The Geological Society of America
Special Paper 458
2009

Postimpact deposition in the Chesapeake Bay impact structure: Variations in eustasy, compaction, sediment supply, and passive-aggressive tectonism

Andrew A. Kulpecz*
Kenneth G. Miller
James V. Browning
Department of Geological Sciences, Rutgers University, Piscataway, New Jersey 08854, USA

Lucy E. Edwards
David S. Powars
U.S. Geological Survey, 12201 Sunrise Valley Drive, Reston, Virginia 20192, USA

Peter P. McLaughlin Jr.
Delaware Geological Survey, 257 Academy Street, Newark, Delaware 19716, USA

Ashley D. Harris
Mark D. Feigenson
Department of Geological Sciences, Rutgers University, Piscataway, New Jersey 08854, USA

ABSTRACT

The Eyreville and Exmore, Virginia, core holes were drilled in the inner basin and annular trough, respectively, of the Chesapeake Bay impact structure, and they allow us to evaluate sequence deposition in an impact crater. We provide new high-resolution geochronologic (<1 Ma) and sequence-stratigraphic interpretations of the Exmore core, identify 12 definite (and four possible) postimpact depositional sequences, and present comparisons with similar results from Eyreville and other mid-Atlantic core holes. The concurrence of increases in $\delta^{18}O$ with Chesapeake Bay impact structure sequence boundaries indicates a primary glacioeustatic control on deposition. However, regional comparisons show the differential preservation of sequences across the mid-Atlantic margin. We explain this distribution by the compaction of impactites, regional sediment-supply changes, and the differential movement of basement structures. Upper Eocene strata are thin or missing updip and around the crater, but they thicken into the inner basin (and offshore to the southeast) due

*Current address: Chevron Energy Technology Company, 1500 Louisiana St., Houston, Texas 77002, USA.

Kulpecz, A.A., Miller, K.G., Browning, J.V., Edwards, L.E., Powars, D.S., McLaughlin, P.P., Jr., Harris, A.D., and Feigenson, M.D., 2009, Postimpact deposition in the Chesapeake Bay impact structure: Variations in eustasy, compaction, sediment supply, and passive-aggressive tectonism, *in* Gohn, G.S., Koeberl, C., Miller, K.G., and Reimold, W.U., eds., The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes: Geological Society of America Special Paper 458, p. 811–837, doi: 10.1130/2009.2458(34). For permission to copy, contact editing@geosociety.org.

to rapid crater infilling and concurrent impactite compaction. Oligocene sequences are generally thin and highly dissected throughout the mid-Atlantic region due to sediment starvation and tectonism, except in southeastern New Jersey. Regional tectonic uplift of the Norfolk Arch coupled with a southward decrease in sediment supply resulted in: (1) largely absent Lower Miocene sections around the Chesapeake Bay impact structure compared to thick sections in New Jersey and Delaware; (2) thick Middle Miocene sequences across the Delmarva Peninsula that thin south of the Chesapeake Bay impact structure; and (3) upper Middle Miocene sections that pinch out just north of the Chesapeake Bay impact structure. Conversely, the Upper Miocene–Pliocene section is thick across Virginia, but it is poorly represented in New Jersey because of regional variations in relative subsidence.

INTRODUCTION

Statement of Purpose

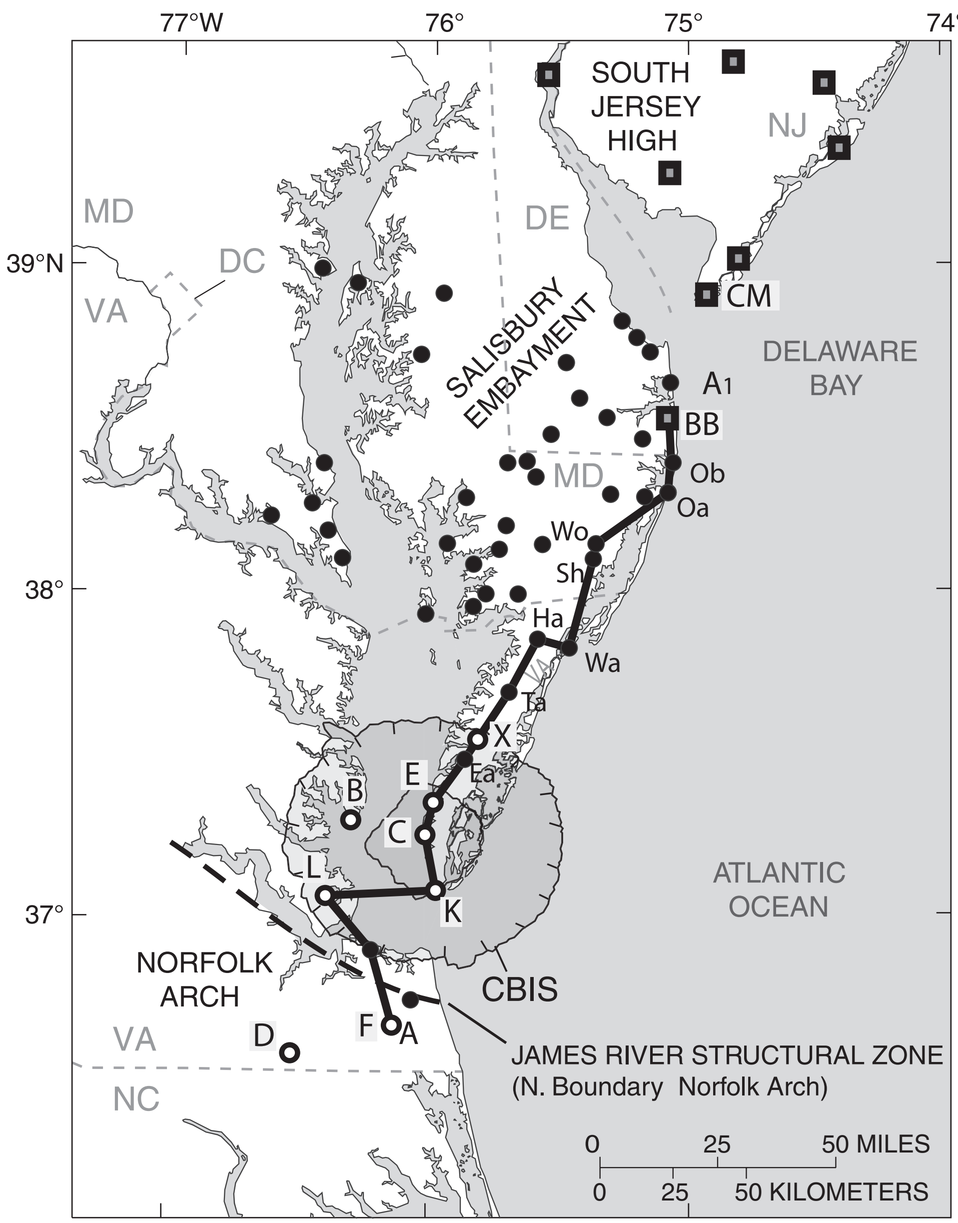
The late Eocene Chesapeake Bay impact structure has been the focus of numerous geological and geophysical studies since its discovery by Poag et al. (1994). Numerous core holes drilled within the annular trough (e.g., Exmore, Langley, Kiptopeke; Fig. 1) by the U.S. Geological Survey (USGS) and Virginia Department of Environmental Quality have penetrated both postimpact and synimpact deposits (e.g., Powars and Bruce, 1999; Powars, 2000; Horton et al., 2005a). However, these drill sites (Fig. 1) generally lack high-resolution (million-year-scale) geochronology, limiting our full understanding of the influence of the Chesapeake Bay impact structure on postimpact sedimentation. Previous sites in the inner basin were either restricted to the rim (Kiptopeke, Fig. 1) or were not continuously cored (Cape Charles, which was drilled on the central uplift), limiting our understanding of the deposition of the thickest postimpact strata that accumulated in the inner basin. The Eyreville core hole provides a thick, continuously cored section within the inner basin, and it provides a critical point of comparison to core holes in the annular trough and contemporaneous sequences across the mid-Atlantic Coastal Plain (Virginia to New Jersey). The comparison of Chesapeake Bay impact structure and regional sequences enables the differentiation of global signals (glacioeustasy), regional processes (regional tectonism and sediment-supply variations), and impact-related effects (e.g., impactite compaction) on the postimpact late Eocene to Pleistocene sedimentary record.

Geologic Framework of the Chesapeake Bay Impact Structure

The late Eocene (35.4 ± 0.1 Ma; Horton and Izett, 2005; Pusz et al., 2009) Chesapeake Bay impact structure is a remarkably intact 85–90-km-diameter crater that underlies the Chesapeake Bay area and lower Delmarva Peninsula in southeastern Virginia, USA (Fig. 1; Poag et al., 1994, 2004; Powars and Bruce, 1999). The Chesapeake Bay impact structure is a complex “inverted sombrero” impact structure, consisting of a central peak ringed by a 38-km-wide inner basin, 24-km-diameter annular trough, and extensive outer fracture zone (Figs. 1 and 2; Poag et al., 1994; Powars and Bruce, 1999; Powars, 2000). The impact structure, one of only a handful of well-preserved marine-impact structures, formed when a 2–3-km-diameter bolide impacted the continental shelf (Poag et al., 2004; Sanford et al., 2004). Following impact, the crater catastrophically infilled with impactites, megablock breccias, and tsunamites, which were subsequently buried by passive-margin sediments (Poag et al., 1994; Powars and Bruce, 1999). Postimpact sediments consist of 200–550 m of Upper Eocene to Holocene marine shelf and coastal-plain sediments that thicken into the impact structure (Fig. 2) (Powars and Bruce, 1999; Poag et al., 1994, 2004).

Scientific investigation of the Chesapeake Bay impact structure dates back to its discovery by Poag et al. (1994). The U.S. Geological Survey (USGS) and the Virginia Department of Environmental Quality cooperatively drilled a series of core holes (Fig. 1), including Exmore, Kiptopeke, Bayside, Cape Charles, Dismal Swamp, Fentress, and Langley (the latter was a cooperative project with the Hampton Roads Planning District Commission), that penetrated both synimpact and postimpact sections. All previous boreholes were drilled in the annular trough, except for the Kiptopeke core hole, which was drilled on the southern rim of the inner basin, and the Cape Charles borehole, which partially cored impactites on the central uplift (Horton et al., 2005b). Although previous studies examined postimpact strata within the annular trough (e.g., Powars, 2000; Horton et al., 2005a), the scarcity of continuous core and associated data in the inner basin limited our understanding of craterwide evolution. Furthermore, a majority of previous interpretations focused on regional mapping (e.g., lithostratigraphic and hydrogeologic units) and had only broad biostratigraphic age control with limited isotopic data (e.g., Powars et al., 1992; Powars and Bruce, 1999; Powars, 2000; Poag, 1997, 2000). Thus, these previous studies lacked high-resolution chronostratigraphic analysis and therefore provided limited information on temporal correlations and the processes that shaped the evolution of postimpact strata. Detailed biostratigraphic work from the recently completed Langley core hole in the western annular trough (Fig. 1; Powars et al., 2005; Edwards et al., 2005) offers an excellent point of calibration to the inner basin at Eyreville.

Cooperative drilling of the Eyreville core holes (funded by the International Continental Scientific Drilling Project [ICDP], USGS, and the National Aeronautics and Space Administration [NASA]) was completed in May 2006, and it provides the thickest complete postimpact section (~444 m) from the inner basin (Fig. 2). Eyreville A (37°19′16.81″N, 75°58′31.89″; elevation 8 ft; Northampton County, Virginia, USGS 7.5 min quadrangle) was continuously cored by Major Drilling under contract from DOSECC in fall of 2005 from 126.89 m to a total depth of 1766 m top, with the base of the postimpact section at 443.88 m (diameter of 8.4 cm with a rock shoe and 7.6 cm with an extended shoe). Eyreville C was continuously cored by the USGS Eastern Earth Surface Processes Team (EESPT) within 10 m of core A in April–May, 2006 from land surface to 139.57 m, overlapping the section cored in core A (core diameter of 6.1 cm with a rock shoe and 5.3 cm with a snout shoe). Recovery was excellent from the postimpact section of core A (95.9% recovered) and good from core C (69.1%), which was hampered by coarser-grained facies. A full suite of geophysical logs was obtained from core C, but only gamma logs and temperature logs through the rods were obtained from core A due to borehole stability problems. The postimpact section of the Eyreville core holes is described for lithostratigaphy by Edwards et al. (this volume) and for sequence



Base from U.S. Geological Survey
Digital Line Graph 1:2,000,000, 1990

Figure 1. Location map of the mid-Atlantic margin showing the distribution of core holes and geophysical logs used in this study. Open gray dots with black outline represent U.S. Geological Survey (USGS) core holes, gray-filled boxes represent Ocean Drilling Program (ODP) 150X and 174AX core holes, and black dots represent geophysical logs. Core holes used in this study are further identified by letter: E—Eyreville (Browning et al., this volume; Edwards et al., this volume; Gohn et al., 2008); X—Exmore; K—Kiptopeke; F—Fentress; D—Dismal Swamp (Powars and Bruce, 1999); C—Cape Charles (Gohn et al., 2007); B—Bayside (Horton et al., 2008); L—Langley (Horton et al., 2005a); CM—Cape May (Sugarman et al., 2007); and BB—Bethany Beach (Browning et al., 2006). Well logs shown in Figure 3 are identified by letters; Ea—Eastville; Ta—Tasley; Ha—Hallwood; Wa—Wallops Island; Sh—Snow Hill; Wo—Wor-Dd80; Oa—Ocean City C30A; and Ob—Ocean City C43B. The regional transect (Fig. 3) is represented by the thick black line that runs from A to A_1. Figure 2 is represented by the same line but depicts mainly the core holes and wells within the Chesapeake Bay impact structure (CBIS). The outline of the Chesapeake Bay impact structure is modified from Powars and Bruce (1999). The base map is adapted from USGS (1990) digital line graph at 1:2,000,000 scale.

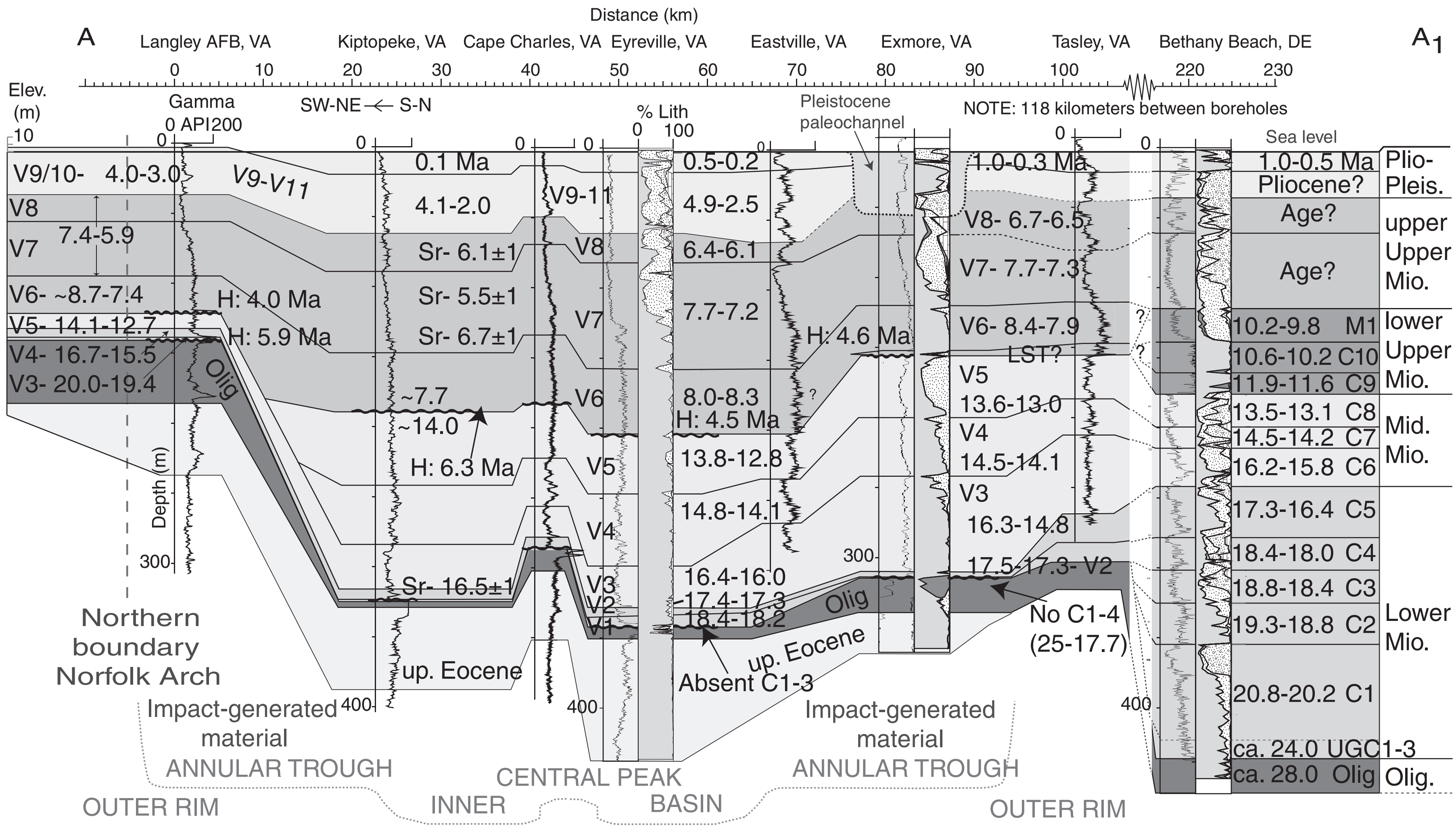


Figure 2. Core hole and well-log cross section from Langley, Virginia, to Bethany Beach, Delaware (A–A1) modified from Gohn et al. (2008). Bethany Beach (Browning et al., 2006), Langley, Kiptopeke, Cape Charles, and Exmore are core holes; Eastville and Tasley are gamma-ray logs. Sequence ages based on age-depth plots primarily using Sr isotopes. Sequences C1–C10 and M1 were defined at Bethany Beach (Browning et al., 2006); V1–V11 were identified at Eyreville and Exmore (this study; Browning et al., this volume). Thin black lines represent sequence boundaries. Thick, wavy black lines indicate coalesced sequence boundaries (unconformities) at which one or more sequences are absent. The numbers after the letter "H" represent the duration of the hiatus across these surfaces. Age ranges at Langley and Kiptopeke are established from biostratigraphy (Edwards et al., 2005; Powars and Bruce, 1999) and are coarser in resolution than Eyreville, Exmore, and Bethany Beach. Ages denoted by "Sr" represent single Sr age estimates from Powars and Bruce (1999). Lithologic columns are coded by the following shades and patterns: large and small dots—coarse quartz sand; small, closely spaced dots—fine quartz sand; box-like pattern—carbonate sand; light gray—silt and clay; dark gray—glauconite sand; and jet black—mica or other. The underlying diagram of the Chesapeake Bay impact structure is not to scale and is only intended to show the position of postimpact sequences relative to crater morphology. Note the change in transect orientation at Kiptopeke from W-E to SW-NE (see Fig. 1). The Eastville and other regional paleovalleys (e.g., modern Chesapeake Bay) are not shown on our regional transect.

stratigraphy and chronostratigraphy by Browning et al. (this volume). Drilling of the Eyreville core holes provided the impetus for this study to closely reexamine the Exmore core hole in the annular trough (Fig. 1) and evaluate other core holes and water wells in the region to expand the regional correlations.

Sequence Stratigraphy and Controls on Mid-Atlantic Margin Deposition

We use sequence stratigraphy, the subdivision of the stratigraphic record into genetically related units bounded by unconformities and their correlative conformities (e.g., Mitchum et al., 1977; Posamentier et al., 1988; Miller et al., 1997), to recognize depositional sequences and present the first continuous, high-resolution (~1 Ma) chronostratigraphic record from the Chesapeake Bay impact structure annular trough (Exmore core; this study) and inner basin (Eyreville core; Browning et al., this volume). Because sequence boundaries form in response to base-level decreases, sequence-stratigraphic analysis of these core holes enables the first process-based evaluation of the mechanisms that shaped the postimpact record, namely: (1) global sea-level changes; (2) variations in sediment supply; (3) regional tectonism (uplift and subsidence); and (4) crater-specific processes (e.g., basement cooling and related subsidence, differential compaction of impact-generated crater sediments, movement of crater-related faults).

Extensive drilling of the New Jersey shelf slope (Ocean Drilling Program [ODP] Legs 150 and 174A) and coastal plain (ODP Legs 150X and 174AX) identified 33 Cenozoic sequences and linked Middle Eocene–Miocene sequence boundaries with $\delta^{18}O$ increases, implicating a glacioeustatic control (e.g., global changes in ice volume) on sequence-boundary genesis (Miller et al., 1998, 2005). These glacioeustatic variations determined the template of available sequences on the Atlantic margin through changes in base level and accommodation (Miller et al., 2005; Browning et al., 2006). However, significant differences in sequence preservation across the southern mid-Atlantic margin reveal the scale and timing (e.g., tens of meters in 1–5 Ma) of other regional and local mechanisms that have influenced the stratigraphic record (Browning et al., 2006).

The cores within the Chesapeake Bay impact structure also provide expanded Upper Eocene through Pliocene sections useful for assessing the influence of noneustatic and thermoflexural (i.e., accommodation made by the flexural coupling of unheated crust to an offshore thermally subsiding basin; Kominz et al., 1998) mechanisms on deposition (Fig. 3). The mid-Atlantic Coastal Plain from northern North Carolina to New Jersey is underlain by a series of alternating crystalline basement embayments and arches (e.g., from south to north: Cape Fear Arch, Albemarle Embayment, Norfolk Arch, Salisbury Embayment, South Jersey High, and Raritan Embayment). The embayments extend inland from the offshore Baltimore Canyon Trough (Fig. 1; Brown et al., 1972; Olsson et al., 1988). Though differential movement of these embayments and arches may have occurred, whether by "wrench tectonic faulting" of Brown et al. (1972) or regional warping of "rolling basins" of Owens et al. (1997), or other mechanisms (Browning et al., 2006), their origin and nature remain unclear. This study attempts to document the timing and influence of these regionally significant basement structures on deposition, and we speculate on possible tectonic controls behind tectonic uplift.

Scientific Objectives

The main objectives of this study are: (1) to provide a high-resolution record of sequences at the Exmore core hole within the Chesapeake Bay impact structure annular trough; (2) compare the Exmore record with similar results from the inner basin at Eyreville (Browning et al., this volume); (3) extend correlations from Exmore and Eyreville to Delaware and northern North Carolina using well logs and age control; and (4) gain insight into the processes that have controlled sequence development within the Chesapeake Bay impact structure and across the greater mid-Atlantic margin. This study builds on the lithostratigraphic descriptions (Edwards et al., this volume) and sequence-stratigraphic framework (Browning et al., this volume) from the Eyreville core hole. We also incorporate results from previous studies at Exmore, Virginia (Powars et al., 1992; Powars and Bruce, 1999; Powars, 2000), Bethany Beach, Delaware (ODP Leg 174AX; Miller et al., 2003; Browning et al., 2006), Langley, Virginia (Horton et al., 2005a; Edwards et al., 2005; Powars et al., 2005), and several New Jersey core holes (Miller et al., 2005). We provide new sequence-stratigraphic interpretations from the Exmore core hole (currently archived at the Rutgers Rift-Drift Core Repository, http://geology.rutgers.edu/corerepository.shtml). We use numerous geophysical logs, USGS core holes (Powars et al., 1992; Powars and Bruce, 1999), and state geological survey reports to extend regional sequence correlations across the mid-Atlantic Coastal Plain (Fig. 3).

METHODS

Sequence Stratigraphic Analysis of the Exmore Core Hole

In this study, sequence-stratigraphic analyses of the USGS Exmore core hole are used to identify sequence boundaries, systems tracts, critical surfaces (e.g., maximum flooding surfaces [MFS], flooding surfaces [FS], etc.), and lithofacies patterns. The Exmore core hole was drilled by the USGS in 1986 and is located in the northern Chesapeake Bay impact structure annular trough several kilometers south of the outer rim (Fig. 1; 37°35′08″N, 75°44′09″W, 9.1 m ground surface elevation, 416.5 m total depth), making it an ideal point of comparison between Chesapeake Bay impact structure sequences and those established in New Jersey and Delaware. The Exmore core was stored at the USGS repository in Reston, Virginia, before relocation to Rutgers University in 2006 (the long duration of storage resulted in the drying out of most sandy intervals, complicating interpretations).

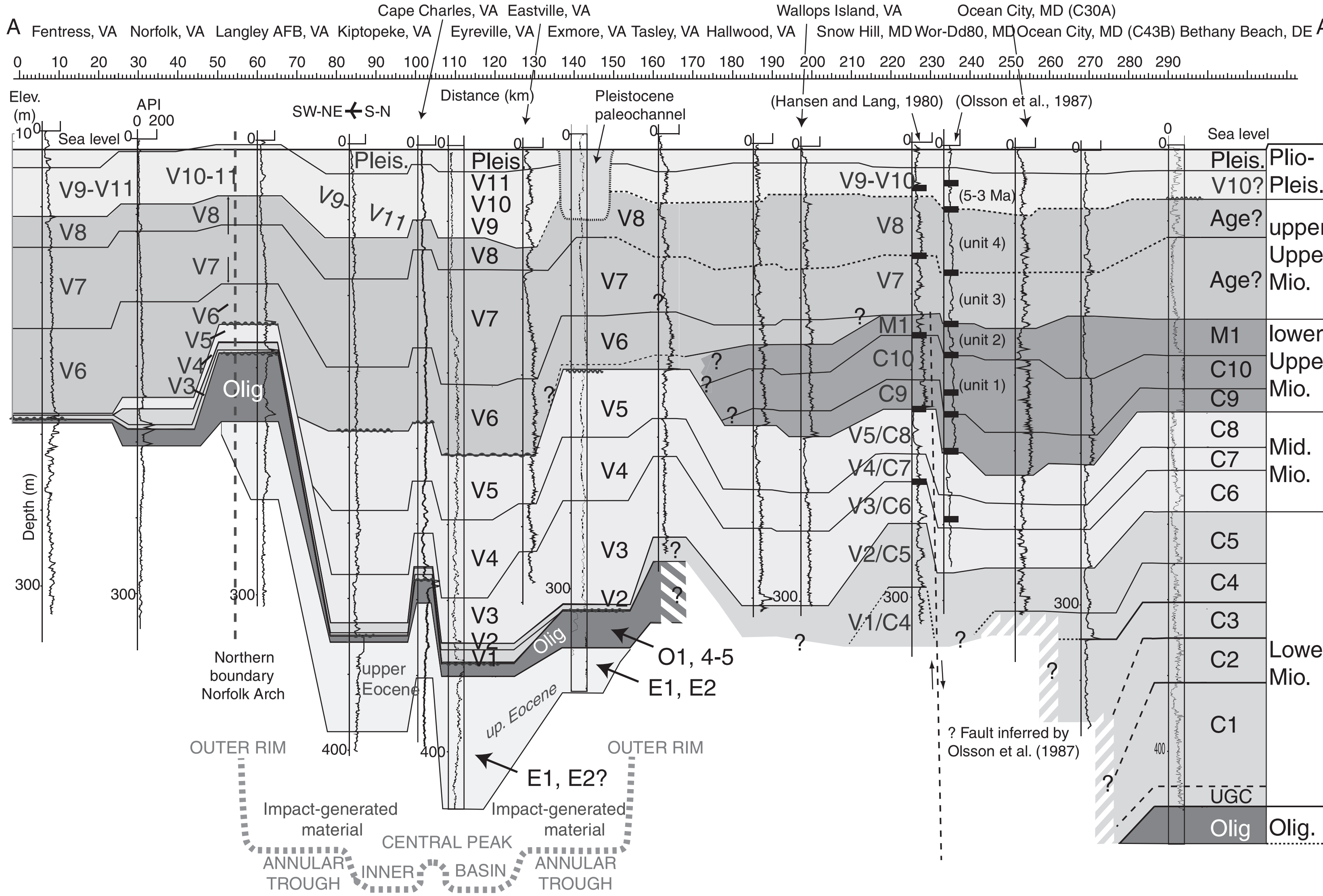


Figure 3. Regional core hole and well-log transect from Fentress, Virginia, to Bethany Beach, Delaware (A–A$_1$) showing Oligocene-Pleistocene sequence distribution as defined at the Bethany Beach (Browning et al., 2006), Eyreville (Browning et al., this volume), and Exmore core holes (this study). We used published reports to supplement correlations outside the crater (e.g., Powars and Bruce, 1999; Olsson et al., 1987). Thin black lines represent sequence boundaries. Thick wavy black lines indicate coalesced sequence boundaries (unconformities) at which one or more sequences are absent. Thick gray lines indicate significant contacts or unconformities identified from lithologic or biostratigraphic breaks identified by previous studies. Dotted lines indicate lower confidence in correlations, whereas hachured areas indicate insufficient data to render interpretations. Sequences are packaged and classified by time. Age ranges at Langley and Kiptopeke are established from biostratigraphy (Edwards et al., 2005; Powars and Bruce, 1999) and are coarser in resolution than Eyreville, Exmore, and Bethany Beach. The underlying diagram of the Chesapeake Bay impact structure is not to scale and is only intended to show the position of postimpact sequences relative to crater morphology. Note the change in transect orientation at Langley from SE-NW to W-E and at Kiptopeke from W-E to SW-NE (see Fig. 1). The Eastville and other regional paleovalleys are not shown on our regional transect.

Prior interpretations examined the lithostratigraphy and biostratigraphy of the ~350 m postimpact section (Powars et al., 1992; de Verteuil and Norris, 1996; Poag, 1997; Powars and Bruce, 1999). We provide new sequence-stratigraphic interpretations, including (1) semiquantitative grain-size analysis; (2) lithofacies and paleoenvironmental interpretation (including trace fossil analysis); and (3) Sr isotopic age estimates.

Sequence boundaries in cores can be represented by: (1) sharp unconformable contacts; (2) lag gravels, phosphate accumulations, and shell beds; (3) rip-up clasts; (4) extensively bioturbated surfaces and reworked microfossils; (5) significant changes in lithofacies successions; and (6) geophysical log characteristics (Sugarman et al., 1995; Miller et al., 2004). Sequence boundaries are also recognized by unconformities (e.g., Van Wagoner et al., 1988) established from Sr isotope stratigraphy and biostratigraphy. Although each sequence boundary is unique, a combination of these criteria can be used to identify significant periods of erosion or nondeposition (Olsson et al., 1988; Sugarman et al., 1995). We defined significant surfaces, such as the MFS and FS, on the basis of lithofacies successions, mineralogy (e.g., increase of glauconite, phosphorite, and carbonate), and geophysical log signatures (e.g., Miller et al., 1998).

Procedures for evaluating the Exmore core hole followed those used for Eyreville (Browning et al., this volume) and previous New Jersey and Delaware cores (Browning et al., 2006). The Exmore core was described for lithology, paying careful attention to changes in grain size, sorting, mineralogy, color, sedimentary structures, critical contacts, and lithofacies changes. Quantitative grain-size data were collected for all three core holes at ~1.5 m (5 ft) sampling intervals. Samples were weighed and then washed through 63 and 250 µm sieves to establish the percentage by volume of clay/silt, fine to medium sand, and coarse sand and gravel (Figs. 5 and 6). The percentage of minerals (quartz, glauconite, lignite, mica, carbonate, pyrite, etc.; Fig. 6) was visually estimated using a microscope. Such data are valuable in establishing fining- or coarsening-upward trends, which can be key indicators of depositional environment and facies-stacking patterns.

Lithofacies Interpretation

Eocene-Pleistocene sequences within the Chesapeake Bay impact structure and at Bethany Beach, Delaware, are generally characterized by either transgressive-regressive "coarsening-upward" facies successions typical of the mid-Atlantic margin (Fig. 4; Owens and Sohl, 1969; Owens and Gohn, 1985; Sugarman et al., 1995), or transgressive, fine-grained, deep-water packages that exhibit very little coarse-grained material. Mid-Atlantic sequences commonly consist of thin, basal, quartz sand, clay, and silt corresponding to the transgressive systems tract (TST of Posamentier et al., 1988), and these are overlain by a regressive coarsening-upward succession of fine to coarse quartz sand equivalent to the highstand systems tract (Fig. 4; HST of Posamentier et al., 1988). Lowstand systems tracts (LST) are largely absent in coastal-plain sequences of Virginia, Delaware, and New Jersey, due to the updip position of coastal-plain strata. Lowstand wedges and fans are generally located much farther offshore, and transgressive ravinement often reworks the updip expression of such deposits. Occasionally, lowstand deposits are preserved within incised valleys (e.g., base of sequence V6; Fig. 2). Although this succession is typical of many sequences at Exmore (V3–V8) and Bethany Beach (C1–M1), many older sequences within the inner basin at Eyreville (e.g., Eocene, Oligocene, V1–V3) and Exmore (Eocene, Oligocene, V2) were deposited in relatively deep paleodepths (outer neritic to upper bathyal, 100–400 m) as the result of excess accommodation from the compaction of impactites. Therefore, they are dominated by fine-grained clay and silt, and sequence expression is subtle and difficult to identify. In cases where HSTs are poorly expressed or eroded, sequences can fine upward or show no distinct coarsening-upward pattern (Fig. 7; consistent with several fining-upward packages identified by Powars et al., 1992).

Lithofacies are similar among the three core holes, and appear to have been deposited on a wave-dominated shoreface (Browning et al., 2006, this volume). Postimpact sediments in the Chesapeake Bay impact structure generally exhibit some parts of the following coarsening-upward succession of lithofacies: (1) basal, offshore, thinly laminated to bioturbated silt, clay, and fine sand deposited below storm wave base; (2) distal, lower shoreface, very fine sand with abundant interbedded silt; (3) lower shoreface, bioturbated, silty fine sand with abundant whole shells deposited below fair-weather wave base; (4) distal, upper shoreface, fine to medium sand exhibiting moderate to heavy bioturbation; (5) upper shoreface to foreshore, well-sorted, fine to medium,

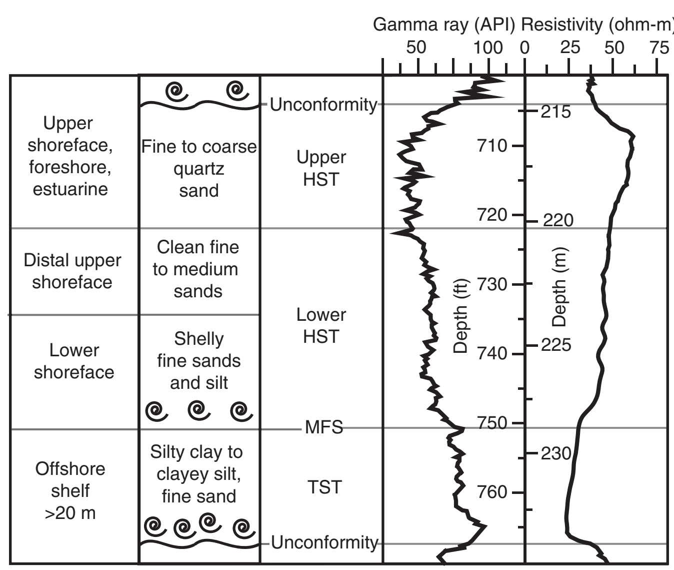


Figure 4. Generalized transgressive-regressive, "shallowing-upward" sequence of the Cenozoic mid-Atlantic margin (modified from Miller et al., 1996, 2004; Kulpecz et al., 2008). Diagram depicts the relationships among paleoenvironment, lithology, sequence components, and geophysical log character. HST—highstand systems tract; TST—transgressive systems tract; MFS—maximum flooding surface.

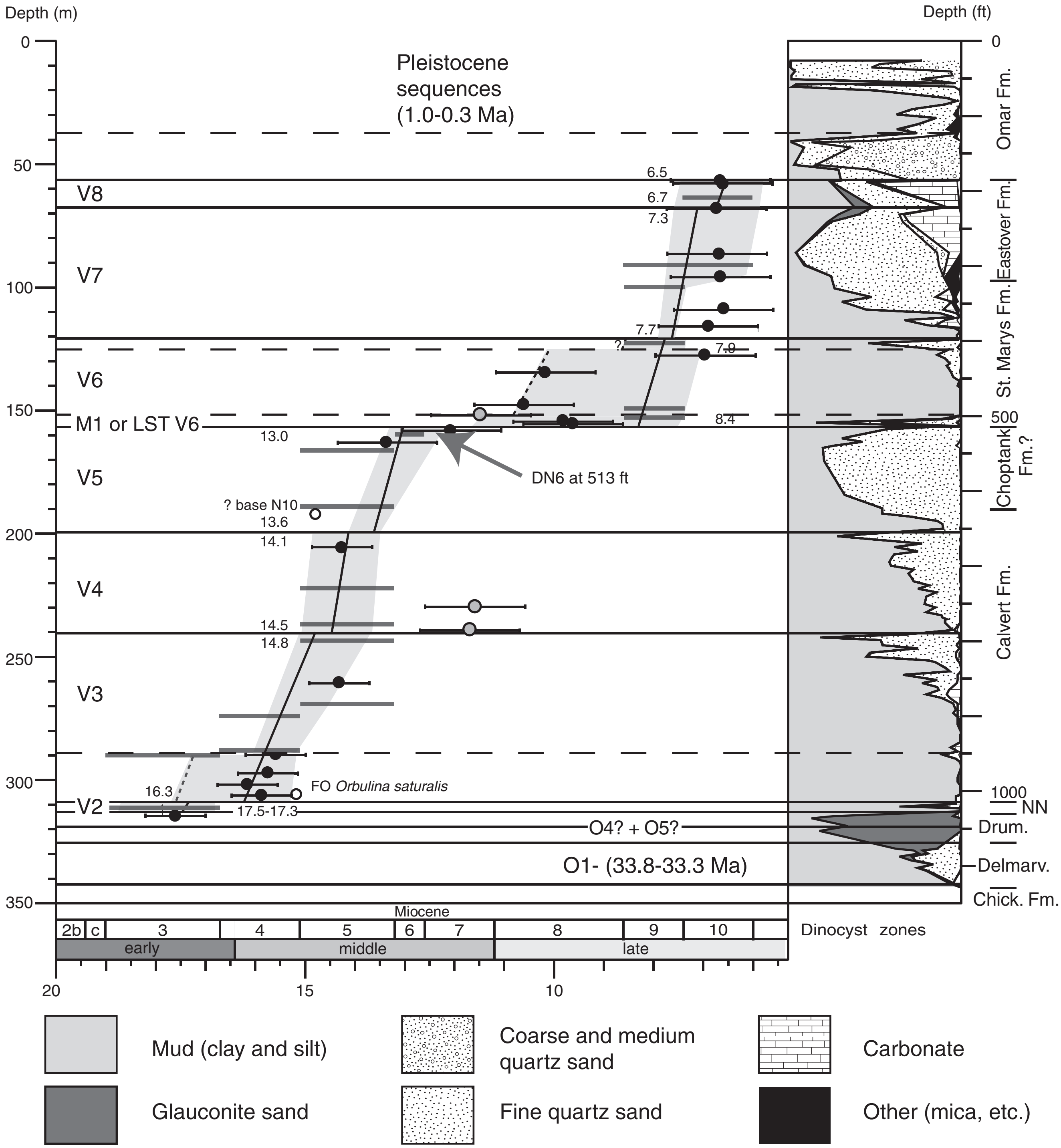


Figure 5. Diagram of age-depth relationships for the Lower through Upper Miocene sequences identified within the Exmore core hole. Sequence boundaries identified in core are represented by the thick horizontal black lines, whereas dotted lines indicate possible sequence boundaries. The subvertical lines that extend from the lower to upper unconformities indicate the time represented by a sequence, assuming a uniform sedimentation rate. Horizontal medium-gray bars represent boundaries of dinocyst zones from de Verteuil and Norris (1996). Zone DN6 at 513 ft represents a reinterpretation of de Verteuil and Norris (1996) sample 1712–22 by L. Edwards. The inferred ages for the top and base of each sequence are annotated by small black numbers. Black dots represent valid Sr isotope datum points, whereas gray dots represent Sr isotope ranges compromised by diagenetic alteration. Error bars (black) are included for all dates. Light-gray shading represents the error range of ages for each sequence. Open circle above upper V2 contact represents the first occurrence (FO) of *Orbulina suturalis*, whereas the open circle in sequence V5 represents the base of zone N10 (Powars and Bruce, 1999). Lithologic units are from Powars et al. (1992), Powars and Bruce (1999), Powars et al. (2005), and Edwards et al. (this volume). Lith % was established by weight. Lithologic columns are coded by the following shades and patterns: large and small dots—coarse quartz sand; small, closely spaced dots—fine quartz sand; box-like pattern—carbonate sand; light gray—silt and clay; dark gray—glauconite sand; and jet black—mica or other. Drum.—Drummond's Corner beds; Delmarv.—Delmarva beds; Chick. Fm.—Chickahominy Formation.

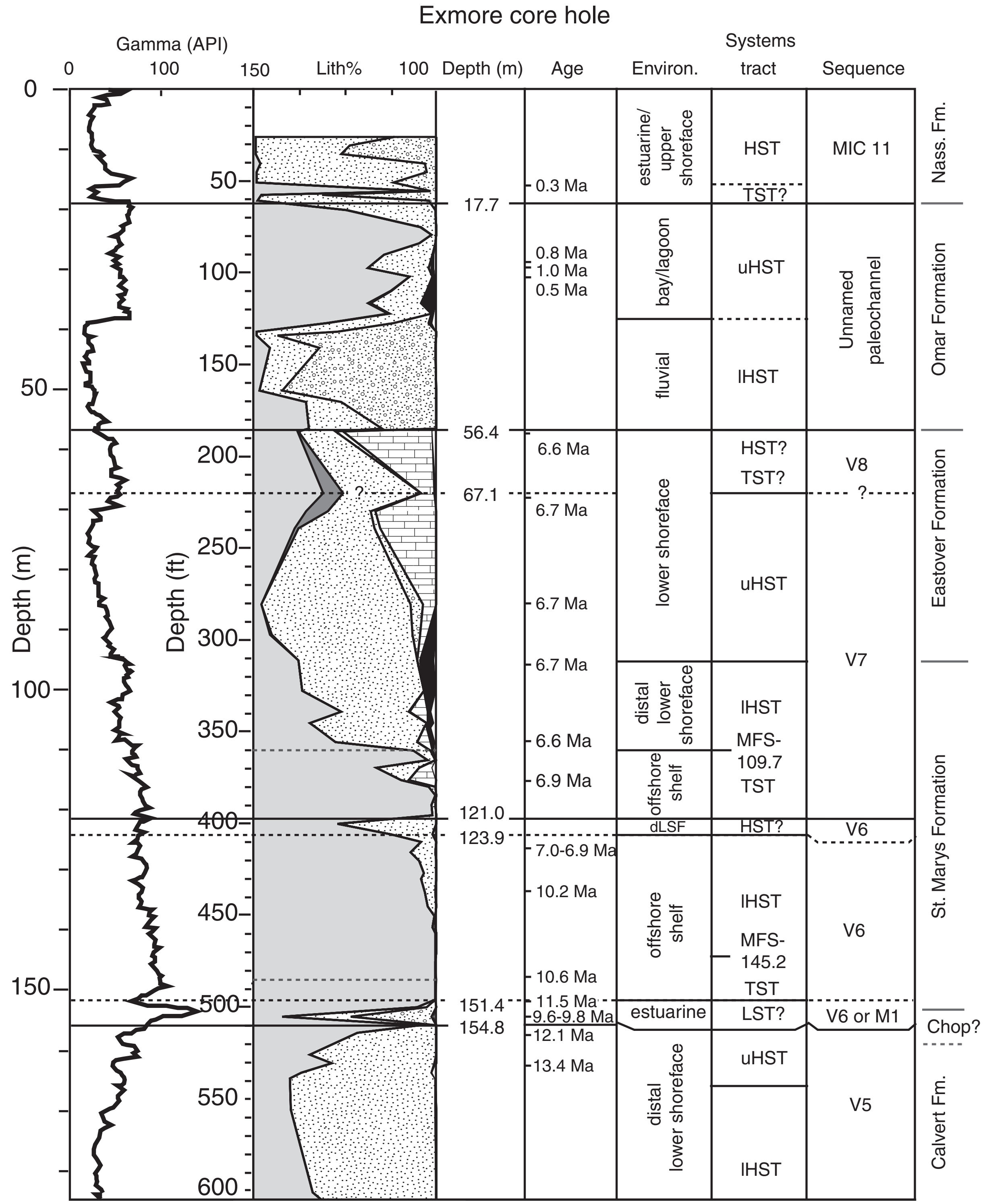


Figure 6. Lithologic, geochronologic, and sequence-stratigraphic interpretations of the Exmore core hole. From left to right: (1) gamma-ray log response; (2) percent lithology; (3) depth column; (4) Sr isotope dates; (5) paleoenvironmental interpretations; (6) sequence-stratigraphic interpretations (e.g., systems tracts, MFS, etc.); (7) the identified sequence; and (8) formations. Solid horizontal lines indicate sequence boundaries identified in core, whereas dashed horizontal lines represent possible sequence boundaries. Dashed gray lines (column two) represent the position of maximum flooding surfaces identified from core and geophysical logs. Lithologic units are from Powars et al. (1992), Powars and Bruce (1999), and Powars et al. (2005). dLSF—distal lower shoreface; lHST—lower highstand systems tract; uHST—upper highstand systems tract; TST—transgressive systems tract; LST—lowstand systems tract; FS—flooding surface; MFS—maximum flooding surface; Chop—Choptank Formation. Lith % was established by weight. Lithologic columns are coded by the following shades and patterns: large and small dots—coarse quartz sand; small, closely spaced dots—fine quartz sand; box-like pattern—carbonate sand; light gray—silt and clay; dark gray—glauconite sand; and jet black—mica or other.

beach-like sand with abundant shell fragments and cross-beds; (6) foreshore, fine to coarse sand with opaque heavy mineral laminae; (7) lower estuarine, poorly sorted sand interbedded with lignitic clay and fine sand; and (8) fluvial to upper estuarine, sandy to gravely, cut-and-fill channels with occasional lignite, mud clasts and sporadic clay laminae (Fig. 4). Erosion during base-level lowering, or the incision and reworking of estuarine and fluvial channels, accounts for the scarcity of upper shoreface and foreshore facies in most sequences. Sequences in the Chesapeake Bay impact structure and Delaware exhibit significantly different lithofacies compared to the deltaically influenced sequences documented from the Cretaceous and Cenozoic New Jersey coastal plain (e.g., basal, glauconitic shelf sand overlain by prodelta clay, delta-front quartz sand, and marginal to nonmarine delta-plain deposits; e.g., Miller et al., 2004; Kulpecz et al., 2008).

Age Control

We derive age control for late Eocene–Pleistocene sequences at Exmore from 32 Sr isotopic age estimates (Fig. 5; Sr isotope ages for Eyreville are presented by Browning et al., this volume) and previously published dinocyst zonations (de Verteuil and Norris, 1996). We used carbonate from mollusk shells, both whole shells and large fragments. However, intervals lacking whole shells required the collection of 5–10 mg of benthic foraminifera for Sr analysis. We applied careful attention when collecting carbonate, avoiding shells with evidence of postdepositional diagenesis, other alteration, or clear signs of redeposition. Strontium was extracted using the ion-exchange techniques of Hart and Brooks (1974) and analyzed on an Isoprobe T multicollector thermal ionization mass spectrometer (TIMS) at Rutgers University. We used the Sr isotopic regressions of Oslick et al. (1994) for the early to early late Miocene (23.8–8 Ma), Reilly et al. (2002) for the Oligocene to earliest Miocene, and McArthur et al. (2001) for the late Miocene–Pliocene. We assign ages using the time scale of Berggren et al. (1995). Age errors for the late Oligocene–earliest Miocene (23.8–27.5 Ma) are ±1 Ma (Reilly et al., 2002). The regression for 15.5–22.8 Ma exhibits errors of ±0.61 Ma, whereas the period from 9.7 to 15.5 Ma exhibits errors of ±1.17 Ma (Miller et al., 1991). Late Miocene to Pleistocene age errors are ±2 to ±0.35 Ma. These errors are calculated at the 95% confidence interval for a single analysis.

An age-depth plot (Fig. 5) depicting Sr isotopic and dinocyst age data for the late Miocene–Pliocene against lithology from the cores established the geochronology of sequences, hiatuses, and the postimpact section. We inferred sedimentation rates consistent with other marginal-marine to marine sections of the mid-Atlantic Coastal Plain (Bethany Beach core hole; Browning et al., 2006) and Chesapeake Bay impact structure (Langley core hole—Edwards et al., 2005; Eyreville core hole—Browning et al., this volume). The error range (the gray shaded interval surrounding the black "best-fit" line of Fig. 5) represents the range of interpretations based on the previously discussed errors of Sr isotopic dating coupled with the limitations of dinocyst age control. Sequence ages were determined by establishing a best-fit line between bounding hiatuses (consistent with reasonable sedimentation rates) that honored the available data. However, in several intervals, multiple interpretations exist due to the divergence of biochronologic and Sr isotopic age data (e.g., sequences V3 and V6; Fig. 5). In these cases, the preferred interpretation is presented, and the error range is extended to include alternative interpretations (represented by dotted gray lines; Fig. 5).

Geophysical Log Interpretation

Downhole gamma-ray logs, a measure of naturally occurring radiation in sediment, are useful tools for facies interpretation and sequence correlation. Because fine-grained sediments, clays, glauconite sands, and phosphorites retain high levels of radioactive elements (K, Ur, Th), gamma-ray logs are good indicators of lithology (Rider, 2002). Although the thick (10–20 m), coarse-grained HST sands observed at Bethany Beach, Delaware, and in New Jersey (Browning et al., 2006) are rare within the Upper Eocene–Middle Miocene sections of the Chesapeake Bay impact structure, many sequences (V4–V8) still exhibit gamma-ray values that gradually decrease upsection until a rapid deflection to high values that marks the capping sequence boundary (Fig. 4). However, in many older Chesapeake Bay impact structure sequences (Eocene, Oligocene, V1–V3), the fine-grained lithologies, lack of thick HST sands, and presence of phosphorite and glauconite often elevate gamma-ray signatures throughout the section (Fig. 2). In these instances, sequence boundaries are indicated by rapid and pronounced gamma-ray inflections that often exceed 100 API units. Maximum flooding surfaces (MFS) also exhibit pronounced gamma-ray peaks in condensed sections, even in fine-grained lithologies. Because coarse-grained intervals are important freshwater aquifers of the mid-Atlantic Coastal Plain, resistivity logs (the measure of pore-fluid resistance to an electrical current) generally exhibit low values (e.g., ~10–50 ohms-m) in fine-grained "confining" intervals (e.g., transgressive shelf clays and silts) and grade upward to increasingly higher values (e.g., ~50–150 ohms-m) in coarse-grained shoreface sands of the HST (Fig. 4) (e.g., Sugarman et al., 2006).

Regional Correlation Methodology

We correlate the sequences identified at the Exmore core hole (this study) to similar results from Eyreville, Virginia (Browning et al., this volume), and Bethany Beach, Delaware (Browning et al., 2006), on the basis of age, lithostratigraphy, sequence stratigraphy, and geophysical log character (Figs. 2 and 3; Table 1 presents a comparison of age data and sequence terminology for each core hole). We used core geophysical log integration from the three core holes to identify log patterns of each sequence (generally repetitive, coarsening-upward packages in the Pliocene and middle Miocene; Browning et al., 2006; Powars and Bruce, 1999) and bounding sequence boundaries (rapid gamma-ray spikes in fine-grained Eocene, Oligocene, and Lower

TABLE 1. SEQUENCE NAMES AND AGE ESTIMATES FROM Sr ISOTOPES AND BIOSTRATIGRAPHY

Virginia sequences	Eyreville ages (Ma)	Exmore ages (Ma)	Bethany Beach ages (Ma)	Bethany sequences
Pleistocene	0.55–0.2	1.0–0.3	1.0–0.5	Pleistocene
V11	2.8–2.5	xxx*	xxx*	xxx*
V10	3.0–2.8	xxx	xxx	xxx
V9	4.9–4.6	xxx	xxx	xxx
V8	6.4–6.1	6.7–6.5	Undated (no carbonate)	Unnamed
V7	7.7–7.2	7.7–7.3	Undated (no carbonate)	Unnamed
V6	8.3–8.0	8.4–7.9	xxx	xxx
M1	xxx*	9.8–9.9?	10.2–9.8	M1
xxx*	xxx	xxx	10.6–10.2	C10
xxx	xxx	xxx	11.9–11.6	C9
V5	13.8–12.8	13.6–13.0	13.5–13.1	C8
V4	14.8–14.1	14.5–14.1	14.5–14.2	C7
V3	16.4–16.0	16.3–14.8	16.2–15.8	C6
V2	17.4–17.3	17.5–17.3	17.3–16.4	C5
V1	18.4–18.2	xxx	18.4–18.0	C4
xxx	xxx	xxx	18.8–18.4	C3
xxx	xxx	xxx	19.3–18.8	C2
xxx	xxx	xxx	20.8–20.2	C1
xxx	xxx	xxx	24.0–28.0	UGC
O5?	26.65–26.5	Undated (no carbonate)	Not cored	Not cored
O4?	27.7–27.6	Undated (no carbonate)	Not cored	Not cored
O1?	xxx	33.8–32.6	Not cored	Not cored
E2	???	???	Not cored	Not cored
E1	35.4–???	35.4–???	Not cored	Not cored

*“xxx” indicates the absence of a sequence in a core hole.

Miocene Chesapeake Bay impact structure sequences), although lateral facies variability, regional unconformities, and stratigraphic pinch-outs complicate regional log correlation. To overcome these limitations, we also used published data (lithostratigraphy and biostratigraphy) from several USGS core holes and wells (e.g., Powars et al., 1992, 2005; Powars and Bruce, 1999; Powars, 2000; Edwards et al., 2005) to increase the accuracy of regional correlations (Fig. 1). Although these additional cores do not provide the same geochronologic resolution of Exmore, Eyreville, and Bethany Beach, they provide valuable age constraints with good (~1–3 Ma) resolution.

For example, sequences V6 and V7 (dated from Sr isotopes at Eyreville as 8.3–8.0 Ma and 7.7–7.2 Ma, respectively; Table 1) were correlated to the USGS Langley core hole on the basis of log character and biostratigraphy by Edwards et al. (2005). The interval from 300.3 to 182.0 ft contains nannofossil zones NN 11–12 (ca. 8.6–5.6 Ma) and dinocyst zones DN 9–10 (8.7–5.8 Ma) that confirm our correlations to sequences V6 and V7. We applied similar methodology to other USGS (Fig. 1; Cape Charles, Fentress, Dismal Swamp, Bayside) and Virginia Department of Environmental Quality (Fig. 1; Kiptopeke) core holes where biostratigraphic data were available.

Correlation north of the crater (Figs. 1 and 3) was difficult because there are no continuous core holes between Exmore, Virginia, and Bethany Beach, Delaware (118 km). Therefore, we used geophysical logs (both gamma ray and electric) from 38 boreholes drilled by state geological surveys, the Virginia Tech Regional Geophysics Laboratory, U.S. Department of Energy, and USGS. We also used existing publications (Olsson et al., 1987, 1988) and numerous state geological survey reports (e.g., Hansen and Wilson, 1984; Hansen and Wilson, 1990; Andreason and Hansen, 1987; Hansen and Lang, 1980; Andres, 2004) to constrain our correlations across the Maryland and Delaware coastal plains (Fig. 1). Many of these reports are based on lithologic and biostratigraphic studies from outcrops and cores and contain useful information regarding regional chronostratigraphic and lithostratigraphic trends. Although the geochronologic resolution is somewhat coarse (2–5 Ma), several reports (e.g., Olsson et al., 1987) document the presence of significant unconformities, which may coincide with sequence boundaries identified in our study. We included additional reports from the Delmarva Peninsula in this study to lend regional context, but they are not depicted on the regional transect (Figs. 1 and 3).

DATA AND RESULTS

Exmore Core Hole

We document twelve definite and four possible late Eocene through Pleistocene depositional sequences in the Exmore (this study) and Eyreville (Browning et al., this volume) core holes within the Chesapeake Bay impact structure (Figs. 5, 6, and 7). We compare these results to the record from Bethany Beach, Delaware, where Browning et al. (2006) identified 16–19 uppermost Oligocene through Pleistocene sequences (Figs. 2 and 3). The difference in number of sequences is caused by: (1) the differential preservation of sequences between core holes; and (2) the presence of possible sequences that lack conclusive geochronology.

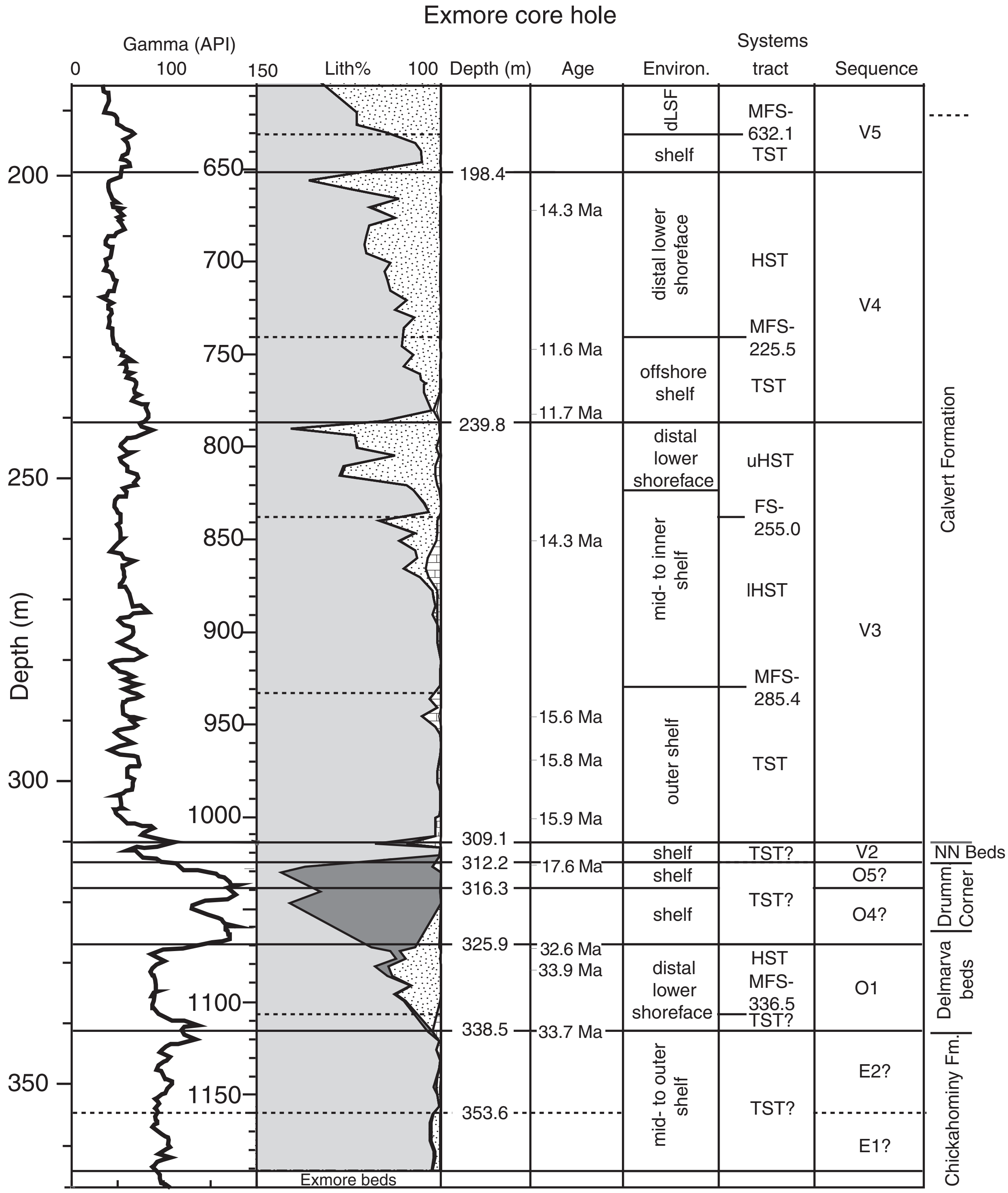


Figure 7. Lithologic, geochronologic, and sequence-stratigraphic interpretations of the Exmore core hole. From left to right: (1) gamma-ray log response; (2) percent lithology; (3) depth column; (4) Sr isotope dates; (5) paleoenvironmental interpretations; (6) sequence-stratigraphic interpretations (e.g., systems tracts, MFS, etc.); (7) the identified sequence; and (8) formations. Solid horizontal lines indicate sequence boundaries identified in core, whereas dashed horizontal lines represent possible sequence boundaries. Dashed gray lines (column two) represent the position of maximum flooding surfaces identified from core and geophysical logs. Lithologic units are from Powars et al. (1992), Powars and Bruce (1999), and Powars et al. (2005). dLSF—distal lower shoreface; lHST—lower highstand systems tract; uHST—upper highstand systems tract; TST—transgressive systems tract; FS—flooding surface; MFS—maximum flooding surface; Drumm. Corner—Drummond's Corner beds; and NN—Newport News beds. Lith % was established by weight. Lithologic columns are coded by the following shades and patterns: large and small dots—coarse quartz sand; small, closely spaced dots—fine quartz sand; box-like pattern—carbonate sand; light gray—silt and clay; dark gray—glauconite sand; and jet black—mica or other.

Figures 6 and 7 present a synthesis of sequence-stratigraphic and geochronologic interpretations for the USGS Exmore core hole, whereas Table 1 presents a comparison of the geochronology for sequences at Exmore, Eyreville, and Bethany Beach. We follow the lithostratigraphic framework of Edwards et al. (this volume) for formational assignments. These lithostratigraphic assignments are consistent with previous studies of the Virginia coastal plain and surrounding areas (e.g., Powars et al., 1992; Powars and Bruce, 1999).

Upper Eocene Sequence(s) (E1, E2): 363.08–338.54 m

We identify one, and possibly two, fine-grained, transgressive sequences within the Upper Eocene Chickahominy Formation at Exmore (Fig. 7). The lower sequence consists of transgressive, outer-shelf, light-gray clay with minor amounts of very fine sand, rare whole shells, trace glauconite, and abundant phosphatized fish scales. This sequence exhibits moderate to intense bioturbation, except for laminated clays from 360.0 to 359.36 m. Light-gray clay extends upward to a subtle burrowed contact and possible sequence boundary at 353.57 m. The overlying possible sequence is dominated by bioturbated, occasionally shelly, slightly silty clay with several pyrite concretions and phosphatized bone material at 353.32 m. The abundance of small clay-filled *Planolites* and *Chondrites* trace fossils, in concentrated intervals, supports the interpretation of a mid- to outer shelf "reducing" paleoenvironment. The upper contact was not recovered due to a coring gap, but it is placed at 338.54 m (consistent with Powars and Bruce, 1999) on the basis of a gamma-ray shift, thus separating the underlying clays from slightly glauconitic sandy silt above (Fig. 7). No Sr dates were obtained for this interval, but it is correlated by geophysical log signatures and superposition to dated sections at Eyreville and Langley (Fig. 2; Table 1). We identify these sequences as transgressive in nature, with no clear HST sands due to the environment of deposition on a deep mid- to outer shelf within the initial bathymetric low of the Chesapeake Bay impact structure (the result of excavation and infilling resulting in 50–200 m paleodepths in the annular trough versus middle shelf conditions [30–100 m] in nearby core holes outside the crater; Poag et al., 1994).

Oligocene Sequences (O1, O4, O5): 338.54–312.15 m

Because the Exmore core was drilled in 1986 and has been moved to multiple locations, the Oligocene core is highly desiccated, complicating the identification of primary sedimentary structures and contacts. However, we identify two bioturbated contacts within this Oligocene section, separating three individual sequences. Bioturbated silty clay (TST) overlies the basal sequence boundary (338.54 m) and coarsens upward (above a MFS at 336.56 m) to slightly glauconitic, slightly micaceous, bioturbated, fine sandy silt with scattered small (>1 mm) shell fragments deposited in a distal lower-shoreface environment (HST). A significant contact at 325.95 m separates green to black glauconite sands above from the largely nonglauconitic sandy silt below and is interpreted as a sequence boundary. This contact was previously recognized as separating the Lower Oligocene Delmarva beds (zone P18–20) from the Upper Oligocene Old Church Formation (zone P21a; Powars et al., 1992; Powars and Bruce, 1999). The Old Church Formation at Exmore was subsequently informally reclassified as the Drummonds Corner beds (Powars et al., 2005). Several glauconite-filled burrows are visible beneath the contact, including a large *Teichichnus* burrow at 326.17 m and an elongate 6-cm-deep vertical burrow at 326.59 m.

The interval above 325.95 m is dominated by coarse-grained glauconite sand with a silty and clayey matrix. Although the interval is poorly recovered, we identify a contact and possible sequence boundary at 319.95 m on the basis of several indurated clasts of glauconitic clay within an interval of indurated silt and clay (Fig. 7). The overlying section is similarly glauconitic and extends to a heavily indurated zone at 316.26 m that preserves a bioturbated contact, also identified as a possible sequence boundary, between a clay-dominated section below and a glauconite-dominated section above. Clayey glauconite sand extends upward to a spectacular contact at 312.15 m that separates an extensive zone (0.2 m) of heavily bioturbated and reworked glauconite sand and silty clay from overlying mid-Miocene sediments (17.5–17.3 Ma). These glauconite-rich Oligocene sequences were deposited in sediment-starved, mid- to outer shelf paleoenvironments and are largely transgressive.

We identify the interval from 338.54 to 325.95 m at Exmore as Lower Oligocene based on Sr age estimates of 33.8–32.6 Ma and previous work (Powars et al., 1992; Powars and Bruce, 1999), and we correlate it to sequence O1 defined from the New Jersey coastal plain (Pekar et al., 2000). There was insufficient carbonate material from 325.95 to 312.15 m for Sr isotopic analysis, although previous work (Powars et al., 1992; Powars and Bruce, 1999; de Verteuil and Norris, 1996) identified this interval as Upper Oligocene (Old Church Formation) from planktonic foraminifera and dinocyst data. We identify two possible sequences in this section that are separated by a sequence boundary at 316.26 m, and we use geophysical logs and lithologic similarity to correlate them to the Eyreville (Browning et al., this volume) and Langley core holes (Edwards et al., 2005). From correlation to a dated section at Eyreville, the interval from 325.95 to 316.26 m is tentatively identified as sequence O4 (27.7–27.6 Ma), whereas the unit from 316.26 to 312.15 m is identified as sequence O5 (26.65–26.5 Ma) as defined in New Jersey (Pekar et al., 2000).

Lower Miocene (V2): 312.15–309.10 m

A heavily burrowed contact at 312.15 m separates Oligocene glauconitic sand from overlying transgressive, slightly glauconitic, carbonaceous clay deposited on a marine shelf. This unit contains many small shell fragments and extends to a heavily bioturbated upper contact with overlying, nonglauconitic silty clay at 309.10 m that is interpreted as a sequence boundary (Fig. 7). The lack of whole shells makes Sr dating difficult. A single Sr age estimate from the lower reworked and burrowed zone (313.06 m) yielded an age of 17.6 Ma (Fig. 5). de Verteuil and Norris (1996) identified this interval as zone DN3 (ca. 19.0–16.7 Ma;

sample from 311.20 m), while Powars et al. (1992) classified this interval as the Newport News unit and recorded possible zone N8 planktonic foraminifera (ca. 16.4–15.2 Ma). We tentatively identify this interval as sequence V2 (17.7–17.5 Ma) based on the overlap of zone DN3 with the single Sr isotope age estimate, and correlate it to similar sequences recognized at the Eyreville and Bethany Beach core holes (Fig. 2; Table 1).

Middle Miocene (V3): 309.10–239.79 m

Overlying a contact at 309.10 m, there is an interval of shelfal, bioturbated, slightly silty clay with scattered small shell fragments, black phosphorite grains, fish scales, and abundant *Planolites* trace fossils interpreted as the TST (Fig. 7). This interval is assigned to the Calvert Formation (Powars and Bruce, 1999). Trace amounts of glauconite overlie this contact, but appear to be reworked from underlying units. The interval consists of fairly uniform bioturbated silty clay to 266.70 m, although laminated clay with minor silt laminae (1–3 mm) extends from 296.30 to 290.60 m. A gamma-ray inflection and increase in clay and carbonate at 285.38 m indicate the MFS. Above this interval, intensely bioturbated clay extends upsection, and individual trace fossils are not well-defined. At 266.70 m, the overall lithology coarsens to clayey silt with small amounts (2%–5%) of carbonate material and very fine sand increasing upsection representing the lower HST. The percent of fine sand peaks below a surface at 255.03 m, which may represent a flooding surface and parasequence boundary (Fig. 7). The section further coarsens upward from clayey silt at 248.53 m to bioturbated silty fine quartz sand with abundant shell fragments deposited in a distal lower shoreface (upper HST) environment. Several large *Thalassinoides*, sand-filled *Planolites*, and other backfilled burrows (e.g., large *Diplocraterion* trace fossil at 245.12 m) characterize this interval. A burrowed contact at 239.79 m separates the underlying fine sands from offshore silts above and caps an extensive (240.91–239.79 m) heavily reworked zone that exhibits abundant trace fossils of the *Cruziana* ichnofacies (marine shelf). We interpret a shallowing-upward progression of paleoenvironments in this thick (69.19 m) sequence to represent a progression from basal outer shelf to inner shelf and distal lower shoreface.

Establishing the geochronology of this sequence was difficult due to the divergence of age estimates from Sr isotopic data and planktonic foraminifera zones from dinocyst zones. Four Sr dates at the base of the sequence clustered from 16.1 to 15.5 Ma, an interval with low Sr age errors (e.g., Miller et al., 1991). Planktonic foraminifera zones N8 and N9 (ca. 16.4–14.8 Ma) reported by Powars and Bruce (1999) are consistent with this interpretation. However, de Verteuil and Norris (1996) identified five samples between 314.25 and 289.86 m as zone DN3 (ca. 19.0–16.7 Ma), which is not consistent with the Sr isotopic and foraminiferal age constraints. Above this interval, de Verteuil and Norris (1996) identified zone DN4 (ca. 16.7–15.1 Ma; 286.82–274.62 m) and zone DN5 (ca. 15.1–13.1 Ma; 269.14–237.44 m), which are consistent with other age estimates. We interpret the base of sequence V3 using planktonic foraminifera and Sr isotopic data (ca. 16.3 Ma), and the upper portion of the sequence with zone DN4 and zone DN5 assignments. The combination of these data sets dates this interval as 16.3–14.8 Ma (Fig. 5), and it is identified as sequence V3 and correlated to the Eyreville core hole and sequence C6 from the Bethany Beach core hole (Fig. 2; Table 1).

Middle Miocene (V4): 239.79–198.39 m

Above a heavily burrowed contact at 239.79 m, there is very uniform, light-gray, fine sandy, slightly clayey, bioturbated silt with abundant backfilled and clay-lined burrows (*Teichichnus*, *Asterosoma*, and *Planolites*) deposited on a marine shelf (TST; Fig. 7). The section coarsens upward to heavily bioturbated, silty fine sand with large (~1-cm-diameter) sand-filled shafts of interconnected *Thalassinoides* burrows (e.g., 201.14–200.56 m). A possible MFS at 225.49 m corresponds to a slight increase in clay and a gamma-ray inflection. These upper sands are interpreted as distal lower shoreface, represent the HST, and underlie a subtle burrowed contact at 198.39 m and shelfal, fine sandy, silt above. Previous studies (Powars et al., 1992; Powars and Bruce, 1999) identified this interval as the Calvert Formation. Carbonate material in this interval is sparse, and three benthic foraminifera samples yielded Sr ages of 14.4, 11.6, and 11.7 Ma (Fig. 5). de Verteuil and Norris (1996) identified this interval as zone DN5 (ca. 15.1–13.1 Ma), while Powars et al. (1992) identified planktonic foraminifera zone N9, both consistent with the older Sr date of 14.4 Ma. The younger Sr age estimates appear to have been diagenetically altered and are excluded from age interpretations. We estimate the age of this sequence as 14.5–14.1 Ma, which correlates to sequence V4 at Eyreville and C7 at Bethany Beach (Fig. 2; Table 1).

Middle Miocene (V5): 198.39–154.78 m

The interval from 198.39 to 154.78 m is a classic coarsening-upward sequence and consists of fairly uniform bioturbated fine sandy silt (above the contact at 198.39 m interpreted as a sequence boundary) with several thin intervals of planar (below 194.52 m) and faint cross-lamination (~190.59 m). Above a burrowed surface and gamma-ray peak at 192.66 m (interpreted as a MFS), these shelfal silts (TST) shallow and coarsen upward to burrowed silty fine sands deposited in a distal lower shoreface environment (HST; Figs. 6 and 7). This sandy interval exhibits several small phosphate nodules at 164.50 m and contains 1%–2% opaque heavy minerals. This sandier unit, assigned to the Calvert Formation by Powars et al. (1992), may be equivalent to the Choptank Formation at Eyreville (Edwards et al., this volume). Regardless of the interpretation, the coarser-grained interval from 191.41 to 154.78 m is interpreted as the HST of sequence V5. Above 159.23 m, the interval gradually fines to sandy, silty, clay until reaching a spectacular burrowed contact at 154.78 m characterized by a network of large chambers filled with coarse quartz sand of the overlying unit. We interpret this as a *Glossifungites* surface, representing an eroded firm ground (e.g., Pemberton, 1998; Pemberton et al., 2004) and recording a major hiatus separating two sequences.

Two Sr isotopic age estimates of 13.4 and 12.1 Ma were recovered in the uppermost portion of the sequence. The older of these is consistent with the interpretations of de Verteuil and Norris (1996), who classified the entire section as zone DN5 (ca. 15.1–13.1 Ma). Subsequent work by L. Edwards reinterpreted sample 1712–22 (156.36 m) as zone DN6 (ca. 13.1–12.6 Ma). Powars et al. (1992) also identified the section below 154.78 m as N9–10 (ca. 15.1–12.8 Ma). Dinocyst and Sr isotope age estimates date this sequence as 13.6–13.0 Ma, and it is identified as V5 as recovered at Eyreville (Fig. 2; Table 1). The surface at 154.78 m records a major hiatus (~4.4 Ma) from sediments below (13.6–13.0 Ma) to those immediately above, which are classified as zone DN9 (ca. 7.4–8.6 at 152.70 m and 150.27 m; de Verteuil and Norris, 1996) and dated at 9.9–9.8 Ma by Sr isotopic analysis.

Upper Miocene (M1 or LST of V6): 154.78–151.36 m

A thin (154.78–151.36 m) unit overlies the *Glossifungites* surface and consists of basal, fine to medium sand that coarsens upward to coarse to slightly clayey, very coarse, quartzose sand at 154.35 m (Fig. 6). This contact was initially recognized as a major unconformity separating the Calvert (Middle Miocene) and St. Marys (Upper Miocene) Formations by Powars and Bruce (1999), although subsequent work indicated the presence of the Choptank Formation below 154.78 m. Within this interval, there are numerous shell fragments ranging from 0.3 to 2.5 cm (153.62–153.56 m), 2–3-cm-long chocolate brown lignitic material with original woody textures preserved at 154.29 m, and a clay rip-up clast at 154.35 m. Above 153.59 m, the section fines to a fine to medium sand that is interbedded with silt and clay and contains sand-filled burrows. We interpret the lower sands of this interval as estuarine or nearshore and the upper heterolithic interbeds as estuary fill. The upper contact is placed at 151.36 m, where it coincides with the uppermost sand burrow and caps the gradational transition from lower coarse sands to overlying marine clay. Multiple interpretations exist for the interval from 154.78 to 151.36 m: (1) the upper contact is a sequence boundary on the basis of a major shift in depositional environments (estuarine below, deep shelf above) and records a possible hiatus; (2) the entire interval represents the LST of the overlying sequence SM (estuarine sands preserved in a possible incised valley), and the upper contact represents a transgressive surface capped by marine shelf facies; or (3) the wood, shell fragments, rip-up clasts, and broad range of ages in this interval represent part of the transgressive lag during a relative rise in sea level (TST).

Sr isotope age estimates are inconclusive for this thin section. Two dates of 9.9 and 9.8 Ma occur within this interval, while a date of 10.8 Ma was recovered in the upper reworked zone. de Verteuil and Norris (1996) identified this interval as zone DN9 (ca. 8.6–7.4 Ma) from samples at 152.70 and 150.27 m. If the two Sr dates are used, this thin interval is dated as 9.9–9.8 Ma, the upper contact is interpreted as a sequence boundary (overlying sequence SM dated 8.4–7.9 Ma), and this thin "sequence" can be correlated to M1 recovered at the Bethany Beach core hole (Fig. 3; Table 1; Browning et al., 2006). The preferred interpretation classifies this interval as entirely zone DN9 (ca. 8.6–7.4 Ma), and this thin unit is interpreted as the LST of sequence V6 (ca. 8.4 Ma; Fig. 2; Table 1). The presence of older Sr age estimates is interpreted as reworked material from lowstand valley incision and subsequent transgressive winnowing.

Upper Miocene (V6): 151.36–121.01 m

Above a contact with the LST of sequence V6 at 151.36 m, there is a very fine-grained interval (151.36–135.94 m) dominated by gray, slightly silty, bioturbated clay (interpreted as the TST) with trace amounts of mica, rare scattered shell fragments, and numerous fish scales and phosphatized material (concentrated below 149.35 m), which are typical of transgressive lag deposits. Bioturbation is intense but dominated by small unidentifiable trace fossils, with several concentrated intervals of *Chondrites*. A slight increase in clay and corresponding gamma-ray peak at 145.24 m may represent a MFS. We interpret the depositional environment as mid- to outer shelf, occurring within the St. Marys Formation. Above 135.94 m, the section coarsens to brown to gray, slightly micaceous, bioturbated clayey silt with small amounts (5%–10%) of fine quartz sand increasing upsection. Numerous large and well-developed trace fossils (distal *Cruziana* ichnofacies) are dominated by *Asterosoma*, but observations also show numerous *Planolites*, *Paleophycus* (125.12 m), and *Teichichnus* burrows (130.15 m). The interval from 135.94 to 123.96 m appears shallower than the underlying clays, and it is interpreted as inner to middle shelf (HST). An irregular, scoured contact at 123.96 m separates this interval of clayey silt from an overlying sandy, shelly interval that consists of numerous 1–2-cm-diameter, well-rounded, rip-up clasts composed of silty clay (similar to underlying units) and a fine-grained shell hash suspended in a clayey matrix. The unit above this reworked interval consists of bioturbated, occasionally shelly, slightly clayey, silty fine sand (interpreted as distal lower shoreface) that persists to a subtle, gradational contact at 121.01 m with overlying silty clay to clayey silt.

There are two possibilities for 123.96–121.01 m: (1) the unit is an individual sequence, and both the upper and lower contacts represent sequence boundaries; or (2) there is no hiatus at 123.96 m, and the contact represents a possible wave ravinement surface (accounting for the rip-up clasts and concentration of shell material) and facies shift to the upper HST of sequence V6. Sr age estimates (10.6, 10.3, and 7.1 Ma) are inconclusive for this sequence. The two older values are not consistent with assignment to zone DN9 (ca. 8.6–7.4 Ma; de Verteuil and Norris, 1996). The uppermost Sr age estimate (7.1 Ma) is consistent with this zone. An apparently coeval sequence is dated as 8.4–7.9 Ma and identified as sequence V6 recovered at the Eyreville core hole (Fig. 2; Table 1; Browning et al., this volume). Biostratigraphic work from the Langley (Edwards et al., 2005) and Kiptopeke core holes (Powars and Bruce, 1999) also support this interpretation. Because no hiatus can be established across the contact at 123.96 m, we believe it represents the transition to the upper HST of sequence V6 (154.78–121.01 m).

Upper Miocene (V7 and V8): 121.01–55.17 m

The interval from 121.01 to 109.76 m is characterized by very fine sandy, silty clay to clayey silt with abundant scattered shells, mainly turritellids. Although several faintly laminated intervals are visible (112.81–118.20 m; 119.18–119.27 m), bioturbation dominates the primary texture, and numerous *Asterosoma* and *Planolites* trace fossils are evident. This paleoenvironment is interpreted as middle to inner shelf and represents the TST (Fig. 6). Above a MFS at 109.76 m (clayey section with corresponding gamma-ray peak), the section coarsens to alternating indurated and nonindurated micaceous, slightly clayey, very shelly, silty fine sand with extensive bioturbation (primarily *Asterosoma* trace fossils) and abundant whole and fragmented turritellids, oyster, and mollusk shells (lower HST). Powars and Bruce (1999) placed the Eastover–St. Marys contact at the base of a nonrecovered interval at 99.36 m, separating sandy shelly fine sand above from finer-grained sediments below. The section from 96.07 to 95.10 m consists of very shelly bioturbated fine sand with evidence of cross-lamination and is interpreted as distal lower shoreface, representing the transition from the lower to upper HST (Fig. 6). Cemented intervals effervesce slightly with hydrochloric acid, exhibit numerous vugs, have moldic porosity, and appear localized around shelly intervals, the likely source of carbonate cement. These indurated zones continue upsection to 70.16 m and resulted in very poor recovery (<20%) from 109.73 to 70.10 m. We interpret the shelly, sandy interval from 109.73 to 55.17 m as predominantly lower shoreface with several coarser intervals representing possible upper shoreface (Fig. 6). A large coring gap from 67.36 to 56.69 m prevents analysis of lithology, although log correlation with Eyreville suggests a sequence boundary at 67.06 m coinciding with a gamma-ray inflection (Fig. 2).

Although seven Sr age dates cluster around 7.2–6.7 Ma, Sr age estimates alone are inconclusive given the error ranges during the late Miocene (Fig. 5). Dinocyst data from de Verteuil and Norris (1996) identified zone DN9 (ca. 8.6–7.4 Ma) at the base of the section, overlain by transitional zone DN9 and zone DN10 (ca. 7.4–6.1 Ma), and exclusively zone DN10 between 67.06 and 55.17 m. These changes in dinocyst zones across the contact at 67.06 m, coupled with Sr age data and regional correlation, lead to the interpretation of two sequences within the Eastover Formation. The sequence from 121.01 to 67.06 m is identified as V7 and dated at 7.7–7.3 Ma (Fig. 5), while the poorly recovered interval from 67.06 to 56.39 m is identified as lower V8 (6.7–6.5 Ma). Both sequences are correlated to the Eyreville core hole (Fig. 2; Table 1; Browning et al., this volume). A bioturbated contact at 55.17 m caps a reworked interval (56.91–55.17 m) consisting of shelly, clayey, silty fine sand intermixed with down-burrowed coarse to very coarse quartz sand, pebbles, shell fragments, and phosphatic material. This contact represents a major erosive surface and is interpreted as the base of a Pleistocene Exmore paleochannel identified by Powars and Bruce (1999) that we date as 1.0–0.3 Ma. The late Miocene–Pliocene sequences (V9, V10, and V11) identified at the Eyreville core hole (Browning et al., this volume) were not recovered, and were eroded by the incision of the paleochannel (Fig. 2) as shown by regional mapping (Powars et al., 1992; Powars and Bruce, 1999).

Pleistocene Sequences: 55.17–7.96 m

The section from 55.17 to 7.96 m consists of a heterolithic interval of predominantly Pleistocene sediments (Fig. 6). Poor core recovery and condition (majority of sands are dried out and disassociated) complicate lithofacies interpretations and the identification of primary sedimentary structures. A sharp basal contact at 55.17 m is overlain by slightly silty, poorly sorted, coarse to very coarse quartz sand. Although the interval from 55.17 to 41.45 m is poorly recovered, large indurated cobbles, clasts, and pebbles were recovered at 55.05 m and 49.74 m. At 40.39 m, the medium to coarse sands are mixed with quartz granules, 2%–3% opaque heavy minerals, and exhibit faint cross-bedding. We interpret this succession as fluvial in origin, consistent with the interpretation of Powars and Bruce (1999). A fining-upward gradational contact from 39.08 to 39.99 m shifts from fluvial coarse sand to interlaminated micaceous silty clay to clayey silt with very fine sand concentrated in planar interbeds. Several laminated intervals change orientation and inclination and exhibit wavy bedding (e.g., 33.71 m). Burrows are generally small, sporadic, and sand filled. Fine-grained shell debris is scattered throughout, and rare organic material is observed above 31.36 m. Postcoring sulfur staining is visible from 25.30 to 22.25 m, and we interpret this paleoenvironment as estuarine or lagoon. A sharp contact at 19.39 m separates finer-grained lithologies from structureless, slightly micaceous, fine to medium quartz sand with granules and small pebbles that extends to another sharp contact at 17.74 m. Above this surface, a thin interval of white to gray bioturbated, sandy, silty clay extends to 16.09 m, where it coarsens upward to a yellow to white structureless fine to coarse quartz sand with 1%–2% opaque heavy minerals and occasional granules and small pebbles. Because of the poor condition of the core, we tentatively identify the depositional environment from 16.09 to 7.92 m as proximal upper shoreface to estuarine, where contacts at 12.62 m and 12.10 m represent facies changes (D.S. Powars, 2008, personal commun.). Sr isotope dates of 1.0–0.5 Ma were obtained for the laminated silts below 22.25 m. An additional date at 16.37 m yielded an age of 0.33 Ma, implicating one of the contacts at 19.39 m or 17.74 m as a possible sequence boundary (Fig. 6). We identify the contact at 19.39 m as an unconformity generated by the incision of an estuarine channel, overlain by finer-grained estuary fill deposits from 17.74 to 16.09 m. These Pleistocene sequences are significantly thicker than those at Eyreville (Fig. 2; Table 1), and they are classified as part of the Nassawadox Formation (from ground surface to 19.5 m after Mixon et al., 1989) and Omar Formation (from 19.5 to 41.5 m after Powars and Bruce, 1999). Mixon et al. (1992) estimated the Exmore paleochannel as either stage 8 (270 ka) or stage 12 (430 ka). The lack of Sr isotopic age data from 41.5 to 55.1 m prevents conclusive assignment of this unit, although it may represent the base of the Pleistocene paleochannel, or it may be significantly older (e.g., Pliocene; K. Ramsay, 2008, personal commun.).

DISCUSSION

Local and Regional Sequence Distribution Related to the Chesapeake Bay Impact Structure

Global sea-level change largely controlled postimpact sedimentation in the inner basin (Browning et al., this volume) and in the annular trough (this study), though deposition was overprinted by the differential compaction of impactites, variations in sediment supply, and periods of differential regional tectonic uplift and subsidence. The ages of sequence boundaries both outside (Bethany Beach) and within the Chesapeake Bay impact structure (Eyreville, Exmore) correlate with ice-volume increases inferred from oxygen isotopic changes from the Oligocene through late Miocene, and this is evidence for a global control (Fig. 8; see discussion in Browning et al., this volume). However, there are significant differences between Chesapeake Bay impact structure sequences and coeval sections dated outside the crater, which can be attributed to regional tectonism and sedimentation changes.

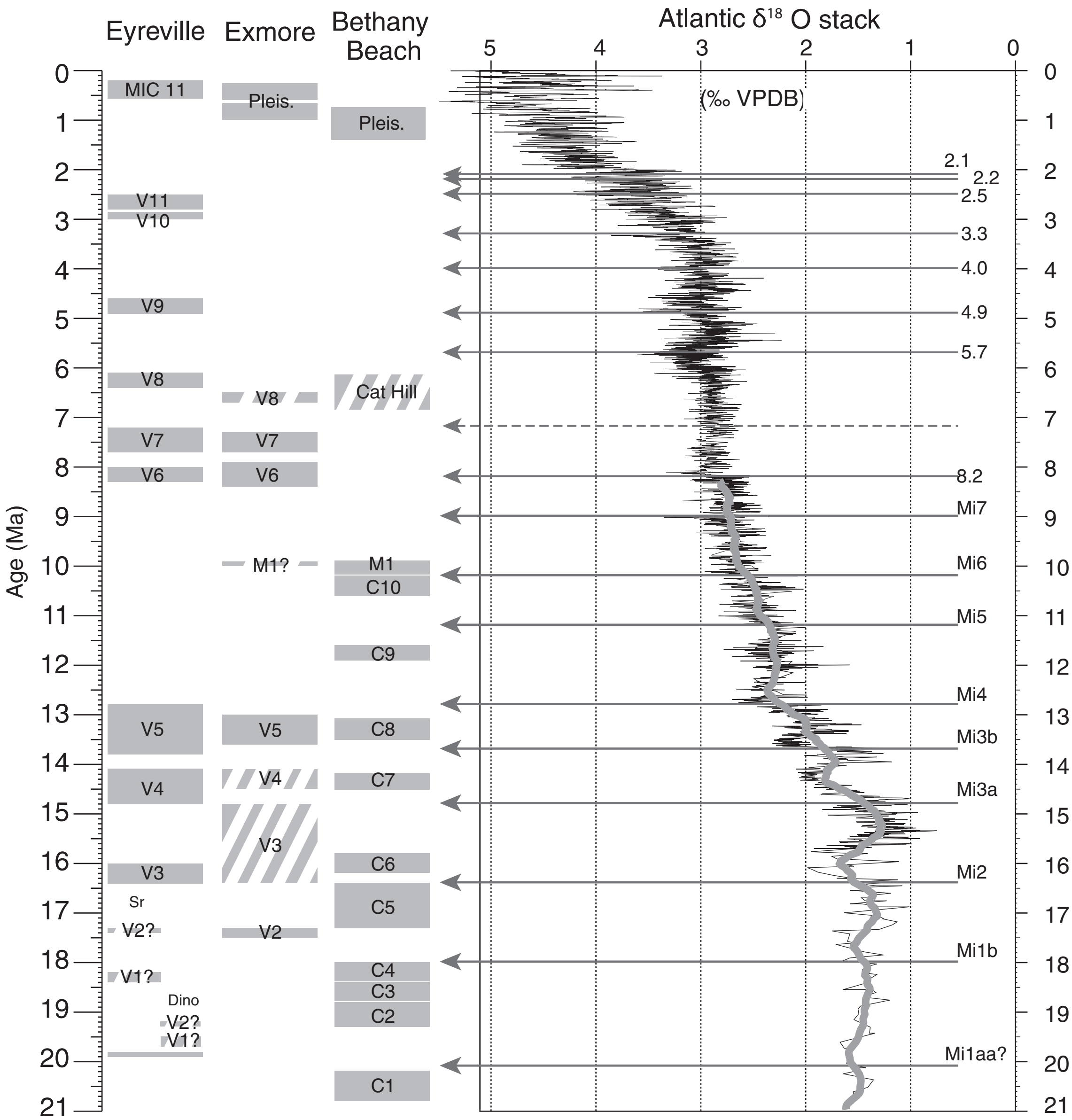


Figure 8. Temporal distribution of sequences for three core holes (Eyreville, Exmore, and Bethany Beach) plotted against oxygen isotope data (adapted from Browning et al., this volume). Geochronology of each sequence was derived from Sr isotope age analysis, with biostratigraphy at Bethany Beach and Eyreville (Browning et al., 2006; this volume). Hachured sequences are poorly dated. Oxygen 18 inflections represent ice-volume increases; these are marked by arrowed lines and are identified next to the right axis. VPDB—Vienna Peedee belemnite.

The Upper Eocene section, where cored, is thickest in the inner basin at Eyreville, but it is thin or missing immediately around the crater. This pattern reflects the depression after the initial crater excavation and infilling (outer neritic to upper bathyal paleodepths estimated as ~300 m by Poag [this volume] and ~200 m by Browning et al. [this volume]) and the compaction and settling of thick impactite deposits within the inner basin, providing high rates of accommodation and an expanded section. Previous interpretations from seismic data (Poag et al., 2004) show that these Upper Eocene units may thicken further offshore to the southeast in the annular trough where there are no core holes. The Oligocene is generally thin and poorly represented throughout the mid-Atlantic region and consists of glauconitic sand and clay deposited on a sediment-starved shelf, except for the southeastern New Jersey coastal plain where the Oligocene is relatively thick (30–60 m; Miller et al., 1997; Pekar et al., 2000; Fig. 3; Table 2). Oligocene sequences (ca. 33–24 Ma) are thin within the inner basin at Eyreville (~15 m) and the annular trough, the exception being at Langley (~50 m; Fig. 2; Table 2), representing sediment starvation in that part of the inner basin. The lower Lower Miocene is relatively thick (>150 m) and well developed in New Jersey and Delaware, but it is patchy and thin to absent in the Chesapeake Bay impact structure and other Maryland–North Carolina sections (hiatus 27–18 Ma; Table 2). Extensive lower Lower Miocene sequences were not recovered at Exmore or Kiptopeke or other Chesapeake Bay impact structure core holes, though some thin and patchy sequences were recovered: (1) biostratigraphic work from the Langley core hole (Edwards et al., 2005) identifies possible sequence C1 (20.0–19.4 Ma; sequence initially defined from Bethany Beach; Browning et al., 2006); (2) dinocyst data from Eyreville identifies a thin package of sediment from 19.7 to 19.2 Ma (Browning et al., this volume); and (3) 10–13 m of Lower Miocene sediment was recovered at the Jamestown core hole (Powars and Bruce, 1999). This southward thinning and patchy distribution of Oligocene–Lower Miocene sequences are interpreted to be the result of differential uplift of the Norfolk Arch and/or subsidence of the Salisbury Embayment, accentuated by decreased sediment supply and possible sediment starvation in the southern Delmarva and Chesapeake Bay impact structure area (Fig. 3).

The Middle Miocene is well represented in New Jersey and across the Delmarva Peninsula, consisting of relatively thick sequences (50–100 m) characterized by high sedimentation rates (Browning et al., 2006). These sequences persist into the Chesapeake Bay impact structure at Exmore, Eyreville, and Kiptopeke, but pinch out rapidly between Kiptopeke and Langley (Fig. 2), and are largely thin or absent south (Fentress, Dismal Swamp) of the crater (Fig. 3). We attribute this thinning to relative uplift of the Norfolk Arch compared to the Salisbury Embayment and regions to the north (Fig. 3). The lower Upper Miocene sequences (C9, C10, M1; 11.9–9.8 Ma) thin progressively southward

TABLE 2. REGIONAL CHARACTERISTICS OF THE MID-ATLANTIC COASTAL PLAIN

Stratigraphic interval	Chesapeake Bay impact structure (CBIS) inner basin Eyreville	Chesapeake Bay impact structure annular trough Exmore	Delaware and New Jersey Bethany Beach
Upper Miocene–Pliocene	(1) Fine grained (St. Marys) to coarse grained (Eastover) (2) Marine shelf to shoreface (3) Thick and widespread (4) Persists south of CBIS (5) Hiatus: 12.8–8.3 Ma	(1) Fine grained (St. Marys) to coarse grained (Eastover) (2) Marine shelf to shoreface (3) Thick and widespread (4) Pleistocene channel eroded Pliocene (5) Hiatus: 13.0–8.4 Ma	(1) Predominantly coarse grained (2) Marine shelf to shoreface in Delaware (3) Deltaic in New Jersey (4) Late Miocene–Pliocene absent (5) Hiatus: 7–2 Ma
Middle Miocene	(1) Fine grained (2) Shelf, distal lower shoreface highstand systems tracts (HSTs) (3) 20–50-m-thick sequences (4) Thickens into central crater (5) Absent south of crater	(1) Fine-grained base, coarsens upward (2) Shelf to shoreface (3) 20–50-m-thick sequences (4) Thickens into the annular trough (5) Abundant in annular trough	(1) Coarse grained (2) Shoreface in Delaware, deltaic in New Jersey (3) 10–20-m-thick sequences (4) Prograding wedges (5) Persistent across Delmarva Pen.
Lower–Middle Miocene	(1) Very fine grained (2) Marine shelf (3) Thin to absent within inner basin (4) Thin, patchy, absent further south	(1) Very fine grained (2) Marine shelf (3) Largely absent within annular trough	(1) Coarse grained (2) Upper shoreface to shelf in Delaware (3) Prograding wedges, deltaic in New Jersey (4) Thick and continuous (20–60 m)
Oligocene	(1) Heavily glauconitic clay and sand (2) Sediment-starved shelf (3) Restricted inner basin (4) Thinly preserved (15 m)	(1) Heavily glauconitic clay and sand (2) Sediment-starved shelf (3) Thicker in annular trough (25–50 m) (4) Thins significantly to south	(1) Glauconitic clay and sand (2) Sediment-starved shelf (3) Locally thick (40–60 m) (4) Patchy distribution
Upper Eocene	(1) Very fine grained (2) Deep shelf, deeper inner basin (3) Thick in inner basin (94 m) (4) Thin to absent in surrounding regions	(1) Very fine grained (2) Deep shelf (3) Thinner than inner basin (24 m) (4) Thins and pinches out updip outside of crater	(1) Fine grained (2) Deep shelf (3) Thick sequences (50 m) (4) Continuous and widespread

(20–60 m) across the Delmarva Peninsula before pinching out north of Exmore between Tasley and Hallwood, as inferred from a significant change in log character and thickness (Fig. 3; Table 2). No lower Upper Miocene sediments were recovered within, or south, of the Chesapeake Bay impact structure (Fig. 3), although Powars and Bruce (1999) documented zone DN8 (ca. 11.1–8.6 Ma) at the Jamestown core hole west of the Chesapeake Bay impact structure. This southward thinning reflects again the coupling of regional tectonic uplift and decreased sediment supply to the Chesapeake Bay impact structure area.

Upper Miocene–Pliocene sequences are marine to marginal-marine, and they are relatively thick in both the Chesapeake Bay impact structure and adjacent regions (120–200 m), but they are poorly represented or absent in New Jersey (e.g., Miller et al., 2005). The scarcity of these sequences is attributed to differential subsidence of the Salisbury Embayment. Within the Chesapeake Bay impact structure, Upper Miocene–Pliocene sections thicken into the crater relative to adjacent sections in Virginia. Surface mapping and seismic data (Powars and Bruce, 1999) show that these intervals are thickest on the southern side of the crater due to greater accommodation than on the northern part of the Chesapeake Bay impact structure, where thick Middle Miocene prograding packages filled much of the available space (Fig. 3; Table 2).

Eustatic Variations

Previous studies of the Cenozoic strata on the mid-Atlantic margin (Miller et al., 1996, 1998, 2005; Browning et al., 2006) concluded that glacioeustasy (sea-level change driven by variations in ice volume) was the dominant control on sequence formation. The age of sequence boundaries at Bethany Beach, Delaware, corresponds one-to-one with ice-volume increases inferred from oxygen isotopic changes from the Oligocene through late Miocene (Fig. 8; Browning et al., 2006), although a period of increased subsidence caused by offshore depocenter loading is inferred from 21 to 12 Ma. Many of these sequences can be correlated across the Delmarva Peninsula toward the Chesapeake Bay impact structure (Fig. 3).

A comparison of oxygen isotope records (Fig. 8; Miller et al., 2005) with sequences within the Chesapeake Bay impact structure shows that sequence-boundary formation was controlled by glacioeustatic falls. Periods of strong correspondence between sequence boundaries and $\delta^{18}O$ isotope increases include the Middle Miocene (sequences V2–V5), the Upper Miocene (sequences V6–V8; although each sequence boundary is only 100–200 ka in duration), the Pliocene recovered at Eyreville (sequences V9–V11; Browning et al., this volume), and the Pleistocene sequences (dated at 400–200 ka and correlated to MIC 11 at Eyreville; Browning et al., this volume) (Fig. 8). Upper Miocene sequences C9, C10, and M1 are absent at both Eyreville and Exmore, but they were recovered at Bethany Beach and are tied to $\delta^{18}O$ isotope increases (Fig. 8). Although this indicates glacioeustatic control on sequence genesis for these intervals, the thickness and preservation of sequences have been modified by impactite compaction, sediment-supply changes, and regional tectonics. Browning et al. (this volume) provide a comprehensive analysis linking sequence-boundary genesis to oxygen isotopic events.

Periods exhibiting weak calibration to $\delta^{18}O$ isotopic records in Virginia include: (1) the Oligocene (sequences are poorly preserved and dated and cannot be conclusively tied to oxygen isotopic changes); (2) Lower Miocene (sequences C1–C3 are poorly preserved or absent within the Chesapeake Bay impact structure and south of the crater); and (3) mid- to Upper Miocene (sequences C9, C10, and M1 are absent within the Chesapeake Bay impact structure, indicating regional uplift that overrode eustasy). These results from the late Eocene–Pleistocene show that although eustasy provided the template for sequences globally, regional tectonics (rates of uplift, subsidence, and accommodation), variations in sediment supply, and local factors (such as impact-related effects) modified and determined the preservation of sequences in this particular region.

Impactite Compaction

Impactites (e.g., the Exmore beds and crater units A and B of Poag, 1996, 1997; Poag et al., 1999; Powars and Bruce, 1999; Horton et al., 2008) are described as brecciated "polymict diamicton" (formalized by Flint et al., 1960) consisting (within the Chesapeake Bay impact structure) of unsorted 2–40-m-diameter sedimentary megablocks with heterolithic cobble-, pebble-, and sand-sized grains suspended in a finer-grained matrix rapidly emplaced during the catastrophic infilling of the Chesapeake Bay impact structure (e.g., Poag et al., 2004; Gohn et al., this volume). The size of sedimentary megablocks generally increases with depth from the upper transition zone, which separates impact-generated materials from overlying normal marine sedimentation (Poag et al., 1994). These large volumes of highly porous (currently >25%–35% from wet porosity samples; Sanford et al., this volume), poorly compacted materials resulting from an unconventional burial process exhibit an unusual compaction history that was influenced by the settling of underlying megablocks and subsequent loading of overlying impact and postimpact units (e.g., Powars, 2000).

Previous work (Hayden et al., 2008) used one-dimensional backstripping (e.g., accounting for the effects of compaction and sediment loading; Watts and Steckler, 1979; Kominz et al., 1998) of annular-trough core hole sections (Exmore, Kiptopeke, and Langley) and regional core holes (Fentress, Dismal Swamp) to examine 10-Ma-scale tectonic trends in and around the crater. They identified a period of excess accommodation in the annular trough for the first 3 Ma caused by the rapid compaction of impact-generated materials. A period of Oligocene uplift of 50–125 m was attributed to thermal blanketing by cold impact materials and the onset of a large negative thermal anomaly, whereas the mid-Miocene through Pliocene was dominated by regional tectonic patterns (Hayden et al., 2008).

We show that the compaction of impactites was not limited to the first 3 Ma as reported by Hayden et al. (2008), but it continued to strongly influence sedimentation within the central crater over the past 35.4 Ma through the Pleistocene (this was also reported by previous studies; Poag et al., 2004; Gohn et al., 2008). Our core hole–well log cross section (Fig. 3) shows that a majority of postimpact sequences (Upper Eocene, Middle-Upper Miocene, and Pliocene) are thicker in the annular trough (Exmore, Langley) than correlative sequences outside the crater (Tasley and sections to the north). These sequences thicken further into the inner basin (Eyreville), but they thin substantially onto the central peak at Cape Charles (Fig. 3; Poag et al., 2004). We contend that differences in accommodation within the Chesapeake Bay impact structure can be attributed to the different thicknesses and compaction of impactites within the inner basin (>1000 m thick at Eyreville) versus the annular trough (~100–200 m thick at Exmore) and the central uplift (~300 m thick at Cape Charles) (Fig. 3). Whereas previous work revealed similar lithostratigraphic trends (Powars and Bruce, 1999; Powars, 2000; Poag et al., 2004), our results provide better geochronologic resolution (~0.5–1.0 Ma) and a sequence-by-sequence examination of the timing and nature of the events that shaped the postimpact record. These results are consistent with high-resolution seismic profiles across the Chesapeake Bay impact structure that show numerous compaction faults that extend to the floor of the modern Chesapeake Bay, offsetting late Eocene–Pleistocene postimpact sediments that dip and thicken into the crater (Poag et al., 2004; Catchings et al., 2007). Previous seismic studies (e.g., Poag et al., 2004) also have discussed the possible influence of impact-generated crystalline ridges, basins, and impact-altered slump-blocks on compaction patterns within the Chesapeake Bay impact structure.

This unique compaction history apparently produced a bathymetric low within the inner crater, resulting in a deep basin at the core sites for much of the late Eocene–middle Miocene (Fig. 2). This inference is based on the comparison of lithofacies, quantitative grain-size measurements, and paleoenvironmental indicators between Eyreville (inner basin) and Exmore (annular trough): (1) Oligocene sections are substantially thicker in the annular trough cores (Exmore and Langley; 35–50 m) than the inner basin at Eyreville (15 m), representing enhanced sediment starvation within the inner basin; (2) Miocene sequences at Exmore are generally coarser-grained, exhibiting >50%–85% fine sands versus <10% at Eyreville in HST intervals (Fig. 2); and (3) while lower Middle Miocene sequences (V3–V5) are dominated by shelf sediments (silt and clay) at both core holes, Exmore sequences shallow upward to distal, lower shoreface, fine-medium sands, whereas Eyreville cores exhibit shelfal, clayey silts even in the HST (Fig. 2). No notable facies differences are documented for Upper Miocene–Pliocene deposits, and coarse-grained and shallow marine facies dominate both sections (Fig. 2).

Passive-Aggressive Tectonism: Regional Insights and Controlling Mechanisms

Although postrift lithospheric cooling and the flexural response to offshore sediment loading are the dominant contributors to "classic" Atlantic-type passive-margin subsidence (Watts and Steckler, 1979; Kominz et al., 1998), several authors have concluded that nonthermoflexural subsidence and uplift have occurred on this margin (e.g., Brown et al., 1972; Owens and Gohn, 1985; Owens et al., 1997). The development of a high-resolution (>1 Ma) sequence-stratigraphic framework across the mid-Atlantic margin (New Jersey, Delaware) and within the Chesapeake Bay impact structure (Virginia) provides the requisite geochronologic resolution to identify such nonthermal events. We contend that the distribution of regional sequences reveals significant periods of nonthermal tectonic uplift and excess subsidence at a scale of tens of meters in 1–5 Ma, overprinting subsidence from simple lithospheric cooling, flexure, and impactite compaction (within the Chesapeake Bay impact structure). This style of "passive-aggressive" tectonism characterizes passive margins otherwise dominated by thermoflexural subsidence.

We attribute the significant craterwide and regional unconformities south of Delaware during the Oligocene (33–25 Ma), early Miocene (24–18 Ma), and mid- to late Miocene (ca. 13.0–8.4 Ma; Figs. 3 and 8) to uplift of the Norfolk Arch relative to the adjacent Salisbury Embayment, possibly enhanced by low rates of sedimentation in southern Virginia. The poor coverage and resolution of seismic data have complicated interpretations of mid-Atlantic basement fabric, and have left the Norfolk Arch as an enigmatic structure. Thus, excess subsidence (on an already subsiding margin) of the broad Salisbury Embayment was also considered as a contributor to the generation of the unconformities across the Chesapeake Bay impact structure region. Such excess subsidence would be expected to produce the thick sections documented within the embayment, but would also result in thin sections and substantial unconformities on the bordering areas (Norfolk Arch to the south, South Jersey High to the north). However, the presence of thick, contemporaneous Eocene–Miocene sections across New Jersey indicates that the thickening of strata was not limited to the Salisbury Embayment, but it also extends to the north across other regionally significant basement structures (the South Jersey High and Raritan Embayment). Because of this distribution, we believe the drastic thinning of sequences and broad unconformities around the Chesapeake Bay impact structure and Norfolk Arch represent uplift of the arch relative to the Salisbury Embayment, although we suggest that synchronous subsidence within the Salisbury Embayment could contribute to these effects.

Evidence for postimpact uplift of the Norfolk Arch is visible from the differential preservation of sequences southward across the Chesapeake Bay impact structure and surrounding regions. At Exmore and Eyreville, sequences V2–V5 are well represented (sequence V1 was also recovered at Eyreville), while an unconformity spans from ca. 13.0 to 8.4 Ma. At the Langley core hole (10 km north of the Norfolk Arch), correlation and biostratigraphy (Edwards et al., 2005) indicate the absence of sequences V1, V2, and V4, coupled with the thin, patchy preservation of sequences V3 and V5. This pattern likely reflects the periodic uplift of the Norfolk Arch during the early Miocene, middle

Miocene, and early late Miocene, because thick and widespread Miocene sections are recovered farther north throughout the Salisbury Embayment and New Jersey (Fig. 3). These results are consistent with previous work by Powars (2000).

The thin to absent upper Upper Miocene to Pliocene section in New Jersey also contrasts with the region to the south, where coeval units are thick and widespread across Delaware, Maryland, and Virginia (Fig. 9; e.g., Browning et al., 2006; Powars and Bruce, 1999; this study). This unique distribution argues for either differential subsidence of the Salisbury Embayment and Norfolk Arch relative to New Jersey, or a period of uplift that was restricted to the New Jersey coastal plain. The lack of regional seismic profiles across the mid-Atlantic Coastal Plain complicates our understanding of the nature of the tectonic mechanism responsible for this event.

The Chesapeake Bay impact structure–area unconformities during the Oligocene and early Miocene are also analogous to patchy to absent Paleocene–Pliocene strata in the region to the south caused by episodic tectonic uplift of the Cape Fear Arch (Gohn, 1988; Weems and Lewis, 2002). Although the Norfolk Arch does not exhibit the modern or historical seismicity of the Cape Fear arch (Weems and Lewis, 2002), the two structures bear several similarities: (1) position adjacent to major structural embayments of the Atlantic margin (the Norfolk Arch borders the Salisbury and Albemarle Embayments, whereas the Cape Fear Arch is bracketed by the Albemarle and Southeast Georgia Embayments; Gohn, 1988); (2) alternating periods of normal coastal-plain deposition interspersed with periodic tectonic uplift and erosion/nondeposition (Coniacian-Campanian strata are undisturbed atop the Cape Fear Arch before Paleocene uplift; Gohn, 1988); and (3) exposure to variations in the North American stress field throughout the Cenozoic (e.g., reaction of the Cape Fear Arch to a regional compressive stress field throughout the Neogene; Weems and Lewis, 2002).

Although we attribute the majority of Oligocene and Miocene uplift of the Chesapeake Bay impact structure to regional

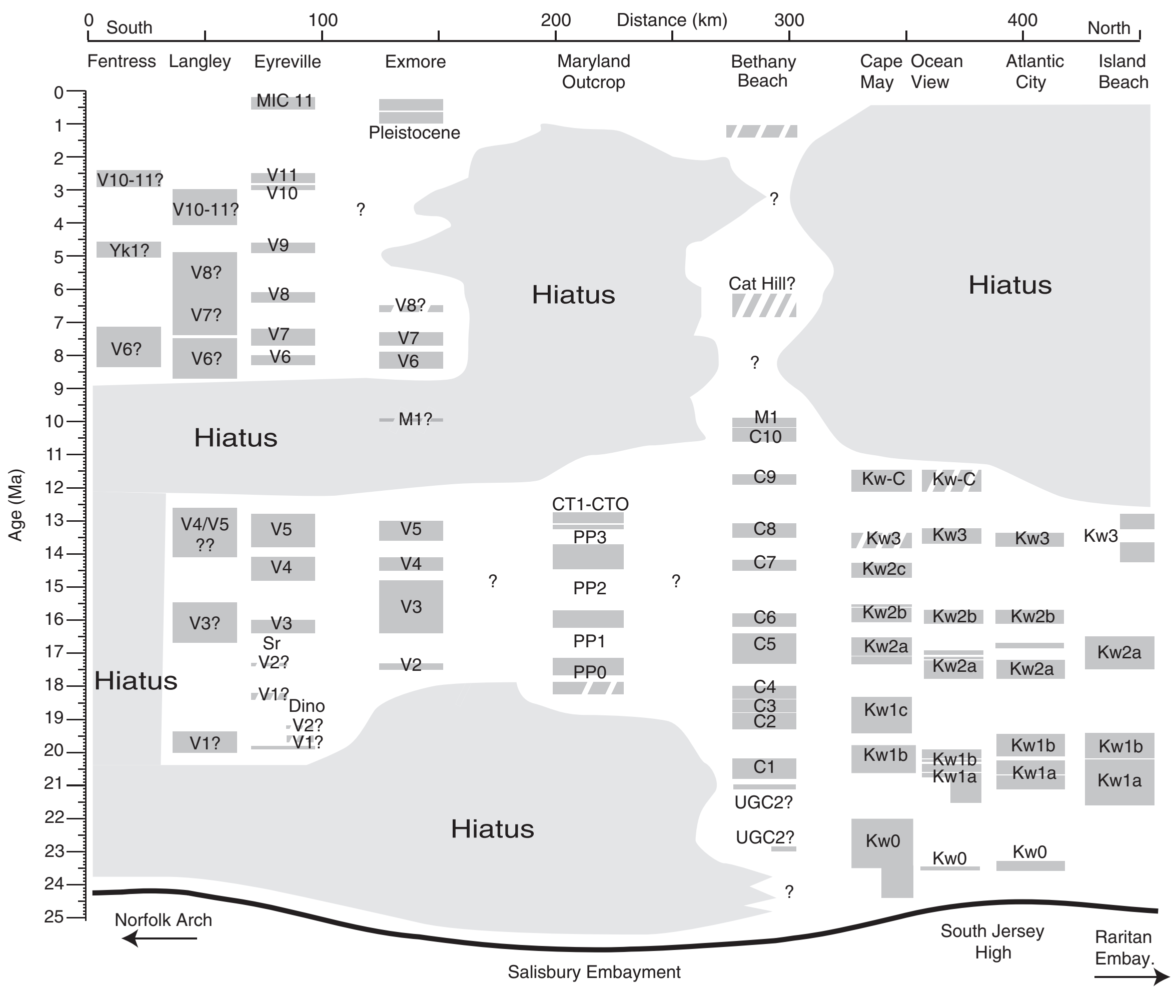


Figure 9. Diagram showing the preservation of sequences (in time) plotted against geographic distance (south to north transect from Fentress, Virginia, to Island Beach, New Jersey). The basement contour is modified from Olsson et al. (1988). Faint gray background represents the extent (in time and distance) of regional unconformities.

tectonism, quantification of the amplitudes and rates of change is necessary to evaluate the controlling mechanisms. Previous efforts on the mid-Atlantic margin used one-dimensional backstripping to document numerous vertical tectonic events of uplift or excess (nonthermal) subsidence. Browning et al. (2006) and Hayden et al. (2008) identified periods of Miocene excess subsidence of 30 ± 10 m across the Delmarva Peninsula attributed to down-flexure from depocenter loading on the offshore shelf. Within the Chesapeake Bay impact structure, Hayden et al. (2008) identified a period of intracrater uplift of 50–120 m caused by the onset and removal of a negative thermal anomaly induced by the thermal blanketing of cold impact materials. We believe that these estimates of thermally induced crater uplift (both amplitude and timing) are complicated by: (1) the unique compaction history of the impact-generated column underlying the postimpact section, and (2) the presence of regional hiatuses during the Oligocene–early Miocene. Hayden et al. (2008) modeled the bulk of impactite compaction within ~3 Ma after impact but did not model the long-term, time-dependent compaction of impact breccias observed in this study (Fig. 2) and Gohn et al. (2008). This resulted in deeper R1 estimates that require greater uplift (100+ m) to achieve subaerial erosion required for unconformity genesis in the Oligocene. Second, these estimates of crater-specific uplift are complicated by the presence of regional hiatuses during the Oligocene–early Miocene (largely absent sections with occasional thin, patchy intervals identified from core holes, geophysical log correlations, and previous studies of the region; Fig. 3; Powars, 2000; Powars and Bruce, 1999). These thin Oligocene–Lower Miocene sections stand in stark contrast to thicker coeval sections recovered in the New Jersey coastal plain (Miller et al., 1998, 2005; Pekar et al., 2000), and they are attributed to a phase of regional uplift by the Norfolk Arch and southern Salisbury Embayment, further compounded by low sedimentation rates during the Oligocene. As a result, establishing the exact amplitude and rate of possible thermal Chesapeake Bay impact structure uplift is difficult and requires further modeling (using higher-resolution geochronology, impactite compaction model, and comparison to eustatic estimates) to quantify and differentiate crater-specific effects from regional tectonic trends.

The genesis and behavior of the Norfolk Arch and other mid-Atlantic basement structures are poorly understood due to the lack of deep regional seismic data and low seismicity along active faults in the mid-Atlantic Coastal Plain (Seeber and Armbruster, 1988). Brown et al. (1972) described these structures as a series of wrench fault–bounded grabens, whereas Owens et al. (1997) attributed regional stratigraphic differences to "rolling basins" or broad warping (~100–300 km wavelength) of the crust. While there are insufficient data to conclusively determine their origin, we conclude that these basement structures represent inherited tectonic trends (basement faults) and fault-bounded terranes emplaced during Paleozoic continental collisions. Such boundaries are critical structural components of passive margins, many of which are reactivated during the subsequent asymmetrical rift stage of a margin (Wernicke, 1989; e.g., the border fault of the Newark Basin; Schlische, 1992; Withjack et al., 1998) and still react to intraplate stresses today (e.g., Cape Fear Arch; Weems and Lewis, 2002). A comprehensive understanding of terrane distribution, character, and structural history is limited by the small number of core holes that penetrate the Paleozoic basement underlying the coastal plain, resulting in widely variable interpretations. However, several studies (e.g., Horton et al., 1989; Glover et al., 1997; Maguire et al., 2004) have identified a mosaic of fault-bounded terranes across the mid-Atlantic margin (Fig. 10), each of which has the capacity for vertical movement given the proper stress conditions. The James River structural zone (Powars, 2000), a structural boundary associated with the Norfolk Arch, appears to separate two accreted terranes emplaced during the assemblage of Pangea: Grenville-Laurentia crystalline basement and Avalonia (Fig. 10). Movement along this structural zone, among others, could contribute to the differential preservation of sequences observed on the mid-Atlantic margin.

We cite two mechanisms that could cause regional upwarping/downwarping and influence existing basement structures: (1) variations in intraplate stress (e.g., Cloetingh, 1988; Karner et al., 1993); and (2) density-driven mantle processes related to the interaction of eastern North America with the subducted Farallon plate (e.g., Müller et al., 2008; Moucha et al., 2008). The accumulation and relaxation of intraplate stresses tied to variations and reorganizations of far-field stress direction and intensity (e.g., changes in mid-ocean-ridge spreading rates, ridge extensions, onset of margin subduction, etc.) could provide the mechanism behind the influence of basement structure on coastal-plain strata. Cloetingh (1988) invoked these stress-field reorganizations as a possible explanation for third-order sea-level cycles (1–3 Ma) with amplitudes of 10–20 m. Although this mechanism fails to account for the observed eustatic driver of sequence-boundary formation (evidenced by the calibration of sequence boundaries with oxygen isotope records), these variations in intraplate stress can be propagated over large distances (thousands of kilometers; Letouzey, 1986; Ziegler and Van Hoorn, 1989; Cloetingh et al., 1990) and enhance or diminish unconformity genesis on intrabasinal scales (Karner et al., 1993). Furthermore, this mechanism can account for the pronounced thinning or truncation of thick (~50–100 m) sedimentary packages (e.g., Norfolk Arch), or result in the complete removal of entire series in the stratigraphic record (e.g., largely absent Paleogene section atop Cape Fear Arch, North Carolina; Weems and Lewis, 2002; Self-Trail et al., 2004).

The periodic uplift of the Cape Fear and Norfolk Arches may represent the adjustment of these structures from prior stress conditions to the current maximum horizontal stress direction of east northeast–west southwest, with the fault-bounded Cape Fear Arch accommodating much of the modern stress and seismicity (Weems and Lewis, 2002). The Oligocene and early Miocene uplifts of these structures are coincident with a major reorganization of the North American stress field (~90° shift) from 35 to 28 Ma (Bird, 2002) due to the collision of the East Pacific Rise along the western North American margin and consequent cessation of subduction, onset of Basin and Range extension, and

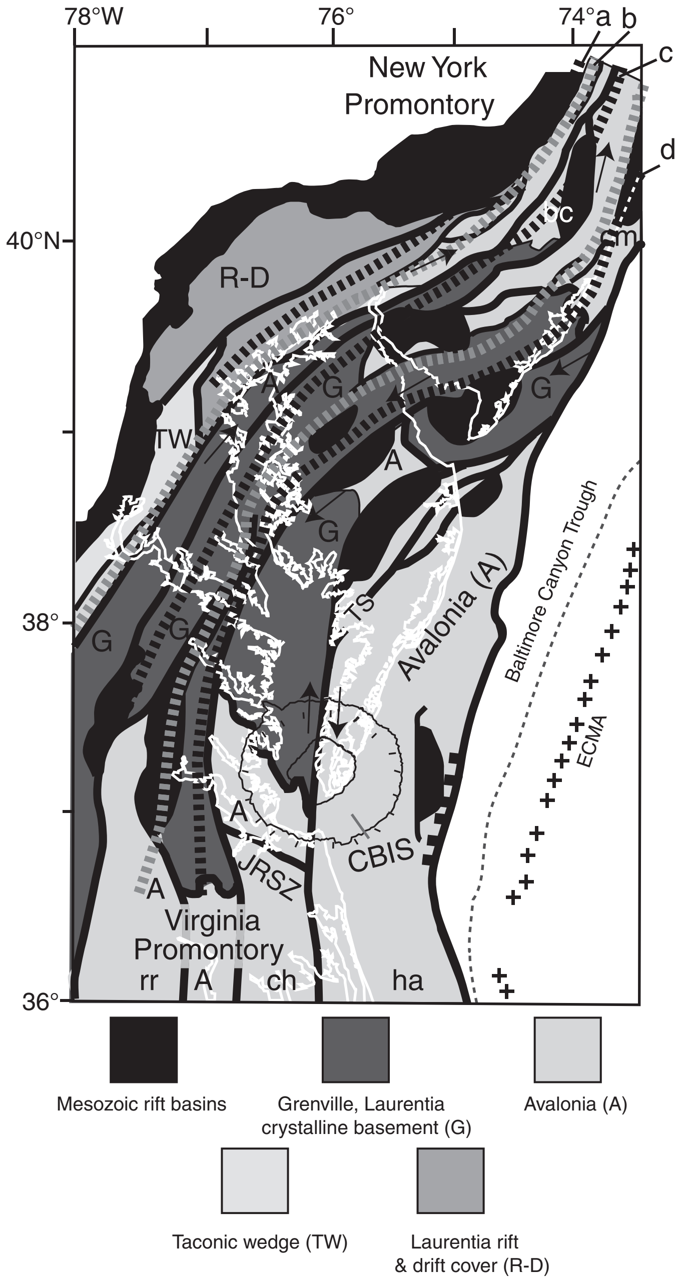


Figure 10. Map showing the distribution of subsurface terranes, boundaries, and key structural elements across the mid-Atlantic margin (modified from Maguire et al., 2004; Glover et al., 1997). Terranes are coded according to the following key. Black dashed lines represent major synforms (a—Shellburne Falls and Chester domes; d—Connecticut Valley–Gaspe synclinorium); gray dashed lines represent major antiforms (b—Manhattan Prong–Berkshire Massif; c—Prehlam dome–Bronson Hill anticlinorium). The mid-Atlantic coastline and Chesapeake Bay impact structure (CBIS) are overlain in white to add geographic perspective. Terranes and other features are identified by letters: rr—Roanoake Rapids; ch—Charleston; ha—Hatteras; bc—Brompton-Cameron; and cm—central Maine. JRSZ—James River structural zone (northern edge of the Norfolk Arch) from Powars (2000). Horton et al. (2005a, 2005b) noted the presence of Avalon basement at the Bayside core hole, different from the shown map. ECMA—East Coast magnetic anomaly; TS—Taconic Suture.

development of the Pacific–North American transform margin through the Miocene (Bird, 2002; Nicholson et al., 1994), among other events (e.g., onset of Cayman Trough transform margin; e.g., ten Brink et al., 2002).

Alternatively, recent studies (Müller et al., 2008; Forte et al., 2007; Spasojević et al., 2008; Moucha et al., 2008) have shown that variations in mantle density structure can result in dynamic topographic changes (e.g., response of Earth's surface to convectively driven vertical stresses; Mitrovica et al., 1989) and broad epeirogenic uplift and downwarp of large crustal segments. Both Müller et al. (2008) and Spasojević et al. (2008) attributed the comparatively low long-term (10-Ma-scale) sea-level events established from the New Jersey margin (Miller et al., 2005) to periods of dynamic subsidence (50–200 m in excess of predicted normal passive-margin thermoflexural subsidence) superimposed on long-term sea-level fall since the Eocene. This subsidence is driven by the interaction of the eastern United States with the underlying subducted Farallon plate (Spasojević et al., 2008). Whereas implications of such studies are profound, they primarily focus on long-term (10–100 Ma) tectonic trends (e.g., Moucha et al., 2008) that fail to account for higher-frequency sequence and unconformity genesis on the mid-Atlantic and other margins, which appear to be on the 1–5 Ma. Recent studies by Forte et al. (2007) invoked mantle density perturbations coupled to the subducted Farallon slab as a possible explanation for the intraplate seismicity observed in the New Madrid fault zone, showing that dynamic topography can drive smaller-scale processes than can broad crustal warping. Further research is needed to determine if subregional, high-frequency (1–10 Ma), differential uplift and subsidence, which may at times be synchronous (as observed on the mid-Atlantic margin; e.g., Cape Fear and Norfolk Arch uplift versus relative subsidence in the Salisbury Embayment), can effectively be explained by dynamic topography, or if they represent the blending of several tectonic processes, or are entirely unrelated to tectonics. Quantitatively modeling (through one-dimensional backstripping) of the rates, amplitudes, and lateral scale of these changes is a topic of ongoing research and will provide better constraints for differentiating these mechanisms. However, until additional seismic and core hole data are acquired across these structures, the underlying causes of uplift and subsidence remain speculative at this stage of understanding.

Regional Sediment-Supply Variations

Variations in sediment supply cannot alone form sequence boundaries (Christie-Blick, 1991), but they can contribute significantly to the distribution of sequences and lithofacies on both regional and local scales. Whereas Cenozoic sequences of the mid-Atlantic margin primarily reflect eustatic and tectonic controls, an increase or reduction of sediment supply can affect sequence thickness, the position of key stratal surfaces, and the presence of particular lithofacies and biofacies (e.g., Reynolds et al., 1991; Galloway, 1989). The mid-Atlantic region was influenced by several major fluvial systems during the Cenozoic (Poag and Sevon, 1989). The ancestral Susquehanna, Potomac, Delaware, and Hudson Rivers, as well as several smaller rivers (e.g., James, York), influenced regional and local sedimentation (Poag and Sevon, 1989; Powars, 2000). Changes in sediment input, tied to variation in the rates of Appalachian uplift and denudation, are often reflected by different styles of regional coastal-plain sedimentation. The Cretaceous–Miocene New Jersey margin was strongly influenced by two deltaic systems that controlled the distribution of sequences, depocenter location, and lithofacies (Sugarman et al., 1995, 2006; Miller et al., 2004; Kulpecz et al., 2008). Coeval Miocene sections in Delaware, Maryland, and Virginia reveal little deltaic influence and exhibit wave-dominated shoreline facies (e.g., Browning et al., 2006), representing increased distance from primary margin sediment sources.

We contend that regional changes in sediment supply, caused by the concentration of major fluvial and deltaic sources in New Jersey, contributed to the preservation of sequences across the mid-Atlantic margin and within the Chesapeake Bay impact structure. Whereas eustasy controls sequence-boundary formation, and regional tectonics can account for absent sequences, decreased sediment supply can result in thin sequences more prone to complete erosion than thick sequences during base-level decreases. An overall decrease in deltaic influence is documented southward, from thick deltaic sections at Cape May, New Jersey (Fig. 1; Sugarman et al., 2007), to wave-dominated sequences at Bethany Beach, Delaware (Browning et al., 2006), and finer-grained shelf- to lower shoreface–dominated sequences in southern Virginia. These regional sedimentation trends likely contributed to: (1) an Oligocene sediment-starved margin (e.g., Miller et al., 1997; Browning et al., 2008), where areas of most intense starvation were concentrated within the crater inner basin (visible at the Eyreville, Cape Charles, and Kiptopeke cores; particularly when compared to cores in the annular trough); and (2) early (C1–C5) and mid- to late Miocene (C9, C10, M1) sequences that persist across the Delmarva but pinch out southward and are patchy, thin, and absent at study sites within the Chesapeake Bay impact structure, representing uplift of the Norfolk Arch coupled with decreased sediment supply. Although the long and regionally extensive unconformities in the Oligocene, early Miocene, and mid- to late Miocene may have been controlled by regional tectonic uplift, we believe the effects were exacerbated by low sedimentation. Seismic data from Powars and Bruce (1999) and Catchings et al. (2007) show the southerly downlap of Miocene units and the northern infilling of the Chesapeake Bay impact structure during the middle Miocene (and subsequent thickening of late Miocene–Pliocene packages in the southern crater), and they are thus consistent with a strong northern sediment source prograding southward and lower levels of sediment delivery in Virginia relative to the north.

CONCLUSIONS

The Exmore and Eyreville, Virginia, cores provide the first continuous, high-resolution (>~1 Ma) chronostratigraphic records linking the annular trough and inner basin of the late Eocene Chesapeake Bay impact structure. We use integrated sequence-stratigraphic analyses to identify twelve definite and four possible postimpact depositional sequences within the inner basin and the annular trough and place them within in a regional framework spanning the mid-Atlantic margin. We conclude that postimpact sedimentation was largely controlled by global sea-level changes (as indicated by calibration with oxygen isotopic records), long-term impactite compaction (consistent with previous studies; Poag et al., 2004), and periods of regional tectonic uplift and subsidence. Differential compaction of the impactites was greatest in the inner crater and caused a bathymetric low during the late Eocene–mid-Miocene, resulting in deeper-water lithofacies than available core holes in the annular trough.

Whereas many Chesapeake Bay impact structure sequence boundaries correspond strongly with ice-volume increases inferred from oxygen isotopic changes, our evaluation of Chesapeake Bay impact structure deposition in relation to other parts of the U.S. mid-Atlantic margin reveals five primary phases of postimpact crater burial influenced by sediment-supply changes and regional tectonism: (1) relatively rapid late Eocene deposition dominated by the initial morphology of the crater basin caused by impact and a rapid phase of impactite compaction; (2) regional Oligocene uplift and sediment starvation in the inner basin; (3) a phase of continued early Miocene regional uplift; (4) mid–Upper Miocene uplift of the Norfolk Arch coupled with low sedimentation rates; and (5) late Miocene to Pliocene subsidence of the southern Salisbury Embayment relative to New Jersey. We identify periods of regional uplift and excess subsidence at a scale of tens of meters in 1–5 Ma, which overprint subsidence from simple lithospheric cooling, flexure, and impactite compaction. We speculate these events were caused by the differential movement of basement structures and fault-bounded terranes in response to variations in intraplate stress.

ACKNOWLEDGMENTS

We thank the National Science Foundation (NSF), International Continental Scientific Drilling Project (ICDP), the U.S. Geological Survey (USGS), and the National Aeronautics and Space Administration (NASA) for funding the Eyreville core hole and postcoring studies. We are grateful for reviews by C.W. Poag and K. Ramsey, and the comments of editor C. Koeberl, which greatly improved this manuscript. We thank members of the USGS-ICDP onsite science party for the collection of data at the Eyreville core hole, and the members of the New Jersey Coastal Plain Drilling Project for their assistance with data sets from Ocean Drilling Program (ODP) Leg 174AX. We thank Greg Gohn and J. Wright Horton Jr. for provision of the Exmore core hole. We thank Pete McLaughlin Jr. for insight into regional stratigraphy in Delaware and Maryland, and Steve Curtain for providing several geophysical logs used in this study. We thank the Buyrn family for use of their land for the Eyreville core hole, and DOSECC, G. Cobb III, and Major

Drilling for drilling operations. This research was supported by NSF grants EAR-0506720 and EAR-0606693 (to Miller, Browning, Kominz), and summer funding through DOSECC's internship program.

REFERENCES CITED

Andreason, D.C., and Hansen, H.J., 1987, Summary of Hydrogeologic Data from a Test Well (1,725 ft.) Drilled in Tuckahoe State Park, Queen Anne's County, Maryland: Maryland Geological Survey Open-File Report 87-02-3, 47 p.

Andres, A.S., 2004, The Cat Hill Formation and Bethany Beach Formation of Delaware: Delaware Geological Survey Report of Investigations 67, 8 p.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995, A revised Cenozoic geochronology and chronostratigraphy, *in* Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J., eds., Geochronology, Time Scales and Global Stratigraphic Correlations: A Unified Temporal Framework for an Historical Geology: SEPM (Society for Sedimentary Geology) Special Publication 54, p. 129–212.

Bird, P., 2002, Stress direction history of the western United States and Mexico since 85 Ma: Tectonics, v. 21, p. 1–12, doi: 10.1029/2001TC001319.

Brown, P.M., Miller, J.A., and Swain, F.M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U.S. Geological Survey Professional Paper 796, p. 1–79.

Browning, J.V., Miller, K.G., McLaughlin, P.P., Kominz, M.A., Sugarman, P.J., Monteverde, D., Feigenson, M.D., and Hernàndez, J.C., 2006, Quantification of the effects of eustasy, subsidence, and sediment supply on Miocene sequences, mid-Atlantic margin of the United States: Geological Society of America Bulletin, v. 118, p. 567–588, doi: 10.1130/B25551.1.

Browning, J.V., Miller, K.G., Sugarman, P.J., Kominz, M.A., McLaughlin, P.P., and Kulpecz, A.A., 2008, A 100 million year record of sequences, sedimentary facies and sea-level change from Ocean Drilling Program onshore coreholes, U.S. mid-Atlantic coastal plain: Basin Research, v. 20, p. 227–248, doi: 10.1111/j.1365-2117.2008.00360.x.

Browning, J.V., Miller, K.G., McLaughlin, P.P., Jr., Edwards, L.E., Kulpecz, A.A., Powars, D.S., Wade, B.S., Feigenson, M.D., and Wright, J.D., 2009, this volume, Integrated sequence stratigraphy of the postimpact sediments from the Eyreville core holes, Chesapeake Bay impact structure inner basin, *in* Gohn, G.S., Koeberl, C., Miller, K.G., and Reimold, W.U., eds., The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes: Geological Society of America Special Paper 458, doi: 10.1130/2009.2458(33).

Catchings, R.D., Powars, D.S., Goldman, M.R., Gohn, G.S., Horton, J.W., Jr., Rymer, M.J., Gandhok, G., and Edwards, L.E., 2007, High-resolution seismic reflection images across the 1.76-km-deep Eyreville core hole within the moat of the Chesapeake Bay impact structure: Geological Society of America Abstracts with Programs, v. 39, no. 6, abstract 167-3.

Christie-Blick, N., 1991, Onlap, offlap, and the origin of unconformity-bounded depositional sequences: Marine Geology, v. 97, p. 35–56, doi: 10.1016/0025-3227(91)90018-Y.

Cloetingh, S., 1988, Intraplate stresses: A tectonic cause for third-order cycles in apparent sea level?, *in* Wilgus, C.K., Hastings, B.K., Posamentier, H., Van Wagoner, J., Ross, C.A., and St. C. Kendall, C.G., eds., Sea-Level Changes: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 19–29.

Cloetingh, S., Gradstein, F.M., Kooi, H., Grant, A.C., and Kaminski, M., 1990, Plate reorganization: A cause of rapid late Neogene subsidence and sedimentation around the North Atlantic?: Journal of the Geological Society of London, v. 147, p. 495–506, doi: 10.1144/gsjgs.147.3.0495.

de Verteuil, L., and Norris, G., 1996, Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia: Micropaleontology, v. 42, supplement, 172 p.

Edwards, L.E., Barron, J.A., Bukry, D., Bybell, L.M., Cronin, T.M., Poag, C.W., Weems, R.E., and Wingard, G.L., 2005, Paleontology of the Upper Eocene to Quaternary postimpact section in the USGS-NASA Langley core, Hampton, Virginia, *in* Horton, J.W., Jr., Powars, D.S., and Gohn, G.S., eds., Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Virginia, and Related Coreholes and Geophysical Surveys: U.S. Geological Survey Professional Paper 1688, p. H1–H47, 9 pls.

Edwards, L.E., Powars, D.S., Browning, J.V., McLaughlin, P.P., Jr., Miller, K.G., Self-Trail, J.M., Kulpecz, A.A., and Elbra, T., 2009, this volume, Geologic columns for the ICDP-USGS Eyreville A and C cores, Chesapeake Bay impact structure: Postimpact sediments, 444 to 0 m depth, *in* Gohn, G.S., Koeberl, C., Miller, K.G., and Reimold, W.U., eds., The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes: Geological Society of America Special Paper 458, doi: 10.1130/2009.2458(04).

Flint, R.F., Sanders, J.E., and Rodgers, J., 1960, Diamictite, a substitute term for symmictite: Geological Society of America Bulletin, v. 71, p. 1809, doi: 10.1130/0016-7606(1960)71[1809:DASTFS]2.0.CO;2.

Forte, A.M., Mitrovica, J.X., Moucha, R., Simmons, N.A., and Grand, S.P., 2007, Descent of the ancient Farallon slab drives localized mantle flow below the New Madrid seismic zone: Geophysical Research Letters, v. 34, p. L04308, doi: 10.1029/2006GL027895.

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis: II. Application to northwest Gulf of Mexico Cenozoic basin: American Association of Petroleum Geologists Bulletin, v. 73, p. 143–154.

Glover, L., III, Sheridan, R.E., Holbrook, W.S., Ewing, J.I., Talwani, M., Hawman, R.B., and Wang, P., 1997, Paleozoic collisions, Mesozoic rifting and structure of the Middle-Atlantic states continental margin: An 'EDGE' Project report, *in* Glover, L., III, and Gates, A.E., eds., Central and Southern Appalachian Sutures: Results of the EDGE Project and Related Studies: Geological Society of America Special Paper 314, p. 107–135.

Gohn, G.S., 1988, Atlantic Coastal Plain: North Carolina to Florida, *in* Sheridan, R.E., and Grow, J.A., eds., The Atlantic Coastal Margin, U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. I-2, p. 107–130.

Gohn, G.S., Sanford, W.E., Powars, D.S., Horton, J.W., Jr., Edwards, L.E., Morin, R.H., and Self-Trail, J.M., 2007, Site Report for the USGS Test Holes Drilled at Cape Charles, Northampton County, Virginia, in 2004: U.S. Geological Survey Open-File Report 1094, 27 p.

Gohn, G.S., Koeberl, C., Miller, K.G., Reimold, W.U., Browning, J.V., Cockell, C.S., Horton, J.W., Jr., Kenkmann, T., Kulpecz, A.A., Powars, D.S., Sanford, W.E., and Voytek, M.A., 2008, Deep drilling yields new insights into the Chesapeake Bay impact event: Science, v. 320, p. 1740–1745, doi: 10.1126/science.1158708.

Gohn, G.S., Koeberl, C., Miller, K.G., and Reimold, W.U., 2009, this volume, Deep drilling in the Chesapeake Bay impact structure—An overview, *in* Gohn, G.S., Koeberl, C., Miller, K.G., and Reimold, W.U., eds., The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes: Geological Society of America Special Paper 458, doi: 10.1130/2009.2458(01).

Hansen, H.J., and Lang, C.M., 1980, Unpublished Well Log Transect from Smith Island to Ocean City Airport, MD: Maryland Geological Survey, 1 plate.

Hansen, H.J., and Wilson, J.M., 1984, Summary of Hydrogeologic Data from a Deep (2,678 ft.) Well at Lexington Park, St. Mary's County, Maryland: Maryland Geological Survey Open-File Report 84-02-1, 61 p.

Hansen, H.J., and Wilson, J.M., 1990, Hydrogeology and Stratigraphy of a 1,515-Foot Test Well Drilled near Princess Anne, Somerset County, Maryland: Maryland Geological Survey Open-File Report 91-02-5, 59 p.

Hart, S.R., and Brooks, C., 1974, Clinopyroxene-matrix partitioning of K, Rb, Cs, and Ba: Geochimica et Cosmochimica Acta, v. 38, p. 1799–1806, doi: 10.1016/0016-7037(74)90163-X.

Hayden, T., Kominz, M., Powars, D.S., Edwards, L.E., Miller, K.G., Browning, J.V., and Kulpecz, A.A., 2008, Impact effects and regional tectonic insights: Backstripping the Chesapeake Bay impact structure: Geology, v. 36, p. 327–330, doi: 10.1130/G24408A.1.

Horton, J.W., Jr., and Izett, G.A., 2005, Crystalline-rock ejecta and shocked minerals of the Chesapeake Bay impact structure, USGS-NASA Langley core, Hampton, Virginia, with supplemental constraints on the age of impact, *in* Horton, J.W., Jr., Powars, D.S., and Gohn, G.S., eds., 2005, Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Virginia, and Related Coreholes and Geophysical Surveys: U.S. Geological Survey Professional Paper 1688, p. E1–E30.

Horton, J.W., Jr., Drake, A.A., Jr., and Rankin, D.W., 1989, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachians, *in* Dallmeyer, R.D., ed., Terranes in the Circum-Atlantic Paleozoic Orogens: Geological Society of America Special Paper 230, p. 213–245.

Horton, J.W., Jr., Powars, D.S., and Gohn, G.S., eds., 2005a, Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Virginia, and Related Coreholes and Geophysical Surveys: U.S. Geological Survey Professional Paper 1688, paginated separately.

Horton, J.W., Jr., Aleinikoff, J.N., Kunk, M.J., Gohn, G.S., Edwards, L.E., Self-Trail, J.M., Powars, D.S., and Izett, G.A., 2005b, Recent research on the Chesapeake Bay impact structure, USA—Impact debris and reworked ejecta, *in* Kenkmann, T., Hörz, F., and Deutsch, A., eds., Large Meteorite Impacts III: Geological Society of America Special Paper 384, p. 147–170.

Horton, J.W., Jr., Gohn, G.S., Powars, D.S., and Edwards, L.E., 2008, Origin and emplacement of impactites in the Chesapeake Bay impact structure, Virginia, USA, *in* Evans, K.R, Horton, J.W., Jr., King, D.T., Jr., and Morrow, J.R., eds., The Sedimentary Record of Meteorite Impacts: Geological Society of America Special Paper 437, p. 73–97.

Karner, G.D., Driscoll, N.W., and Weissel, J.K., 1993, Response of the lithosphere to in-plane force variations: Earth and Planetary Science Letters, v. 114, p. 397–416, doi: 10.1016/0012-821X(93)90072-H.

Kominz, M.A., Miller, K.G., and Browning, J.V., 1998, Long-term and short-term global Cenozoic sea-level estimates: Geology, v. 26, p. 311–314, doi: 10.1130/0091-7613(1998)026<0311:LTASTG>2.3.CO;2.

Kulpecz, A.A., Miller, K.G., Sugarman, P.J., and Browning, J.V., 2008, Response of Late Cretaceous migrating deltaic facies systems to sea level, tectonics, and sediment supply changes, New Jersey coastal plain U.S.A.: Journal of Sedimentary Research, v. 78, p. 112–129, doi: 10.2110/jsr.2008.009.

Letouzey, J., 1986, Cenozoic paleo-stress pattern in the Alpine foreland and structural interpretation in a platform basin: Tectonophysics, v. 132, p. 215–231, doi: 10.1016/0040-1951(86)90033-8.

Maguire, T.J., Sheridan, R.E., and Volkert, R.A., 2004, Geophysical modeling of the northern Appalachian Brompton-Cameron, central Maine, and Avalon terranes under the New Jersey coastal plain: Journal of Geodynamics, v. 37, p. 457–485, doi: 10.1016/j.jog.2004.02.016.

McArthur, J.M., Howarth, R.J., and Bailey, T.R., 2001, Strontium isotope stratigraphy: LOWESS Version 3. Best-fit line to the marine Sr-isotope curve for 0 to 509 Ma and accompanying look-up table for deriving numerical age (look-up table version 4: 08/03): The Journal of Geology, v. 109, p. 155–169, doi: 10.1086/319243.

Miller, K.G., Wright, J.D., and Fairbanks, R.G., 1991, Unlocking the ice house: Oligocene-Miocene oxygen isotopes, eustasy, and margin erosion: Journal of Geophysical Research, v. 96, p. 6829–6848, doi: 10.1029/90JB02015.

Miller, K.G., Mountain, G.S., the Leg 150 Shipboard Party, and Members of the New Jersey Coastal Plain Drilling Project, 1996, Drilling and dating New Jersey Oligocene-Miocene sequences: Ice volume, global sea level, and Exxon records: Science, v. 271, p. 1092–1094.

Miller, K.G., Rufolo, S., Sugarman, P.J., Pekar, S.F., Browning, J.V., and Gwynn, D.W., 1997, Early to middle Miocene sequences, systems tracts, and benthic foraminiferal biofacies, New Jersey coastal plain, *in* Miller, K.G., and Snyder, S.W., et al., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 150X: College Station, Texas, Ocean Drilling Program, p. 169–186.

Miller, K.G., Mountain, G.S., Browning, J.V., Kominz, M.A., Sugarman, P.J., Christie-Blick, N., Katz, M.E., and Wright, J.D., 1998, Cenozoic global sea-level, sequences, and the New Jersey transect: Results from coastal plain and slope drilling: Reviews of Geophysics, v. 36, p. 569–601, doi: 10.1029/98RG01624.

Miller, K.G., McLaughlin, P.P., Browning, J.V., Benson, R.N., Sugarman, P.J., Hernandez, J., Ramsey, K.W., Baxter, S.J., Feigenson, M.D., Aubry, M.-P., Monteverde, D.H., Cramer, B.S., Katz, M.E., McKenna, T.E., Strohmeier, S.A., Pekar, S.F., Uptegrove, J., Cobbs, G., III, and Curtin, S.E., 2003, Bethany Beach site, *in* Miller, K.G., Sugarman, P.J., Browning, J.V., et al., Proceedings of the Ocean Drilling Program, Initial Reports, Volume 174AX (suppl.): Washington, D.C., U.S. Government Printing Office, p. 1–84.

Miller, K.G., Sugarman, P.J., Browning, J.V., Kominz, M.A., Olsson, R.K., Feigenson, M.D., and Hernàndez, J.C., 2004, Upper Cretaceous sequences and sea-level history, New Jersey coastal plain: Geological Society of America Bulletin, v. 116, p. 368–393, doi: 10.1130/B25279.1.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293–1298, doi: 10.1126/science.1116412.

Mitchum, R.M., Vail, P.R., and Thompson, S., 1977, The depositional sequence as a basic unit for stratigraphic analysis, *in* Payton, C.E., ed., Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 53–62.

Mitrovica, J.X., Beaumont, C., and Jarvis, G.T., 1989, Tilting of continental interiors by the dynamic effects of subduction: Tectonics, v. 8, p. 1079–1094, doi: 10.1029/TC008i005p01079.

Mixon, R.B., Berquist, C.R., Jr., Newell, W.L., and Johnson, G.H., 1989, Geologic Map and Generalized Cross Sections of the Coastal Plain and Adjacent Parts of the Piedmont, Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I-2033, 3 sheets.

Mixon, R.B., Powars, R.B., and Daniels, D.L., 1992, Nature and timing of deformation of Upper Mesozoic and Cenozoic deposits in the inner Atlantic Coastal Plain, Virginia and Maryland, *in* Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey Workshop on the Geology and Geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 65–74.

Moucha, R., Forte, A.M., Mitrovica, J.X., Rowley, D.B., Quere, S., Simmons, N.A., and Grand, S.P., 2008, Dynamic topography and long-term sea level variations: There is no such thing as a stable continental platform: Earth and Planetary Science Letters, v. 271, no. 1–4, doi: 10.1016/j.epsl.2008.03.056, p. 101–108.

Müller, R.D., Sdrolias, M., Gaina, C., Steinberger, B., and Heine, C., 2008, Long-term sea-level fluctuations driven by ocean basin dynamics: Science, v. 319, p. 1357–1362, doi: 10.1126/science.1151540.

Nicholson, C., Sorlien, C.C., Atwater, T., Crowell, J.C., and Luyendyk, B.P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas as a low-angle fault system: Geology, v. 22, p. 491–495, doi: 10.1130/0091-7613(1994)022<0491:MCROTW>2.3.CO;2.

Olsson, R.K., Melillo, A.J., and Schreiber, B.L., 1987, Miocene sea level events in the Maryland coastal plain and the offshore Baltimore Canyon Trough, *in* Ross, C.A., and Haman, D., eds., Timing and Depositional History of Eustatic Sequences: Constraints on Seismic Stratigraphy: Cushman Foundation for Foraminiferal Research Special Publication 24, p. 85–97.

Olsson, R.K., Gibson, T.G., Hansen, H.J., and Owens, J.P., 1988, Geology of the northern Atlantic Coastal Plain: Long Island to Virginia, *in* Sheridan, R.E., and Grow, J.A., eds., The Atlantic Coastal Margin, U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. I-2, p. 87–105.

Oslick, J.S., Miller, K.G., Feigenson, M.D., and Wright, J.D., 1994, Oligocene-Miocene strontium isotopes: Stratigraphic revisions and correlations to an inferred glacioeustatic record: Paleoceanography, v. 9, p. 427–443, doi: 10.1029/94PA00249.

Owens, J.P., and Gohn, G.S., 1985, Depositional history of the Cretaceous series in the U.S. Atlantic Coastal Plain: Stratigraphy, paleoenvironments, and tectonic controls of sedimentation, *in* Poag, C.W., ed., Geologic Evolution of the United States Atlantic Margin: New York, Van Nostrand Reinhold, p. 25–86.

Owens, J.P., and Sohl, N.F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey coastal plain, *in* Subitzky, S., ed., Geology of Selected Areas in New Jersey and Eastern Pennsylvania and Guidebook of Excursions: New Brunswick, New Jersey, Rutgers University Press, p. 390–408.

Owens, J.P., Miller, K.G., and Sugarman, P.J., 1997, Lithostratigraphy and paleoenvironments of the Island Beach borehole, New Jersey Coastal Plain Drilling Project, *in* Miller, K.G., and Snyder, S.W., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 150X: College Station, Texas, Ocean Drilling Program, p. 15–24.

Pekar, S.J., Miller, K.G., and Kominz, M.A., 2000, Reconstructing the stratal geometry of latest Eocene to Oligocene sequences in New Jersey: Resolving a patchwork distribution into a clear pattern of progradation: Sedimentary Geology, v. 134, p. 93–109, doi: 10.1016/S0037-0738(00)00015-4.

Pemberton, S.G., 1998, Stratigraphic applications of the *Glossifungites* ichnofacies delineating discontinuities in the rock record: American Association of Petroleum Geologists Bulletin, v. 82, p. 2155.

Pemberton, S.G., MacEachern, J.A., and Saunders, T., 2004, Stratigraphic applications of substrate-specific ichnofacies: Delineating discontinuities in the rock record, *in* McIlroy, D., ed., The Application of Ichnology to Paleoenvironmental and Stratigraphic Analysis: Geological Society of London Special Publication 228, p. 29–62.

Poag, C.W., 1996, Structural outer rim of Chesapeake Bay impact crater: Seismic and bore hole evidence: Meteoritics & Planetary Science, v. 31, no. 2, p. 218–226.

Poag, C.W., 1997, The Chesapeake Bay bolide impact: A convulsive event in Atlantic Coastal Plain evolution: Sedimentary Geology, v. 108, p. 45–90, doi: 10.1016/S0037-0738(96)00048-6.

Poag, C.W., 2000, Nature and distribution of deposits derived from the Chesapeake Bay submarine impact: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-163.

Poag, C.W., and Sevon, W.D., 1989, A record of Appalachian denudation in postrift Mesozoic and Cenozoic sedimentary deposits of the U.S. middle Atlantic continental margin: Geomorphology, v. 2, p. 119–157, doi: 10.1016/0169-555X(89)90009-3.

Poag, C.W., Powars, D.S., Poppe, L.J., and Mixon, R.B., 1994, Meteoroid mayhem in Ole Virginny—Source of the North American tektite strewn field: Geology, v. 22, p. 691–694, doi: 10.1130/0091-7613(1994)022<0691:MMIOVS>2.3.CO;2.

Poag, C.W., Hutchinson, D.R., Coleman, S.M., and Lee, M.W., 1999, Seismic expression of the Chesapeake Bay impact crater; Structural and morphologic refinements based on new seismic data, *in* Dressler, B.O., and Sharpton, V.L., eds., Large Meteorite Impacts and Planetary Evolution–II: Geological Society of America Special Paper 339, p. 149–164.

Poag, C.W., Koeberl, C., and Reimold, W.U., 2004, The Chesapeake Bay Crater: Geology and Geophysics of a Late Eocene Submarine Impact Structure: New York, Springer-Verlag, 522 p.

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988, Eustatic controls on clastic deposition: I. Conceptual framework, *in* Wilgus, C.K., Hastings, B.K., Posamentier, H., Van Wagoner, J., Ross, C.A., and St. C. Kendall, C.G., eds., Sea-Level Changes: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 109–124.

Powars, D.S., 2000, The Effects of the Chesapeake Bay Impact Crater on the Geological Framework and Correlation of Hydrogeologic Units of Southeastern Virginia, South of James River: U.S. Geological Survey Professional Paper 1622, 53 p.

Powars, D.S., and Bruce, T.S., 1999, The Effects of the Chesapeake Bay Impact Crater on the Geological Framework and Correlation of Hydrogeologic Units of the Lower York–James Peninsula, Virginia: U.S. Geological Survey Professional Paper 1612, 82 p.

Powars, D.S., Mixon, R.B., and Bruce, T.S., 1992, Uppermost Mesozoic and Cenozoic geologic cross section, outer coastal plain of Virginia, *in* Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey Workshop on the Geology and Geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 85–101.

Powars, D.S., Bruce, T.S., Edwards, L.E., Gohn, G.S., Self-Trail, J.M., Weems, R.E., Johnson, G.H., Smith, M.J., and McCartan, C.T., 2005, Physical stratigraphy of the Upper Eocene through Quaternary postimpact section in the USGS-NASA Langley core, Hampton, Virginia, *in* Horton, J.W., Jr., Powars, D.S., and Gohn, G.S., eds., Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Virginia, and Related Coreholes and Geophysical Surveys: U.S. Geological Survey Professional Paper 1688, p. G1–G44.

Pusz, A., Miller, K.G., Wright, J.D., Katz, M.E., Cramer, B.S., and Kent, D.V., 2009, Stable isotopic response to the late Eocene extraterrestrial impacts, *in* Koeberl, C., ed., The Late Eocene Earth: Hothouse, Icehouse, and Impacts: Geological Society of America Special Paper 452, p. 83–95, doi: 10.1130/2009.2452(06).

Reilly, T.J., Miller, K.G., and Feigenson, M.D., 2002, Late Eocene to Oligocene Sr-isotopic reference section, Site 522, eastern South Atlantic: Paleoceanography, v. 18, p. 1–9.

Reynolds, D.J., Steckler, M.S., and Coakley, B.J., 1991, The role of sediment load in sequence stratigraphy: The influence of flexural isostasy and compaction, *in* Cloetingh, S., ed., Special Section on Long-Term Sea-Level Change: Journal of Geophysical Research, ser. B, Solid Earth and Planets, v. 96, p. 6931–6949, doi: 10.1029/90JB01914.

Rider, M.H., 2002, The Geological Interpretation of Well Logs (2nd edition): Sutherland, Scotland, Rider-French Consulting Ltd., 280 p.

Sanford, W.E., Gohn, G.S., Powars, D.S., Horton, J.W., Jr., Edwards, L.E., Self-Trail, J.M., and Morin, R.H., 2004, Drilling the central crater of the Chesapeake Bay impact structure: A first look: Eos (Transactions, American Geophysical Union), v. 85, p. 369, 377.

Sanford, W.E., Voytek, M.A., Powars, D.S., Jones, B.F., Cozzarelli, I.M., Cockell, C.S., and Eganhouse, R.P., 2009, this volume, Pore-water chemistry from the ICDP-USGS core hole in the Chesapeake Bay impact structure—Implications for paleohydrology, microbial habitat, and water resources, *in* Gohn, G.S., Koeberl, C., Miller, K.G., and Reimold, W.U., eds., The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes: Geological Society of America Special Paper 458, doi: 10.1130/2009.2458(36).

Schlische, R.W., 1992, Structural and stratigraphic development of the Newark extensional basin, eastern North America: Evidence for the growth of basin and its bounding structures: Geological Society of America Bulletin, v. 104, p. 1246–1263, doi: 10.1130/0016-7606(1992)104<1246:SASDOT>2.3.CO;2.

Seeber, L., and Armbruster, J.G., 1988, Seismicity along the Atlantic seaboard of the U.S.: Intraplate neotectonics and earthquakes, *in* Sheridan, R., and Grow, J., eds., The Atlantic Continental Margin, U.S.: Geological Society of America, Geology of North America, v. I-2, p. 437–444.

Self-Trail, J.M., Powell, D.C., and Christopher, R.A., 2004, The Collins Creek and Pleasant Creek Formations: Two new Upper Cretaceous subsurface units in the Carolina/Georgia coastal plain: Southeastern Geology, v. 42, p. 237–252.

Spasojević, S., Liu, L., Gurnis, M., and Muller, R.D., 2008, The case for dynamic subsidence of the U.S. East Coast since the Eocene: Geophysical Research Letters, v. 35, L0835, doi: 10.1029/2008GL033511.

Sugarman, P.J., Miller, K.G., Bukry, D., and Feigenson, M.D., 1995, Uppermost Campanian-Maestrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey coastal plain: Geological Society of America Bulletin, v. 107, p. 19–37, doi: 10.1130/0016-7606(1995)107<0019:UCMSIB>2.3.CO;2.

Sugarman, P.J., Miller, K.G., Browning, J.V., Kulpecz, A.A., McLaughlin, P.P., Jr., and Monteverde, D.H., 2006, Hydrostratigraphy of the New Jersey coastal plain: Sequences and facies predict the continuity of aquifers and confining units: Stratigraphy, v. 2, p. 259–275.

Sugarman, P.J., Miller, K.G., Browning, J.V., Monteverde, D.H., Uptegrove, J., McLaughlin, P.P., Jr., Stanley, A.M., Wehmiller, J., Kulpecz, A.A., Harris, A.D., Pusz, A., Kahn, A., Friedman, A., Feigenson, M.D., Barron, J., and McCarthy, F.M.G., 2007, Cape May Zoo site, *in* Miller, K.G., Sugarman, P.J., Browning, J.V., et al., Proceedings of the Ocean Drilling Program, Initial Reports, Volume 174AX (Suppl.): Washington, D.C., U.S. Government Printing Office, p. 1–66.

ten Brink, U.S., Coleman, D.F., and Dillon, W.P., 2002, The nature of the crust under the Cayman Trough from gravity: Marine and Petroleum Geology, v. 19, p. 971–987, doi: 10.1016/S0264-8172(02)00132-0.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* Wilgus, C.K., Hastings, B.K., Posamentier, H., Van Wagoner, J., Ross, C.A., and St. C. Kendall, C.G., eds., Sea-Level Changes: An Integrated Approach Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 39–45.

Watts, A.B., and Steckler, M.S., 1979, Subsidence and eustasy at the continental margin of eastern North America, *in* Talawani, M., Hay, W., and Ryan, W.B.F., eds., Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironments: American Geophysical Union, Maurice Ewing series, v. 3, p. 218–234.

Weems, R.E., and Lewis, W.C., 2002, Structural and tectonic setting of the Charleston, South Carolina, region: Evidence from the Tertiary stratigraphic record: Geological Society of America Bulletin, v. 114, p. 24–42, doi: 10.1130/0016-7606(2002)114<0024:SATSOT>2.0.CO;2.

Wernicke, B., 1989, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108–125.

Withjack, M.O., Schlische, R.W., and Olsen, P.E., 1998, Diachronous rifting, drifting, and inversion on the passive margin of central eastern North America: An analog for other passive margins: American Association of Petroleum Geologists Bulletin, v. 82, p. 817–835.

Ziegler, P.A., and Van Hoorn, B., 1989, Evolution of the North Sea rift system, *in* Tankard, A.J., and Balkwell, H., eds., Extensional Tectonics and Stratigraphy of the North Atlantic Margins: American Association of Petroleum Geologists Memoir 46, p. 471–500.

Manuscript Accepted by the Society 3 March 2009