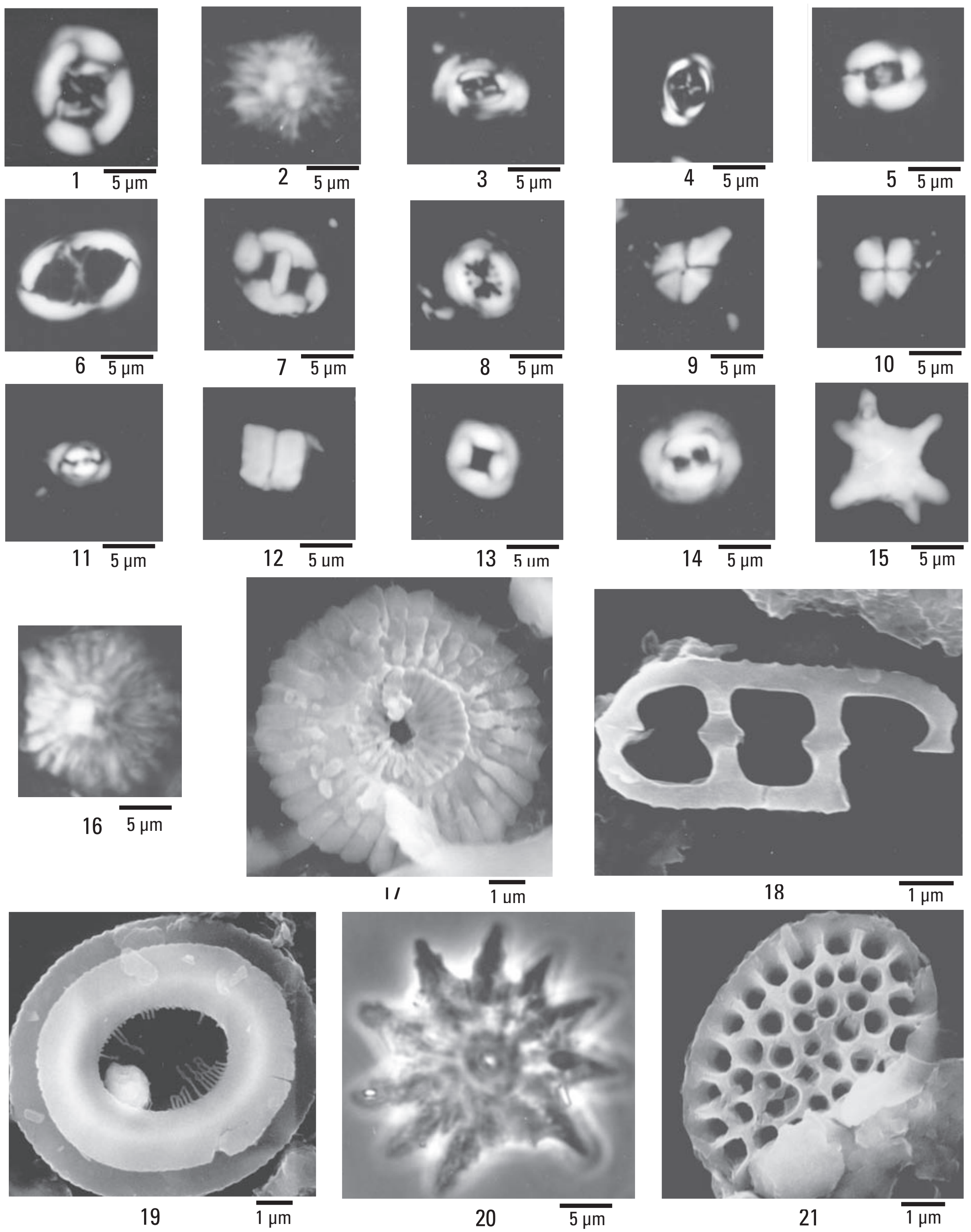
1. *Chiasmolithus bidens* (Bramlette & Sullivan 1961) Hay & Mohler 1967; 239.7 m (786.5 ft), XP.
2. *Discoaster multiradiatus* Bramlette & Reidel 1954; 243.7 m (799.7 ft), XP.

3, 4. *Camplyosphaera dela* (Bramlette & Sullivan 1961) Hay & Mohler 1967; 3, 245.0 m (804.0 ft), XP; 4, 243.7 m (799.7 ft), XP.

5. *Dictyococcites callidus* Perch-Nielsen 1971; 247.1 m (810.7 ft), XP.
6. *Neochiastozygus concinnus* (Martini 1961) Perch-Nielsen 1971; 243.7 m (799.7 ft), XP.
7. *Zygodiscus herlynii* Sullivan 1964; 245.0 m (804.0 ft), XP.
8. *Toweius serotinus* Bybell & Self-Trail 1995; 239.7 m (786.5 ft), XP.

9, 10. *Sphenolithus anarrhopus* Bukry & Bramlette 1969; 9, 245.0 m (804.4 ft), XP; 10, same specimen, 45°.

11. *Prinsius bisulcus* (Stradner 1963) Hay & Mohler 1967; 245.0 m (804.0 ft), XP.
12. *Fasciculithus involutus* Bramlette & Sullivan 1961; 243.7 m (799.7 ft), XP.
13. *Toweius callosus* Perch-Nielsen 1971; 245.0 m (804.0 ft), XP.
14. *Toweius occultatus* (Locker 1967) Perch-Nielsen 1971; 239.7 m (786.5 ft), XP.
15. *Rhomboaster bramlettei* (Brönnimann & Stradner 1960) Bybell & Self-Trail 1995; 243.7 m (799.7 ft), XP.
16. *Discoaster multiradiatus* Bramlette & Riedel 1954; 245.0 m (804.0 ft), T.
17. *Discoaster lenticularis* Bramlette & Sullivan 1961; 243.7 m (799.7 ft), SEM, distal view.
18. *Isthmolithus recurvus* Deflandre 1954; 247.1 m (810.7 ft), SEM.
19. *Reticulofenestra umbilica* (Levin 1965) Martini & Ritzkowski 1968; 247.1 m (810.7 ft), SEM, distal view.
20. *Discoaster falcatus* Bramlette & Sullivan 1961; 239.7 m (786.5 ft), PC.
21. *Pontosphaera multipora* (Kamptner 1948) Roth 1970; 247.1 m (810.7 ft), SEM, proximal view.



Calcareous Nannofossils from Clasts in the Exmore Beds, USGS-NASA Langley Core, Hampton, Va.

Plate D5

Calcareous Nannofossils from Matrix Material in the Exmore Beds, USGS-NASA Langley Core, Hampton, Va.

[Sample depths are given in meters (feet) below land surface. XP, cross-polarized light; SEM, scanning-electron micrograph]

Figure 1. *Pemma basquense* (Martini 1959) Bybell & Gartner 1972; 245.0 m (803.8 ft), XP.

2, 7. *Isthmolithus recurvus* Deflandre 1954; 2, 236.0 m (774.4 ft), XP; 7, 239.3 m (785.0 ft), SEM.

3. *Heliolithus riedelii* Bramlette & Sullivan 1961; 246.0 m (807.0 ft), XP.

4, 14. *Cribrocentrum reticulatum* (Gartner & Smith 1967) Perch-Nielsen 1971; 4, 236.0 m (774.4 ft), XP; 14, 260.0 m (853.0 ft), distal view, SEM.

5. *Dictyococcites bisectus* (Hay & others 1966) Bukry & Percival 1971; 245.0 m (803.8 ft), XP.

6. *Ellipsolithus macellus* (Bramlette & Sullivan 1961) Sullivan 1964; 258.0 m (846.4 ft), XP.

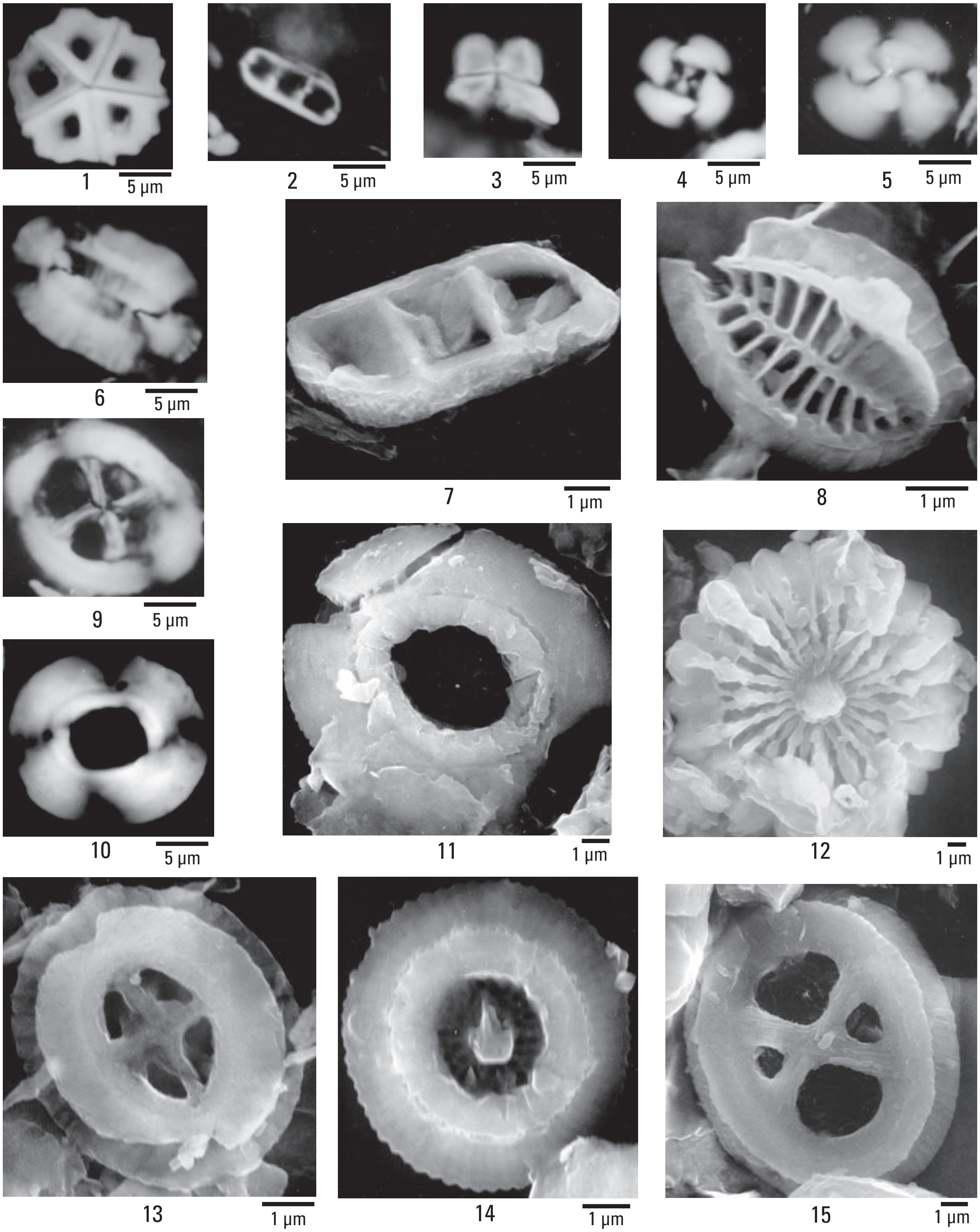
8. *Hornibrookina arca* Bybell & Self-Trail 1995; 260.0 m (853.0 ft), distal view, SEM.

9, 15. *Chiasmolithus oamaruensis* (Deflandre 1954) Hay, Mohler, & Wade 1966; 9, 236.0 m (774.4 ft), XP; 15, 244.3 m (801.5 ft), distal view, SEM.

10, 11. *Reticulofenestra umbilica* (Levin 1965) Martini & Ritzkowski 1968; 10, 246.0 m (807.0 ft), XP; 11, 244.3 m (801.5 ft), distal view, SEM.

12. *Discoaster multiradiatus* Bramlette & Reidel 1954; 260.0 m (853.0 ft), distal view, SEM.

13. *Cruciplacolithus primus* Perch-Nielsen 1977; 239.3 m (785.0 ft), proximal view, SEM.



Calcareous Nannofossils from Matrix Material in the Exmore Beds, USGS-NASA Langley Core, Hampton, Va.