

Foraminiferal repopulation of the Late Eocene Chesapeake Bay Impact Crater

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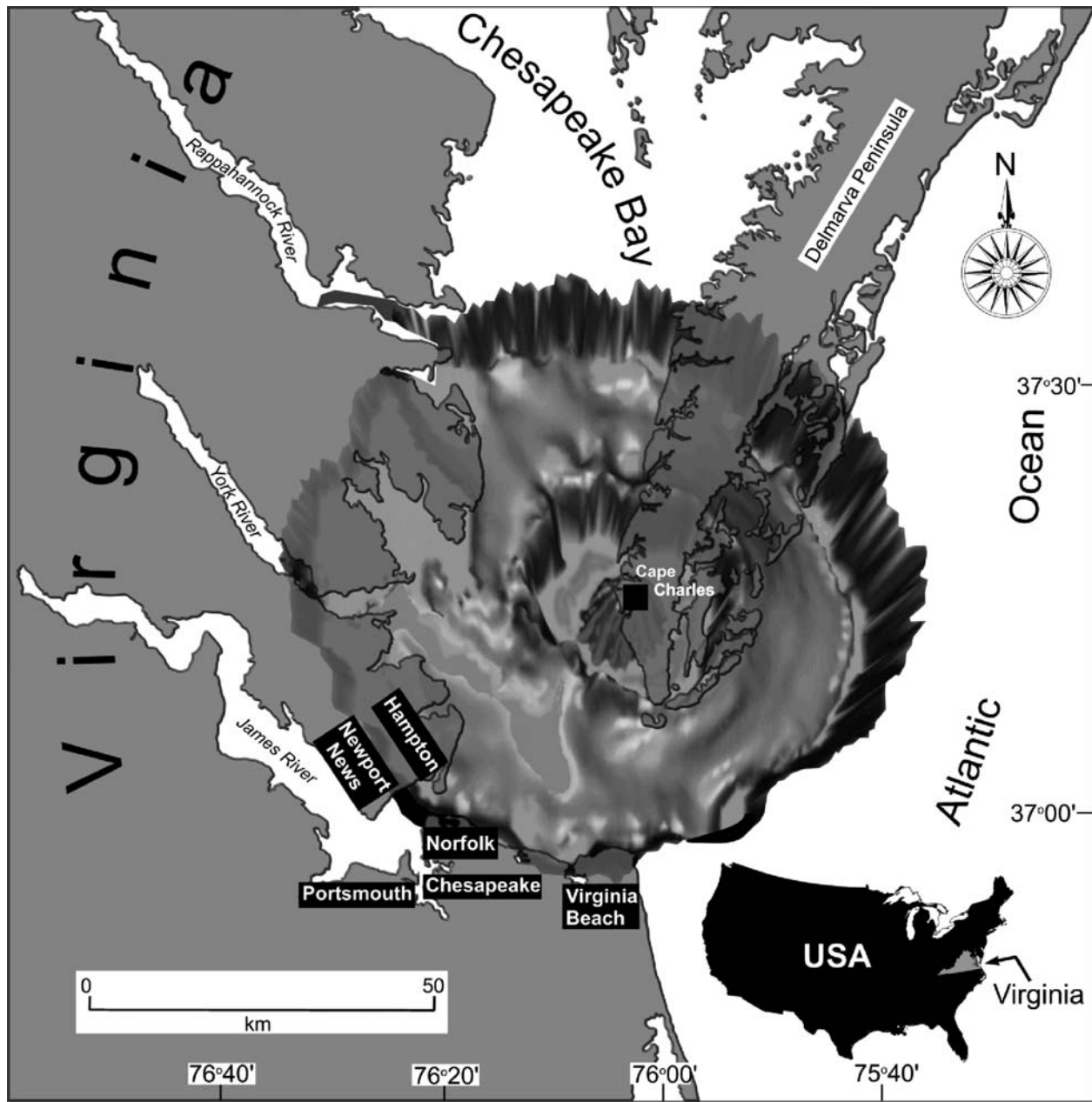
ABSTRACT: The Chickahominy Formation is the initial postimpact deposit in the 85km-diameter Chesapeake Bay impact crater, which is centered under the town of Cape Charles, Virginia, USA. The formation comprises dominantly microfossil-rich, silty, marine clay, which accumulated during the final ~1.6myr of late Eocene time. At cored sites, the Chickahominy Formation is 16.8-93.7m thick, and fills a series of small troughs and subbasins, which subdivide the larger Chickahominy basin. Nine coreholes drilled through the Chickahominy Formation (five inside the crater, two near the crater margin, and two ~3km outside the crater) record the stratigraphic and paleoecologic succession of 301 indigenous species of benthic foraminifera, as well as associated planktonic foraminifera and bolboformids. Two hundred twenty of these benthic species are described herein, and illustrated with scanning electron photomicrographs. The Chickahominy Formation can be categorized as a single benthic foraminiferal biozone (*Cibicidoides pippeni* Biozone), subdivided into five subzones, in stratigraphic order from bottom to top: *Bulimina jacksonensis* Subzone; *Lagenoglandulina virginiana* Subzone; *Uvigerina dumblei* Subzone; *Bolivina tectiformis* Subzone, and; *Siphonina jacksonensis* Subzone. Two planktonic datums and four benthic datums provide a biochronostratigraphic framework in which to estimate the duration and temporal distribution patterns of discrete microfossil assemblages. A paleoseral succession from pioneer to equilibrium paleocommunities reflects the temporal and spatial evolution from early unstable benthic paleoenvironments to later stable benthic paleoenvironments. Initial reoccupation of the newly formed crater basin is marked by a dramatic immigration of 32 indigenous species, which replaced the sparse, entirely reworked (allochthonous) foraminiferal assemblages of a preceding inhospitable dead zone. At all nine core sites, attainment of benthic paleoenvironmental equilibrium (29-190kyr postimpact) is signaled by a notable reduction in the number of new immigrant species arriving in the Chickahominy basin. In addition, at five sites inside the crater, early unstable benthic paleoenvironments can be differentiated from later stable benthic paleoenvironments by the presence of an agglutinated *Psammosiphonella* biofacies in basal Chickahominy strata and a shift from short-term to long-term benthic foraminiferal generic dominance facies. Restriction of the dead zone and *Psammosiphonella* biofacies to intracrater sites indicates unusual benthic paleoenvironmental conditions (warm, saline bottomwater and porewater) derived from the impact, which lasted as long as ~350kyr postimpact at one site. Absence of key planktonic foraminiferal and *Bolboforma* species in early Chickahominy sediments indicates that detrimental effects of the impact also disturbed the upper oceanic water column for at least 80-100kyr postimpact. Nine genera (*Bolivina*, *Uvigerina*, *Gyroidinoides*, *Globocassidulina*, *Angulogerina*, *Nuttallides*, *Cibicidina*, *Caucasina*, *Epistominella*) and two generic groups (buliminids, stilostomellids) are the most abundant taxa among 17 generic dominance facies that characterize Chickahominy core sites. Most dominant taxa were epifaunal or shallow infaunal opportunists, which thrived under conditions of oxygen depletion (dysoxia) and high organic flux rates. After an average of ~73kyr of stressed, rapidly fluctuating paleoenvironments, which were destabilized by after-effects of the impact, most of the cored Chickahominy subbasins maintained stable, nutrient-rich, low-oxygen bottom waters and interstitial microhabitats for the remaining ~1.3myr of late Eocene time.

INTRODUCTION

Approximately 35.3 million years ago, a large (~3.2km diameter) asteroid or comet struck the US middle Atlantic portion of the North American Continental Shelf. This location is now occupied by the lower reaches of the Chesapeake Bay, the bounding land masses of southeastern Virginia and the Delmarva Peninsula, and a small segment of the Virginia Continental Shelf (Poag et al. 1994; Poag 1997a; Poag, Koeberl, and Reimold 2004; text-fig. 1). The hypervelocity impact released a pulse of kinetic energy equivalent to ~1.4-1.75 x 10⁶Mt of TNT (Collins and Wünnemann 2005; Kenkmann et al. 2009), created a crater 85km in diameter and 1.3-2.0km deep, and temporarily excavated and sterilized ~6400km² of the late Eocene seafloor (Poag 1997a; Poag, Koeberl, and Reimold 2004; text-fig. 1). In its present form, the crater is characterized by five chief structural/geomorphic features: an outer sedimentary rim; a shallow annular trough; a crystalline inner ring; a deep inner basin, and; a crystalline central peak (text-figs. 2, 3).

The rim of the crater is a steep, roughly circular fault scarp, ~85km in diameter, constructed entirely of sedimentary rocks (text-figs. 2, 3). The outer rim scarp extends downward to the surface of crystalline basement. At the toe of the scarp, the surface of the crystalline basement is relatively flat, and forms a subcircular annular trough. The annular trough extends inward toward the crater center for ~15-28km, where the basement rises 40-300m to form a subcircular inner ring, ~10km wide on average, and 35-45km in diameter. The inward flank of the crystalline inner ring forms a steep scarp, which plunges to ~700m below the ring crest to form a deep inner basin ~30km in diameter. In the center of the impact structure, a rugged block of uplifted crystalline basement rises ~1km above the floor of the inner basin to form an irregular central peak.

The crater filled at a phenomenal rate of ~1500m/hr (Kenkmann et al. 2009), beginning with a basal layer of shocked and melted rocks, which is overlain by km-scale megablocks (avalanche



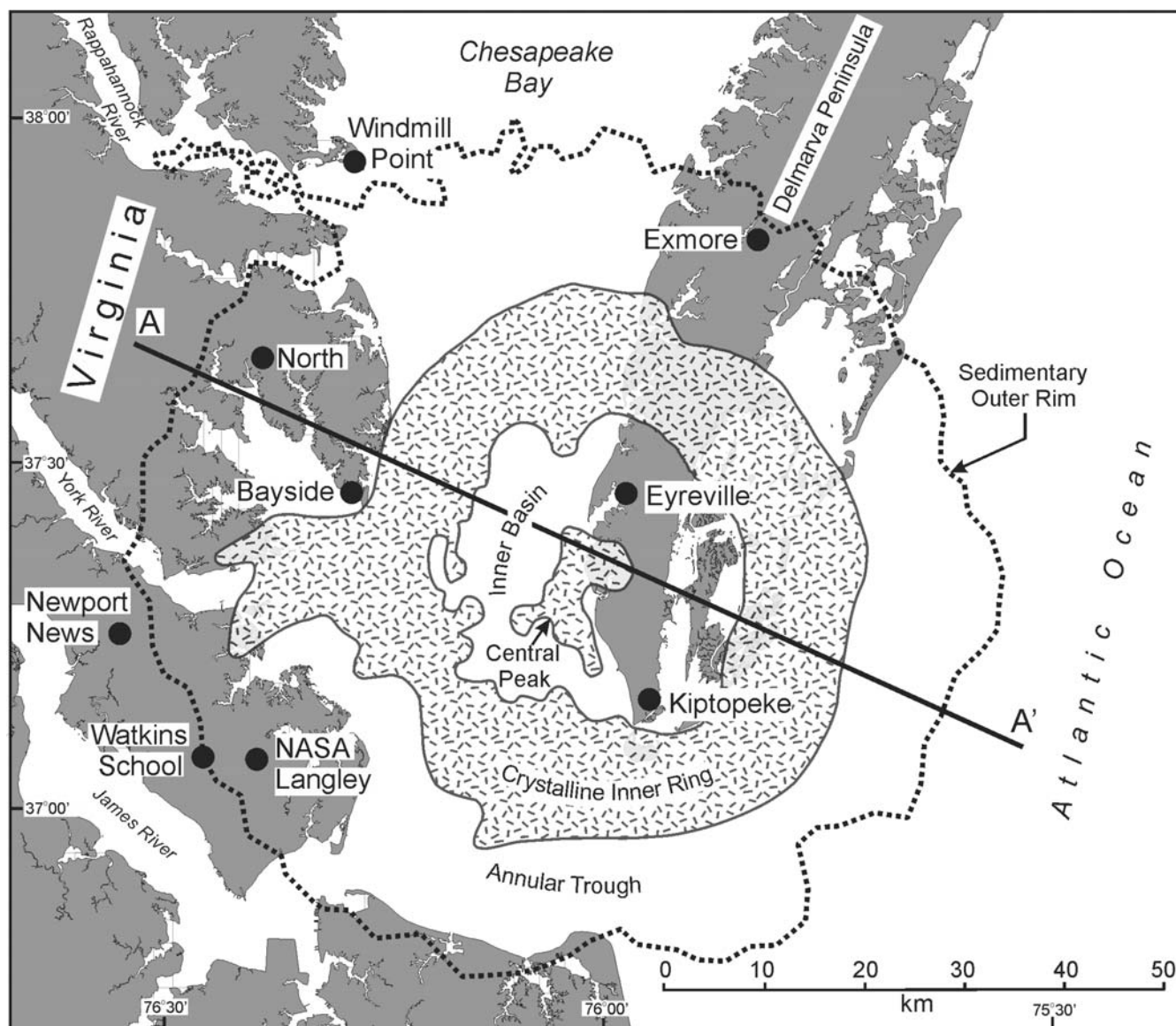
TEXT-FIGURE 1

Location map showing Virginia topography superimposed on a three-dimensional model of the Chesapeake Bay impact crater, from which all crater-fill deposits have been removed (the floor of the crater is composed of crystalline basement rocks). From Poag, Koeberl, and Reimold (2004).

deposits of Gohn et al. 2009). The megablocks are composed of mostly Lower Cretaceous nonmarine siliciclastics. The megablocks are covered by a thick layer (maximum thickness >1km) of matrix-supported impact breccia (resurge and tsunami deposits) of mainly Late Cretaceous, Paleocene, and early to middle Eocene lithoclasts, which comprise the Exmore Formation (Poag 1997a; Poag, Koeberl, and Reimold 2004; Horton et al. 2008; Gohn et al. 2009; text-fig. 3). Subsequent paleoecologic recovery took place in a stepwise succession of depositional events, accompanied by sequential development and temporal reorganization of the seafloor microbiota during deposition of the Chickahominy Formation, the initial post-

impact deposit (Poag, Koeberl, and Reimold 2004; Poag 2009; table 1).

Relatively rapid burial by 300-500m of late Cenozoic and Quaternary siliciclastic (predominantly marine) sediments on the slowly subsiding, passive, US Atlantic continental margin has allowed unusually complete and undistorted preservation of nearly the entire postimpact sedimentary record within the crater margins. Scientists of the US Geological Survey and their collaborators have mapped the crater structure and the overlying seismostratigraphic units using mainly >2,000km of marine seismic reflection profiles, supplemented by several land-based



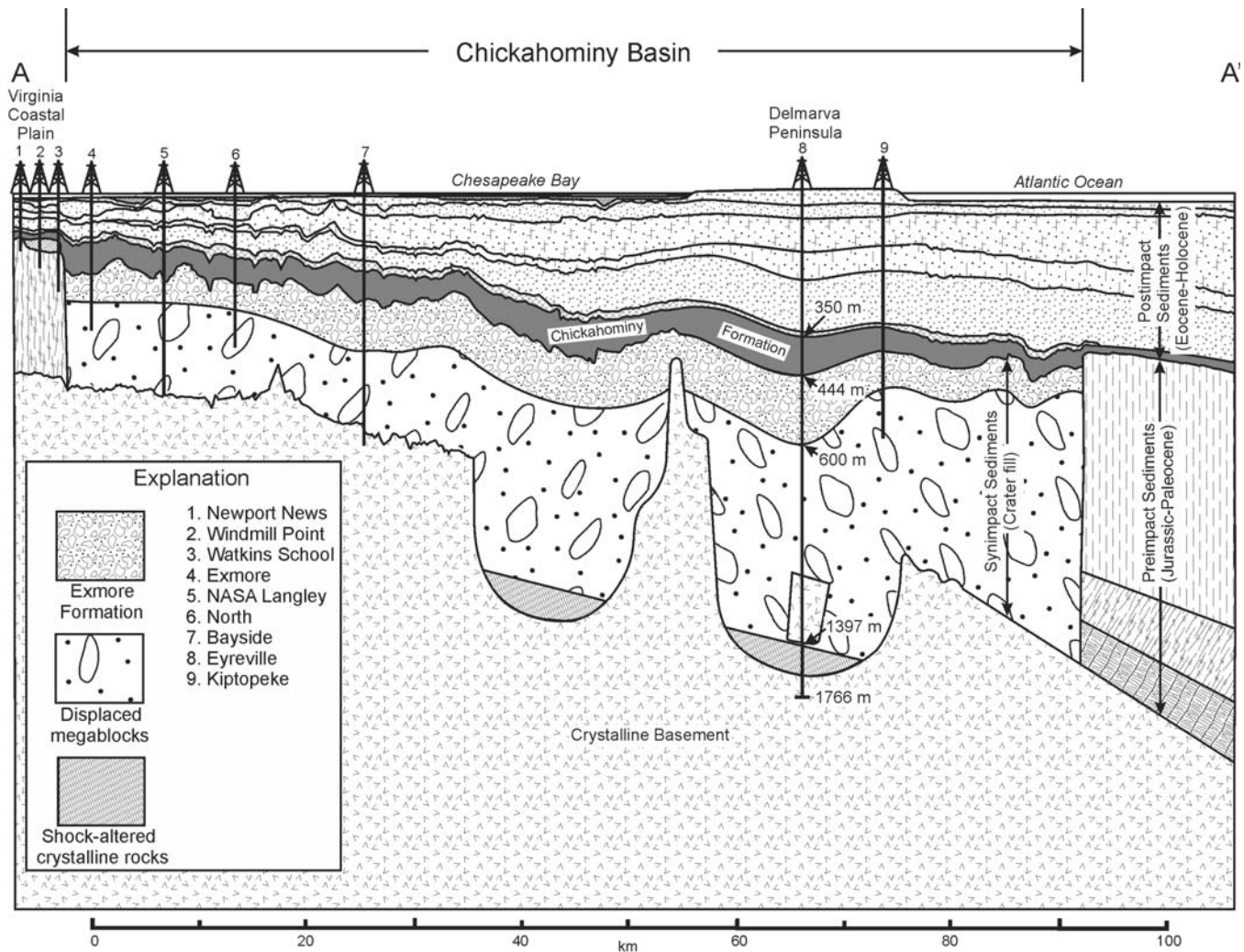
TEXT-FIGURE 2

Location map showing nine core sites analyzed in this study (black dots) and their positions relative to Virginia topography and Chesapeake Bay crater morphology. Heavy line A-A' marks the cross section shown on text-figure 3, to which the core-sites are projected. Modified from Poag, Koeberl, and Reimold (2004).

seismic surveys (Poag, Koeberl, and Reimold 2004; Horton, Powars, and Gohn 2005; Gohn et al. 2009; Powars et al. 2009; text-fig. 4). Nine continuously cored boreholes in southeastern Virginia (text-figs. 2, 3) provide sediment and fluid samples, as well as downhole geophysical logs, which allow ground-truth correlations with the seismostratigraphic data (Powars and Bruce 1999; Powars 2000; Poag, Koeberl, and Reimold 2004; Horton, Powars, and Gohn 2005; Gohn et al. 2009; text-fig. 4; table 2). Two core sites (Newport News, Windmill Point) are located on the western side of Chesapeake Bay, each ~3km outside the crater rim. Two other core sites (Watkins School, Exmore) are located approximately at the crater rim. Watkins School is in the southwest quadrant of the crater, and Exmore is in the northeast quadrant on the Delmarva Peninsula. Three core sites (North, NASA Langley, Bayside) are located in the

annular trough in the western half of the crater. At the latter two sites, the drill penetrated crystalline basement. The remaining two core sites (Eyreville, Kiptopeke) are located in the inner basin of the crater. The Eyreville corehole is the most recently cored (2006), reached the greatest depth (1766m), and is the only corehole to encounter shock-altered and melted crystalline rocks in the deepest cores.

The principal objectives of this study are: 1) To thoroughly document the sequential biostratigraphic and paleoecologic evolution of benthic foraminifera preserved in the initial postimpact marine sedimentary unit, the Chickahominy Formation, inside and near the Chesapeake Bay impact crater; 2) To describe, enumerate, and illustrate specimens of most species represented in the Chickahominy benthic foraminiferal assemblage, along



TEXT-FIGURE 3

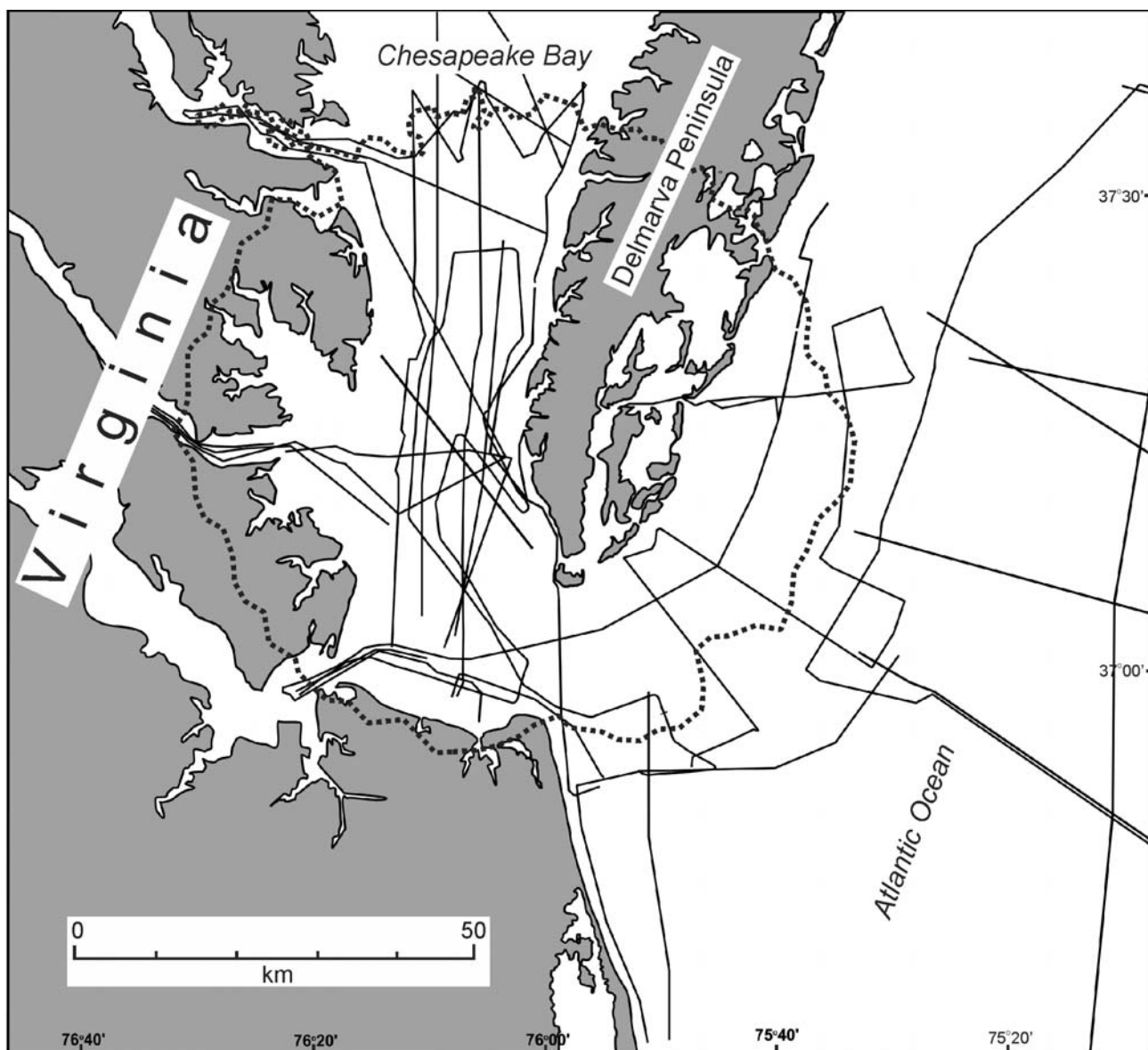
Scaled cross section of the Chesapeake Bay impact crater showing crater structure and morphology, projected positions of the nine core sites used in this study, and the stratigraphic position of the Chickahominy Formation relative to underlying crater-fill deposits. The scale of the cross section is based on drill depths and marine seismic-reflection profiles. Modified from Poag, Koeberl, and Reimold (2004).

with key planktonic foraminiferal and bolboformid species, and; 3) To compare the postimpact succession at Chesapeake Bay with those of other late Eocene sections in the US, and with other impact-related deposits outside the US.

PREVIOUS STUDIES

Prior to discovery of the Chesapeake Bay impact crater, Cushman and Cederstrom (1945) published the initial biostratigraphic study of the Chickahominy Formation and formalized its name. Poag et al. (1994) and Poag (1997a) established the presence and general characteristics of the Chesapeake Bay impact crater, and documented the main properties of the Chickahominy Formation within it. Poag, Koeberl, and Reimold (2004) followed those studies seven years later with a comprehensive analysis and summary of all interim studies. Published depositional and paleoenvironmental studies that focus on the synimpact-postimpact transition include those of Poag and Aubry (1995), Poag (2002b), Poag, Koeberl, and Reimold (2004), Poag and Norris (2005), Poag (2007a, b), and

Poag (2009). In the second of these studies (Poag 2002b) I recognized in the NASA Langley core a thin fallout layer characterized by unusual microlattices formed of pyrite (table 1). Later, Poag, Koeberl, and Reimold (2004) described a four-step succession from synimpact-to-postimpact depositional regimes (fallout regime; flow-in regime; dead zone; bathyal marine regime) inferred from the eight pre-Eyreville cores (table 1). In addition, Poag, Koeberl, and Reimold (2004) and Poag and Norris (2005) provided detailed analyses of the benthic foraminiferal record through the transition interval in the Kiptopeke and NASA Langley cores, respectively, and erected a temporal scale for the duration of each step. Later, I elaborated on the four-step succession and refined the time scale (Poag 2007a, b). Horton et al. (2008) gave a general description of lithic changes in the synimpact-to-postimpact transition in four of the Chesapeake Bay coreholes studied herein. These authors informally designated the uppermost (laminated) pre-Chickahominy sediments as an "upper stratified member" of the Exmore Formation. This designation was modified later by Gohn et al. (2009) to recognize a two-fold subdivision of the



TEXT-FIGURE 4

Location map showing tracklines for >2,000km of marine seismic-reflection profiles that document the structure and morphology of the Chesapeake Bay impact crater. The heavy dotted line marks the outer edge of the crater. Modified from Poag, Koeberl, and Reimold (2004).

stratified member into a lower part (Es1) and upper part (Es2). I previously studied the Eyreville core to produce the first detailed analysis of contiguous samples through the synimpact-postimpact transition interval (Poag 2009). I presented evidence for paleoseral succession of the benthic foraminiferal community, determined the duration of impact-altered paleoenvironments, and compared the Chickahominy succession to the Cretaceous-Paleocene succession in the Chicxulub crater, Yucatán, Mexico. A comprehensive analysis of the NASA-Langley corehole (Horton, Powars, and Gohn 2005) included lithic and paleontological studies of the Chickahominy Formation (Edwards et al. 2005; Powars et al. 2005). In a compilation of studies of the Eyreville corehole (Gohn et al. 2009), several authors addressed various aspects of crater-fill deposition: (Edwards et al.; Sanford et al.; Gohn et al.; Browning et al.; Schulte

et al.). Ormö et al. (2010) focused on defining the synimpact-postimpact depositional boundary using chemostratigraphic techniques.


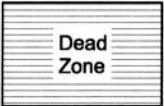
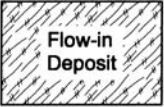
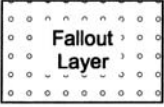
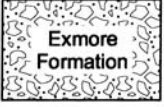
Biostratigraphy and paleoecology of Chickahominy-equivalent strata have been studied elsewhere in the US Atlantic Coastal Plain (Cushman 1948a; Browning 1996; Browning, Miller, and Bybell 1997) and US Gulf Coastal Plain (Howe and Wallace 1932; Cushman 1935b; Bandy 1949; Deboo 1965; Miller, Thompson, and Kent 1993, 2008).

SAMPLING AND ANALYSIS

Sampling and analysis of the Chickahominy Formation for this study has taken place over a 21-year time period. I took the first samples from the Newport News, Windmill Point, and Exmore

TABLE 1

Summary of stratal characteristics for the late synimpact to early postimpact depositional regimes of the Chesapeake Bay impact crater.

Depositional Regime	Depositional Unit	Lithology/ Genesis	Maximum Thickness	Fossil Content	Duration of Accumulation
Early Postimpact	 Chickahominy Formation	Indistinctly laminated, bioturbated, dark, dense, silty, sandy clay; pyrite in platy crusts, aggregates of framboids and euhedral crystals, burrow casts; intensely burrowed at base and top; marine basin deposit	>220m	Species- and specimen-rich assemblages of well-preserved indigenous nannofossils and microfossils, with fewer invertebrate and vertebrate remains	~1.6myr
Transitional	 Dead Zone	Very thin, parallel-to-subparallel, distinct-to-indistinct, regular horizontal silt/clay laminae; crusts of euhedral and framboidal pyrite; suspension drape deposit	~49cm	Few microfossils reworked from late Cretaceous to late Eocene sedimentary target strata	<0.1myr
	 Flow-in Deposit	Structureless to cross-laminated sandy, silty clay with siltstone clasts and laminae; mica, glauconite, lignite, pyrite; small-scale turbidites	18-100cm	Few microfossils reworked from late Cretaceous to late Eocene sedimentary target strata	Months to years
Late Synimpact	 Fallout Layer	Laminated silt-rich clay with 1mm-diameter spherical pores in framboidal pyrite lattices; remnants of air-fall deposition of glassy impact spherules	~3cm	No fossil content	Minutes to hours
	 Exmore Formation	Polymictic, upward-fining, lithic impact breccia of pebble-to-boulder size sedimentary and crystalline clasts supported by glauconite/quartz sand matrix; oceanic resurge and tsunami washback deposition	>1000m	Abundant reworked microfossils in matrix and in individual clasts of Late Cretaceous to late Eocene target strata	Minutes to days

cores in 1990, and the final samples from the Eyreville corehole in 2007. Sampling strategies changed over time as the importance and consequences of the impact were more clearly realized. I took early samples (e.g., Newport News) at irregular, relatively wide-spaced intervals. Later samples (e.g., Eyreville) came from more closely and evenly spaced intervals. The only interval of contiguous samples, however, is the synimpact-postimpact transition interval in the Eyreville core (Poag 2009). All foraminiferal specimens came from ~20cm³ core sections of relatively uncompacted silty clay (and a few sand-enriched burrow casts), using standard micropaleontological extraction techniques. Core samples were boiled in a solution of water and hexametaphosphate to disperse the clay, and then wet-sieved over a 63µm screen to separate benthic and planktonic foraminifera, specimens of *Bolboforma*, examples of associated microfossils, invertebrate and vertebrate remains, and selected mineral grains. Oven-dried (70°C) specimens were identified to species level when possible, using optical and scanning-electron microscopy.

Taxonomic nomenclature used herein is based on comparison with published literature and my own collection of foraminiferal assemblages from the US Gulf and Atlantic Coastal Plain and offshore continental-margin sites. Species-level taxonomy for benthic foraminifera is primarily from Howe and Wallace (1932), Cushman (1935b), Cushman and Cederstrom (1945); planktonic foraminifera from Pearson, Premec-Fucek, and Primoli Silva (2006), and; *Bolboforma* from Spiegler and Daniels (1991). The work of Loeblich and Tappan (1988) is the principal source of benthic generic taxonomy. Assemblage

slides from all samples can be found in the collections of the Smithsonian Institution, National Museum of Natural History, Washington, DC.

I examined comparative foraminiferal assemblages from: 1) the Jackson beds at Danville Landing, Louisiana; 2) the Yazoo Clay near Jackson, Alabama; 3) the Cocoa Sand near Cocoa Post Office, Alabama; 4) the ACGS #4 corehole near Mays Landing, New Jersey, and; 5) the Ohio Oil Hammond No. 1 corehole near Salisbury, Maryland.

I created the text-figures using CorelDRAW Graphics Suite X4 and earlier versions. Plates were initially prepared with Adobe Photoshop CS4 and earlier versions, and then imported to CorelDRAW. Any use of trade, product, or firm names is for descriptive purposes only, and does not imply endorsement by the US Government.

Eight tables containing supplementary data analysis may be found online at www.micropress.org.

STRATIGRAPHIC FRAMEWORK OF STUDY AREA

General overview

Sedimentary deposits of the Virginia Coastal Plain constitute a seaward-thickening wedge of dominantly unconsolidated to poorly consolidated siliciclastic sands, silts, and clays of both marine and nonmarine origin. The deposits range in age from Early Cretaceous to Holocene, and generally comprise the updip lithofacies of an ~18km-thick column of sediments that fills the southern end of an elongate offshore basin known as the Balti-

TABLE 2

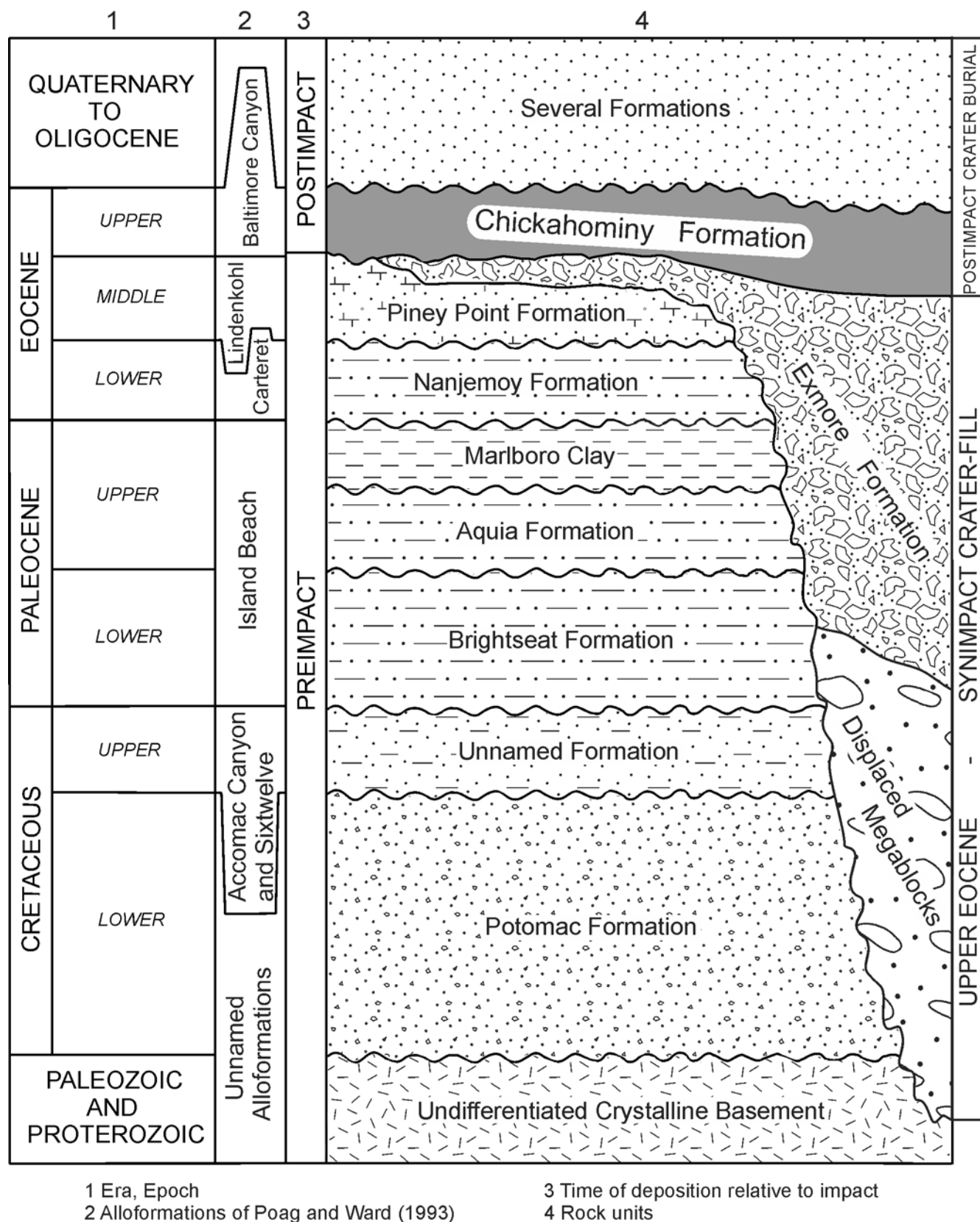
Principal coreholes discussed in this study arranged chronologically according to year drilled.

Name/Location	Year Drilled	Latitude (N) Longitude (W)	Chickahominy Interval (m)	Total Depth (m)	Well Head Elevation (m)	Location Relative to Crater
Ohio Oil L.G. Hammond Well- Maryland	1944	38°20'48" 75°21'54"	353.6 – 371.9 (equivalent)	1692.3	+17.4	On Maryland Coastal Plain, 95km NE of crater
DSDP Site 612 Corehole-New Jersey Continental Slope	1983	38°49.21' 72°46.43'	137.4 – 180.0 (equivalent)	675.3 below sea floor	-1400 at seafloor	In North American Tektite Strewn Field, 275km NE of crater
USGS Exmore Corehole-Virginia	1986	37°58.08' 75°49.09'	325.9 – 369.0	425.5	+9.1	At outer rim
Virginia Dept. of Environmental Quality Kiptopeke Corehole- Virginia	1989	37°08'07" 75°57'08"	327.7 – 394.1	609.6	+2.1	In inner basin
Virginia Dept. of Environmental Quality Newport News Park II Corehole-Virginia	1990	37°12'08" 76°34'11"	113.7 – 130.2	189.6	+15.9	Outside outer rim
USGS Windmill Point Corehole-Virginia	1992	37°36'50" 76°16'55"	135.6 – 162.8	227.9	+1.2	Outside outer rim
USGS-NASA Langley Corehole-Virginia	2000	37°05'44" 76°23'09"	183.3 – 235.7	635.1	+2.4	In annular trough
USGS North Corehole-Virginia	2001	37°26'41" 76°24'02"	155.5 – 225.3	435.1	+4.6	In annular trough
USGS Bayside Corehole-Virginia	2001	37°19'34" 76°17'33"	231.4 – 278.2	729.4	+1.2	In annular trough
USGS Watkins Elementary School Corehole-Virginia	2002	37°04'32" 76°27'31"	148.7 – 189.6	300.3	+8.2	At outer rim
USGS-ICDP Eyreville Corehole-Virginia	2006	37°19'18" 75°58'32"	350.1 – 443.9	1766.3	+1.2	In inner basin

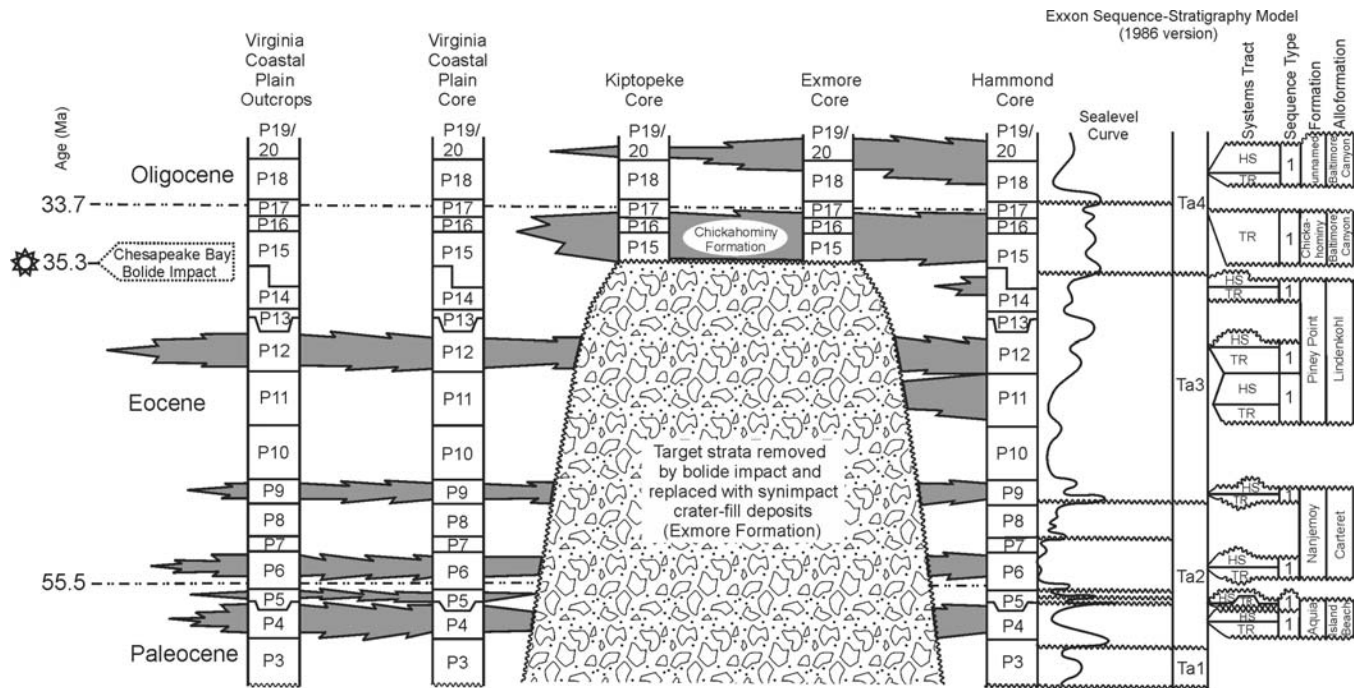
more Canyon trough (Maher 1965; Poag 1985; Grow, Klitgord, and Schlee 1988; Poag and Ward 1993; Poag, Koeberl, and Reimold 2004). In Virginia, a hierarchy of 28 formal formations (text-fig 5) has been developed for these deposits over a period of more than 100 years (Darton 1891; Clark 1896; Cederstrom 1945a,b,c, 1957; Richards 1945, 1967; Cushman and Cederstrom 1945; Bennett and Collins 1952; Otton 1955; Murray 1961; Brown, Miller, and Swain 1972; Oaks and Coch 1973; Teifke 1973; Ward and Blackwelder 1980; Gibson 1983; Ward and Krafft 1984; Mixon 1985; Owens and Gohn 1985; Ward and Strickland 1985; Meng and Harsh 1988; Powars, Mixon, and Bruce 1992; Poag and Ward 1993; Powars and Bruce 1999; Powars 2000; Edwards et al. 2009).

Modern emphasis on unconformity-bounded depositional units (Vail et al. 1977; North American Commission on Stratigraphic Nomenclature 1983) has resulted in additional formalization of alloformations, which can be traced, onshore and offshore, across the entire US Atlantic margin north of Cape Hatteras, including the outcrops and subsurface beds of southeastern Vir-

ginia (Poag and Ward 1993; Poag and Commeau 1995). Few sequence-stratigraphic analyses exist, however, for the Virginia Coastal Plain. The initial published study documented 15 depositional units that correlate with third-order sequences of the Exxon model (Poag and Commeau 1995; text-fig. 6). Virginia systems tracts are dominated by transgressive and highstand types, with little or no record of lowstand deposits (Poag, Koeberl, and Reimold 2004). Poag and Commeau (1995) interpreted the Chickahominy Formation to be a single, transgressive, Type I systems tract. Browning et al. (2008) documented Eocene sequences cored at several coastal-plain sites in New Jersey and Maryland, and Browning et al. (2009) speculated that a single sequence boundary (E1-E2) might divide the Chickahominy Formation in the Eyreville core. Kulpecz et al. (2009) constructed a regional sequence-stratigraphic framework for the US middle Atlantic Coastal Plain, which includes the Exmore and Eyreville cores. Kulpecz et al. (2009) also tentatively recognized the E1-E2 sequence boundary in the Chickahominy Formation at both the Eyreville and Exmore sites.



TEXT-FIGURE 5
Summary illustration of surficial and subsurface stratigraphic units that comprise the Virginia Coastal Plain, showing the relative position of the Chesapeake Bay impact crater. Modified from Poag (1997a).



TEXT-FIGURE 6

Conceptual regional cross section from southeastern Virginia to southern Maryland showing Paleogene chronostratigraphic units represented (shaded) and their positions within the 1986 sequence-stratigraphy model of Exxon. Low sealevel is indicated by leftward inflections of the curve. P3-20 = planktonic foraminiferal biozone of Berggren and Miller (1988); T1-4 = supercycles; HS = highstand systems tract; TR = transgressive systems tract. Modified from Poag and Commeau (1995).

Preimpact deposits

Preimpact sediments of the Virginia Coastal Plain constitute thick (~1-1.5km) Lower Cretaceous to lowest upper Eocene deposits. Seven preimpact coastal plain formations are recognized on the composite basis of lithology and biozonation (text-fig. 5).

Potomac Formation

Oldest outcropping sedimentary strata in the Virginia Coastal Plain are mainly nonmarine, quartz sand- and silt-dominated lithofacies of the Potomac Formation (Ward and Krafft 1984; Mixon et al. 1989; Powars and Bruce 1999; Powars 2000; text-fig. 5). The Potomac Formation extends into the subsurface, and underlies the entire study area, except where excavated by the Chesapeake Bay bolide impact. Potomac strata constitute the oldest sediments above crystalline basement rocks, except for a possibly Triassic or Jurassic subsurface unit inferred by some investigators (Hansen 1978; Dysart, Coruh, and Costain 1983; Hansen and Wilson 1984) from seismic profiles. The Potomac Formation is by far the thickest sedimentary unit recognized on the Virginia Coastal Plain, and reaches as much as 1.3km on the Delmarva Peninsula (Poag, Koeberl, and Reimold 2004). From a thickness of ~600m at the western margin of the crater, the Potomac thickens to >1km at the eastern (downdip) margin (Grow, Klitgord, and Schlee 1988). No allostratigraphic units have been proposed for US East Coast Lower Cretaceous units.

Unnamed Upper Cretaceous beds

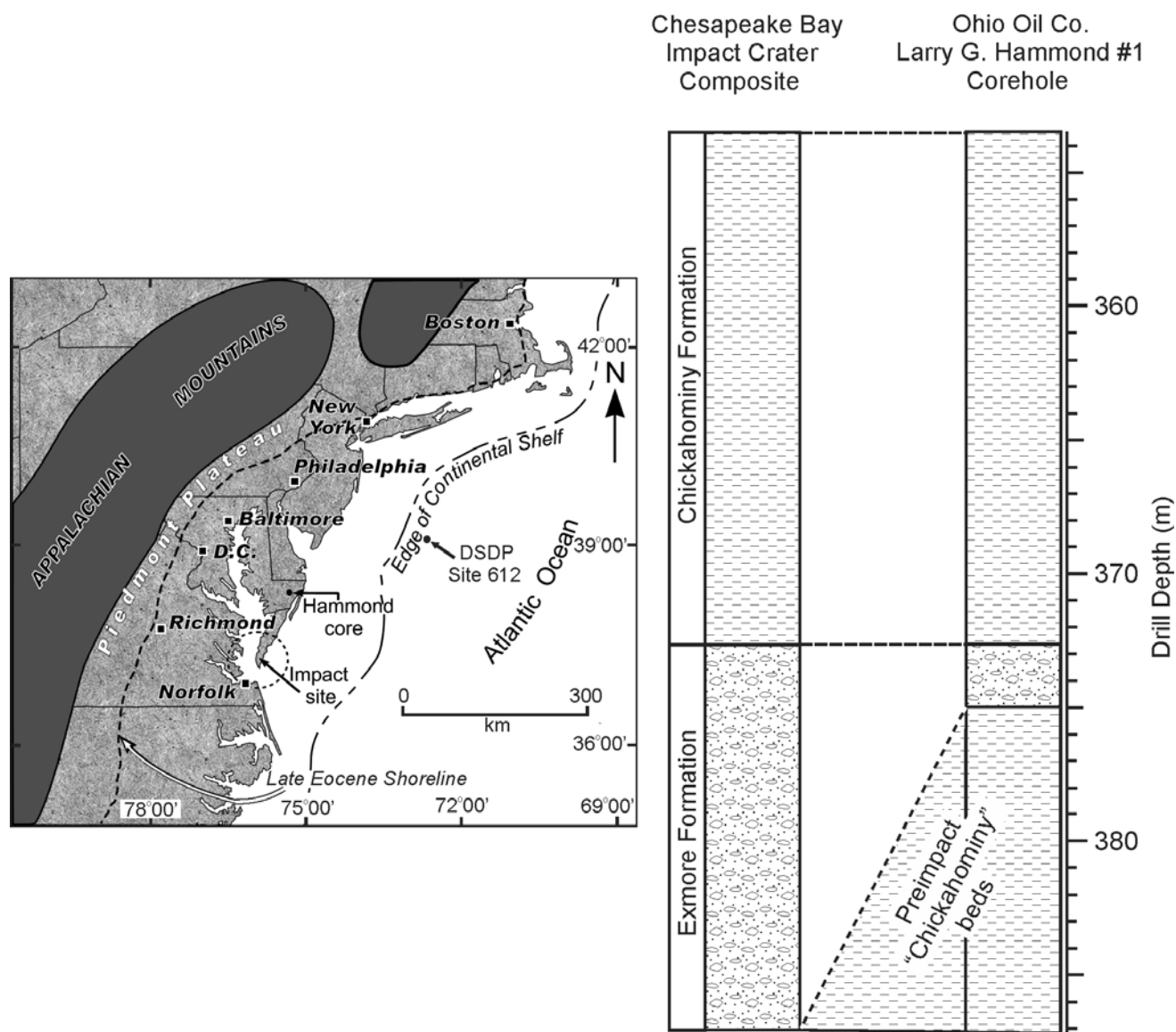
Upper Cretaceous beds have not been found cropping out in the Virginia Coastal Plain. A few downdip wells have encountered Late Cretaceous (Cenomanian and Campanian) megafossils and microfossils, however, in nonmarine (red beds), deltaic (micaceous, lignitic, glauconitic, quartz sand), and marine beds (shelly, glauconitic silt, clay, and quartz sand), 40-110m thick (text-fig. 5; Clark and Miller 1912; Powars, Mixon, and Bruce 1992; Powars and Bruce 1999; Powars 2000). Poag and Ward (1993) included some beds of this interval in the Sixtytwo Alloformation.

Brightseat Formation

Oldest Cenozoic deposits of the Virginia Coastal Plain belong to the lower Paleocene Brightseat Formation (Bennett and Collins 1952), a dominantly subsurface unit consisting of mainly clayey, sparsely glauconitic, quartz sand (text-fig. 5). In outcrop, Brightseat beds are confined to the northeastern part of the state, and are known only along the Potomac and Rappahannock Rivers (Ward 1984), but equivalent strata have been reported in the subsurface (Reinhardt, Newell, and Mixon 1980; Powars and Bruce 1999; Powars 2000). The Brightseat is included in the Island Beach Alloformation of Poag and Ward (1993).

Aquia Formation

Clayey, silty, glauconitic, shell-rich, quartz sands of the upper Paleocene Aquia Formation (Clark and Martin 1901; text-fig. 5)



TEXT-FIGURE 7

Location map and comparative stratigraphic sections for Chickahominy and Exmore units in the Chesapeake Bay impact crater and equivalents in the Ohio Oil-Larry G. Hammond #1 corehole. Note also the location of Deep Sea Drilling Project Site 612.

crop out in river banks in a continuous arc from north of Baltimore on upper Chesapeake Bay to around Hopewell, Virginia, on the James River (Ward 1984). Equivalent beds are present throughout the subsurface (Powars, Mixon, and Bruce 1992; Powars and Bruce 1999; Powars 2000), and are included in the Island Beach Alloformation (Poag and Ward 1993).

Marlboro Clay

A second upper Paleocene unit is the Marlboro Clay (Clark and Martin 1901; Glaser 1971; text-fig. 5). The Marlboro Clay is present at scattered outcrops on the western side of Chesapeake Bay from southern Maryland to the James River in Virginia (Ward 1984), and is widespread in the subsurface (Powars, Mixon, and Bruce 1992; Powars and Bruce 1999; Powars 2000). The thin, silver-gray to pale red, plastic clays interbedded with yellowish-gray to reddish silts of the Marlboro, are

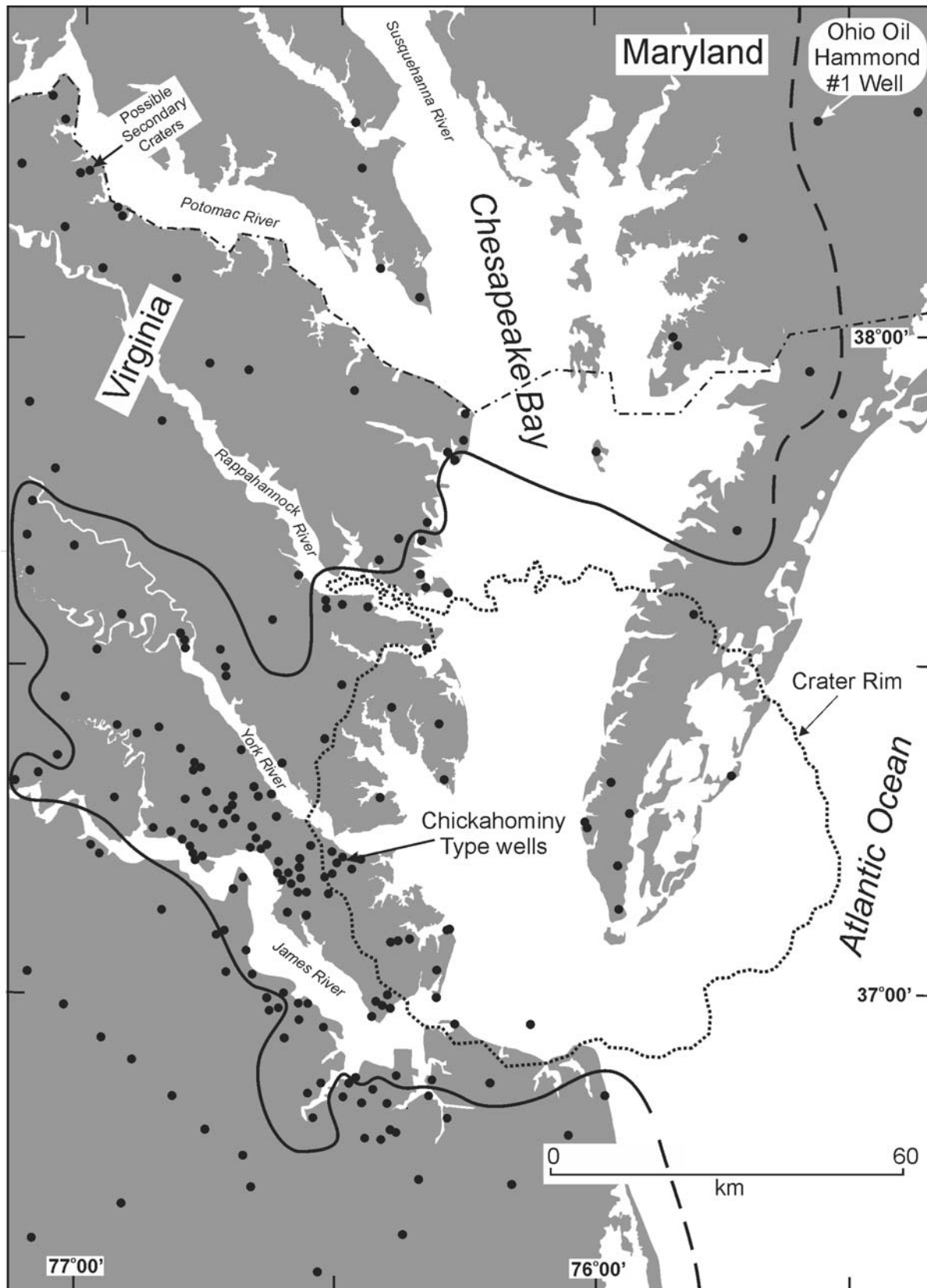
part of the Island Beach Alloformation of Poag and Ward (1993).

Nanjemoy Formation

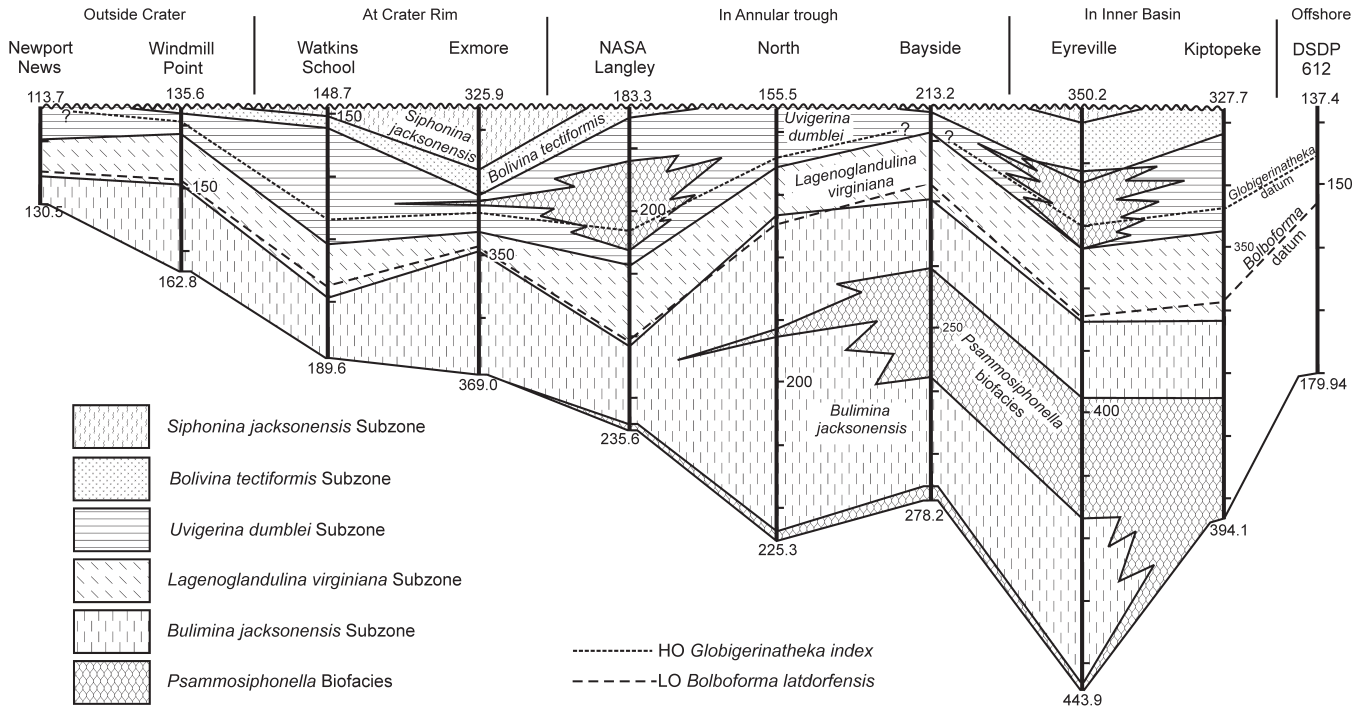
Oldest Eocene strata in Virginia belong to the lower Eocene Nanjemoy Formation (Clark and Martin 1901; text-fig. 5). Glauconitic sands with variable amounts of clay and silt characterize the Nanjemoy in outcrop (Ward 1984) and subsurface occurrences (Powars, Mixon, and Bruce 1992; Powars and Bruce 1999; Powars 2000), which extend throughout the Virginia Coastal Plain. The Nanjemoy Formation was included by Poag and Ward (1993) in the Carteret Alloformation.

Piney Point Formation

The olive-gray, clayey, poorly sorted, glauconitic, fossil-rich sand of the Piney Point Formation represents middle Eocene de-



TEXT-FIGURE 8
Location map showing distribution of boreholes (most are not cored) that delineate the areal extent of the Chickahominy Formation in the subsurface of southeastern Virginia, southern Maryland, and the Chesapeake Bay impact crater (updip limit approximated by heavy outline). Note the lack of boreholes in the southeastern part of the crater and offshore. Modified from Poag, Koeberl, and Reimold (2004).



TEXT-FIGURE 9

Vertically scaled biostratigraphic cross section (northwest to southeast) through nine coreholes from outside the crater to the inner basin. Also shown is one offshore corehole (DSDP Site 612; see text-figure 7 for location) that encountered ejecta from the Chesapeake Bay crater ~330km northeast of the crater. Correlations between one planktonic foraminiferal datum (*Globigerinatheka* index), one *Bolboforma* datum (*B. latdorfensis*), five benthic foraminiferal subzones (*Bulimina jacksonensis*, *Lagenoglandulina virginiana*, *Uvigerina dumblei*, *Bolivina tectiformis*, and *Siphonina jacksonensis*), and one benthic foraminiferal biofacies (*Psammosiphonella*) are shown. Drill depths given in meters.

position (text-fig. 5). This formation was originally described from rotary cuttings derived from a well on Piney Point, Maryland, on the Potomac River (Otton 1955). The Piney Point characteristically contains thick beds and lenses dominated by rich accumulations of oyster shells [*Cubitostrea sellaeformis* (Conrad 1832)], which are cemented into concrete-hard layers of glauconitic, bioclastic limestone. The Piney Point is best exposed on the Pamunkey River, a tributary of the York River (Virginia), but also occurs along the James River and in the subsurface (Ward 1984; Powars, Mixon, and Bruce 1992; Powars and Bruce 1999; Powars 2000). The Piney Point Formation is included in the Lindenkohl Alloformation of Poag and Ward (1993).

Unnamed upper Eocene deposits

The bulk of late Eocene deposition in Virginia is represented by the displaced megablocks and the Exmore Formation inside the Chesapeake Bay crater (text-figs. 3, 5). The presence of late Eocene foraminifers and calcareous nannofossils within the Exmore Formation, however, indicates that some late Eocene deposits of unknown lithology were already present in the target area prior to impact. A 33.5m late Eocene section of dominantly waxy marine clays (353.6-387.1m core depth) has been documented in the Ohio Oil Co. Larry G. Hammond #1 corehole near Salisbury, Maryland, 85km northeast of the crater rim (Cushman 1948a; Poag and Commeau 1995; Poag 1997a; text-fig. 7). Near the middle of this clay section is a 2.1m inter-

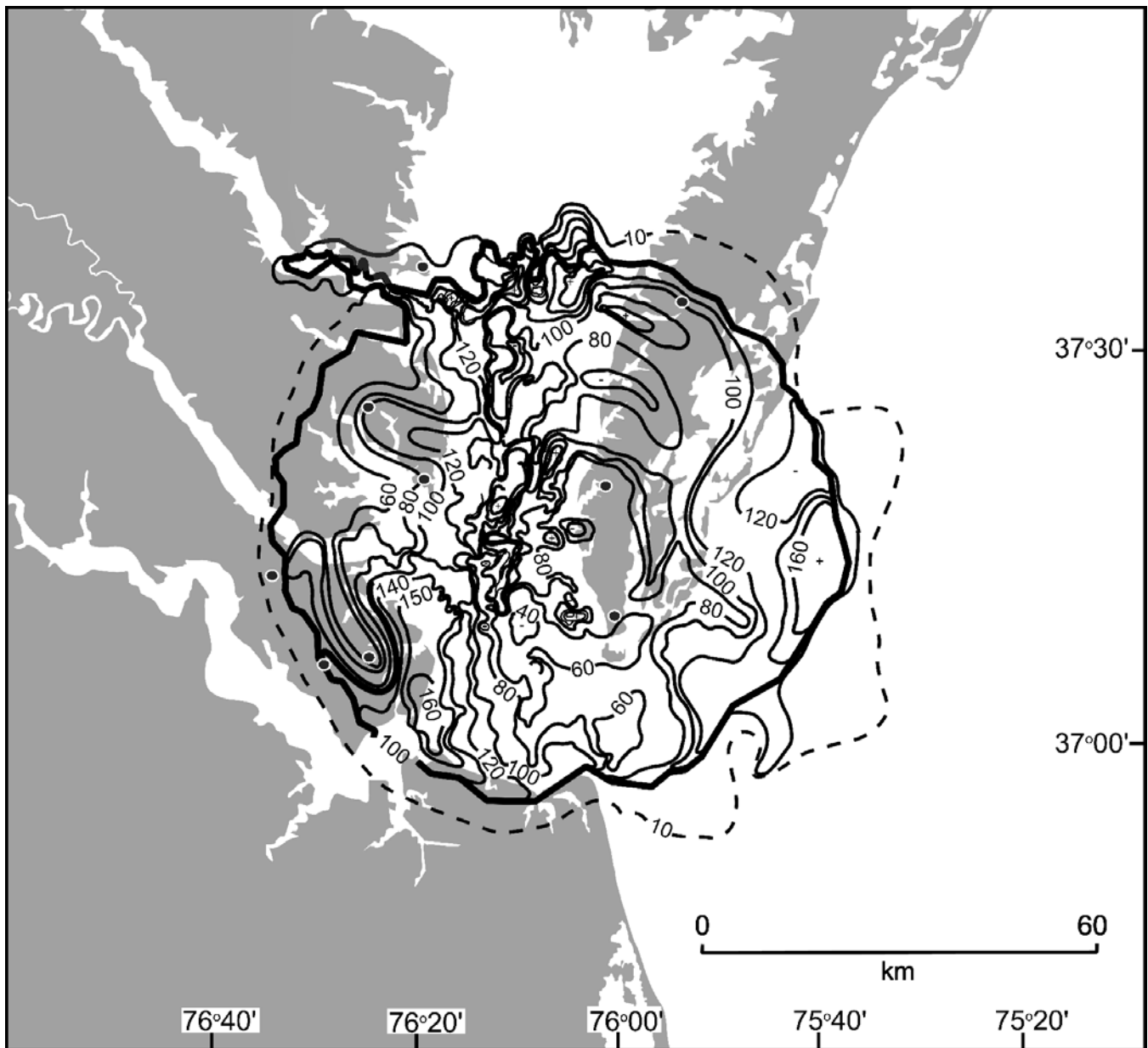
val (372.8-374.9m) of micaceous sand and clay-pebble conglomerate, which appears to be a distal product of the bolide impact (equivalent to the Exmore Formation). The whereabouts of the original Hammond core material is not known (it was drilled in 1944), and cannot be checked for diagnostic indications of impact origin. I speculate that the basal 12.2m of marine clay in the Hammond core represents preimpact deposition, the equivalent of which was removed from the Chesapeake Bay crater site by the bolide impact.

Synimpact deposits

Synimpact deposits comprise those units instantaneously emplaced (a few minutes to days; table 1) within the crater by impact-driven depositional processes. Three distinctive units make up the bulk of crater-fill material.

Shock-altered units

The deepest impact-altered unit cored to date in the Chesapeake Bay crater consists of a complex sequence of fractured mica schist, suevitic and lithic impact breccias, and clast-rich melt rocks (Gohn et al. 2008, 2009; Horton et al. 2008, 2009; Skála, Langenhorst, and Deutsch 2009; Wittmann et al. 2009; text-fig. 3). This unit records a wide range of shock deformation caused by the impact. This deepest unit has been cored only at the bottom of the deep Eyreville corehole (1397-1766m; Gohn et al. 2009).



TEXT-FIGURE 10

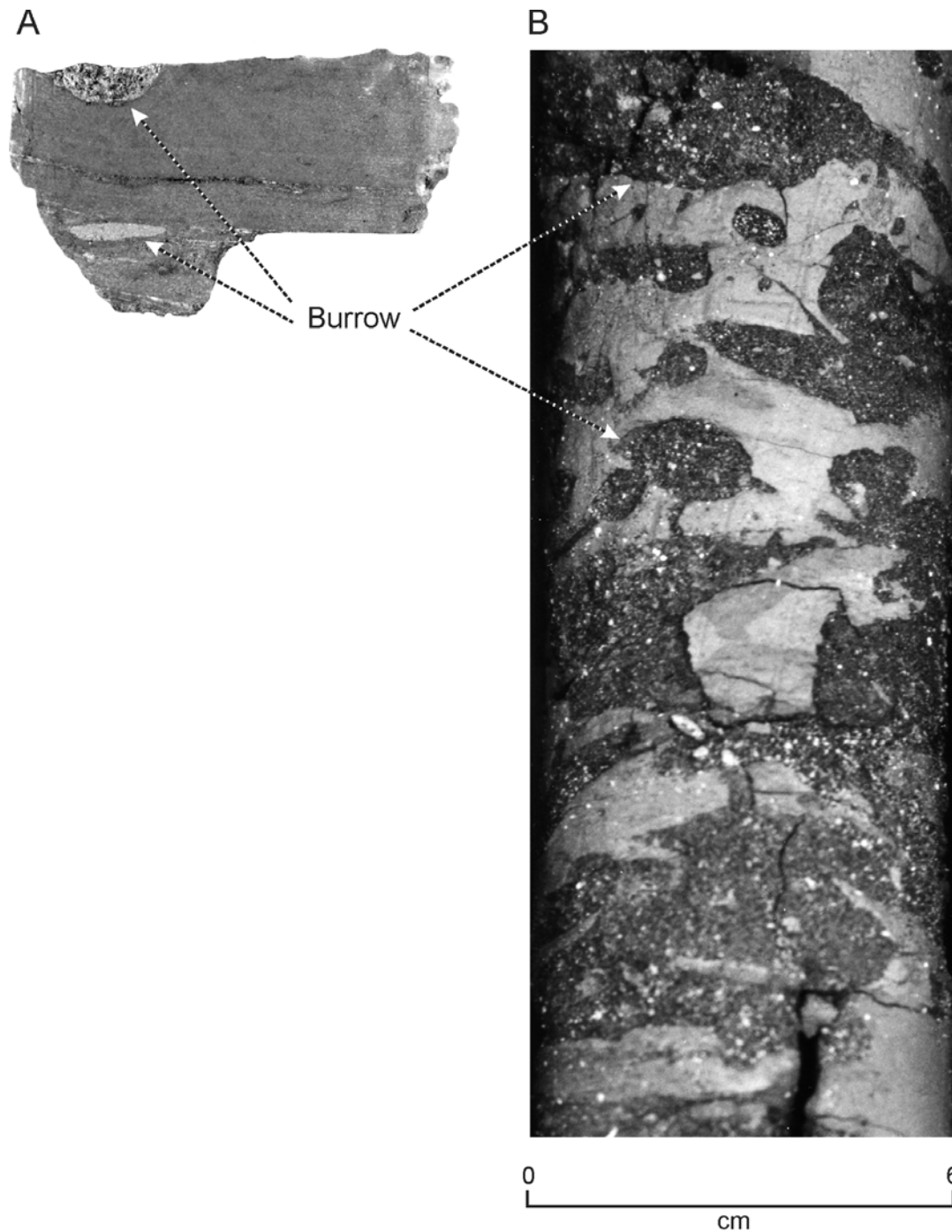
Isopach map of the Chickahominy Formation in and near the Chesapeake Bay impact crater, based on coreholes (black dots) and marine seismic-reflection profiles. Thickness given in meters. From Poag, Koeberl, and Reimold (2004)

Displaced megablocks

Above the shock-altered unit is a thick section consisting mainly of decimeter- to kilometer-scale slump and slide blocks derived primarily from early collapse and displacement of the Potomac Formation from the outer walls of the expanding crater (Poag, Koeberl, and Reimold 2004; Gohn et al. 2008, 2009; Horton et al. 2008; text-figs. 3, 5; table 1). Maximum cored thickness of the megablock section is 779m (600–1397m) at Eyreville.

Exmore Formation

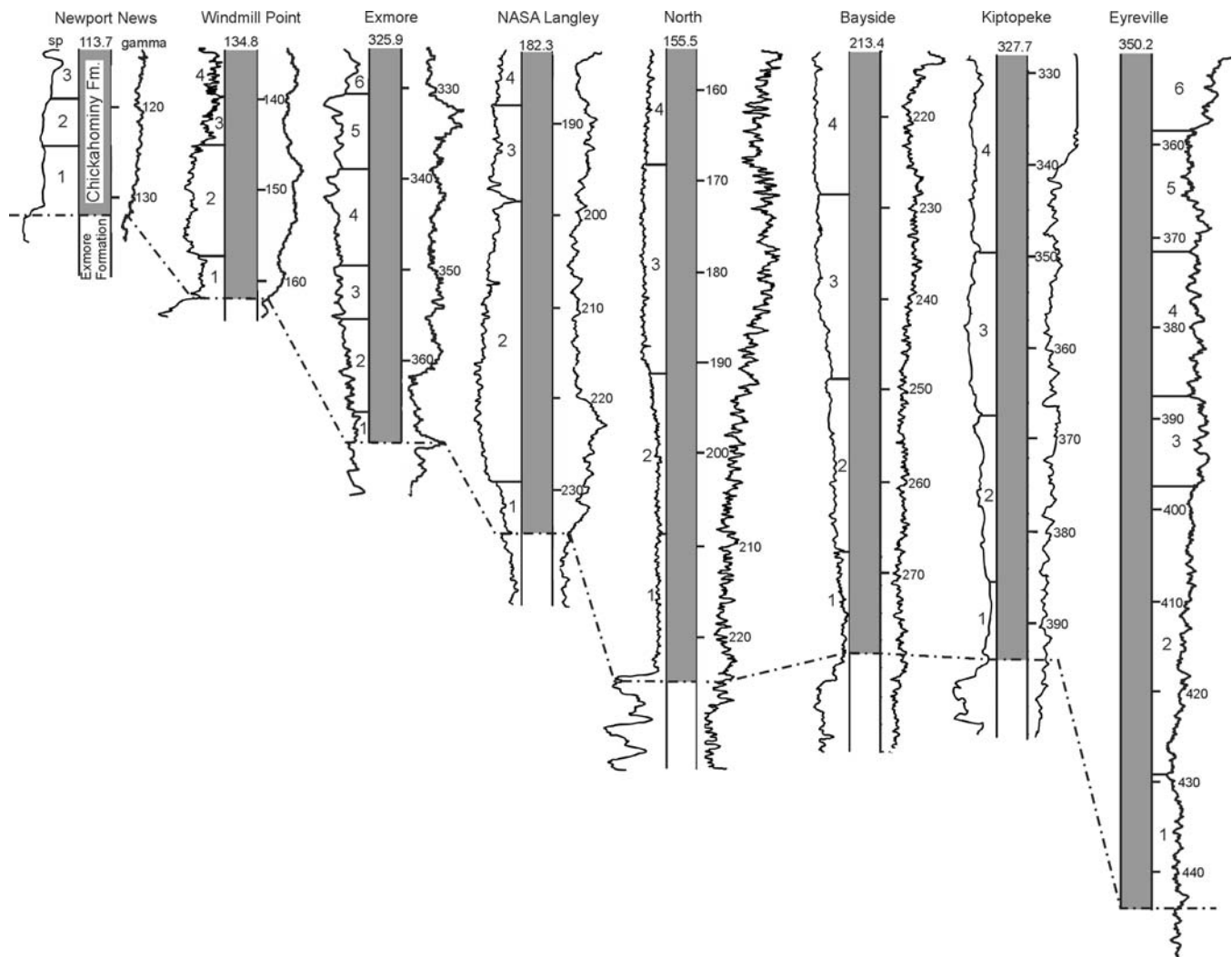
The ultimate synimpact unit in the Chesapeake Bay crater is an unusually thick deposit of impact breccia (maximum cored thickness ~230m at Eyreville site; text-figs. 3, 5; table 1). This breccia was originally informally named the Exmore breccia, after the town of Exmore, Virginia, where the deposit was first cored (Powars, Mixon, and Bruce 1992; Poag 1997a; Poag, Koeberl, and Reimold 2004; Horton et al. 2008), but Edwards et al. (2009) elevated the unit to formal status as the Exmore For-



TEXT-FIGURE 11
Photographs of burrowed core segments at the base (A, split core from NASA Langley corehole) and top (B, whole core from NASA Langley corehole) of the Chickahominy Formation.

mation. The bulk of the breccia incorporates clasts (sand-sized particles to meter-scale boulders) derived mainly from Lower Cretaceous and lower Cenozoic sedimentary strata of the target area. The breccia is supported by a poorly compacted matrix of glauconitic quartz sand derived from glauconitic Paleocene and Eocene deposits. The Exmore Formation has a complicated depositional history. Genesis of the breccia began violently, as

the bolide impact shattered the Cenozoic and Cretaceous strata beneath the late Eocene seafloor. Turbulent mixing by subsequent water-column collapse and surgeback into the crater further deformed the fragmented strata, and ultimately, runup and washback of the resultant tsunami wave-train completed the upward-fining depositional process (Poag, Koeberl, and Reimold 2004; Horton et al. 2008; Ferrell and Dypvik 2009; Gohn et al.



TEXT-FIGURE 12

Cross section of nine core sites analyzed for this study, showing downhole geophysical log patterns (SP = self potential; gamma = Gamma-ray). Gray column represents Chickahominy Formation. Self potential values increase to the left, gamma-ray values increase to the right. Note the general upward increase in gamma values at all sites as the relative volume of glauconite increases in each core. Single-digit numbered intervals are log-defined lithic subunits. Drill depths given in meters. Modified from Poag, Koeberl, and Reimold (2004).

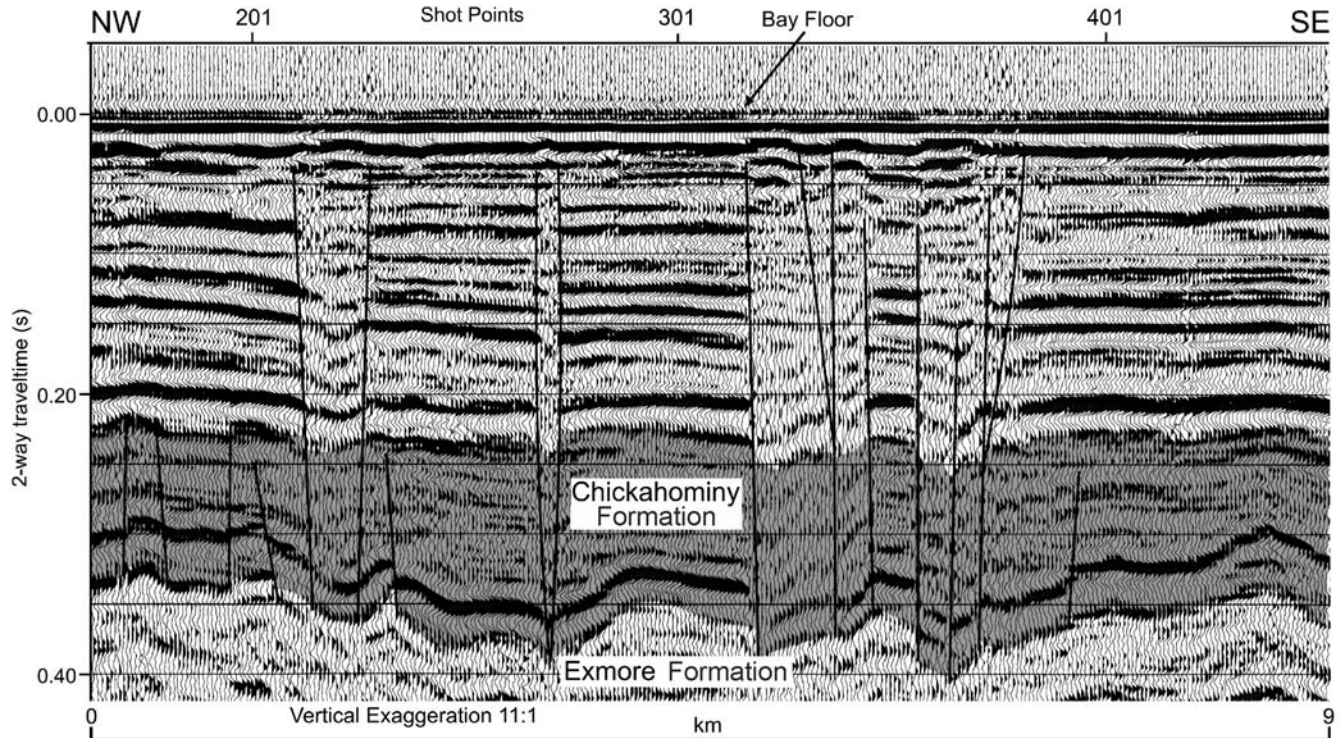
2009; Kenkmann et al. 2009; Ormö et al. 2009; Self-Trail, Edwards, and Litwin 2009). The upper surface of the Exmore Formation is horizontal to subhorizontal and relatively smooth on a kilometer scale, but is quite irregular on a scale of tens to hundreds of meters. The upper surface of the breccia is easily traceable over the entire crater, and characteristically sags into the crater along radial transects that cross the outer rim (text-figs. 3, 5). The upper boundary of the Exmore Formation, in contrast, is a gradational contact. I place the upper boundary at the level above which the sediment no longer contains impact-derived sedimentary and crystalline clasts that can be discerned with the naked eye.

In short, the Exmore Formation is a polymictic breccia, mainly matrix-supported and upward fining, the entrained clasts of which consist mostly of poorly consolidated Cenozoic sediments. Microfossils generally are common to abundant within

the Exmore matrix and constitute a stratigraphically mixed assemblage of marine and nonmarine taxa (ostracodes, planktonic and benthic foraminifera, calcareous nannofossils, dinoflagellate cysts, spores, and pollen) ranging in age from Albian to late Eocene (Poag and Aubry 1995; Poag 1997a; Poag, Koeberl, and Reimold 2004; Horton, Powars, and Gohn 2005; Self-Trail, Edwards, and Litwin 2009). The mixed assemblages are derived from the entire succession of preimpact sedimentary formations present in the target area (text-fig. 5). Individual lithic fragments ripped from each of these preimpact formations can easily be identified within the breccia by their characteristic lithologies and individual microfossil suites.

Fallout layer

A concentration of millimeter-sized, porous lattices of framboidal pyrite is present in the upper ~3cm of the laminated silt-rich interval at NASA Langley (Poag 2002b; table 1). The



TEXT-FIGURE 13

Segment of a marine seismic-reflection profile across the Chesapeake Bay impact crater, showing the variable thickness of, and location of compaction faults in, the Chickahominy Formation. From Poag, Koeberl, and Reimold (2004).

key impact-related feature of the pyrite lattices is their pore structure. Each pore is nearly perfectly spherical, ~1mm in diameter, and spatially arranged as if the lattice originally had enveloped a layer of microspherules at least three-microspherules-thick (~3-4mm). These properties are quite similar to those of impact-derived layers of glass (or glass altered to clay) microspherules (microtektites) reported from other fallout ejecta deposits (Bohor 1990; Olsson et al. 1997; French 1998). Poag (2002b), Poag, Koeberl, and Reimold (2004), and Poag and Norris (2005) inferred that the pores in the pyrite lattices originally contained glass microspherules ejected from the Chesapeake Bay crater. We speculated that after the spherules settled out as sedimentary particles, the framboidal pyrite encompassed them, like foam rubber around ball bearings. Over time, the microspherule glass dissolved, or altered to clay, which was inadvertently washed away during sample preparation. The pyrite lattices have been found only in the NASA Langley core.

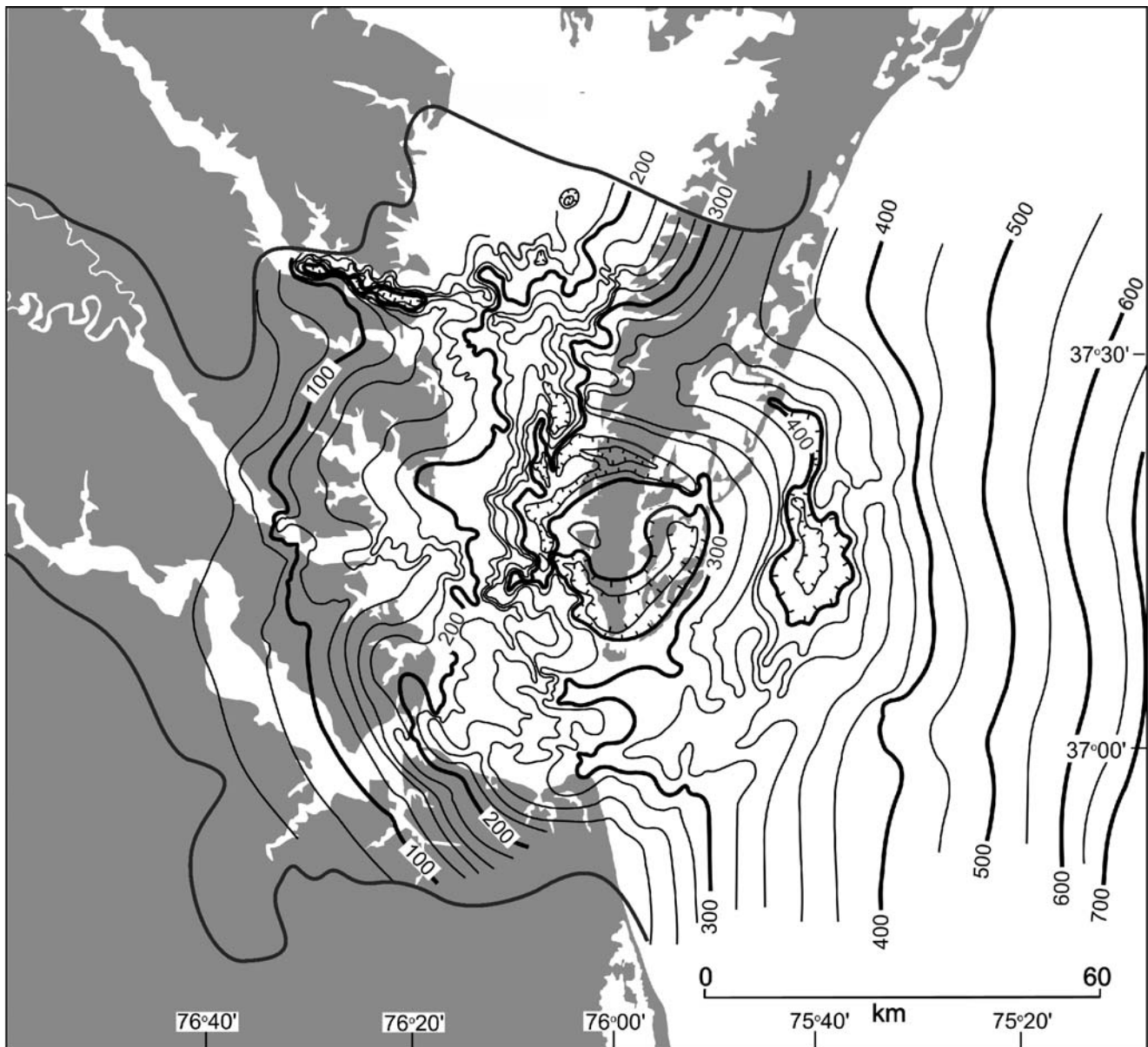
Synimpact-to-postimpact transition deposits

Between the instantaneously formed synimpact deposits and the million-year-scale postimpact formations, is a thin interval (0.4-1.7m) of two deposits, the accumulation of which can be measured in historical terms (a few years) to a short geological interval (a few kyr). These two units constitute an upward-fining succession of generally siliciclastic silts and clays, which culminate in the calcareous silty clay of the Chickahominy Formation (Poag, Koeberl, and Reimold 2004; Poag and Norris 2005; Poag 2009; table 1). This three-step transitional succession can be recognized on the basis of depositional style and bi-

otic content of the cores (Poag, Koeberl, and Reimold 2004; Poag 2009).

Step one: Flow-in

The thin interval (18-120cm in cores) immediately above the Exmore Formation consists of mainly structureless, sandy, silty clay containing white, silica- and pyrite-cemented siltstone clasts and laminae, with abundant mica, common glauconite, and rare lignite (table 1). This interval also contains a few fossil specimens (mainly benthic foraminifera) reworked from older deposits (Late Cretaceous, Paleocene, early and middle Eocene), but lacks specimens of indigenous late Eocene species. At its thickest locations in the North and Bayside cores, the flow-in deposit displays multidirectional cross lamination (Poag, Koeberl, and Reimold 2004). Poag, Koeberl, and Reimold (2004) and Poag (2007a, b; 2009) interpreted the flow-in deposit as a series of small-scale turbidites that resulted from impact-derived storm activity (possibly hypercanes; Emanuel et al. 1995; Poag 2002a), which stirred up sediments on the shallow continental shelf northwest of the crater. The flow-in unit is generally structureless (lacking cross lamination) at inner-basin sites located downdip from the North and Bayside sites. The upper boundary of the flow-in deposit is abrupt to gradational. The flow-in unit is equivalent to the lower part (Es1) of the informally cited "stratified member" (Es) of the Exmore Formation, as described in the Eyreville core by Gohn et al. (2009).



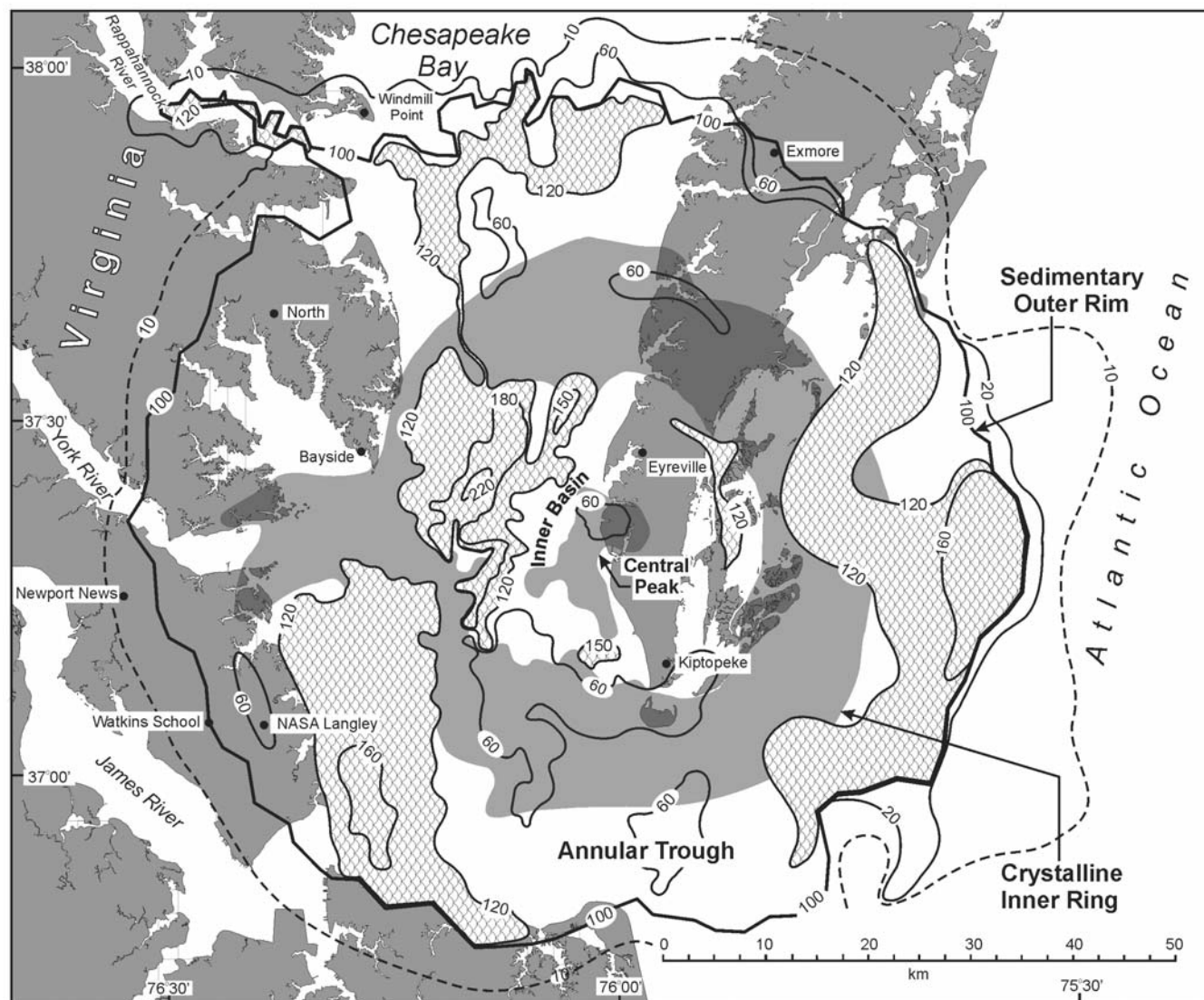
TEXT-FIGURE 14

Structure map on top of the Chickahominy Formation in and near the Chesapeake Bay impact crater, based on >2,000km of marine seismic-reflection profiles. Contour interval variable, given in meters. From Poag, Koeberl, and Reimold (2004).

Step two: Dead zone

The section comprising the dead zone (19–49cm thick) consistently displays very thin, parallel-to-subparallel, distinct-to-indistinct, regular silt/clay laminae (Poag 2009; table 1). Many of the white silt laminae are cemented by silica or pyrite, and numerous crusts (laminae?) of euhedral and framboidal pyrite are present in the sieved residues. I have interpreted the lithic properties of the dead zone to represent suspension-derived drape lamination (Poag 2009). The dead zone is present at all sites inside the crater, but is absent outside and at the crater rim (Poag, Koeberl, and Reimold 2004; Poag and Norris, 2005; Poag, 2007a, b; 2009). The dead zone is best represented at the NASA Langley core site, where its lower boundary can be determined

by the presence of the fallout layer. There, the base of the dead zone rests conformably on the layer containing pyrite lattices. The dead zone differs from the underlying silty flow-in deposit primarily in the more uniform, horizontal, parallel distribution of laminae, and the lack of nodular concentrations of pyrite (pyrite is concentrated instead in horizontal laminae). The dead zone reaches its maximum known thickness (~49cm) in the Bayside core. Microfossils are even less abundant in the dead zone than in the underlying flow-in deposit, and all specimens have been derived from older sediments (no indigenous late Eocene species represented; table 1). From the lack of indigenous microfauna, the abundance of pyrite, and the inferred relatively quiet-water deposition, Poag (2007a, b; 2009), Poag, Koeberl, and Reimold (2004), and Poag and Norris (2005) have



TEXT-FIGURE 15

Simplified isopach map (thickness in meters) of the Chickahominy Formation in and near the Chesapeake Bay impact crater, emphasizing the four thickest (>120m) sections in the largest troughs and subbasins (scalloped patterns) that make up the Chickahominy basin. Note that no corehole has yet penetrated one of these thick subbasins. Black dots indicate core sites.

inferred that unfavorable paleoenvironmental conditions excluded marine organisms from this interval. The dead zone is equivalent to the upper part (Es2) of the informally cited “stratified member” (Es) of the Exmore Formation, as described in the Eyreville core by Gohn et al. (2009).

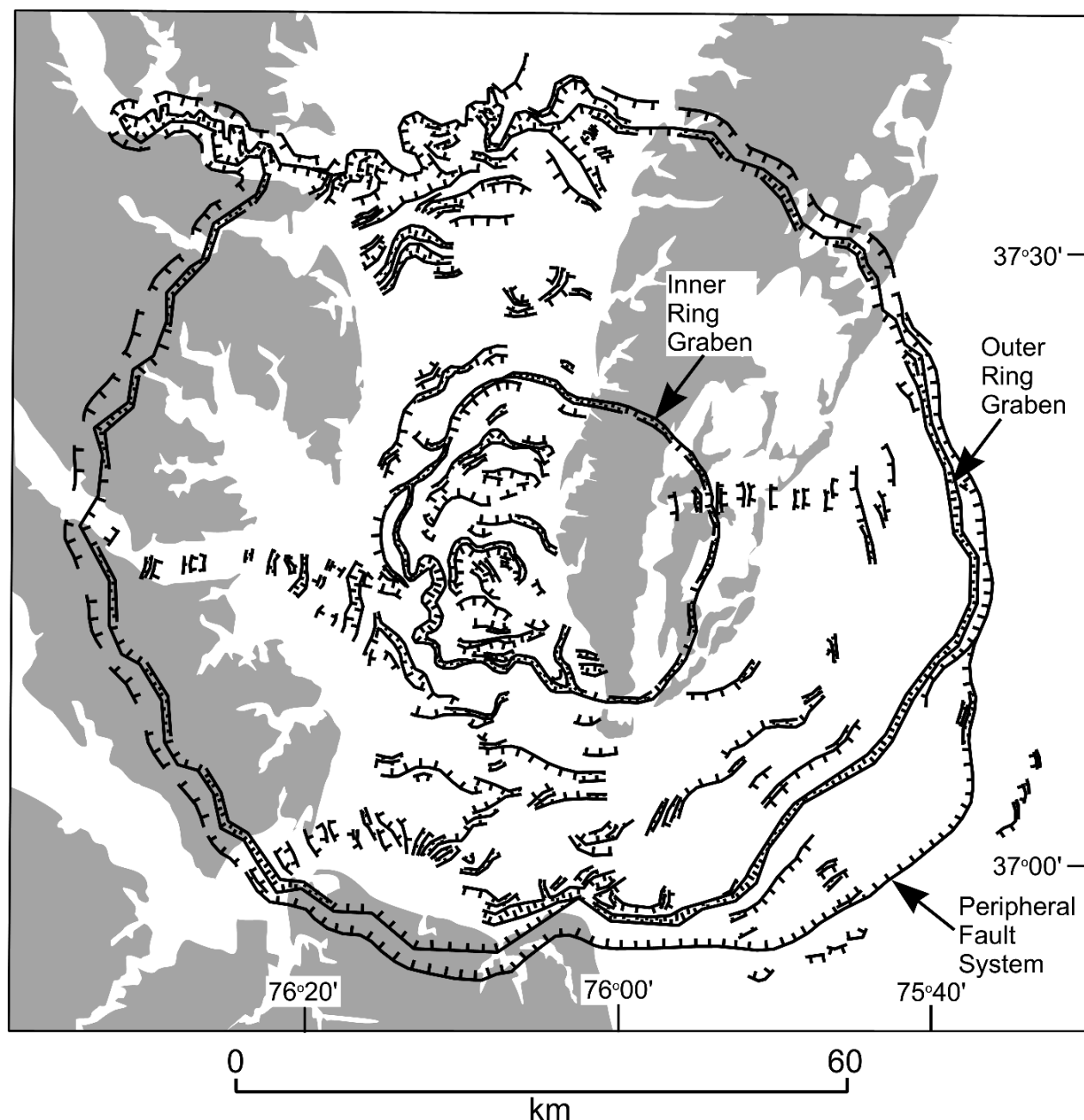
Step three: Basal Chickahominy Formation

In sharp contact above the dead zone is the base of the Chickahominy Formation, composed mainly of dark, dense, silty, sandy marine clay (table 1). Lamination is generally indistinct, but a few dark gray, horizontal, pyrite-rich laminae are present at some sites. In washed residues, pyrite is present as thin platy crusts, burrow casts, and small aggregates of framboids and euhedral crystals. In contrast to the lack of indigenous microfossils in the flow-in and dead zone deposits, the Chickahominy Formation in all nine coreholes contains a rich diversity of indigenous marine microfauna, microflora, and

nannoflora, which appear abruptly in great numbers in stratigraphically lowest Chickahominy samples at each site (Poag and Aubry 1995; Poag, Koeberl, and Reimold 2004; Edwards et al. 2005; Poag and Norris 2005). Bivalves, echinoid spines and plates, as well as fish bones, teeth, and scales are common. Specimens of the solitary coral *Flabellum* are present in fewer numbers. Örmö, Hill, and Self-Trail (2010) used carbon-isotope ratios from the Eyreville core to suggest that postimpact deposition did not begin at that site until 69cm of the Chickahominy Formation had accumulated. These authors did not acknowledge contradictory sedimentological, biostratigraphical, and paleoecological interpretations published previously (e.g., Poag 2009).

Postimpact deposits

Marine sedimentation was maintained at the crater site for the rest of Cenozoic time following deposition of the Chicka-



TEXT-FIGURE 16

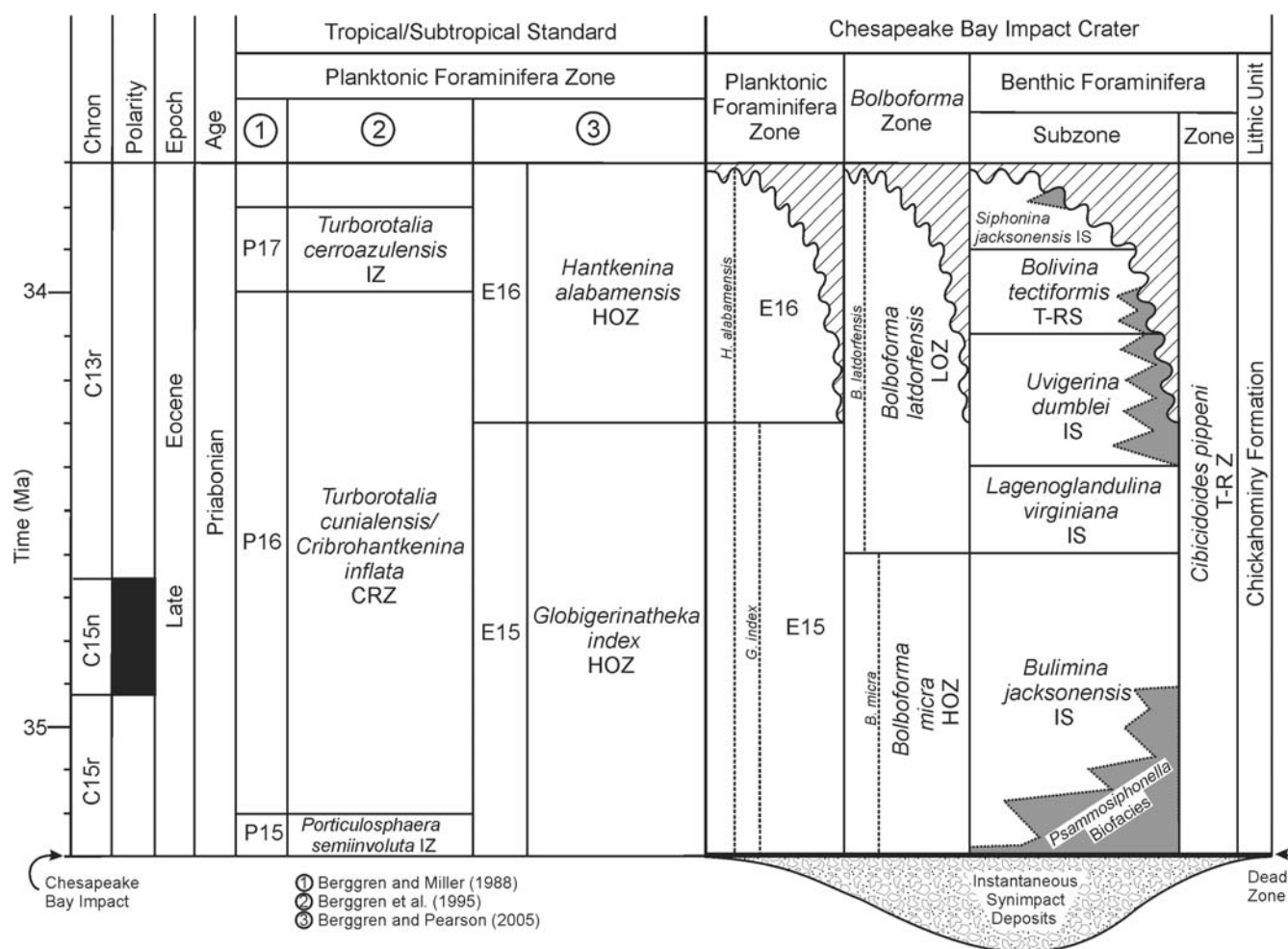
Map showing locations of principal faults and fault systems that cut the Chickahominy Formation. Fault locations based on >2,000km of marine seismic-reflection profiles. From Poag, Koeberl, and Reimold (2004).

hominy Formation, except for erosional intervals during low-stands of sealevel. The crater is now covered by 200–550m of postimpact sediments, principally siliciclastic silts and sands of marine origin (text-figs. 3, 5). The postimpact sedimentary column is thickest over the crater, because of increased accommodation space produced by differential compaction and subsidence of the water-saturated Exmore Formation (Poag 1997a). Twenty postimpact formations are formally recognized in southeastern Virginia (Powars and Bruce 1999; Poag, Koeberl, and Reimold 2004).

CHICKAHOMINY FORMATION

General nature and distribution

Cushman and Cederstrom (1945) originally described the upper Eocene Chickahominy Formation from cable-tool cuttings taken from three water wells drilled in 1942 on the grounds of the US Navy Mine Depot, Yorktown, Virginia (lat. 37°12' N; long. 76°30' W; text-fig. 8). These wells are located ~4km inside the western rim of the crater, in the annular trough. Cushman and Cederstrom (1945) designated Navy Mine Depot



TEXT-FIGURE 17

Correlation of Chickahominy biozones, subbiozones, and biofacies with three different published planktonic foraminiferal biozonation frameworks. T-RS = total-range subzone; IS = interval subzone; T-RZ = total range zone; IZ = interval zone; CRZ = concurrent range zone; HOZ = highest occurrence zone; LOZ = lowest occurrence zone. Note: *Porticulusphaera semiinvoluta* of Berggren and Miller (1988) is equivalent to *Globigerinatheka semiinvoluta* of Berggren et al. (1995) and Berggren and Pearson (2005).

wells No. 3 and No. 4 as the composite type section. Those authors combined cuttings from these two wells so that each sample they examined represented a 3.3m drilled interval. They described the lithic composition of the Chickahominy as dominantly blue, brown, and dull gray clays with abundant glauconite. They estimated the thickness of the Chickahominy Formation in wells 3 and 4 to be ~24m. Cushman and Cederstrom (1949) recorded 88 species of benthic foraminifera and four species of planktonic foraminifera from the three wells.

The Chickahominy Formation overlies either the flow-in deposit or the dead zone at all sites (uncored as well as cored) within the crater and at several extracrater sites near the crater rim (text-figs. 3, 5, 8; table 2). The Chickahominy Formation is an entirely subsurface unit, which prior to the crater drilling, was known mainly from water wells drilled into the Virginia Coastal Plain, west of the crater rim. The northwest limit of the formation forms an irregular lobate pattern. One lobe extends ~65km northwest of the crater rim, but in most other locations, where known, the formation extends no farther than ~10-15km

outside the crater rim (text-fig. 8). Notable exceptions include two isolated wells on the southern shore of the Potomac River which appear to have penetrated Chickahominy strata within small secondary craters that protected the Chickahominy sediments from later erosion (Poag, Koeberl, and Reimold 2004; text-fig. 8). The southeastern (offshore) extent of the Chickahominy Formation has not been determined, but equivalent late Eocene sediments and foraminiferal assemblages have been reported from cores in the Ohio Oil, L.G. Hammond #1 oil test well, near Salisbury, Maryland (Poag and Commeau 1995; text-figs. 7, 8). Seismostratigraphic equivalents have been documented from several offshore seismic reflection profiles (Poag, Koeberl, and Reimold 2004), but their lithic and microfossil characteristics have not yet been documented.

In the nine continuous coreholes drilled within and near the crater, the Chickahominy Formation is composed mainly of hard, massive to laminated, silty to sandy, highly fossiliferous, greenish-gray marine clay, containing variable amounts of finely comminuted or sand-size glauconite, quartz sand, and

Newport News Core									
Sample number	Sample Depth ft (m)	<i>Bolboforma micra</i>	<i>Bolboforma latdorfensis</i>	<i>Hantkenina alabamensis</i>	<i>Globigerinatheka inflata</i>	<i>Cribrohanthkenina inflata</i>	<i>Turbotallia cunialensis</i>	<i>Acarinina</i> spp.	<i>Morozovella</i> spp.
		Benthic Subzone							
		Benthic Zone							
		Planktonic Zone							
		<i>Bolboforma</i> Zone							
		Depositional unit							
		Age							
		Correlation Datum (Ma)							
14	372.05-372.30 (113.40-113.48)								
13	374.90-375.10 (114.27-114.33)								
12	378.10-378.40 (115.25-115.34)								
11	387.10-387.30 (117.99-118.05)								
10	398.70-399.00 (121.52-121.62)								
9	405.90-406.10 (123.72-123.75)								
8	414.70-415.00 (126.40-126.49)								
7	418.88-419.00 (127.68-127.71)								
6	420.88-421.00 (128.28-128.32)								
5	423.85-424.00 (129.19-129.24)								
4	426.00-426.20 (129.85-129.91)								
3	427.15-427.27 (130.20-130.23)								
2	428.00-428.20 (130.45-130.52)								
		Exmore Formation							
		Benthic Subzone							
		Benthic Zone							
		Planktonic Zone							
		<i>Bolboforma</i> Zone							
		Depositional unit							
		Age							
		Correlation Datum (Ma)							
		Olig.							
		34.2							
		34.4							
		34.6							
		Late Eocene							
		Chickahominy Fm.							
		35.3							

TEXT-FIGURE 18

Chronostratigraphic chart showing drill-depth range of *Bolboforma* and key planktonic foraminifera, and their correlations with Chickahominy biozones and subbiozones in the Newport News corehole, ~3km west of the Chesapeake Bay impact crater outer rim. X=taxon present; A=abundant specimens; C=common specimens; R=rare specimens.

mica. Silt-filled, sand-filled, and pyrite-filled burrows are common in the upper and lower few meters of the formation. Cores and seismic reflection profiles indicate that the thickness of the Chickahominy varies considerably (20-220m) across the crater (text-figs. 9, 10), compared to the more uniform thickness of most younger postimpact units. Inside the crater, Chickahominy sediments represent deep-water (outer neritic to upper bathyal) basin-fill deposits (Poag, Koeberl, and Reimold 2004). Outside the crater (to the northwest), increased quartz sand and coarse-grained glauconite, along with middle-to-outer neritic foraminifera, indicate somewhat shallower paleodepths (see further discussion in Paleoeology section herein). The presence of moderately deep-water microfaunas in its updip occurrences indicates that the Chickahominy Formation was originally much more widespread, and that much of its original landward extent has been eroded during repeated Cenozoic lowstands of sealevel. Long-term compaction and subsidence of the underlying Exmore Formation has provided accommodation space in which to accumulate and preserve a thick body of Chickahominy sediments only inside the crater. Poag and Ward (1993) included the Chickahominy Formation as part of the Baltimore Canyon Alloformation.

Core lithology

The thickest, most complete lithic records of the Chickahominy Formation come from five sites inside the crater (text-figs. 3, 9, 10, table 2): the North corehole (69.49m thick); the Bayside corehole (65.53m thick); the NASA Langley corehole (52.70m thick), the Eyreville corehole (93.8

thick), and the Kiptopeke corehole (63.4m thick). At all core sites, fresh cores of the Chickahominy Formation are typically gray-green clay that weathers to yellowish olive brown, and contains variable amounts of finely comminuted glauconite and muscovite. The clay is silty to sandy, richly fossiliferous (sand-size grains are mainly microfossils), and generally massive (bioturbated), but commonly displays fine to coarse (often faint) lamination. In some cores the Chickahominy displays burrowed horizontal surfaces or zones. The biota are mainly marine microfossils (benthic and planktonic foraminifera, calcareous nannofossils, bolboformids, ostracodes, dinoflagellates, radiolarians), but also include common to abundant remains or evidence of invertebrates (sponge spicules, echinoid spines and plates, ophiuroid plates, solitary corals, thin bivalves, scaphopods, pyritized burrow casts, fecal pellets), and vertebrates (fish bones, scales, and teeth). Sediments subjacent to the upper boundary of the Chickahominy Formation are usually intensely burrowed; those near the lower boundary are moderately burrowed. Larger burrows are filled with coarser material (sand) than the Chickahominy clay, and the upper burrows can be identified as far as two meters down into the Chickahominy. Burrows at the top of the Chickahominy are filled with glauconitic quartz sand and microfossils, which have been reworked downward from overlying Oligocene strata (text-fig. 11). At the base of the Chickahominy Formation, the smallest, most abundant burrows are filled with framboidal pyrite. The largest burrows in this basal interval are filled with quartz sand and mixed microfossil assemblages reworked upward from the Exmore Formation.

Windmill Point Core									
Sample number	Sample Depth ft (m)	<i>Bolboforma micra</i> <i>Bolboforma latdorfensis</i> <i>Hantkenina alabamensis</i> <i>Globigerinatheka index</i> <i>Cibicides inflata</i> <i>Turbostratia cunialensis</i> <i>Acarinina</i> spp. <i>Morozovella</i> spp.	Benthic Subzone	Benthic Zone	Planktonic Zone	<i>Bolboforma</i> Zone	Depositional unit	Age	Correlation Datum (Ma)
57	441.40-441.60 (134.54-134.60)	.						Olig.	
56	443.20-443.40 (135.09-135.15)	.							34
55	445.00-445.20 (135.64-135.70)	F	<i>Bolivina tectiformis</i>						
54	446.50-446.70 (136.09-136.15)	A							34.1
53	447.00-447.20 (136.25-136.31)	.							
52	449.00-449.20 (136.86-136.92)	X							
51	451.00-451.20 (137.47-137.53)	X X							
50	453.00-453.20 (138.07-138.14)	X							
49	455.00-455.20 (138.68-138.75)	.							
48	456.80-457.00 (139.23-139.29)	A A	<i>Uvigerina dumblei</i>						
47	457.00-457.20 (139.29-139.36)	X X X							34.3
46	459.00-459.20 (139.90-139.96)	X X X							
45	461.00-461.20 (140.51-140.57)	F X X							
44	462.60-462.80 (141.00-141.06)	X							
43	463.00-463.20 (141.12-141.18)	X X							34.4
42	465.00-465.20 (141.73-141.79)	C X X							
41	466.80-467.00 (142.28-142.34)	A C R							
40	467.00-467.20 (142.34-142.40)	F F							
39	470.00-470.20 (143.26-143.32)	A							
38	471.60-471.90 (143.74-143.84)	A C							
37	472.30-472.50 (143.96-144.02)	F							
36	473.29-473.56 (144.26-144.34)	C C X							
35	475.00-475.26 (144.78-144.86)	C C							
34	476.30-476.50 (145.18-145.23)	F X							
33	477.80-478.00 (145.63-145.69)	A X	<i>Lagenoglandulina virginiana</i>						
32	478.20-478.40 (145.76-145.82)	X X							
31	479.50-479.75 (146.15-146.23)	X X X							
30	480.20-480.40 (146.37-146.43)	.							
29	481.40-481.65 (146.73-146.81)	A A X							
28	483.70-483.95 (147.43-147.51)	F							
27	485.35-485.65 (147.94-148.03)	C X X							
26	488.20-488.40 (148.80-148.86)	F C A C							
25	489.75-490.00 (149.28-149.35)	X X X X							
24	490.00-490.30 (149.35-149.44)	A A X X							
23	491.75-492.00 (149.89-149.96)	X A X							34.6
22	493.45-493.70 (150.40-150.48)	X A X							
21	495.00-495.25 (150.88-150.95)	X X							
20	499.50-499.70 (152.25-152.31)	X X X							
19	500.85-501.10 (152.66-152.74)	X X X							
18	502.45-502.70 (153.15-153.22)	X X X							
17	506.15-506.40 (154.28-154.35)	.							
16	507.75-508.00 (154.76-154.84)	X							
15	509.80-510.05 (155.39-155.46)	.							
14	513.70-513.95 (156.58-156.65)	X							
13	516.00-516.25 (157.28-157.35)	X							
12	518.25-518.50 (157.96-158.04)	.							
11	522.25-522.50 (159.18-159.26)	C							
10	524.25-524.50 (159.79-159.87)	C							
9	526.25-526.50 (160.40-160.48)	C							
8	528.25-528.50 (161.01-161.09)	C X							
7	530.30-530.50 (161.64-161.70)	C X							
6	531.30-531.70 (161.94-162.06)	X							
5	532.25-532.50 (162.23-162.31)	.							
4	532.50-532.80 (162.31-162.40)	.							
3	532.70-533.10 (162.47-162.49)	.							
2	533.50-533.60 (162.61-162.64)	.							
1	534.20-534.30 (162.82-162.86)	.							35.3
		Exmore	Formation						

TEXT-FIGURE 19

Chronostratigraphic chart showing drill-depth range of *Bolboforma* and key planktonic foraminifera, and their correlations with Chickahominy biozones and subbiozones in the Windmill Point corehole, ~3km west of the Chesapeake Bay impact crater outer rim. F=few specimens; other symbols as in text-figure 18.

Watkins School Core																		
Sample number	Sample Depth ft (m)		<i>Bolboforma micra</i>	<i>Bolboforma latdorfensis</i>	<i>Hantkenina alabamensis</i>	<i>Globigerinatheka index</i>	<i>Cribrohantkenina inflata</i>	<i>Turbotallia cumalensis</i>	<i>Acarina</i> spp.	<i>Morozovella</i> spp.	Benthic Subzone	Benthic Zone	Planktonic Zone	<i>Bolboforma</i> Zone	Depositional unit	Age	Correlation Datum (Ma)	
54	485.4-485.6	(147.95-148.01)	·	X	·	·	·	·	·	·								
53	487.4-487.6	(148.56-148.62)	·	·	·	·	·	·	·	·								
52	488.2-488.4	(148.80-148.86)	·	X	X	·	·	·	·	·	<i>Siphonina jacksonensis</i>						33.8	
51	489.4-489.8	(149.17-149.29)	·	·	·	·	·	·	·	·								
50	493.0-493.4	(150.27-150.39)	·	·	·	·	·	·	·	·								
49	496.0-496.4	(151.18-151.30)	·	·	X	·	·	·	·	·	<i>Bolivina tectiformis</i>						33.9	
48	499.0-499.4	(152.10-152.22)	·	·	X	·	·	·	·	·								
47	502.0-502.4	(153.01-153.13)	·	·	·	·	·	·	·	·								
46	505.1-505.5	(153.95-154.08)	·	·	·	·	·	·	·	·	<i>Uvigerina dumblei</i>						34.1	
45	508.0-508.4	(154.84-154.96)	·	·	·	·	·	·	·	·								
44	511.0-511.4	(155.75-155.87)	·	·	·	·	·	·	·	·								
43	514.0-514.4	(156.67-156.79)	·	·	X	·	·	·	·	·								
42	517.0-517.4	(157.58-157.70)	·	·	·	·	·	·	·	·								
41	520.0-520.4	(158.50-158.62)	·	·	·	·	·	·	·	·								
40	523.2-523.6	(159.47-159.59)	·	·	X	·	·	·	·	·								
39	527.6-528.0	(160.81-160.93)	·	·	·	·	·	·	·	·								
38	531.3-531.7	(161.94-162.06)	·	·	X	·	·	·	·	·								
37	534.0-534.4	(162.76-162.85)	·	·	·	·	·	·	·	·								
36	537.0-537.4	(163.68-163.80)	·	·	X	·	·	·	·	·	<i>Cibicides pippeni</i>						34.3	
35	540.0-540.4	(164.59-164.71)	·	·	·	·	·	·	·	·								
34	543.3-543.7	(165.60-165.72)	·	·	·	·	·	·	·	·								
33	546.0-546.4	(166.42-166.54)	·	·	·	·	·	·	·	·								
32	549.0-549.4	(167.34-167.46)	·	·	·	X	·	·	·	·								
31	552.7-553.1	(168.46-168.59)	·	·	·	X	·	·	·	·								
30	556.0-556.4	(169.47-169.59)	·	·	·	·	·	·	·	·								
29	559.0-559.4	(170.38-170.51)	·	·	·	X	·	·	·	·								
28	562.0-562.4	(171.30-171.42)	·	·	·	X	·	·	·	·								
27	564.9-565.3	(172.18-172.30)	·	·	·	X	·	·	·	·								
26	568.0-568.4	(173.13-173.25)	·	·	·	X	·	·	·	·	<i>Lagenoglandulina virginiana</i>						34.4	
25	571.3-571.7	(174.13-174.25)	·	A	A	·	·	·	·	·								
24	574.9-575.3	(175.23-175.35)	R	C	X	·	·	·	·	·								
23	578.5-578.9	(176.33-176.45)	·	·	·	·	·	·	·	·								
22	581.55-581.95	(177.26-177.38)	·	A	·	·	·	·	·	·								
21	586.0-586.4	(178.61-178.74)	X	·	C	X	·	·	·	·								
20	589.0-589.4	(179.53-179.65)	·	·	X	·	·	·	·	·								
19	592.0-592.4	(180.44-180.56)	·	·	·	·	·	·	·	·								
18	595.0-595.4	(181.36-181.48)	·	·	·	·	·	·	X	·								
17	598.0-598.4	(182.27-182.39)	·	·	·	·	·	·	·	·								
16	601.0-601.4	(183.18-183.31)	·	·	·	·	·	·	·	·	<i>Bulimina jacksonensis</i>						34.6	
15	604.0-604.4	(184.10-184.22)	·	·	·	·	·	·	·	·								
14	607.0-607.4	(185.01-185.14)	·	·	·	·	·	·	·	·								
13	610.0-610.4	(185.93-186.05)	·	·	·	·	·	·	·	·								
12	612.95-613.35	(186.83-186.95)	·	·	·	·	·	·	·	·								
11	617.8-618.2	(188.31-188.43)	·	·	X	·	·	·	X	X								
10	618.87-619.0	(188.63-188.67)	X	·	·	·	·	·	X	·								
9	619.3-619.4	(188.76-188.79)	·	·	·	·	·	·	X	·								
8	619.40-619.55	(188.79-188.84)	X	·	·	·	·	·	X	·								
7	619.55-619.57	(188.84-188.85)	X	·	·	·	·	·	X	X								
6	619.57-619.68	(188.85-188.88)	·	·	·	·	·	·	X	·								
5	619.68-619.78	(188.88-188.91)	X	·	·	·	·	·	X	X								
4	621.90-622.00	(189.56-189.59)	·	·	·	·	·	·	X	X								
Exmore Formation																		35.3
Chickahominy Formation																		
Late Eocene																		
<i>Cibicides pippeni</i>																		
E15																		
E16																		
<i>Bolboforma latdorfensis</i>																		
<i>Bolboforma micra</i>																		
E15?																		

TEXT-FIGURE 20

Chronostratigraphic chart showing drill-depth range of *Bolboforma* and key planktonic foraminifera, and their correlations with Chickahominy biozones and subbiozones in the Watkins School corehole, approximately at the outer rim of the Chesapeake Bay impact crater. Symbols as in text-figure 18.

Sample number	Sample Depth ft (m)		Exmore Core						Benthic Subzone	Benthic Zone	Planktonic Zone	Bolboforma Zone	Depositional unit	Age	Corelation Datum (Ma)
			<i>Bolboforma micra</i>	<i>Bolboforma latdorfensis</i>	<i>Hankenina alabamensis</i>	<i>Globigerinatheka index</i>	<i>Cibicides inflata</i>	<i>Turbotalia cumalensis</i>							
64	1068.3-1068.5	(325.62-325.67)	-	-	-	-	-	-							
63	1068.8-1069.0	(325.77-325.83)	-	X	-	-	-	-							
62	1069.4-1069.6	(325.95-326.01)	-	X	-	-	-	-							33.75
61	1070.3-1070.5	(326.23-326.29)	-	C	-	-	-	-							
60	1071.1-1071.3	(326.47-326.53)	-	A	-	-	-	-							
59	1072.0-1072.2	(326.75-326.81)	-	-	-	-	-	-							
58	1072.9-1073.3	(327.08-327.14)	-	A	-	-	-	-							
57	1074.0-1074.2	(327.36-327.42)	-	F	-	-	-	-							
56	1075.4-1075.6	(327.78-327.84)	-	A	-	-	-	-							
55	1076.1-1076.3	(328.00-328.06)	-	F	-	-	-	-							
54	1077.8-1078.0	(328.51-328.57)	-	R	-	-	-	-							
53	1079.2-1079.5	(328.94-329.03)	-	A	-	-	-	-							
52	1080.2-1080.4	(329.25-329.31)	-	R	-	-	-	-							
51	1084.0-1084.2	(330.40-330.46)	-	X	-	-	-	-							
50	1085.7-1086.0	(330.92-331.01)	-	C	-	-	-	-							
49	1090.0-1090.2	(332.23-332.29)	-	F	-	-	-	-							
48	1091.7-1092.0	(332.75-332.84)	-	C	-	-	-	-							
47	1094.2-1094.4	(333.51-333.57)	-	F	-	-	-	-							
46	1099.0-1099.3	(334.98-335.07)	-	F	-	-	-	-							
45	1100.0-1100.2	(335.28-335.34)	-	C	-	-	-	-							
44	1104.0-1104.2	(336.50-336.56)	-	F	-	-	-	-							
43	1104.8-1105.2	(336.74-336.87)	-	C	-	-	-	-							33.9
42	1108.0-1108.2	(337.72-337.78)	-	A	-	-	-	-							
41	1112.7-1113.1	(339.15-339.27)	-	A	X	-	-	-							
40	1116.0-1116.2	(340.16-340.22)	-	C	C	-	-	-							
39	1117.5-1117.7	(340.61-340.67)	-	A	X	-	-	-							34.1
38	1120.0-1120.2	(341.38-341.44)	-	C	X	-	-	-							
37	1124.8-1125.0	(342.84-342.90)	-	A	-	-	-	-							
36	1128.0-1128.2	(343.81-344.88)	-	X	C	-	-	-							
35	1130.0-1130.2	(344.42-344.49)	-	C	X	-	-	-							
34	1134.4-1134.6	(345.77-345.83)	-	C	-	-	-	-							
33	1137.3-1137.7	(346.63-346.77)	R	A	-	-	-	-							
32	1140.0-1140.2	(347.47-347.53)	-	A	-	-	-	-							
31	1144.3-1144.5	(348.78-348.84)	-	A	X	-	-	-							
30	1148.1-1148.3	(349.94-350.00)	A	-	-	-	-	-							
29	1150.6-1150.9	(350.70-350.79)	A	F	X	-	-	-							
28	1154.0-1154.0	(351.74-351.80)	X	-	-	-	-	-							
27	1158.0-1158.2	(352.96-353.02)	X	-	X	-	-	-							
26	1159.6-1160.0	(353.45-353.57)	-	-	X	X	-	-							
25	1162.4-1162.6	(354.30-354.36)	-	-	X	-	-	-							
24	1165.8-1166.0	(355.34-355.40)	-	-	X	-	-	-							
23	1168.8-1169.0	(356.25-356.31)	-	-	X	-	-	-							
22	1171.6-1171.8	(357.10-357.17)	C	-	-	-	-	-							
21	1175.0-1175.2	(358.14-358.20)	X	-	-	-	-	-							
20	1178.2-1178.5	(359.12-359.21)	X	-	-	-	-	-							
19	1181.0-1181.2	(359.97-360.03)	-	-	X	-	-	-							
18	1184.5-1184.7	(361.04-361.10)	-	-	X	-	-	-							
17	1188.5-1188.7	(362.25-362.32)	-	-	X	-	-	-							
16	1192.2-1192.4	(363.38-363.44)	-	-	X	-	-	-							
15	1198.0-1198.2	(365.15-365.21)	X	-	X	X	-	-							
14	1201.9-1202.2	(366.34-366.43)	X	-	-	-	-	-							
13	1203.3-1203.7	(366.77-366.88)	X	-	-	-	-	-							
12	1203.7-1203.8	(366.89-366.92)	X	-	-	-	-	-							
11	1205.4-1205.7	(367.40-367.50)	X	-	-	-	-	-							
10	1207.0-1207.3	(367.89-367.96)	X	-	X	-	-	-							
9	1207.3-1207.4	(367.97-368.00)	X	-	X	-	-	X							
8	1207.5-1207.7	(368.10-368.12)	X	-	-	-	-	-							
7	1207.7-1207.9	(368.11-368.17)	X	-	-	-	-	-							
6	1208.2-1208.3	(368.26-368.29)	-	-	-	-	-	X							
5	1208.3-1208.5	(368.29-368.35)	-	-	X	-	-	-							
4	1208.7-1209.0	(368.41-368.50)	-	-	-	-	-	X	X						
3	1209.2-1209.3	(368.56-368.60)	-	-	-	-	-	X	-						
2	1209.5-1209.8	(368.66-368.75)	-	-	-	-	-	X	-						
			Exmore						Formation						35.3

TEXT-FIGURE 21

Chronostratigraphic chart showing drill-depth range of *Bolboforma* and key planktonic foraminifera, and their correlations with Chickahominy biozones and subbiozones in the Exmore corehole, approximately at the outer rim of the Chesapeake Bay impact crater. Symbols as in text-figure 18.

NASA Langley Core									
Sample number	Sample Depth ft (m)	<i>Bolboforma micra</i> <i>Bolboforma latdorfensis</i> <i>Hankenina alabamensis</i> <i>Globigerinatheka index</i> <i>Cibicides inflata</i> <i>Turbothalia cunialensis</i> <i>Acarinina</i> spp.	Benthic Subzone	Benthic Zone	Planktonic Zone	<i>Bolboforma</i> Zone	Depositional unit	Age	Correlation Datum (Ma)
68	601.3-601.5	(183.28-183.34)	X						34
67	602.15-602.35	(183.54-183.60)	X						
66	602.7-602.9	(183.70-183.76)	X						
65	603.4-603.6	(183.92-183.98)	X						
64	605.7-605.9	(184.62-184.68)	X X						
63	608.7-608.9	(185.53-185.59)	X						34.1
62	611.7-611.9	(186.45-186.60)	X						
61	614.7-614.9	(187.36-187.42)	X						
60	617.7-617.9	(188.28-188.34)	X X X						
59	620.7-620.9	(189.19-189.25)	X						
58	623.7-623.9	(190.10-190.16)	X						
57	626.8-627.0	(191.05-191.13)	X X						
56	629.8-630.0	(191.96-192.02)	X						
55	632.7-632.9	(192.85-192.91)	X						
54	635.7-635.9	(193.76-193.82)	X						
53	638.4-638.6	(194.58-194.64)	X						
52	641.0-641.2	(195.38-195.44)	X						
51	644.2-644.4	(196.35-196.41)	X						
50	647.2-647.4	(197.27-197.33)	X X X						
49	650.2-650.4	(198.18-198.24)	X						
48	653.7-653.9	(199.25-199.31)	X						
47	656.2-656.4	(200.01-200.07)	X X						
46	662.2-662.4	(201.84-201.90)	X						
45	665.2-665.4	(202.75-202.81)	X						
44	668.2-668.4	(203.67-203.73)	X X X						34.3
43	671.2-671.4	(204.58-204.64)	X X X						
42	674.2-674.4	(205.50-205.56)	X						
41	676.8-677.0	(206.29-206.35)	X						
40	680.0-680.2	(207.26-207.32)	X						
39	683.2-683.4	(208.24-208.30)	X						
38	686.1-686.3	(209.12-209.18)	X X X						34.4
37	689.1-689.3	(210.04-210.10)	X X X						
36	692.2-692.4	(210.98-211.04)	X						
35	695.2-695.4	(211.90-211.96)	X X X						
34	698.3-698.5	(212.84-212.90)	X						
33	701.1-701.3	(213.70-213.76)	X X X						
32	704.8-705.0	(214.82-214.88)	X X						
31	708.0-708.2	(215.80-215.86)	X X						
30	710.5-710.7	(216.56-216.62)	X X X						
29	720.0-720.2	(219.46-219.52)	X						
28	723.0-723.2	(220.37-220.43)	X						
27	726.4-726.6	(221.41-221.47)	X X X						
26	729.0-729.2	(222.20-222.26)	X X X						34.6
25	732.2-732.4	(223.18-223.24)	X X						
24	735.1-735.3	(224.06-224.12)	X						
23	737.96-738.16	(224.93-224.99)	X X						
22	741.0-741.2	(225.86-225.93)	X						
21	743.9-744.1	(226.74-226.80)	X						
20	747.0-747.2	(227.69-227.75)	X						
19	750.0-750.2	(228.60-228.66)	X						
18	753.0-753.2	(229.51-229.57)	X						
17	756.1-756.3	(230.46-230.52)	X						
16	759.3-759.5	(231.44-231.50)	X						
15	762.0-762.2	(232.26-232.32)	X						
14	764.95-765.15	(233.16-233.22)	X						
13	768.1-768.3	(234.12-234.18)	X						
12	770.7-770.8	(234.91-234.94)	X						
11	772.6-772.7	(235.49-235.52)	X						
10	772.90-773.05	(235.58-235.63)	X						
9	773.05-773.20	(235.63-235.67)	X						
8	773.20-773.35	(235.67-235.72)	X						
7			Dead	Zone					35.3

TEXT-FIGURE 22

Chronostratigraphic chart showing drill-depth range of *Bolboforma* and key planktonic foraminifera, and their correlations with Chickahominy biozones and subbiozones in the NASA Langley corehole, in the annular trough of the Chesapeake Bay impact crater. Symbols as in text-figure 18.