Onshore–offshore correlations of Cretaceous fluvial-deltaic sequences, southern Baltimore Canyon trough

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ABSTRACT

We evaluate Cretaceous depositional sequences on approximately 4400 km (~2700 mi) of newly released multichannel seismic profiles and five wells on the continental shelf in the southern Baltimore Canyon trough and tie the data to three wells drilled onshore in the Maryland coastal plain. Seismic geometries coupled with facies and biostratigraphy from the wells are used to delineate mid-Cretaceous (Aptian–Turonian) depositional sequences and paleogeography. Beneath these sequences, 400–1000 m (1300–3300 ft) of Lower Cretaceous sedimentary rocks underlie the modern shelf. They thicken along strike to the southwest, implying a southern sediment source. Aptian to Cenomanian sediments were deposited in shelf to nearshore settings. A landward movement of the depocenter and a shift toward facies indicative of deeper paleodepths marks a 107-yr mid-Cretaceous transgression, within which we identify five sequences. A composite maximum flooding surface (MFS) within the uppermost of these retrogradational units is associated with the Cenomanian–Turonian boundary and ocean anoxic event 2. Shingled, lower Turonian seismic reflections prograde across the outer shelf, downlapping onto the composite MFS, and are truncated by a mid-Turonian sequence boundary. The Upper Cretaceous section thickens seaward and along strike to the northeast, implying a northern source and little Late Cretaceous accommodation beneath the modern shelf. Mid-Cretaceous strata offshore Maryland are likely sand-prone, considering their proximity to the correlative fluvial facies of the onshore Potomac Group. These potential reservoir sands are capped by regional confining units generated by 107-yr global mean sea-level
flooding events and are excellent targets for supercritical carbon storage.

INTRODUCTION

Geometries observed on seismic reflection profiles allow objective recognition of genetically related strata bound by unconformities and their apparent correlative surfaces (Mitchum et al., 1977b). Integrating reflection seismic data with well logs, cuttings, and core samples (including biostratigraphy and other chronological control) can significantly improve temporal resolution and paleoenvironmental interpretations (Van Wagoner et al., 1990). Depositional sequences may be objectively recognized in seismic, well-log, cutting, and core data and do not need to be uniquely tied to sea-level curves (Neal and Abreu, 2009; Miller et al., 2018).

Sequence stratigraphy provides a tool to place paleoenvironmental reconstructions and basin evolution into a local and regional context through mapping depositional environments and evaluating their trajectories through space and time as a result of changes in subsidence, global mean sea level (GMSL), and sediment supply. Further, sequence stratigraphy allows reconstruction of the stratigraphic record from its geomorphological origins and provides the most reliable way of examining strata for the purpose of basin scale correlation and lithological prediction for the distribution of reservoirs and seals (Posamentier and James, 1993).

The geologic record on the mid-Atlantic margin off the coast of New Jersey has been intensely studied, providing a “natural laboratory” for understanding passive-margin evolution and sea-level change (e.g., Poag, 1985b; Sheridan and Grow, 1988; Poag and Sevon, 1989; Miller et al., 1998, 2005; Mountain et al., 2010). The 1970s–1980s saw exploration for hydrocarbon reservoirs in the thick (2–16 km [6600–52,500 ft]) postrift (upper Lower Jurassic and younger) strata of the Baltimore Canyon trough (BCT) (summary in Poag, 1985b; e.g., Grow and Sheridan, 1988). Recently, efforts have focused on the Quaternary stratigraphy, as part of the STRATAFORM initiative (Nittrouer et al., 2007), and the Miocene, with drilling by the Integrated Ocean Drilling Program Expedition (IODP) 313 on the New Jersey shallow shelf (e.g., Mountain et al., 2010; Miller et al., 2013a, b). Early studies looked at the offshore Cretaceous as part of studies related to hydrocarbon exploration that delineated Cretaceous reservoir sandstones (e.g., Libby-French, 1984; Poag, 1985b; Prather, 1991). Later studies on the onshore Cretaceous coastal plain used a sequence stratigraphic approach (Olsson et al., 1988; Kulpecz et al., 2008). With increased interest in supercritical carbon storage, recent studies have begun to evaluate the
offshore Cretaceous of the mid-Atlantic margin, focusing on the northern BCT (NBCT) and the adjacent coastal plain (Miller et al., 2017, 2018) because it contains numerous industry wells and thick reservoir sands.

The mid-Cretaceous (Aptian to Cenomanian) section within the offshore southern BCT (SBCT; ~38°–39°N; offshore northern Virginia, Maryland, Delaware, and southern New Jersey; Figure 1) has been sparingly studied (e.g., Prather, 1991; Klitgord et al., 1994) because of a paucity of wells and a previously sparse database of low-quality (by modern standards) multichannel seismic (MCS) profiles collected by the US Geological Survey (USGS) in the 1970s. As a result, there are a number of outstanding questions regarding the spatial variability and general continuity of Cretaceous sedimentation across the basin. In particular, the strata comprising the continental shelf, slope, and rise off the coast of Maryland have been given little attention, aside from the aforementioned regional correlation of Klitgord et al. (1994) that characterized the entire sedimentary section from basement to sea floor from Virginia to Canada using the USGS MCS profiles. Moreover, the knowledge of the stratigraphy from onshore rotary wells (Doyle, 1982; Hansen, 1982; Andreasen et al., 2015; Miller et al., 2017) was not considered in the seismic interpretations, and, by extension, depositional sequences have not been correlated from the coastal plain to the continental shelf. These data from the onshore coastal plain provide an important constraint on any seismic stratigraphic interpretation of the continental shelf off the coasts of Maryland to southern New Jersey. For this region, the nearest offshore wells are the outer continental shelf (OCS) wells off the coast of New Jersey over 100 km (>62 mi) to the north and Shell 93-1, which is located on the rise in over 2 km (>6600 ft) of water (Figure 1), on a margin where shelf-to-slope facies are difficult to correlate (Mountain and Tucholke, 1985; Poag, 1985a).

With the recent release of hundreds of thousands of kilometers of industry seismic data covering the BCT (Triezenberg et al., 2016), it is now possible to examine the sedimentation history of this margin in greater detail. The seismic profiles not only provide data for interpretation of the Cretaceous sedimentary structure within the SBCT but also the opportunity to integrate information from the extensive literature and industry wells of the NBCT and the mid-Atlantic Coastal Plain. To address the opportunity for new insight on the larger-scale evolution of sedimentation on this margin, this work examines fluvial-deltaic sedimentary sequences within Cretaceous strata of the SBCT. We rely primarily on a dense grid of marine MCS reflection profiles integrated with biostratigraphical and geophysical data from drill sites on the mid-Atlantic Coastal Plain, OCS, and continental slope (Figure 1). Integrated sequence stratigraphic methods are used to map the depositional sequences of the continental shelf.
from southern New Jersey to Maryland. We identify depositional sequences off the coast of Maryland that correlate to depositional sequences present on the Maryland coastal plain (Miller et al., 2017) and to the NBCT (Miller et al., 2018), generating basin-scale sequence stratigraphic maps.

The basin-scale depositional sequences we interpret have implications for the identification of variations in depositional environments through space and time. Because the cyclicity of shallow marine siliciclastic environments at a passive margin is a function of GMSL change, subsidence within the basin, and sediment supply to the margin (e.g., Reynolds et al., 1991), a regional sequence stratigraphic framework provides insight into how these factors have contributed to the development and preservation of the sedimentary

Figure 1. Map of the seismic and drill site data within the Baltimore Canyon trough; black rectangles outline the southern and northern subareas discussed in the text. Generalized outcrop areas of coastal plain strata are distinguished by color. Depth contours to prerift basement are shown in dashed lines. The yellow lines identify seismic profiles shown in figures herein. COST = Continental Offshore Stratigraphic Test; DEM = digital elevation model; fig. = figure; MD = Maryland; USGS = US Geological Survey.

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architectures of the SBCT, both from sedimentological and tectonostratigraphic perspectives. The improved constraints on sedimentary architecture provide predictability not only for hydrocarbon reserves but also for supercritical storage of carbon dioxide.

BACKGROUND

The BCT, an offshore basin containing as much as 16 km (52,500 ft) of Middle Jurassic to Holocene strata (Grow and Sheridan, 1988), is bounded to the west by the basement hinge zone (approximated by the 5 km [16,400 ft] basement contour; Figure 1). Accretion of Paleozoic terranes and subsequent uplift was followed by Late Triassic to earliest Jurassic rifting and extensional separation of the North American and African plates (Klitgord et al., 1988; Withjack et al., 1998; Seton et al., 2012). The remnant heat from the extension and rifting phase resulted in a subsequent period of thermal subsidence (i.e., McKenzie, 1978) and flexural sedimentary loading on an elastic lithospheric plate (Steckler and Watts, 1978; Watts et al., 1982; Klitgord et al., 1988). The rift phase (ca. 230–198 Ma in this region; Withjack et al., 1998; Schlische et al., 2003) was characterized by faulting, minor folding, and Late Triassic–Early Jurassic synrift sedimentary deposition that occurred in two sets of elongate northeast-trending half-graben basins, one landward and one seaward of the basement “hinge zone” (Figure 1; Manspeizer and Cousminer, 1988). Sedimentation was punctuated by the circa 201.6–200.5 Ma central Atlantic magmatic province (CAMP; Blackburn et al., 2013) prior to the formation of the postrift unconformity (PRU) horizon that separates syn- and postrift sedimentary rocks across the entire margin (Withjack et al., 1998). The PRU has an estimated age of circa 175 Ma that is poorly constrained by assuming a constant sea-floor spreading rate and extrapolating a regression of ages from magnetic lineations on oceanic crust landward (Klitgord and Schouten, 1986), although the PRU is diachronous across its extent (Klitgord et al., 1988).

The uppermost Jurassic and Cretaceous sedimentation within the BCT, the focus of this paper, began approximately 50 m.y. after CAMP. The presence of postrift Lower Jurassic strata is uncertain (cf., Klitgord et al., 1988; Manspeizer and Cousminer, 1988), and because of the location of deep-penetration wells, there are few samples of Middle to lower Upper Jurassic strata. An initial postrift period of evaporite precipitation in the embryo of the present-day Atlantic Ocean was followed by a carbonate shelf regime with a fringing progradational reef that was subsequently buried in the mid-Cretaceous by siliciclastic deposition (Jansa, 1981). For the majority of the BCT, the reef was buried in the Barremian when sediments overtopped the reef structure and were deposited on top of the Neocomian (Hauterivian, Valanginian, and Berriasian) deep-sea reflector β identified beneath the modern continental rise (Mountain and Tucholke, 1985). The carbonate platform was generally progradational (Poag and Valentine, 1988), with continentally sourced siliciclastics locally interfingering with the Upper Jurassic and Lower Cretaceous carbonates (Poag, 1985b). Proximally, the subsurface Neocomian sediments of the New Jersey coastal plain record the fluvial deposition of the Waste Gate Formation in Maryland and southern New Jersey (Doyle, 1982; Hansen, 1982; Miller et al., 2017). Under the modern shelf, the heterolithic Valanginian to Barremian interval contains facies equivalent to the Missisauga Formation of the Scotian Shelf (Libby-French, 1984). The siliciclastic sediments that eventually buried the carbonate platform are coarser than the finer mid- to Upper Cretaceous sediments they were buried by (Poag and Valentine, 1988); the upward-finining succession reflects an increase in base level that began in the mid-Cretaceous. These transitions, including the death of the great barrier reef, reflect the structural evolution of the margin within a changing global climate (Jansa, 1981; Poag, 1985b).

The mid-Cretaceous sandstones of the BCT, described as the lithological equivalent to the Logan Canyon (LC) Formation of the Scotian Shelf (Libby-French, 1984; Poag, 1985b), were deposited following the mixed siliciclastic carbonates of the Barremian to Neocomian Missisauga Formation equivalent (Libby-French, 1984; Poag, 1985b). The sandstones were originally partitioned into an upper and lower LC sandstone by Libby-French (1984). These two sands were thought to be separated by a fine-grained unit called the Sable Shale. Closer examination of the lithological transitions and biostratigraphy in the NBCT led Miller et al. (2018) to conclude that the
LC was actually composed of three distinct depositional sequences, the LC3 (oldest), LC2, and LC1 (youngest), each possessing (1) lower regressive, lowstand systems tract (LST) interbedded silts and sands; (2) transgressive systems tract (TST) silts; and (3) upper regressive, highstand systems tract (HST) sands (Table 1). The revised stratigraphic packaging presents a more-detailed portrayal of the sand-prone units in the regressive LST and HSTs and offers a predictive framework for reservoir sand and confining shale-prone capstone units associated with the major flooding surfaces. These three depositional sequences are best observed in the NBCT on a well log transect between the Great Stone dome (GSD) and the OCS (Miller et al., 2018). In this location, they were apparently deposited within estuarine, delta front, and prodelta paleoenvironments (Miller et al., 2018) that follow a first-order deepening upsection. These offshore sands are coeval with the predominantly terrestrial Potomac Formation sequences of the mid-Atlantic Coastal Plain (Table 1; Miller et al., 2004, 2017, 2018; Browning et al., 2008).

The Upper Cretaceous of the BCT is characterized by a number of transgressive-regressive cycles that have been subdivided into depositional sequences on the mid-Atlantic Coastal Plain, where sedimentation was predominantly deltaic, with some terrestrial and nondenites marine sedimentation during major sea-level lowstands and highstands, respectively (Miller et al., 2004; Browning et al., 2008). Offshore, the section is largely comprised of the shaly Dawson Canyon equivalent (Table 1; Libby-French, 1984). A single regionally persistent sandstone unit, the Middle Sandstone, was identified by Libby-French (1984) that ranges from Coniacian to Campanian in age, according to biostratigraphic reports associated with wells drilled on the OCS (Seker, 2012). It may be coeval with any of several onshore sand units, from the Coniacian Magothy to the Campanian Mount Laurel Formation of the New Jersey coastal plain. The highest Late Cretaceous global sea levels occur close to the Cenomanian–Turonian boundary (Miller et al., 2005; Haq, 2014), producing the prodelta and shelfal sediments of the onshore Raritan and Bass River Formations (Browning et al., 2008) that cap the underlying, sand-prone fluvial sediments of the Potomac Formation. This onshore interval of Raritan and Bass River Formation shales corresponds to the Dawson Canyon Formation offshore, similarly capping the deltaic sands of the LC sequences identified by Miller et al. (2018). Additionally, Maastrichtian strata are deposited during a second long-term rise in sea level that ultimately culminates with a regional sea-level peak in the Eocene (Miller et al., 2005). The strata deposited during this base level increase also comprise a major confining unit both onshore (the composite confining unit of Zapecza, 1989) and offshore (Table 1).

### METHODS

#### Overview

We evaluate the subsurface of the SBCT using seismic profiles and well data (sequence stratigraphy, biostratigraphy, geophysical logs, and velocity surveys) to document the spatiotemporal variations of Cretaceous strata. Seismic stratigraphic principles (Mitchum et al., 1977b) were applied to subdivide the strata into relatively conformable stratigraphic packages. The well data provided chronological constraints using biostratigraphy for these seismic

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**Table 1. Correlation of the Variety of Names Used to Identify the Cretaceous Strata in the Baltimore Canyon Trough**

<table>
<thead>
<tr>
<th>Seismic boundary</th>
<th>Well log sequence</th>
<th>Lithologic Units (Libby-French, 1984)</th>
<th>Onshore equivalent</th>
<th>Age/stage</th>
<th>Reservoir characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC1</td>
<td>LC</td>
<td>Logan Canyon Sandstone &amp; Sable Shale</td>
<td>Navesink</td>
<td>Maastrichtian</td>
<td>Equivalent of onshore Composite Confining Unit (CCU)</td>
</tr>
<tr>
<td>LC2</td>
<td>LC</td>
<td>Lower Logan Canyon Sandstone &amp; Naskapi Shale</td>
<td>Potomac I</td>
<td>APT</td>
<td>HST sandstone reservoir shales into basin</td>
</tr>
<tr>
<td>LC3</td>
<td>LC</td>
<td>Lower Logan Canyon Sandstone &amp; Sable &amp; Naskapi Shale</td>
<td>Potomac I</td>
<td>APT</td>
<td>HST sandstone reservoir shales into basin</td>
</tr>
<tr>
<td>Miss.</td>
<td></td>
<td>Naskapi Shale &amp; Mississauga Sandstone</td>
<td>Washakie</td>
<td></td>
<td>High porosity &amp; permeability? in HST sandstone reservoir</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mississauga Shale</td>
<td></td>
<td></td>
<td>Heterolithic reservoirs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle, Mohawk, and other units</td>
<td></td>
<td></td>
<td>Upper Jurassic</td>
</tr>
</tbody>
</table>

Abbreviations: Bass R. = Bass River; DX = Dawson Canyon “x”; HST = highstand systems tract; LC = Logan Canyon; LK = Lower Cretaceous; Marshall = Marshalltown; Miss. = Mississauga; MK = mid-Cretaceous; SBCT = southern Baltimore Canyon trough; UK = Upper Cretaceous.

*Marshalltown, Englishtown, Merchantville, Cheesequake, Magothy, and Bass River onshore sequences.
surfaces. Integrating the two data sources allowed for the extrapolation of chronological information available at the drill sites across the more-extensive seismic grid.

Specifically, we integrated the biostratigraphy and well-log correlations with a sequence stratigraphic framework established for the NBCT (Miller et al., 2018) to build a chronological framework of the SBCT. Gamma-ray logs were used for correlation to the LC sequences identified by Miller et al. (2018) and provided lithological information to supplement the seismic stratigraphy. Velocity surveys facilitated the integration of the wells with the seismic profiles. Moreover, information from onshore wells, including deep wells on the Maryland coastal plain, were juxtaposed with the seismic interpretation. Similar to the offshore wells, the onshore wells provided chronological constraints through biostratigraphy (Anderson, 1948; Doyle, 1982) and previous sequence stratigraphic analyses (Miller et al., 2017) that were calibrated to the Geological Time Scale 2012 (Gradstein et al., 2012).

Once the sequence stratigraphy was defined, structural contour maps, isopach maps, and Wheeler (age–distance) diagrams were constructed from the seismic data to evaluate the movement of sedimentary depocenters through the Cretaceous. The stratigraphic architectures within the depositional sequences allowed for assessment of lithological variations through this interval.

Seismic Stratigraphy

Data

Seismic Data—The seismic data used were collected for hydrocarbon exploration purposes within the BCT by a number of exploration companies from 1975 to 1982. They were recently released as a part of the National Archive of Marine Seismic Surveys (NAMSS) packaged by Triezenberg et al. (2016). Two groups of surveys from this database were used, consisting of 36- to 240-fold MCS reflection profiles (Table 2). These data included 19,000 km (7300 mi²) of trackline that cover approximately 62,000 km² (−24,000 mi²) of the margin, from which we used approximately 4400 km (−2700 mi), spanning 12,000 km² (4600 mi²). The data were provided in standard Society of Exploration Geophysicists “Y” single-trace common midpoint format and imported onto a workstation running IHS Kingdom® software. Processing applied to most surveys (and some lines within individual surveys) included standard filtering, spiking deconvolution, velocity analysis, normal moveout, stacking, and migration.

The NAMSS seismic data have a peak frequency of approximately 14 Hz at all depths, whereas the spectral density in the 20- to 40-Hz bandwidth decreases with depth. Within the interval of interest for this study, the calculated seismic resolution (defined by a quarter of a wavelength and calculated from peak frequency and interval velocity from check shot data) ranges from 30 m (100 ft) at the top to 70 m (230 ft) in the deeper part of the section (−3000 m [−9800 ft]).

Mapping Seismic Stratigraphic Surfaces

The seismic sections were mapped to subdivide the record into depositional sequences according to procedures described originally by Mitchum et al. (1977b) and Mitchum and Vail (1977). These procedures emphasize the primary importance of concordant and discordant relationships, expressed by reflector terminations: downlap, onlap, toplap, or erosional truncation (e.g., Mitchum et al., 1977b; Vail, 1987; Catuneanu, 2006; Neal and Abreu, 2009; Abreu et al., 2010; Miller et al., 2018). Reflector terminations objectively delineate significant regional unconformities that result from erosion or nondeposition and bind the relatively conformable, genetically related units that comprise depositional sequences (Mitchum et al., 1977b). A secondary

<table>
<thead>
<tr>
<th>Survey</th>
<th>Originator</th>
<th>Year</th>
<th>Lines (Used)</th>
<th>Distance (Used)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-01-75-AT</td>
<td>Offshore Atlantic Group Survey</td>
<td>1975</td>
<td>149 (52)</td>
<td>11,734 km [7291 mi]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2800 km [1740 mi]</td>
</tr>
<tr>
<td>B-16-76-AT</td>
<td>Offshore Atlantic Group Survey</td>
<td>1976</td>
<td>80 (18)</td>
<td>6728 km [4181 mi]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1600 km [994 mi]</td>
</tr>
</tbody>
</table>

Surveys were collected for exploration purposes and made available to the public within the National Archive of Marine Seismic Surveys (Triezenberg et al., 2016).
interpretation characterizes packages of strata as prograding or retrograding, typically using the clinoform rollover (the change in gradient that partitions the topset and the foreset) as a geomorphological benchmark. The newly released data allow imaging of mid-Cretaceous clinoforms in the SBCT for the first time. Prograding strata are assigned within the upper regressive HST or lower regressive LST, whereas transgressive surfaces are placed within the TST. Assigning stratal packages within the depositional system and systems tract framework and identifying their stratigraphically significant bounding surfaces (Brown and Fisher, 1977; Posamentier et al., 1988; Abreu et al., 2010) has implications for predicting depositional environments and lithological characteristics within a depositional sequence (Mitchum et al., 1977a; Mitchum and Vail, 1977; Sangree and Widmier, 1977; Posamentier and James, 1993).

Following the procedure of Vail (1987) and Abreu et al. (2010), we (1) identified reflection terminations by type: onlap, downlap, toplap, or truncation; (2) identified stratal configurations as progradational, retrogradational, or aggradational; (3) mapped stratigraphically significant bounding surfaces; (4) assigned biostratigraphic ages; and (5) inferred depositional environment and lithology based on all of the above.

### Well Stratigraphy and Integration with Seismic Data

**Well Data**

We used data from 5 of 32 shelf exploration wells drilled off the mid-Atlantic Coast from 1978 to 1984, in addition to 3 wells (Maryland Esso 1, Mobil Bethards, and Ohio Oil Hammond) drilled onshore on the Maryland coastal plain (Table 3). We used three types of data from these wells: (1) biostratigraphy to provide chronological constraints; (2) geophysical logs to interpret transitions in lithologies and depositional environments and to generate synthetic seismograms to make well–seismic ties; and (3) velocity surveys to export the biostratigraphic and lithological data to the seismic section and test accuracy of the regional time–depth conversion.

Biostratigraphic data were obtained from technical reports and paleontological summaries produced by the (since-dissolved) US Department of the Interior Minerals Management Service (MMS) or other published work (e.g., Anderson, 1948; Doyle, 1982; Poag, 1985b). The sources of biostratigraphic picks are provided in Table 3.

The gamma-ray (GR) well log was used as the preferred lithological indicator, but the spontaneous potential (SP) log was used if GR was not available. The SP log was used to represent lithology in the Maryland coastal plain wells. Sonic logs and bulk density were available for each of the OCS wells used herein. The velocity surveys were primarily used to convert log measurements and biostratigraphic picks from depth to two-way traveltime (TWTT).

### Regional Time–Depth Conversion for Integration of Onshore Drill Site Data with Seismic Sections and Creation of Isopach Maps

The conversion of TWTT to depth is required to generate structural contours and isopach maps in

### Table 3. Locations of the Wells in the Southern Baltimore Canyon Trough Used for This Study, Geophysical Logs Available for Each Site, and Citations for the Biostratigraphy

<table>
<thead>
<tr>
<th>Well</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Total Depth, m (ft)</th>
<th>Biostratigraphy</th>
<th>Velocity Survey</th>
<th>Well Logs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maryland Esso 1</td>
<td>38.408</td>
<td>–75.063</td>
<td>2346 (7697)</td>
<td>Doyle (1982)</td>
<td>–</td>
<td>SP, SN</td>
</tr>
<tr>
<td>Mobil Bethards</td>
<td>38.304</td>
<td>–75.487</td>
<td>2195 (7201)</td>
<td>Doyle (1982)</td>
<td>–</td>
<td>SP, SN</td>
</tr>
<tr>
<td>Ohio Oil Hammond</td>
<td>38.346</td>
<td>–75.275</td>
<td>1665 (5463)</td>
<td>Doyle (1982)</td>
<td>–</td>
<td>SP, SN</td>
</tr>
<tr>
<td>Mobil 17-2</td>
<td>38.968</td>
<td>–73.049</td>
<td>4260 (13,976)</td>
<td>Steinkraus (1981)</td>
<td>Yes</td>
<td>GR, RHOB, DT</td>
</tr>
<tr>
<td>Shell 272-1</td>
<td>38.702</td>
<td>–73.540</td>
<td>4114 (13,497)</td>
<td>Steinkraus et al. (1985b)</td>
<td>No</td>
<td>GR, RHOB, DT</td>
</tr>
<tr>
<td>Shell 273-1</td>
<td>38.716</td>
<td>–73.456</td>
<td>5334 (17,500)</td>
<td>Steinkraus and Bebout (1985)</td>
<td>Yes</td>
<td>GR, RHOB, DT</td>
</tr>
<tr>
<td>Tenneco 495-1</td>
<td>38.466</td>
<td>–73.378</td>
<td>5578 (18,301)</td>
<td>Steinkraus et al. (1985a)</td>
<td>Yes</td>
<td>GR, RHOB, DT</td>
</tr>
</tbody>
</table>

The Maryland Esso 1, Ohio Oil Hammond, and Mobil Bethards wells were drilled in the 1940s on the eastern Maryland coastal plain. The Mobil 17-2, Shell 272-1, Shell 273-1, and Tenneco 495-1 wells were drilled in 1978 and 1979 on the outer continental shelf offshore southern New Jersey.

Abbreviations: COST = Continental Offshore Stratigraphic Test; DT = sonic; GR = gamma ray; RHOB = bulk density; SN = short normal resistivity; SP = spontaneous potential.
meters. We initially used the velocity–depth grids generated by Klitgord et al. (1994), as described in Appendix 1. We supplemented their database to incorporate a more-detailed time–depth profile for the upper second (TWTT) of sediments generated by Mountain and Monteverde (2012) based on seismic data acquired from the research vessel (R/V) Oceanus expedition OC270 and well data from IODP expedition 313 (Figure 2). The accuracy of the conversion of the seismic data (TWTT) to depth was checked against values obtained from OCS well velocity surveys at the well locations (check shot surveys and velocity logs).

**Study Area**

The northern half of the study area is off the coast of southern New Jersey (Figure 1), containing the B-01-75-AT (survey nomenclature from NAMSS; Triezenberg et al., 2016) seismic survey and the offshore wells used for chronological control. The southern part of the study area contains the B-16-76-AT seismic survey, with control provided by deep stratigraphic test wells on the Maryland coastal plain.

We projected the depth-registered chronological control from the wells in the northern part of the study area onto the B-01-75-AT seismic grid. Stratigraphic horizons were then interpreted across this grid to establish a seismic stratigraphic framework. Lines from the B-16-76-AT data that intersected the B-01-75-AT grid were used to correlate seismic data from the northern to the southern subareas. Seismic stratigraphy in the southern subarea was correlated to the Maryland wells onshore by extrapolating the dips of onshore sequence boundaries (i.e., Miller et al., 2017) seaward. This required a projection of approximately 20 km (~12 mi) from the most seaward well to the most landward traces of the seismic sections.

In the area offshore southern New Jersey, well–seismic ties to survey B-01-75-AT were made at the Mobil 17-2, Shell 272-1, Shell 273-1, and Tenneco 495-1 OCS exploration wells (Figure 3). The data from these sites were projected onto the nearest seismic profiles from B-01-75-AT using the correlations of acoustic travel time to depths established with check shot surveys at each of these wells. Projected onto the seismic data, the MMS biostratigraphic interpretations and geophysical log data facilitated correlations among Shell 272-1, Shell 273-1, Mobil 17-2, and Tenneco 495-1, guided by the seismic profiles that connect the wells (Figures 4–6). The seismic sections were interpreted using stratal terminations to identify the significant seismic surfaces.

![Figure 2](image-url)

*Figure 2.* (A) One of 4400 resampled time–depth (T–D) curves that comprise a three-dimensional (3-D) T–D model used to convert seismic profiles and interpretations on them from a reference in two-way traveltime (TWTT) to depth. The resampled curve is an interpolation at 0.1-s intervals of data from Mountain and Monteverde (2012) in the uppermost second of sediments and the Geophysical Database of the United States North Atlantic Margin (Klitgord et al., 1994) below 1 s. The accuracy of the depth model at a given location, represented by the thin red lines bounding the interpolated curve, was determined through a statistical comparison of the T–D model to check shot data at well locations. (B) All of the 3-D T–D model data points from locations within the Baltimore Canyon trough (BCT) with less than 200 m (<650 ft) of water depth. The average T–D relationship for the continental shelf within the BCT is plotted with a solid black line, and the dotted black lines bound 95% of the variation at each TWTT interval, approximated by two standard deviations (2σ) from the mean. mbsl = meters below sea level.
Figure 3. Well-log correlation of Continental Offshore Stratigraphic Test (COST) B-2, Mobil 17-2, Shell 272-1, and Shell 273-1. Well-log correlations of Logan Canyon (LC) 1, 2, and 3 from the well-log transect of Miller et al. (2018) are plotted as red, dashed lines. The seismic surfaces mid-Cretaceous (MK) 1, 2, and 3 were converted to depth using the velocity surveys associated with the individual wells and plotted onto the well logs as dashed blue lines. The lithostratigraphic Sable Shale and Naskapi Shale units of Libby-French (1984) are identified by blue and purple shading, respectively. Boundaries of biofacies zones in the COST B-2 and Shell 272-1 wells (Sikora and
Biostratigraphic age assignments that bound or fall within these sedimentary packages provide preliminary chronological control. In all, 7 distinct horizons and stratal packages were mapped, within 10 biostratigraphic datum levels.

To the south, two shelf-parallel seismic lines, ma-005 (Figure 7) and ma-007 of survey B-16-76-AT tie seven dip lines to the northern B-01-75-AT grid (Figure 1). Dip line ma-004 (Figure 8) originates approximately 20 km (~12 mi) seaward of Ocean City, Maryland, and was projected onshore (Figure 9). Dip lines ma-004 and ma-006 were used to generate Wheeler diagrams (Figures 10, 11) to evaluate changes in Cretaceous depocenters on the Maryland shelf. Finally, we combined the stratigraphic interpretations on the northern B-01-75-AT and southern B-16-76-AT seismic grids with sequence stratigraphic interpretations made on the coastal plain (Miller et al., 2017) to generate basin-scale sequence stratigraphic maps.

RESULTS

Upper Jurassic and Lowermost Lower Cretaceous (Tithonian–Berriasian to Barremian)

Two distinct reflections, Lower Cretaceous (LK) 2 and LK1, were traced throughout the northern subarea with varying confidence. These surfaces bound the LK2 sedimentary package (named for its basal reflection; Table 1). The LK2 reflection corresponds with the top of the Jurassic strata, and the LK1 reflection (Miller et al., 2018) falls beneath a Barremian biostratigraphic marker in the offshore wells and an unconformity in the seismic data in the NBCT and is a likely mid-Barremian hiatus (Miller et al., 2018). This interval between the Barremian unconformity (LK1) and the approximate Jurassic–Cretaceous boundary (LK2) is generally 600–1000 m (~2000–3300 ft) thick on the shelf (Figure 12). The LK1 reflection lies below 1.75 s of TWTT (~1750 m [~5750 ft] depth below mean sea level [MSL]). The underlying LK2–LK1 interval is composed of shallow-water heterolithic siliciclastics of the Missisauga Formation equivalent, overlying the similarly heterolithic Upper Jurassic Mic-Mac Formation (Poag, 1985b). As a result, the Jurassic–Cretaceous boundary occurs within heterolithic strata within Shell 272-1 and Shell 273-1 (Figure 4) and Mobil 17-2 (Figure 5), exemplified by a serrated GR log expression. The upper bounding surface (LK1) is the basal surface to the LC3 sequence of Miller et al. (2018) and is more prominent and traceable than the underlying LK2 reflection.

The LK2 reflection is associated with the top Tithonian biomarker in the OCS wells. Because of the discontinuous nature of the LK2 reflection and reflections contained within this sequence, the identification of this surface relied heavily on reregistering the correlations at each well. Coherently stacked internal reflections representing systems tracts are difficult to identify. On the OCS, the LK2 package is also highly faulted, which obscures the genetic basis for terminating reflections (i.e., terminations may be because of displaced strata rather than by erosion or nondeposition). A best effort was made to loop correlate LK2 around the seismic grid; however, tracings of this deepest stratigraphic surface have the greatest uncertainty of all those prepared in this study (see Appendix 2).

The Missisauga Formation (Libby-French, 1984), which comprises the 10' year scale LK2 sequence between LK2 and LK1 (Table 1), is likely estuarine to fluvial coastal plain deposits. The offshore LK2 sequence correlates to the Waste Gate Formation onshore, based on biostratigraphic age estimates (Doyle, 1982) and our correlations (Figure 9). At Tencoco 495-1 (Figure 6), the Lower Cretaceous interval is no longer overlain by shale but rather by an interval of low-GR values interpreted to be carbonate, potentially correlative to the Aptian “blanketlike facies” identified by Edson (1987a) in Shell 586-1 that consists of limestone and sporadic interbedded shale
deposited on a carbonate platform. Poag (1985b) correlated the Missisauga in Continental Offshore Stratigraphic Test (COST) B-2 and COST B-3 to the Potomac I sequence at Island Beach. However, based on correlations to onshore Maryland (Figure 9; Miller et al., 2017), we favor correlation of the Missisauga to the onshore Waste Gate Formation. Offshore New Jersey, this package is influenced by the “Gemini” fault system (Poag, 1987).

Similar to the northern subarea, it is difficult to trace the lowest stratigraphic horizons around the B-16-76-AT seismic grid offshore Maryland in the southern subarea. The horizon attributed to the Jurassic–Cretaceous boundary (LK2) is particularly challenging to trace across the 100-km (62-mi) ma-005 seismic line (Figure 7). The likely heterolithic character of the strata and low vertical resolution (>50 m [>160 ft]) of the seismic data contributes to

Figure 4. Seismic correlation between the Shell 272-1 and Shell 273-1 wells, located on the outer continental shelf offshore southern New Jersey, using the a-207 and a-142 seismic profile lines of the B-01-75-AT seismic survey. The biostratigraphic picks within the wells are used to assign preliminary ages to the mapped seismic packages. A fault surface is mapped in light blue, near the intersection of lines a-207 and a-142. TWTT = two-way traveltime.
the chaotic reflections in this interval. On the dip lines, these strata produce similarly chaotic reflections, with few clearly terminating reflections (Figure 8). The LK1 reflection, at the top of the Missisauga Formation and the base of the LC3 sequence, is easier to trace because it, and the reflections above it, are more continuous.

Having traced these horizons around the B-16-76-AT grid offshore Maryland, we correlated the Lower Cretaceous reflections to the wells located onshore Maryland. The Jurassic–Cretaceous boundary identified in the cross section of onshore wells (Miller et al., 2017) was projected onto the depth-converted ma-004 profile (Figure 9). The projection of this basal Cretaceous surface seaward results in a correlation with LK2 that is within approximately 200 m (~650 ft) of the seismic reflection (at ~2400–2600 m [~7900–8500 ft] below MSL; Figure 9). Projecting the top of the Waste Gate Formation, which has a pre–Zone I Early Cretaceous palynological age (Doyle, 1982) identified in the well cross section offshore, correlates very well with the LK1 reflection. Therefore, the “blocky” log pattern typical of fluvial sands and interbedded varicolored shales that characterize the onshore Waste Gate Formation...
(Hansen, 1982; Andreasen et al., 2015; Miller et al., 2017) transition downdip to the heterolithic shallow-water siliciclastics of the Missisauga Formation in the offshore.

The Lower Cretaceous sequences are thicker in the southern subarea than they are in the northern subarea, both onshore and on the continental shelf (Figure 12). The onshore Waste Gate sequence is approximately 500 m (~1600 ft) thick at the modern-day shoreline on the Maryland coastal plain and thins along strike to the northeast, apparently pinching out south of the Island Beach well in New Jersey (Miller et al., 2017). The LK2 strata that correlate with the Waste Gate Formation similarly thickens (>1 km >3300 ft) to the southeast (basinward) and to the southwest (along strike) on the continental shelf (Figure 12).

**Middle Cretaceous (Aptian to Lower Cenomanian)**

This interval is bound by the LK1 and mid-Cretaceous 1 (MK1) seismic sequence boundaries and is composed
of the LC3 (equivalent to the LK1 seismic sequence), LC2 (equivalent to the mid-Cretaceous 3 [MK3] seismic sequence), and LC1 (equivalent to the mid-Cretaceous 2 [MK2] seismic sequence) sequences (Table 1) identified to the north of the study area by Miller et al. (2018). The GR logs and biostratigraphy from the Shell 272-1, Shell 273-1, and Mobil 17-2 wells allow for the direct correlation to the stratigraphic sequences of Miller et al. (2018) via COST B-2 (Figure 3). Projecting the well-log correlations onto the seismic data, the three LC sequences (LC3, LC2, and LC1) on the well logs correlate with identified seismic surfaces (MK3, MK2, and MK1, respectively). This correlation is supported by seismic tracing between COST B-2 (where these sequences were originally identified by Miller et al., 2018) and Mobil 17-2 (Baldwin et al., 2017) and by biostratigraphic constraints. The entire interval between

**Figure 7.** Correlation of Cretaceous seismic surfaces along strike on the outer continental shelf using seismic line ma-005 from survey B-16-76-AT. This line connects the northern subarea (offshore from southern New Jersey) and seismic survey B-01-75-AT with the southern subarea (offshore Maryland) and the rest of seismic survey B-16-76-AT. The stratal character of the reflections transition from chaotic to parallel and subparallel upwards through the section. TWTT = two-way traveltime.
the LK1 and MK1 reflections in the northern subarea is between 400 and 800 m (1300–2600 ft) thick on the OCS, where it thins from north to south. The uppermost MK1 surface is between 1000 and 2250 m (3300–7380 ft) below MSL. The mid-Cretaceous interval is thicker in the middle shelf, whereas the Lower Cretaceous strata thicken significantly offshore toward the shelf edge and slope.

The base of the LC3 sequence is reflection LK1, the middle Barremian seismic sequence boundary (Miller et al., 2018), and the top of the Missisauga Formation. The package of strata above this surface is largely undifferentiated shale at Shell 272-1 and Shell 273-1 (Figures 3, 4); the GR log within this interval records only minor variations, and the benthic foraminiferal biofacies of Sikora and Olsson (1991) indicates paleodepths of 130 to more than 200 m (430 to >650 ft). The base of the LC2 sequence within the Shell 272-1 and 273-1 wells occurs within this deep-water facies that comprises

Figure 8. Seismic stratigraphic interpretation of Cretaceous strata using seismic profile ma-004, a dip line that originates approximately 20 km (~12 mi) downdip from Ocean City, Maryland, and extends southeast to the continental rise. The seismic surfaces were correlated to the northern subarea using line ma-005. TWTT = two-way traveltime.
Correlation of the Potomac and Waste Gate sequences (Miller et al., 2017) from a well-log cross section composed of the three deep stratigraphic test wells on the Maryland coastal plain, interpreted by Miller et al. (2017), to the ma-004 seismic section (Figure 8) converted from two-way traveltime to depth using a splice of the geophysical database of the United States North Atlantic margin (Klitgord et al., 1994) and the time–depth function of Mountain and Monteverde (2012) (in the upper 1 s of sediments). The onshore Potomac and Waste Gate sequences (Miller et al., 2017) are projected onto the seismic line through extrapolation of a spatial linear regression through the sequence picks in each of the wells across the transect. The resulting correlation matches the Potomac and Waste Gate sequence boundary surfaces with the Cretaceous seismic sequences interpreted herein. ftbKB = feet below kelly bushing; MSL = mean sea level; OCS = outer continental shelf; RES = resistivity.
Figure 10. Uninterpreted and interpreted seismic profiles and Wheeler diagram for mid-Cretaceous depositional sequences identified on line ma-004 (Figure 8). Units bound by the reflections marked with blue lines are assigned to the lowstand systems tract (LST), green lines to the transgressive systems tract (TST), and yellow lines to the highstand systems tract (HST). The red lines are sequence boundaries (SB). LK = Lower Cretaceous; MK = mid-Cretaceous; UK = Upper Cretaceous.
Figure 11. Uninterpreted and interpreted seismic profiles and Wheeler diagram for mid-Cretaceous depositional sequences identified on line ma-006, which is 10 km (6 mi) south of ma-004. Units bound by the reflections marked with blue lines are assigned to the lowstand systems tract (LST), green lines to the transgressive systems tract (TST), and yellow lines to the highstand systems tract (HST). The red lines are sequence boundaries (SB). LK = Lower Cretaceous; MK = mid-Cretaceous; UK = Upper Cretaceous.
Figure 12. Isopach and contour maps of the uppermost Upper Cretaceous (UK) (A), mid-Cretaceous (MK) (B), and lowermost Lower Cretaceous (LK) (C) intervals in the southern Baltimore Canyon trough. These maps were created from the depth-converted seismic stratigraphic surfaces interpreted herein, and coeval depositional sequences correlated between 19 wells on the Mid-Atlantic Coastal Plain (Miller et al., 2017). The arrows indicate likely sediment source regions and pathways of sediment transport.
nearly the entirety of the LC2 and LC3 sequences. A conservative approximation of the basal LC2 boundary relies on the biostratigraphic pick for the top of (or within) the Aptian in the Shell 272-1 and Shell 273-1 wells (Figure 3). Seismic correlation of MK3, the seismic LC2 equivalent of Miller et al. (2018), between COST B-2 and Mobil 17-2 (Figure 3; Baldwin et al., 2017) supports this correlation within the limitations of seismic resolution. The biofacies transition between coeval LC2 strata in COST B-2 and Shell 272-1 (Figure 3; Sikora and Olsson, 1991) indicates a deepening to the south toward the SBCT. Libby-French (1981, 1984) identified a composite shale that comprises the majority of the LC2 and LC3 sequences as a single unit (i.e., the purple shading in Figure 3), assigning it as the equivalent to the Scotian Shelf Naskapi Formation and correlating it to a shale of predominantly Barremian age (Scholle, 1977) (compared to the Aptian and Albian age of this interval in Shell 272-1). In contrast, we correlate this interval of shale to the two individual depositional sequences that become sandy to the north on the GSD (Miller et al., 2018), based on (1) biostratigraphic constraints provided by both well reports and re-evaluation by Miller et al. (2018) and (2) a depositional model of a deltaic unit transitioning from sand to shale, consistent with increasing paleodepths at COST B-2 and Shell 272-1 (Sikora and Olsson, 1991).

The base of the LC1 sequence can be correlated from COST B-2 to the southern wells (Figure 3). It is marked by the top of an approximately 50-m (~160-ft)-thick progradational unit composed of three condensed, coarsening-upward parasequences. Both this study and Libby-French (1984) correlate the boundary at the top of our LC2 to the same approximate surface in the COST B-2 well (i.e., the upper LC sandstone in Libby-French, 1984). Moreover, the “top Albian” marker lies just above the identified sandstones in multiple wells, providing additional support for this boundary as the base of LC1. Seismically, the base of the LC1 sequence is marked by the MK2 seismic sequence boundary (Figures 3, 4).

The MK1 seismic sequence (equivalent to the LC1 log sequence) in the southern wells can be correlated to the MK1 seismic sequence boundary identified by Miller et al. (2018) on the GSD and OCS (their supplemental online material figure 1). Gamma-ray logs at the Shell 272-1, Shell 273-1, and Mobil 17-2 wells show a distinctive bell-shaped pattern that overlies the top of the LC1 sequence and coincides with a Cenomanian biomarker (Figure 3). This surface produces a high-amplitude reflection in the seismic data (MK1) that can be loop correlated through the study area. The LC1 is a thin interval within this subarea (~75–150 m (~250–490 ft) thick), and the bounding upper surface (MK1) is characterized by downlap.

Farther south, offshore Maryland, strata coeval with the LC sequences of the NBCT (Table 1; Miller et al., 2018) have more continuous, curvilinear to parallel or subparallel internal reflections than in the NBCT. This is particularly evident on the dip line ma-004 (Figure 8), where cliniforms can be seen in the strata coeval with the LC3 sequence (bound by the LK1 and MK3 reflections). We interpret this as reflecting closer proximity to deltaic sources compared to offshore New Jersey. The LC depositional sequences on this part of the shelf appear to contain onlapping transgressive strata that thin landward below vertical seismic resolution (Figures 10, 11). This creates composite maximum flooding surface (MFS) and sequence boundary reflections. Upsection, thick transgressive HSTs prograde over the thin TSTs and MFSs.

Three prominent transgressive-regressive packages (i.e., above reflections MK3, MK2.1, and MK2) can be identified on the seismic data in the strata bounded by reflections MK3 and MK1 (Figures 10, 11). These packages appear to be three distinct seismic sequences on the Maryland continental shelf. The interval between MK3 and MK1 thickens from north to south alongshelf (Figures 7, 12), and the internal reflections transition upsection from curvilinear cliniforms to planar and subplanar reflection geometries. The three sequences are coeval with the LC1 and the LC2 sequences on the GSD, with the intervening MK2.1 pinching out to the north, limiting its identified spatial extent to the shelf offshore Maryland.

The Potomac I, Potomac II, and Potomac III sequences identified in the onshore wells (Miller et al., 2017) correlate to the LK1, MK3-MK2.1, and MK2 sequences in the offshore, respectively (Figure 9; Table 1). The top of the Potomac I sequence projects seaward to the top of the LK1 sequence. Moreover, the geometric projection of the top of the Potomac III seaward correlates with the top of the MK1 sequence boundary, which is likely mid-Cenomanian. The Potomac III base projects seaward to MK2.
The mid-Cretaceous interval (LK1, MK3, and MK2 and MK2.1 in the south) also thickens along strike from northeast to southwest, both in the coastal plain and on the continental shelf (Figure 12). Coeval with the Potomac Formation in New Jersey and the Potomac Group (excluding the Waste Gate Formation) in Maryland, this unit is approximately 1000 m (~3300 ft) thick under the Maryland coastal plain at the shoreline, thinning to approximately 300 m (~980 ft) updip between Cambridge, Maryland, and Fort Mott, New Jersey. At the northernmost limit of our study area, 20 km (12 mi) south of Island Beach, New Jersey, the Potomac Formation is approximately 400 m (~1300 ft) thick. This interval is 800–1000 m (2600–3300 ft) thick on the middle to outer shelf off the coast of Maryland, compared to 500–800 m (1600–2600 ft) thick on the southern New Jersey Shelf. Compared to the underlying LK2 strata, the mid-Cretaceous depositional sequences were deposited in a more-proximal location, with a depocenter near the modern shoreline (Figure 12).

Upper Cretaceous (Upper Cenomanian to Maastrichtian–Campanian)

Two Upper Cretaceous horizons are identified on the seismic data, UK2 and UK1. They correlate roughly to the top Turonian and the top Campanian biomarkers in the OCS wells, respectively (Table 1). The Upper Cretaceous interval lies above the LC sequences and is 200–600 m (650–2000 ft) thick on the shelf (Figure 12). The upper UK1 surface lies between 1000 and 1750 m (3300–5700 ft) below MSL offshore New Jersey. The Upper Cretaceous thickens significantly toward the shelf edge and coarsens upward from the basal Dawson Canyon Formation to the Campanian Middle Sandstone Formation of Libby-French (1984).

In addition to the Middle Sandstone, a sand within the MK1 sequence appears in the well-log data at Shell 272-1 (at 2000 m [6500 ft] in Figure 4) that shales out toward the more-distal Shell 273-1 and Mobil 17-2 wells (Figures 4, 5). The interval above reflector MK1 consists of high-relief clinoforms that prograde across the OCS (Figure 6). These internal structures make the upper bounding surface (UK2) easy to identify via toplapping and downlapping internal reflections. Like the other Cretaceous packages in this northern subarea, this interval is heavily faulted near the shelf edge (Figure 6). Within the interval above reflector MK1 (Figures 3, 4), a local peak GR value in the Shell 272-1 GR log (at 2063 meters below kelly bushing [mbKB] [6770 feet below kelly bushing [ftbKB]] or 2038 mbsl [6686 ftbsl]) lies within a fining-upward trend (1) above the top of well-log sequence LC1, (2) above the converted depth of seismic surface MK1, and (3) above the highest occurrence (HO) of Rotalipora cushmani that likely corresponds to the GMSL high coincident with ocean anoxic event (OAE) 2 at or near the Cenomanian–Turonian boundary (Kennedy et al., 2005). The GR peak also lies within an interval of maximum upper Albian to upper Turonian paleodepth in Shell 272-1 and in COST B-2 indicated by the biofacies of Sikora and Olsson (1991) (Figure 3). The LC1 (equivalent to the MK2 seismic) sequence is older than the OAE 2 and supports the correlation of MK2 to the early to mid-Cenomanian Potomac III sequence onshore.

The overlying uppermost Cretaceous seismic package is bounded by the top Turonian reflection (UK2) at its base and the prominent top Campanian reflection (UK1 of Miller et al., 2018 and “Red” of Greenlee and Moore, 1988 and Greenlee et al., 1992, their “top Cretaceous”) at its top. Toplapping or truncating internal reflections are associated with the top Campanian (UK1) surface that generally coincides with a Campanian biomarker in the OCS wells (Figures 5–8). In general, the Maastrichtian strata on the shelf are quite thin (<30 m [<100 ft]; Olsson and Wise, 1987), and, therefore, Greenlee et al. (1992) equated the top Campanian with the top Cretaceous. This Campanian interval can likely be subdivided again, especially because it thickens in the vicinity of Mobil 17-2 and seaward. There are Coniacian and Santonian biomarkers in the wells that might indicate additional unconformities noted onshore by Olsson et al. (1988) and Miller et al. (2004) that are not resolved in our seismic stratigraphic data.

In the southern subarea offshore Maryland, shingled, offlapping strata that are bound at the base by MK1 and at the top by UK2 are probably Cenomanian to mid-Turonian and directly overlying the LC equivalents (Figure 8). On strike line ma-005, this interval is a package of downlapping, curvilinear reflections that generally dips gently to the north and thins to the south (Figure 7). This interval is approximately...
500 m (~1600 ft) thick on the outer half of the New Jersey Shelf but only 100–300 m (330–980 ft) thick off the coast of Maryland where most of the internal reflections dip to the south. Moreover, there are two distinct seismic lobes (inferred to be deltaic lobes), separated by a potential onlap surface on line ma-005 (at ~1.75 s in the center of the image in Figure 7). This interval correlates to a thin Upper Cretaceous section on the Maryland coastal plain that thickens to the north into New Jersey (Owens and Gohn, 1985; Olsson et al., 1988; Miller et al., 2017). On the Wheeler diagrams (Figures 10, 11), the strata bound by MK1 and UK2 show a distinct LST and TST and a prograding HST. The HSTs of this sequence mark a return of regressive sedimentation to the outermost continental shelf.

The top Campanian (UK1) can be traced confidently from the northern subarea to the south as a high-amplitude reflection, with overlying reflections terminating onto it as downlap. Similar to the northern subarea, the interval below this horizon thickens seaward toward the shelf edge (Figures 8, 12). Seismically, this Upper Cretaceous package bound by UK2 and UK1 appears to thin and seismically pinch out in the landward direction before reaching the Maryland coastal plain. There is also significant toplap or truncation associated with the bounding upper reflection (UK1). However, considering that the vertical seismic resolution is approximately 35 m (~115 ft), there may be a veneer of undetected sediment. Together, the combined MK1 and UK2 strata thin from approximately 300 m (~980 ft) thick at the shoreline in the New Jersey coastal plain to approximately 100 m (~330 ft) thick in Maryland. The thicknesses on the OCS thins similarly, along strike, from 700 m (2300 ft) in the northern subarea to 400 m (1300 ft) in the southern subarea.

DISCUSSION

Spatiotemporal Variations in Depositional Environments

Wells provide a lithological ground truth for seismic facies in the northern subarea that were seismically traced to the southern subarea that lacks shelf wells. In the seismic data of the northern subarea of the SBCT we observe (1) chaotic seismic facies in the Lower Cretaceous (e.g., Figures 6, 7); (2) thin, poorly defined clinoform geometries (e.g., Figure 6) in the mid-Cretaceous; and (3) progradational packages within a generalized regression in the Upper Cretaceous section that are capped by the high-amplitude UK1 surface (Figure 6). The offshore well data from Shell 272-1, Shell 273-1, and Mobil 17-2 (Figure 3) reveal (1) heterolithic facies in the Lower Cretaceous, (2) a transition from shallow marine sandstone and shale parasequences in the mid-Cretaceous, and (3) thin Upper Cretaceous sandstones deposited between predominantly offshore (>30 m (>100 ft) paleo-depth) shales. We infer that these sedimentary rocks were deposited within deltaic or deltaically influenced environments at a variety of water depths. From oldest to youngest, they are as follows.

1. The heterolithic strata of the Lower Cretaceous are terrestrial silty, lignitic, coal-bearing shales (Poag, 1985b) to terrestrially influenced coarsening-upward packages of delta-front sandstones (Libby-French, 1984) deposited beneath the modern OCS; these heterolithic strata lie landward of the thick, deltaic Neocomian section of interbedded siltstone and fine-grained sandstone containing glauconite, oxidized pyrite, and red shales in the Shell 93-1 well drilled on the continental rise offshore Maryland (Amato, 1987).

2. The mid-Cretaceous strata are interpreted to be primarily deltaic, delta-front to prodelta deposits sections in the NBCT on the basis of well-log character and lithological characteristics (Miller et al., 2018). Additionally, the shale-prone Aptian and Albian strata of the northern SBCT were interpreted to be part of a prograding deltaic succession by Libby-French (1981). Although much of the onshore mid-Cretaceous section consists of nonmarine fluvial deposits, portions of the correlative Albian and Cenomanian Potomac Formation sediments drilled in New Jersey are deltaic or influenced by deltaic processes (Browning et al., 2008).

3. The Upper Cretaceous sediments drilled onshore in New Jersey are also deltaic or deltaically influenced (Browning et al., 2008), and it would follow that the predominately shale-prone intervals seaward of these onshore sediments were deposited in a prodeltaic to deltaically influenced
shelf environment that is likely to be exclusively marine downdip.

The seismic facies of the southern subarea are largely similar to those of coeval facies in the northern subarea but differ slightly in important ways. In the southern subarea, the lowermost Lower Cretaceous interval similarly has a predominantly chaotic seismic character (Figures 7, 8). This would imply a similarly heterolithic lithology to the Missisauga Formation of the LK2 sequence of the northern subarea. A coastal plain or paralic depositional environment for the LK2 interval also fits appropriately with the coeval, proximally positioned, fluvial sands of the Waste Gate Formation in the subsurface of the Maryland coastal plain. Moreover, the Shell 93-1 well captured the record of anomalously thick deltaic sedimentation in the Neocomian section within a “foundered” part of the Upper Jurassic and Lower Cretaceous Abenaki Formation (Poag, 1985b) reefal structure (Amato, 1987). The LK2 package is thicker in the southern than the northern subarea and is thickest toward the shelf edge (Figures 7, 8, 12).

The isopach maps (Figure 12) indicate a predominately southern source of sediment during the pre-Aptian Early Cretaceous. It is possible that the influx of sediment from the south and high rates of siliciclastic sedimentation were responsible for the “foundered” carbonate reef described by Amato (1987) under the continental rise offshore Maryland. Regardless, it is logical that the deltaic Neocomian sedimentation observed in the lower slope (i.e., Amato, 1987) is connected to the fluvial Waste Gate Formation in the Maryland coastal plain by the intervening paralic sediments of the Missisauga Formation.

Upsection, the mid-Cretaceous interval on the shelf in the southern subarea contains packages of onlapping, downlapping, and truncated reflections that can be identified as distinct depositional sequences with transgressive and regressive components (Figures 8, 10, 11). The transition from the chaotic seismic reflections of the Missisauga Formation to mid-Cretaceous clinoform reflection geometries likely reflects a rise in relative sea level (RSL). Compared to the northern subarea, the mid-Cretaceous in the southern subarea contains a greater thickness under the modern middle shelf region (Figures 7, 12) and contains better-developed clinoforms with less evidence of post depositional deformation from faults (cf. Figures 6, 7). From the base of the mid-Cretaceous (the LK1 surface), the clinoforms flatten gradually upsection (Figure 8). The shoaling of reflection surface slopes may indicate a deepening from the relatively shallow paleodepths in the Early Cretaceous (Figure 13) and a transition from a deltaically influenced shelf environment to middle to outer shelf and deeper deposits (e.g., between sequence LK1 and sequence MK2 in Figures 10, 11; Sangree and Widmier, 1977). Moreover, the HST of sequence MK2.1 (Figures 8, 10, 11) is truncated erosionally at the most-landward point of any mid-Cretaceous sequence, suggesting that a base level fall eroded preexisting topography at an updip location relative to other sequences in this succession. This landward position of the most basinal clinoform in sequence MK2.1, as well as the relatively flatter geometries, is evidence indicating that MK2.1 contained the most-proximal depocenter through this section. However, it is more likely that the overlying strata, coeval with the onshore Potomac III and Bass River sequences (Table 1), which are more deltaic and marine than the underlying Potomac Formation on the New Jersey coastal plain (Browning et al., 2008), were deposited in deeper water with an even more proximal deltaic depocenter that is not entirely captured within our seismic sections (Figures 9, 12). Further, upsection from sequence MK2.1 (Figures 8, 10, 11), the clinoforms regain relief and display shingled geometries in the internal reflections of sequences MK2 and MK1, suggestive of deposition in a deltaic depocenter.

The LC2 and LC3 sequences in the northern subarea shale out in the Shell 272-1, Shell 273-1, and Mobil 17-2 wells, with a few coarsening-upward, sandy HST parasequences present at the top of the LC2 (in all three wells) and LC3 (at Mobil 17-2) sequences (Figure 3). This contrasts with thick LST and HST sandstones in the LC3 and the LC2 on the GSD (Miller et al., 2018). Moving farther south, it is likely that there are sand-prone intervals within the LC3 and LC2 sequences offshore Maryland, based on proximity to the fluvial facies of the Potomac Group in Maryland and the clinoform features observed on the seismic data in our southern subarea (Figure 9).

As noted above, the Potomac I, Potomac II, and Potomac III sequences of the Maryland coastal plain correspond to the LK1, MK3-MK2.1, and MK2 seismic
sequences, respectively (Figure 9; Table 1). The Potomac Group in Maryland has been described as transitioning from fluvial to deltaic sedimentation (Anderson, 1948; Owens and Gohn, 1985), although the preponderance of evidence indicates that these are fluvial units (Miller et al., 2017). The nonmarine interpretation fits more reasonably with the Potomac strata of the New Jersey coastal plain, which is composed of facies associated with an anastomosing river system (Browning et al., 2008). Nonmarine fluvial to terrestrially influenced deltaic strata on the Maryland coastal plain suggest delta-front to prodelta mid-Cretaceous facies beneath the modern continental shelf. This is supported by isopach maps (Figure 12)
that indicate a depocenter landward of the modern shelf edge and the distal LK2 depocenter. Like the LK2 depocenter, the LK1, MK3, MK2.1, and MK2 strata also appear to have a southern source (Figure 12).

In contrast to the Lower and mid-Cretaceous intervals, the Upper Cretaceous section is thicker in the northern subarea than it is in the south (Figures 7, 12). The seismic sections in the northern subarea appear to show steeply dipping clinoforms above reflection MK1 that are truncated by the UK2 reflection (Figures 5, 6). These are some of the most distinct clinoforms of the Cretaceous section despite the heavy growth faulting that disrupts the stratigraphic continuity of the northern subarea (Figure 6). In the southern subarea, MK1 is thinner and is composed of shingled clinoforms that appear to offlap as they prograde across the shelf (Figure 8). The strike line is particularly revealing for the section above reflection MK1 because it shows downlapping reflections that dip to the south (Figure 7). In plan view, the MK1 sequence forms an apparent paleo- line is particularly revealing for the section above reflection MK1 because it shows downlapping reflections that dip to the south (Figure 7). In plan view, the MK1 sequence forms an apparent paleo-

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These observations are consistent with other isopach observations of a more prominent northern source area for the coeval Cenomanian to Turonian packages mapped by Poag and Sevon (1989).

Like the MK1 sequence, the UK2 sequence thins from north to south (Figure 7). However, in contrast to the mid-Cretaceous interval and the MK1 sequence, UK2 thickens significantly toward the shelf edge in the SBCT like LK2 (Figure 8). The lower part of the UK2 sequence onlaps the UK2 surface, but progradational clinoforms are absent within the interval under the modern shelf (Figure 8). It is possible that there was progradation seaward of the modern shelf to slope break or erosion of the upper part of this cycle or both. Poag and Sevon (1989) also show Coniacian to Campanian sedimentation had a more distally located depocenter on this margin relative to their underlying Cenomanian to Turonian package. There is significant toplap or truncation associated with the UK1 reflection (Figures 5–8), and this would indicate that at least some erosion occurred or a period of nondeposition elapsed. The cause of this erosion is uncertain, but the widespread middle to outer shelf distribution of a major hiatus prompted Olsson and Wise (1987) to attribute it to submarine erosion by the lateral movement of an ancestral shore parallel current system (landward and seaward movement of the current’s axis as sea level rises and falls, respectively) analogous to the modern Gulf Stream. Alternatively, the erosion could be attributed to slope failure associated with the shelf edge in response to large earthquake associated with the Chicxulub impact at the end of the Cretaceous (Norris and Firth, 2002).

Age control on the mid-Cretaceous sequences is particularly coarse (e.g., stage or age level) because of shallow-water facies, lack of marine biostratigraphic markers, and widely spaced wells with samples taken largely from cuttings. As a result, we are not able to detect or quantify hiatuses associated with the sequence boundaries from the biostratigraphy. The age of the hiatus between the Mississauga and the LC3 (LK1 equivalent) sequence is inferred from various geological constraints on the GSD to be middle Barremian (ca. 126–127 Ma); the LC3 sequence apparently captured the MFS associated with early Aptian OAE 1a (ca.125 Ma) at COST B-2 supporting this interpretation. Age breaks between the Albian and Aptian sequences are currently a matter of conjecture; we adopt a conservative minimal 2-m.y. break for each: (1) the break between the LK1 and the MK3 spans the Albian–Aptian boundary and is assumed to be 112–114 Ma; (2) the MK3 sequence is within the Albian (assumed to be 107–110 Ma), whereas the MK2.1 sequence is only represented in the SBCT, implying a significant hiatus within the Albian (ca. 107–105 Ma); and (3) the MK2.1 sequence is Albian and presumed to be 105–102.5 Ma, with a hiatus from 102.5–100.5 Ma. Study of onshore sequences with biostratigraphic constraints suggests that the breaks between the Magothy and the Bass River were 92.5–91.5 Ma (Miller et al., 2004) and approximately 98–97 Ma between the Bass River and the Potomac Formation (Miller et al., 2017). We adopt these durations for the hiatuses between UK2 and MK1, respectively.

Additionally, the 1970s vintage seismic profiles that we rely upon have a relatively coarse vertical resolution, ranging from 30 to 70 m (100–230 ft) from the top to the bottom of our section, and the boundaries of the depositional sequences we identify are based on geometric criteria we observe on the seismic profiles. The “back to basics” perspective on sequence stratigraphy stresses that the
temporal resolution of the sequences that we identified are tied to the resolution of the data (Neal and Abreu, 2009; Miller et al., 2018) relative to their sedimentary thicknesses. Our work integrating lithological, paleontological, and well-log criteria with the seismic data strengthens the case for defining the sequences we have identified and correlating them with established basin-specific sequence stratigraphic frameworks (Miller et al., 2017, 2018). However, because the appearance of “relatively conformable” and “genetically related” strata according to the geometric criteria picked on the seismic data are so closely tied to the vertical resolution, higher-resolution seismic images might allow for the identification of higher-order depositional sequences within the sequences that we have identified using the seismic profiles presently available to us.

Further, a primary assumption we make is that the along strike (northern to southern) movements in depocenter location through the Cretaceous are representative of changes in sediment supplied from various source regions (Figure 12). The factors controlling Cretaceous accommodation and sedimentation in the BCT include the following: (1) the North American plate, and the developing BCT, were moving, in part, northward during the Late Jurassic and into the Cretaceous (Müller et al., 2016); (2) regional sea-level variations on the order of 10–35 m (30–115 ft) (short-term) to more than 100 m (>330 ft) (long-term) (Miller et al., 2005); (3) the lithosphere beneath the deposited Jurassic strata was cooling, and the thermal subsidence rates were decreasing exponentially (Parsons and Sclater, 1977; McKenzie, 1978; Steckler and Watts, 1978; Kominz et al., 2008); (4) flexural compensation and compaction began to generate a larger proportion of the long-term accommodation in the Cretaceous as the elastic plate thickness increased and the sediment column thickened (Steckler and Watts, 1978; Poag, 1985b); and (5) sediments are being generated from the erosion of highland source terrains and are being routed via Cretaceous rivers and deposited in the marine realm in the BCT (Poag and Sevon, 1989). The northward component of the movement of the North Atlantic plate combined with the decaying rate of thermal subsidence likely explains the basin-wide reduction in deposited sedimentary volumes, and the variations in sea level could provide a mechanism for onshore–offshore migration of depocenters. However, the provenance, perhaps coupled with the flexural compensation and compaction that occurs when sediments are deposited locally in a sedimentary basin, is the variable that is most likely to control the along-strike variations in depocenter position that we observe in our data.

Our observations showing the evolution of sediment sources to the BCT generally agree with those shown by Poag and Sevon (1989), who examined our study area and beyond, albeit at a coarser resolution. They hypothesize that the shifts in depocenters were related to the magnitude of erosion and transport of material from different “highland source terrains.” Poag and Sevon (1989) inferred that the spatial gradient in sediment supply was an effect of differential uplift between the central Appalachians, Adirondacks, and the New England Appalachians distributed through southern (ancient Potomac, Susquehanna, Delaware, and James), central (the ancient Hudson), and northern (the ancient Connecticut and Eastern Massachusetts) river dispersal routes. However, the interpretations of Poag and Sevon (1989) were also based upon stratigraphic observations of the BCT, and more independent information is needed on provenance, paleorivers, and Appalachian uplift history to test our interpretations of sediment sources.

Spatial variations in sediment source and the “seesaw” differential preservation of sequences (e.g., the Lower Cretaceous is better developed in the south and the Upper Cretaceous in the north; see also Miller et al., 2017) could be explained by tectonic mechanisms, including mantle dynamic topography (MDT), flexural loading changes through time, and/or more active tectonics. In particular, MDT, or the dynamic subsidence or uplift of topography from anisotropic convection of the underlying mantle (Mitrovica et al., 1989; Gurnis, 1992; Spasojevic and Gurnis, 2012; Flament et al., 2013), might have been a factor in the shifting depocenters. This process has long been understood to shift elevations of passive continental margins over long timescales (2–10+ m.y.; Moucha et al., 2008; Moucha et al., 2008; Petersen et al., 2010), but can MDT explain the movement of depocenters on the relatively shorter timescale we examine herein? The scale of the deformation from mantle-influenced processes is relatively large, on the order of approximately...
500–2000 km (~310–1200 mi) horizontally and approximately 500–1000 m (~1600–3300 ft) vertically (Mitrovica et al., 1989; Gurnis, 1992; Liu and Nummedal, 2004); the vectors of movement of zones of subsidence and uplift related to this process can be relatively slow, for example, the zone of topographical subsidence associated with the subducted Farallon plate traveled across the United States at a rate of approximately 25–40 km/m.y. (~15–25 mi/m.y.) in the time since 90 Ma (Spasojevic et al., 2009). So, presuming a topographical profile based on the aforementioned parameters and the potential rate of movement of that slope, this long-wavelength MDT subsidence could potentially span rates of approximately 6–80 m/m.y. (~20–260 ft/m.y.).

The facies variations in this study indicate a major regional transition from the heterolithic Lower Cretaceous facies to the more marine shale-prone Upper Cretaceous. The seismic facies appear to show that this generalized transition occurs within a wide swath of the basin in the SBCT. Within this generalized RSL rise, there are higher-order RSL rises and falls that, in part, alter accommodation and contribute to the formation of the surfaces (MFSs and sequence boundaries) mapped herein. Focusing on the mid-Cretaceous, we delineate at least five stratigraphic sequences (Figure 13) that could be identified offshore Maryland, that is, the LK2, MK3, MK2, MK2.1, and MK1 sequences shown on the Wheeler diagrams (Figures 10, 11). Using the biostratigraphic age constraints within our database and physical correlations to the mid-Atlantic Coastal Plain, we have integrated these sequences into a relatively coarse stratigraphic framework for comparison with global events, including cycle charts (Hardenbol et al., 1998; Haq, 2014), Cretaceous OAEs (Figure 13), and regional RSL records. Although the sea-level amplitudes associated with the cycle charts have been shown to be incorrect (i.e., too high by a factor of 2–3, with even the relative change uncertain), the timing of the events has been shown to be generally correct for the last 100 m.y. (Miller et al., 2005).

The 10^7-yr scale transgression we identify above matches both basin-specific RSL and GMSL variations inferred from cycle charts (Figure 13). Within the BCT, both Poag (1985b) and Olsson et al. (1988) identified shallower paleodepths in the Aptian and Albian than the Cenomanian and Turonian, where they both identified peak water depths. The global cycle charts generally agree in placing a major global flooding event at the Cenomanian–Turonian boundary (Haq et al., 1987; Miller et al., 2005; Haq, 2014) that coincides roughly with OAE 2 (Friedrich et al., 2012).

Within the 10^7-yr interval of the aforementioned transgression, we can track the cross-margin transitions in depocenter position and depositional facies as a record of the combined accommodation history that includes sea-level change. The isopach maps (Figure 12) show a transition from a distal Early Cretaceous depocenter with maximum thicknesses beneath the modern slope to a more-proximal depocenter in the mid-Cretaceous. Coupling this observation with the landward mid-Cretaceous shift in facies (observed seismically and in the wells) indicates movement of the deltaic sediment source landward through this period of time toward a composite MFS at the aforementioned flooding event at the Cenomanian–Turonian boundary. Within this retrogradational package, we observe five transgressive-regressive cycles that comprise depositional sequences (LK1, MK3, MK2.1, and MK2 and MK1). Moreover, we observe at least two additional progradational Upper Cretaceous

Sea-Level Variations and Integration with Global Climate History

The facies variations in this study indicate a major RSL rise from the Early to the Late Cretaceous. In the offshore wells, this change is exemplified by the transition from the heterolithic Lower Cretaceous facies to the more marine shale-prone Upper Cretaceous. The seismic facies appear to show that this generalized transition occurs within a wide swath of the basin in the SBCT. Within this generalized RSL rise, there are higher-order RSL rises and falls that, in part, alter accommodation and contribute to the formation of the surfaces (MFSs and sequence boundaries) mapped herein. Focusing on the mid-Cretaceous, we delineate at least five stratigraphic sequences (Figure 13) that could be identified offshore Maryland, that is, the LK2, MK3, MK2, MK2.1, and MK1 sequences shown on the Wheeler diagrams (Figures 10, 11). Using the biostratigraphic age constraints within our database and physical correlations to the mid-Atlantic Coastal Plain, we have integrated these sequences into a relatively coarse stratigraphic framework for comparison with global events, including cycle charts (Hardenbol et al., 1998; Haq, 2014), Cretaceous OAEs (Figure 13), and regional RSL records. Although the sea-level amplitudes associated with the cycle charts have been shown to be incorrect (i.e., too high by a factor of 2–3, with even the relative change uncertain), the timing of the events has been shown to be generally correct for the last 100 m.y. (Miller et al., 2005).

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sequences overlying it, with a combined depocenter located seaward of that of the mid-Cretaceous. We infer that this seaward depocenter represents a period of regression succeeding the Early to mid-Cretaceous transgression. The higher-order variations in accommodation in the mid-Cretaceous are relatively long period events, with likely durations of several million years. The magnitude of the higher-order variations in sea level and the rate of sea-level change required to form these sequences are unknown but is of substantial interest considering the insight it would provide regarding the mechanisms forcing the genesis of these mid-Cretaceous sequences.

In addition to the sedimentary and stratigraphic inferences, we show a probable tie of the MK1 MFS to OAE 2. We place the MK1 sequence boundary in the early Cenomanian within calcareous nanofossil Zone CC9 (Figure 13; Table 1). We make this correlation based on geometric projection of the top of the Potomac III sequence boundary from the Maryland coastal plain to the MK1 boundary on the Maryland shelf (Figure 9). The Potomac Formation extends into Zone CC9 and is separated from the overlying mid-Cenomanian to lower Turonian Bass River Formation by a regional unconformity (Miller et al., 2004). On this basis, we correlate the MK1 surface to this regional unconformity with an inferred mid-Cenomanian age. Benthic biofacies studies of the COST B-2, Shell 272-1, and Shell 586-1 wells (Sikora and Olsson, 1991) show the deepest water depths of the mid-Cretaceous and thus indicate the general location of the composite MFS within this sequence, with a specific location identifiable from the GR log. This composite MFS location occurs just above the Cenomanian–Turonian boundary in the wells, as indicated by the HO of R. cushmani; this demonstrates that the regional RSL peak correlates with the GMSL peak near the Cenomanian–Turonian boundary (Miller et al., 2005). A GR high above a bell-shaped GR expression in the upper Cenomanian section of many OCS wells (Miller et al., 2018) is interpreted as the deepest paleodepths within the MK1 (Dawson Canyon “x” equivalent) sequence and tie in roughly with OAE 2 (Figures 10, 11). The seismic facies above the MK1 MFS appear to be shingled and progradational and may be related to the base level lowerings that generate late Cenomanian to early Turonian sequence boundaries.

In addition to the correlation of the OAE 2 to the MK1 MFS (Figure 13), OAE 1a correlates with the LK1 (LC3 equivalent) sequence. This early Aptian OAE 1a occurs at COST B-2 at approximately 2895 mbKB (~9500 ftbKB) and 2778 mbsf (~9114 ftbsf), where total organic carbon spikes to 5.45% coupled with a δ^{13}C increase (Scholle, 1977)—within the TST of the LC3 sequence (Figure 3; Miller et al., 2018). One hypothesized mechanism for the production of OAEs is increased burial of organic carbon as a result of the increase in shallow shelf areas at continental margins related to marine transgression (Schlanger and Jenkyns, 1976), which is associated with and can be caused by increasing global temperatures. More-recent evidence suggests the addition of a magmatic trigger for the generation of OAEs (e.g., Turgeon and Creaser, 2008), which does not exclude the original hypothesis because increased atmospheric CO2 concentrations would presumably increase paleotemperatures and sea level. This provides a causal basis for the coincidence of GMSL peaks, rising water levels in the BCT, and global OAEs, exemplified by their correlation to flooding events in our LK1 and MK1 sequences (Figure 13).

The correlation of the other potential Cretaceous global OAEs 1b, 1c, and 1d (Arthur et al., 1990; Erbacher and Thurow, 1997; Lehmann, 2000) to our sequences is more speculative than the two major events. The OAE 1b appears to correlate to our sequence MK3, whereas OAE 1c and OAE 1d likely fall within hiatuses associated with seismic sequence boundaries MK2.1 and MK2, respectively. These other OAEs do not appear to be readily distinguishable in the well data. However, the mechanisms for these less-pervasive OAEs may differ from the global OAE 1a and OAE 2. Erbacher et al. (1996) identified OAE 1c as a “detrital” event caused by an increased terrigenous supply of nutrients associated with a sea-level fall supported, in part, by coincidence of this event with type III kerogen. This characterization of the OAE 1c would fit its placement in a hiatus in a shallow marine section. However, OAE 1b and OAE 1d may well correlate to flooding surfaces in sequences MK3 and MK2. The OAE 1b occurs during a period of rising water levels in the BCT and likely corresponds to the transgressive package we observe in MK3 (Figure 13). The age of the base of the MK2 (LC1 equivalent) sequence is loosely constrained, and MK2 might actually include a
GMSL flooding event coincident with OAE 1d. The development of a higher-resolution chronostatigraphy would help to resolve the relationship between the “minor” OAE and sea-level fluctuations on this margin.

We did not examine the Lower Cretaceous, LK2, section in as much detail as the mid-Cretaceous, in part because the apparent sedimentary characteristics and depositional environments of this interval make the Wheeler diagram and trajectory analyses less informative. We suspect that this interval is composed of shallow marine to estuarine siliciclastics, deposited landward of a fringing carbonate platform. We expect the transitions of sedimentation, and the preservation of those deposits, to be driven by a three-dimensional (3-D) movement of distributary channels and might expect relatively chaotic and stochastic depositional patterns in the dip lines of two-dimensional seismic data. In contrast, the overlying strata appear to be relatively neatly stacked clinoforms that produce observable transgressive and regressive patterns on dip lines ma-004 and ma-006 (Figures 10, 11).

**Implications for the Reservoir Characterization of the Waste Gate and Potomac Formations and the Missisauga and Logan Canyon Sandstones**

The work herein supports the correlations of the onshore Waste Gate Formation and Potomac Formation sequences (Miller et al., 2017) with the offshore Missisauga and LC units, respectively (Libby-French, 1984; Miller et al., 2018). Each of the onshore and offshore units has been evaluated in terms of potential to be either an aquifer (Hansen, 1982; Andreasen et al., 2015), a hydrocarbon reservoir (Libby-French, 1984; Prather, 1991), or a carbon storage unit (Sugarman et al., 2011; Miller et al., 2017, 2018). Our mapping and facies interpretations have implications for the extent and continuity of these previously identified reservoirs.

Miller et al. (2017) identified the fluvial Waste Gate and Potomac I sequences as an onshore target for carbon storage on the basis that it is thick and confined in the New Jersey coastal plain while noting that the confinement of the unit is less certain updip in the Maryland coastal plain. On the basis of our correlation, the lower half of this unit, the Waste Gate, would connect seaward with the Missisauga equivalent of Libby-French (1984), who characterized the unit as containing alternating thick-bedded sandstone, siltstone, and shale. The heterolithic strata are terrestrial (Poag, 1985b) to terrestrially influenced delta-front (Libby-French, 1984) deposits beneath the modern OCS. Seaward, there are thick Neocomian deltaic sandstones in the Shell 93-1 well drilled on the continental rise offshore Maryland (Amato, 1987). However, farther north, the seaward margin of the paleoshelf is predominantly carbonate into the Barremian, evidenced by the carbonate structure found in the Shell 586-1 (Edson, 1987a) and Shell 587-1 (Edson, 1987b) wells that were drilled at a present-day water depth of nearly 2000 m (6500 ft).

The isopach of the combined LK2 reservoir suggests large volumes for storage. The LK2 measures at approximately 15,000 km$^3$ (~529,000 BCF) volumetrically within the boundaries of the digital elevation model (DEM) in Figure 12. This interval is sand prone throughout the region, although the individual sandstone bodies are likely to be discontinuous with uncertain hydrologic connectivity. These deeper, lower Lower Cretaceous rocks of our LK2 sequences are also more likely to contain thermally mature deposits than those of the overlying mid-Cretaceous. Lower Cretaceous rocks in some wells have been buried to reach borderline maturity (e.g., Shell 586-1 [Edson, 1987a] and Shell 93-1 [Amato, 1987]) but are largely immature in others (e.g., Shell 587-1 [Edson, 1987b] and Murphy 106-1 [Adinolfi, 1987]). These strata are also more likely to contain gas-prone kerogen than oil (Post et al., 2012), considering the terrestrial nature of the deposits. The underlying Jurassic strata, also likely to contain terrestrial-derived kerogen, are buried to sufficient depths. As a hydrocarbon reservoir, the economic viability would depend, in part, on the primary concern identified for carbon storage potential—how continuous and hydrologically connected are the individual sandstone bodies?

Considering the offshore alone, the best reservoir targets are the sandstones within the HSTs of the LC sequences in the vicinity of the GSD (Miller et al., 2018). In particular, the HSTs of the LC3 and the LC2 sequences, representing two of the five to seven sand-prone zones identified by Miller et al. (2018) within the original LC sandstones (Libby-French, 1984), are highly porous and permeable at the
COST B-2 well. These two sequences have sand-prone zones within the HSTs and LSTs that extend across the OCS in the NBCT. However, the LC1 sandstones shale out into the basin (Miller et al., 2018) and to the SBCT, as shown here. Similarly, the LC3 and LC2 sequences appear to thin and shale out toward the wells south of the GSD (i.e., Mobil 17-2, Shell 273-1, and Shell 272-1 in Figure 3), representing the lateral limitation of these porous lower LC sequences. In these southern locations, the LC1 is also a thin shale deposited in greater than 80 m (>260 ft) of water (Sikora and Olsson, 1991).

Although they shale out in the northern part of the study area, LC sequences may provide significant storage potential in the southern part of the study area. Although there are no well data south of Shell 272-1, the section thickens to the south, offshore Maryland, where the isopach maps (Figure 12) indicate a nearby mid-Cretaceous sediment source. These strata are likely to be sand prone, particularly closer to the modern shoreline where the Lower Cretaceous sedimentation was nonmarine. This is particularly true of LK1, which correlates to the Potomac I sequence that Miller et al. (2017) documented as approximately 50% sand in the downdip Ocean City, Maryland, well. All of the LC sequences onshore and offshore are overlain by our MK1 that correspond to the shales of the Bass River and Dawson Canyon, onshore and offshore, respectively. Although this interval might not be entirely homogenous (see sandstone bodies and clinoforms represented in the GR logs and seismic sections in Figures 4–6), the Upper Cretaceous RSL high likely forms a sufficient capstone. Offshore, this cap is of sufficient depth for the purpose of storing supercritical CO₂ (~800 m [~2600 ft]). However, the top of the Potomac Formation is more than 800 m (2600 ft) below the ground surface onshore and may not be fully confined, making the continuity of the seal overlying the Potomac I a consideration. In all, the LK1, MK3, and MK2 units comprise approximately 25,000 km³ (~882,000 BCF) within the boundaries of the DEM in Figure 12. In terms of potential as a commercial reservoir, the LC sequences and its equivalents (Table 1) are likely to contain the stratigraphic successions necessary to store hydrocarbon reserves. However, it is unproven whether or not an underlying source rock has been buried to a depth sufficient to produce thermally mature oil or natural gas with a migration pathway to the deltaic sandstones, and thus this sand-prone reservoir is likely primarily a CO₂ storage reservoir.

**CONCLUSION**

We generated an integrated sequence stratigraphic framework for the uppermost Jurassic and Cretaceous strata of the SBCT using recently released seismic data (Triezenberg et al., 2016), legacy well data, and objective criteria to recognize the bounding surfaces of depositional sequences. We update and build upon the relatively limited evaluations within the literature (Libby-French, 1981, 1984; Poag and Sevon, 1989; Prather, 1991; Klitgord et al., 1994) and reconcile our observations with the regional sequence stratigraphic framework established for the onshore mid-Atlantic Coastal Plain (Miller et al., 2017) as well as the more-recent evaluation of mid-Cretaceous sedimentation on the OCS of the NBCT (Miller et al., 2018).

We identify seven seismic stratigraphic surfaces that can be traced from a northern subarea offshore New Jersey to the south to the continental shelf off the coast of Maryland, constrained in age by biostratigraphic data from five wells offshore southern New Jersey and a cross section of three wells on the Maryland coastal plain. A regional velocity–depth model is developed to convert the legacy seismic data to depth, and an onshore–offshore correlation is made between the depth-converted seismic surfaces of the Maryland Shelf and the onshore well-log stratigraphy (Miller et al., 2017) within the three deep stratigraphic test wells in Maryland. The onshore–offshore correlation provides additional, albeit coarse, constraints on absolute age.

We integrate the onshore stratigraphy for the mid-Atlantic Coastal Plain (Miller et al., 2004, 2017) with the depth-converted seismic stratigraphy ultimately producing regional structural contour maps and isopachs for the entire SBCT. These maps combine with Wheeler diagrams we generate for dip lines of the Maryland shelf to establish a better understanding of spatiotemporal variations of Cretaceous sedimentation in the SBCT. We delineate the 3-D movement (planimetric space and time) of the sedimentary depocenter from a distal and southerly Early Cretaceous position to a more-proximal but still southerly location in the mid-Cretaceous, followed by predominantly northerly
and distal Late Cretaceous sedimentation. These spatial variations in sedimentary thickness correspond to a deepening of depositional environment from the Early Cretaceous to a maximum paleodepth at the Cenomanian–Turonian boundary, followed by a Late Cretaceous shoaling.

Using the coarse chronostratigraphic framework derived from the integrated onshore and offshore interpretations, we also correlate five of the mid-Cretaceous depositional sequences to global cycle charts and RSL records for the BCT. These five sequences fall within a major 10^-2-yr transgression that spans the mid-Cretaceous, reaching a GMSL high near the Cenomanian–Turonian boundary (Haq et al., 1987; Miller et al., 2005; Haq, 2014), corresponding with the deepest paleodepths observed within the BCT (Poag, 1985b; Olsson et al., 1988; Sikora and Olsson, 1991) and the concomitant OAE 2. Seismic facies corroborate this deepening trend and reveal higher-order transgressive–regressive packages that produce a retrogradational set of depositional sequences. We propose that OAE 1a and OAE 2 are associated with MFSs of the lowermost and uppermost mid-Cretaceous sequences and suggest that these observations support a causal relationship between rising GMSL and these OAEs.

Based on the seismic facies we observe and our correlation to coeval fluvial depositional facies in well data from the Maryland and New Jersey coastal plains (Browning et al., 2008; Miller et al., 2017), we suggest there are likely mid-Cretaceous, sand-prone deltaic facies offshore Maryland. This interval is largely shale offshore southern New Jersey but thickens to the south, indicating a location more proximal to a deltaic sediment source. This package is thick and is likely to contain sedimentary facies that comprise a viable reservoir for storage of supercritical CO₂ or oil and natural gas. It is also capped by muds and shales onshore and offshore. However, a viable source rock for hydrocarbon accumulation in these potential reservoir sandstones has yet to be identified, relegating this to a CO₂ storage reservoir. Beneath this mid-Cretaceous interval, there is also a thick package of Lower Cretaceous strata that likely contain sand-prone siliciclastics deposited behind a fringing carbonate platform. These sandstones might also present attractive targets for CO₂ storage or hydrocarbon exploration if they are locally amalgamated and hydrologically connective.

**APPENDIX 1: CONVERSION OF SEISMIC TWO-WAY TRAVELTIME TO DEPTH BELOW MEAN SEA LEVEL**

A regional geoaoustic study that established a Geophysical Database of the United States Northern Atlantic Margin (GDUSNAM; Klitgord et al., 1994) was conducted for the US Naval Oceanographic Office by the USGS. The velocity structure was calculated using the stacking velocities generated as a process step of the aforementioned USGS marine MCS profiles that canvas the margin and calibrating those velocities to sonic log and check shot surveys collected at the OCS industry wells along a few select seismic profiles (Klitgord and Schneider, 1994). Geologically improbable velocity variations (that were likely left in the original data because they were not significant enough to affect the visual character of the finished seismic product) were smoothed by Klitgord and Schneider (1994) and subsequently converted to interval velocities using the Dix formula (Dix, 1955; Taner and Koehler, 1969). The velocity information was evaluated at approximately 3000-m (~9800-ft) spacing along the USGS seismic lines and then subsequently gridded at 5-min spacing in terms of both latitude and longitude, with a cubic spline interpolation routine.

The gridded database is organized around 19 stratigraphic horizons delineated across the margin. At each spatial location within the database, each of the stratigraphic horizons representing a stratigraphic section present at that location contains the TWTT to that horizon and its depth in meters below sea level, in addition to information about density, seismic velocities, attenuation, and broad sedimentary classifications. This stratigraphically oriented database was reorganized into a database of monotonically increasing TWTTs and associated depths across the margin. We extracted the depth and TWTT information from the original database structure for each location in the database and replaced the values in the first second of TWTT below the sea floor with a time-depth relationship derived from modern data collected during the R/V Oceanus 270 cruise and tested against data from IODP Exp. 313 (Mountain and Monteverde, 2012). Having made this replacement, at every location, an interpolation was then performed to calculate the time and depth information at consistent intervals of travel time, 0.1 s (Figure 2).

Therefore, the stratigraphically oriented GDUSNAM was transformed to a record of depths at monotonically increasing TWTT isochrons; that is, the depth data were no longer tied to TWTT through the 19 horizons that are variably present throughout the margin. Instead, the data were organized into 90 surfaces of depth at TWTT isochrons spanning, at most, 0–8.9 s at 0.1-s intervals.

For import to IHS Kingdom software and to facilitate tests of accuracy, the data were converted from the geographic coordinate system that it was provided in (latitude and longitude) to a Cartesian Mercator projection, using the Universal Transverse Mercator 18N coordinate system. This conversion was carried out using the open-source python-based software pyproj. The conversion resulted in irregularly spaced data points that cannot be imported into an IHS
Kingdom project. Therefore, a linear interpolation was applied to make a regularly spaced grid for each of the depth surfaces. The new depth grids with 2500-m (8200-ft) spacing were imported into IHS Kingdom and used to convert the entire seismic database, including interpreted horizons from TWTT to depth.

**APPENDIX 2: UNCERTAINTY OF DATA AND INTERPRETATIONS**

The largest sources of uncertainty are the paucity of wells in the southern subarea, the interpretation of seismic data with a coarse vertical resolution, the time–depth conversions obtained from velocity surveys for the projection of drill site data onto the seismic grid, and the accuracy of the regional time–depth model. Compared to the northern subarea, there are relatively few constraints on accuracy of the seismic interpretations in the southern area because of the absence of well locations on the shelf. The coarse vertical resolution of the seismic data most strongly affects the seismic stratigraphic interpretations. Seismic artifacts, not limited to those generated by low vertical resolution, might alter perceptions of thickness and continuity for some stratal packages. The accuracy of the site velocity surveys affects the projection of data (e.g., biostratigraphy) from the wells onto the seismic data. Inaccurate projections of biostratigraphic levels within the wells because of inaccuracies associated with the velocity surveys could result in problematic absolute age constraints on the seismic surfaces, along with complications because of cavings and other issues. Finally, localized artifacts within the regional time–depth model might create anticlines or synclines within structural contours that do not exist in reality. Additionally, because this time–depth model was used to correlate the onshore and offshore stratigraphy, artifacts could also affect the onshore–offshore correlations. The magnitudes of each of the identified errors are likely small enough to retain reasonable confidence in our results, especially considering the scales associated with this analysis (i.e., the mapped seismic surfaces are typically separated by hundreds of meters of sediment and are mapped regionally). Moreover, the integrated nature of our analysis (that includes seismic stratigraphic interpretation, well-log correlation, and biostratigraphic constraints) produces checks and redundancies that minimize the likelihood of misconstructions.

The vertical resolution of the seismic data is a product of the wavenumber of the seismic data through the section. As interval velocities increase moving down through the section, the wavenumber decreases for a given source frequency, and the distance between beds that can be resolved increases. The increasing distance between resolvable bedding variations naturally generates challenges to the application of seismic stratigraphic methods. However, even if many bedding interfaces are contained within a canonical 1/4–1/8 λ (Widess, 1973), the largest impedance contrasts through the section are likely to be preserved and recorded as a response to the source signal, whereas minor variations surrounding the larger contrast will be overshadowed. This lends credibility toward tracing continuous, high-amplitude reflections even if the seismic resolution is poor. Additionally, the seismic geometries associated with internal reflections of deltaic depositional sequences are geomorphological in their genesis. So the identification of their characteristic forms, and the surfaces bounding them, mitigates the limitation of low-resolution data. Although, in attempting to trace single reflectors, there were instances in which depositional sequences thinned to a thickness that is near or within the vertical resolution and preclude identification of internal reflections. Loop correlation was applied to resolve uncertainties. Within the Cretaceous section of the BCT, vertical seismic resolution typically ranged from 30 to 70 m (100–230 ft). However, in most areas, and at the scale of analysis, internal reflections were observable, and many of the high- amplitude reflections were continuous, indicating a genetically related origin for the consistent impedance contrasts (Figure 7).

Assuming a ±10% error for the time–depth conversion obtained from the velocity surveys, errors associated with projecting the biostratigraphy and GR logs onto the seismic data would be, very conservatively, within ±75–175 m (±250–570 ft), with the better accuracies higher in the section. This conservative estimate of error is relatively large, and it is likely a maximum constraint because we did not account for the contribution of frequency content higher than the peak frequency at a given depth interval. Still, the coarse resolution inherently associated with seismic stratigraphic interpretation of deeply buried (>1–1.5 km [>3300–4900 ft]) strata can influence the assignment of age to a particular package. To mitigate adverse effects from potential inaccuracy, sequences were correlated between multiple wells and ages assigned based on information from each. The correlations between wells were generally within the seismic resolution of the well-log correlation and biostratigraphic markers (Figure 3).

Using the check shot data as a reference, the regional velocity–depth model was calculated to have an accuracy of better than ±150 m (±490 ft) for sedimentary depths up to 3000 m (9800 ft). Like the velocity survey error, the accuracy of the regional velocity–depth model could affect stratigraphic correlations. The onshore–offshore correlation is dependent upon converting the seismic data to depth, but a ±150-m (±490-ft) offset would not appear to significantly change the proposed correlations (Figure 9).

**REFERENCES CITED**


Anderson, J. L., 1948, Cretaceous and Tertiary subsurface geology - The stratigraphy, paleontology, and sedimentology of

Andreasen, D. C., A. W. Staley, and G. Achmad, 2015, Maryland coastal plain aquifer information system: Hydrogeologic framework: Baltimore, Maryland, Maryland Department of Natural Resources Open-File Report 12-02-20, 121 p.


