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LOWER TO MID-CRETACEOUS SEQUENCE STRATIGRAPHY AND CHARACTERIZATION OF CO_2 STORAGE POTENTIAL IN THE MID-ATLANTIC U.S. COASTAL PLAIN

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ABSTRACT: **The Mid-Atlantic U.S. Coastal Plain (New Jersey, Delaware, Maryland, and northern Virginia) contains thick (> 500 m) mid-Cretaceous sand–sandstone reservoirs confined by thick clay–shale confining units and thus has high potential for storage of CO_2 captured from nearby point sources. The predictability of the continuity of the reservoir and confining units can be improved by applying principles of sequence stratigraphy, including integration of lithostratigraphy, biostratigraphy, paleoenvironmental proxies, and a novel application of fluvial aggradation cycles (FACs). We evaluate the storage and confinement potential for the Lower Cretaceous Waste Gate Formation and mid-Cretaceous Potomac Formation/Group in New Jersey and Maryland, which we divide into three major reservoirs (Waste Gate-Potomac Unit I, Potomac Unit II, and Potomac Unit III). We use new core data to ground-truth well-logs and paleoenvironmental changes, sequence stratigraphic stacking patterns (including FACs), and pollen biostratigraphy to update previous well-log correlations in New Jersey and extend these correlations into deep holes in Maryland. While individual sand beds are typically local in extent, zones of sands are broadly correlative over distances of 60 km. These regionally traceable sand-prone zones should be useful for carbon storage. Cenomanian Potomac Unit III sands are relatively thick (~ 70 m) in New Jersey, but generally thin (average of ~ 50 m) into Maryland; they are near the updip limit for supercritical storage (800 m) in New Jersey and Maryland and may not be suitable due to updip migration above the supercritical level. Potomac Unit II sands (Albian Pollen Zone II) appear to be discontinuous and less suitable in both states. Potomac Unit I (Aptian Pollen Zone I) and Waste Gate Formation sands (?early Aptian to Berriasian pre-Pollen Zone I) are relatively thick (~ 88–223 m and ~ 81–288 m, respectively) and confined in New Jersey and appear to be widespread and continuous; the updip confinement of this reservoir in Maryland is less certain. Volume storage estimates for the Potomac I-Waste Gate in the Mid-Atlantic Coastal Plain are 8.4–33.5 Gt CO_2, adequate to store CO_2 captured from 24–95 GW of natural gas generation for a century.**

INTRODUCTION

Carbon capture and storage (CCS) in geologic reservoirs is an important strategy for reducing anthropogenic emissions of carbon dioxide (CO_2) into the atmosphere (Metz et al. 2005; International Energy Agency 2014). Capture of CO_2 may be done pre- or post-combustion from power plants (Metz et al. 2005) or with innovative technology through direct air capture (Broecker 2013). Both capture of CO_2 produced by combustion of biomass and direct air capture provide mechanisms for achieving negative emissions by removing CO_2 from the atmosphere. Such removal also plays an important role in many emissions scenarios consistent with the goal of limiting global mean warming to 1.5–2.0°C above a pre-Industrial baseline (Edmonds et al. 2013; Smith et al. 2016).

Geological carbon sequestration, or carbon storage, usually assumes storage in a subsurface reservoir as a supercritical fluid, with initial structural trapping transitioning to mineralization over centennial to millennial time scales (Metz et al. 2005). Storage of supercritical CO_2 in structural traps requires both a reservoir and a seal/cap, with burial pressure greater than 7.38 MPa at temperatures > 31.1°C (Bachu 2000). Thus, assuming a typical geothermal gradient of 25°C/km, 12°C surface temperatures, and a lithostatic gradient of 27 MPa/km, supercritical storage requires burial depths greater than 800 m (Bachu 2000), the line of supercritical storage (Fig. 1). Large volume reservoirs are needed; these can be in depleted oil and gas fields (where CO_2 injection is often used in enhanced oil recovery [EOR]) or in saline reservoirs. Saline reservoirs have larger volumes than oil and gas reservoirs and are more widely distributed. However, because fewer wells are drilled in areas lacking hydrocarbon exploration, reservoirs and seals are not as well characterized geologically there as in oil and gas fields. CO_2 can be sequestered in saline reservoirs either on land or in offshore geological formations, with porous limestones or sandstones the preferred targets. Ideally, CO_2 sources should be proximal to injection sites, minimizing the cost and environmental impacts of CO_2 transport.

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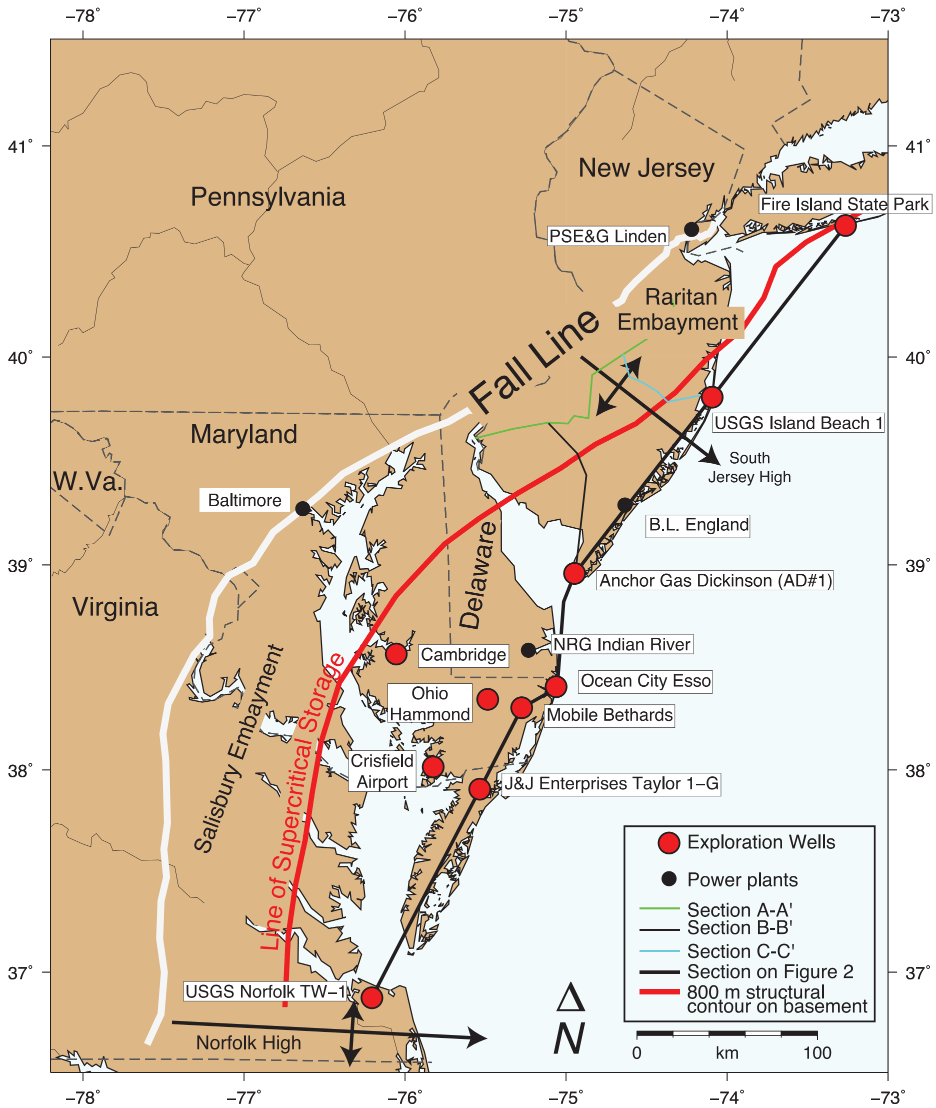

FIG. 1.—Location map of Mid-Atlantic margin. Thick white line is the Fall Line separating bedrock from the coastal plain. Thick red line is 800 m line of supercritical storage. Thick red line shows 800 m depth of supercritical storage.

The Mid-Atlantic Coastal Plain was identified in early studies as one of several suitable targets in the U.S. for carbon storage, because it has sufficiently deep, porous, and permeable sand–sandstone reservoirs that are capped by confining beds that hydraulically isolate them from overlying freshwater aquifers (Hovorka et al. 2000). Studies conducted as part of the Midwest Regional Carbon Sequestration Partnership (MRCSP; http://www.mrcsp.org) provided preliminary evaluations of carbon-storage opportunities in sand and sandstone reservoirs in the New Jersey Coastal Plain (Sugarman et al. 2011) (Fig. 1) and its offshore region (Monteverde et al. 2011).

In this study, we build on and extend the work from New Jersey and place carbon storage into a regional geological context from New Jersey to northern Virginia. We use new core data and sequence stratigraphy to ground-truth gamma logs, update previous well-log and pollen correlations in New Jersey for the Waste Gate-Potomac Unit I, Unit II, and Unit III, and correlate New Jersey sections to four deep wells in Maryland using well-logs and pollen biostratigraphy (Fig. 1). This allows us to define regional reservoir units consisting of multiple permeable sand–sandstone layers and low-permeability clay–shale confining layers that are potential seals. We update the previous assessment of storage capacity in the Potomac reservoirs and extend this approach to assess the entire Mid-Atlantic Coastal Plain. We conclude that there is high storage resource potential for storing large volumes (8.4–33.5 Gt CO_2 in the Waste Gate-Potomac Unit I) of CO_2 in these porous ($>$ 20%) saline reservoirs and conclude with a discussion of the practical feasibility of carbon sequestration in the Mid-Atlantic Coastal Plain.

Geological History of the Mid-Atlantic Margin

The Mid-Atlantic Coastal Plain is the emergent portion of a classic passive continental margin. The Coastal Plain lies between the Atlantic Ocean and the Fall Line, which separates it from surficially exposed bedrock (Fig. 1). It consists of largely unconsolidated sands, silts, and clays, with occasional gravels, and dips gently ($<$ 1°) and thickens seaward. The Coastal Plain formed following Late Triassic–earliest Jurassic rifting (~ 230–198 Ma; Olsen and Kent 1999), followed by extrusion of ?Early Jurassic seaward dipping basalts and post-rift uplift associated with a diachronous unconformity (Grow and Sheridan 1988). Seafloor spreading began prior to the Callovian (~ 165 Ma; Middle Jurassic; Sheridan et al. 1978), with the likely opening beginning off Georgia ca. 200 Ma and progressing northward off the mid-Atlantic margin (Withjack et al. 1998).

Thick sediments (over 16 km) accumulated in the offshore Baltimore Canyon Trough (BCT) basin and thinner (0–2.4 km) uppermost Jurassic to

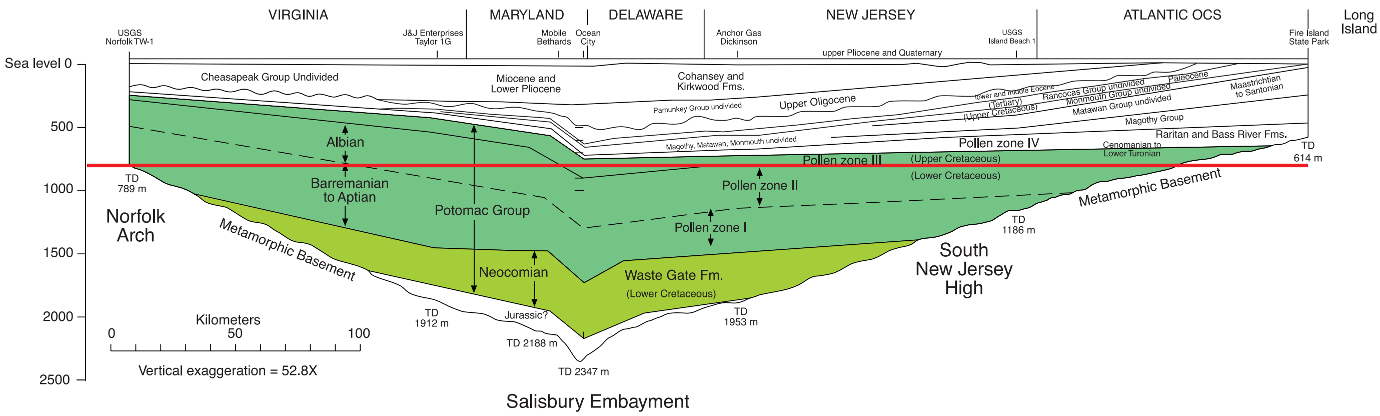

FIG. 2.—Cross section shown in Figure 1 showing the Potomac Formation and Group (dark green) and Waste Gate Formation (light green). Thick red line shows 800 m depth of supercritical storage. White areas above green are Cenozoic and below green are Jurassic. Modified after Olsson et al. (1988).

Holocene sediments accumulated in the onshore Coastal Plain in the Salisbury Embayment (Fig. 1; Grow and Sheridan 1988). Subsidence began offshore prior to 180 Ma and progressively moved onshore from the Late Jurassic to Early Cretaceous (ca. 150 to 125 Ma) as a thermoflexural response due to increased crustal rigidity (Watts 1981; Olsson et al. 1988; Kominz et al. 1998). Upper Jurassic strata (145.3–163.5 Ma) have been identified in Maryland (Fig. 2; Hansen and Doyle 1982) and tentatively extended into New Jersey based on well-log correlations (Fig. 2; Olsson et al. 1988; this study). Accommodation (the creation of vertical space needed for accumulation of sediments) in the coastal plain has been dominated by sediment loading, thermoflexural subsidence, and compaction (Kominz et al. 1998; Kominz et al. 2008), with little evidence for more active tectonics or faulting other than growth faults (Sheridan et al. 1991). Recent studies have shown that epeirogenic uplift and subsidence due to changes in mantle dynamic topography have influenced the stratigraphic record of this margin (Moucha et al. 2008; Müller et al. 2008; Spasojević, et al. 2008; Rowley et al. 2013), providing a mechanism for differential movement of the arches (e.g., the South Jersey High; Fig. 1) and basins (Salisbury and Raritan Embayments; Fig. 1) that characterize this margin (Brown et al. 1972). Glacial isostatic adjustment due to the ice ages of the past 2.7 Myr (e.g., Peltier 1998) also drives subsidence in the region, but its net effect on the older record over multiple glacial cycles is small.

Sequence Stratigraphy and Carbon Sequestration

Sequence stratigraphy is an approach to the stratigraphic record that potentially enables greater predictability of the presence and character of reservoir sands and confining units (e.g., Posamentier et al. 1988). Sequence stratigraphy divides the stratigraphic record into units bounded by unconformities or their correlative conformities (sequence boundaries; Mitchum et al. 1977). Sequences were first recognized based on seismic criteria (Mitchum et al. 1977). Sequences can be readily identified in cores by irregular contacts, rip-up clasts, other evidence of reworking, intense bioturbation, major facies changes, stacking pattern changes (e.g., changes in coarsening versus fining upward), and evidence for hiatuses (Van Wagoner et al. 1987; Miller et al. 2013). Sequences can also be recognized on geophysical logs by distinct stacking patterns, particularly of parasequences (those bounded by flooding surfaces (FS); Van Wagoner et al. 1987; Van Wagoner et al. 1990), and by the common association of sequence boundaries with large (usually sharp) gamma-log increases, though these are not unique to unconformities. Sequence stratigraphy has long provided predictions about petroleum reservoirs and seals (Vail et al. 1977) and can be applied to aquifer and confining-unit distributions (e.g., Sugarman et al. 2005a) and carbon storage (this study). Onshore coring in New Jersey and Delaware by Ocean Drilling Program (ODP) Legs 150X and 174AX (Miller and Snyder 1997; Miller 2002) provided numerous examples of the application of sequence stratigraphy to Upper Cretaceous to Holocene marine and nonmarine strata (e.g., Sugarman et al. 2005; Thornburg 2016) and their relevance to sea-level change (Miller et al. 2005).

Recent studies of the New Jersey and Delaware coastal plains have demonstrated the utility of sequence stratigraphy for understanding the distribution of aquifers and confining beds/caps/seals (Sugarman et al. 2005a; Thornburg 2016). Initial hydrostratigraphic investigations in the New Jersey Coastal Plain delineated aquifers and confining units chiefly from outcrops and subsurface geophysical logs (Zapecza 1989). Sugarman et al. (1995, 2005a) applied sequence stratigraphy to ODP Leg 150X and 174AX cores to improve hydrogeologic frameworks and predictions for continuity of aquifer sands and confining unit muds. They identified sequence boundaries in cores and correlated them regionally using geophysical logs. Facies changes in marine sequences generally follow predictable patterns, with upper highstand system tract (HST) aquifer sands confined by transgressive system tract (TST) silts and clays of the overlying sequence. They showed marine aquifer sands were generally continuous on the 10+ km scale and traceable for > 60 km along strike and > 25 km along dip. Confining beds for these units are typically laterally continuous shelf or prodelta silts and clays. Marginal to nonmarine sequences were less predictable, though some show surprising lateral continuity along strike (> 60 km; Sugarman et al. 2005a).

Preliminary characterization of geologic carbon-storage potential in New Jersey found that saline reservoirs in the coastal plain warranted further investigation (Sugarman et al. 2011). These saline reservoirs are attractive for storage because their high total dissolved solids (TDS) precludes their use as a source for human consumption or agriculture (since the term "aquifer" in some definitions implies such use, we use the more generic term "reservoir"). Evaluating the New Jersey Coastal Plain, Sugarman et al. (2011) eliminated the Cenozoic and the Campanian Mount Laurel and Englishtown reservoirs as too shallow for storage potential (< 800 m) and evaluated Cretaceous reservoirs of the Potomac–Raritan–Magothy Formation ("PRM") (Zapecza 1989). They constructed structural contour and isopach maps of the PRM reservoirs and concluded that only Potomac Formation reservoirs (named Units I, II, and III as described below) were suitable based on depth, thicknesses, and presence of suitable confining units. Here, we build on the well-log correlations of Sugarman et al. (2011), testing and improving them with new core data and sequence stratigraphic interpretations, and extending these correlations to Maryland.

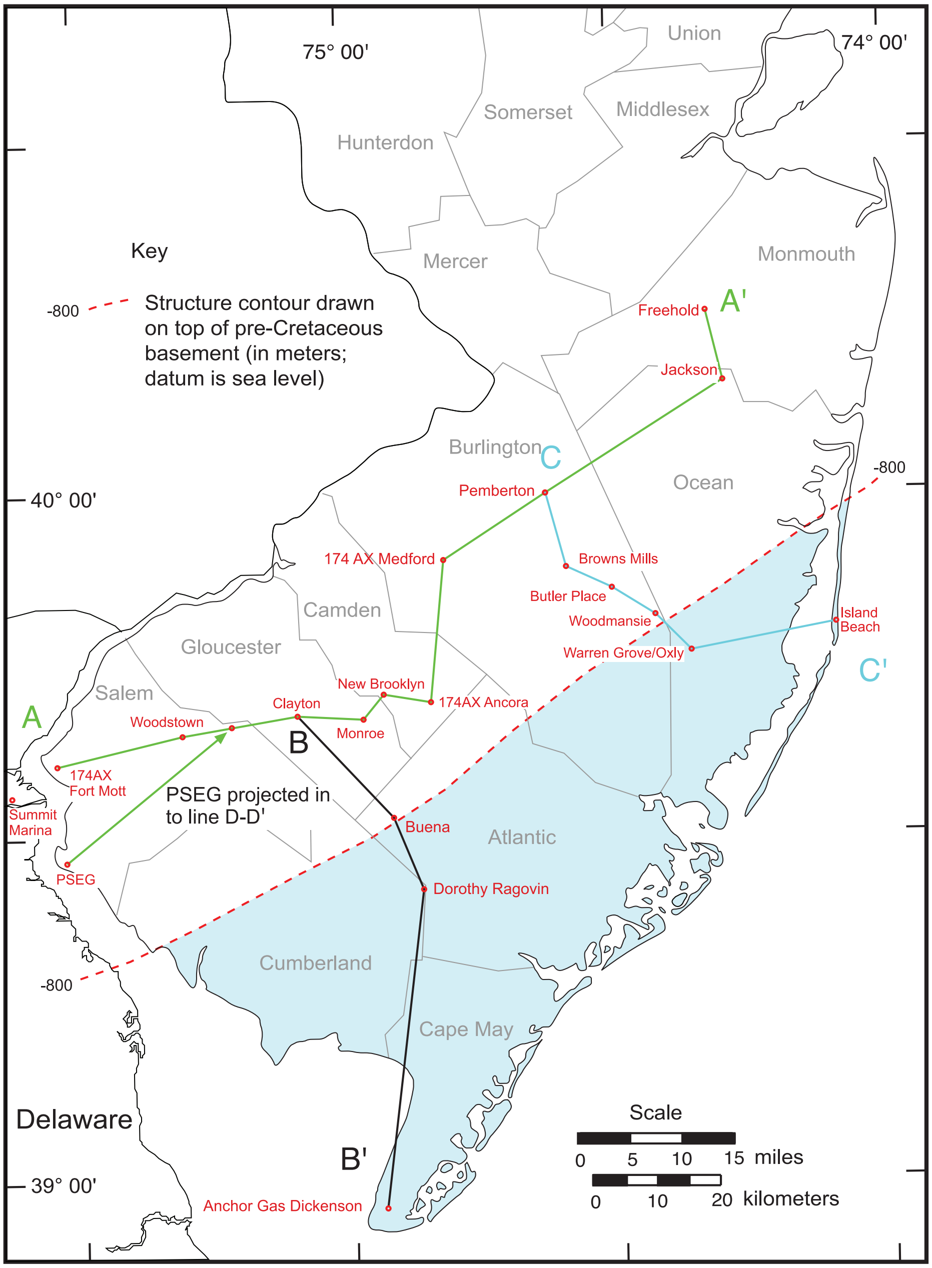

FIG. 3.—Location map of wells and well-log cross section for the New Jersey Coastal Plain. Dashed red line is 800 m structural contour of supercritical storage. Modified after Sugarman et al. (2011).

The Potomac Formation/Group and Waste Gate Formation

We evaluate the Potomac in New Jersey, Delaware (where it is a formation), and Maryland (where it is a group; see below) and extrapolate our studies to Virginia (where has been termed both a formation and a group). The Potomac Formation was first named for a unit with an "upper portion consisting of highly color-mottled and color-banded clays, with intercalations of sand and quartzose gravel, and the lower of sand and gravel with intercalations of clay" in outcrop sections in Maryland and Virginia (McGee 1886). These nonmarine sediments overlie saprolite and crystalline basement and were considered the oldest in the coastal plain, possibly being Jurassic according to Marsh (1896), though the paleoflora indicated correlation to the Lower Cretaceous (Gilbert 1896). The Potomac in New Jersey and Delaware is a formation (e.g., Owens et al. 1998; Ramsey 2005); in Maryland, it was raised to group status with the designation of the Patapsco, Arundel, and Patuxent formations (units given younger to older; Clark and Bibbins 1897) and later a lower Waste Gate Formation (Hansen and Doyle 1982). The Waste Gate Formation has received considerable attention for carbon storage (Hovorka et al. 2000; Wickstrom et al. 2005; Gunnulfsen et al. 2013; U.S. Geological Survey Geological Carbon Dioxide Storage Resources Assessment Team 2013). It is not clear if the Waste Gate Formation is represented in New Jersey, though it was correlated as a distinct formation based on logs to the Anchor Gas Dickinson #1 (AD#1) Cape May, New Jersey well (Figs. 1–3; Olsson et al. 1988).

Correlations of the Potomac Formation and Group largely rely on log signatures and pollen biostratigraphy that provide the only age control on these nonmarine units. A palynological zonation was developed in Cretaceous Atlantic Coastal Plain continental sections, with the Potomac Formation initially assigned to Pollen Zones I and II (Brenner 1963) and later expanded to include Pollen Zone III (Doyle and Robbins 1977). In this study, we continue the use of Roman numerals for Units I, II, and III to

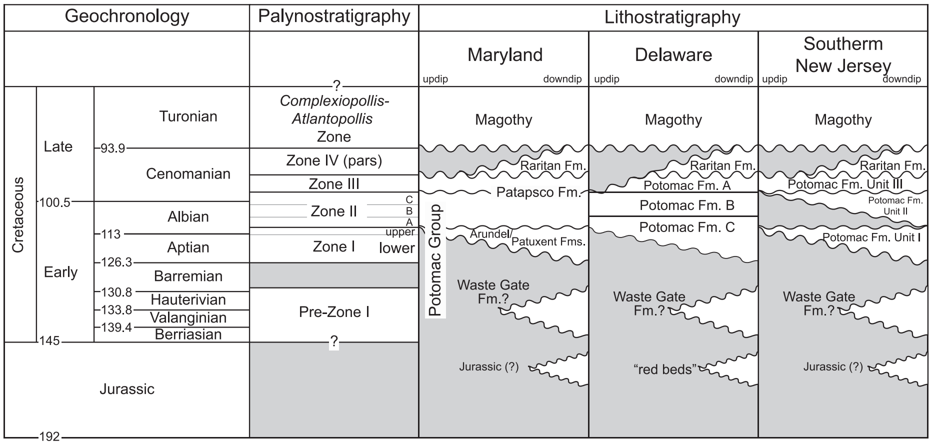

FIG. 4.—Stratigraphic correlation chart of pollen zones and lithologic units.

be consistent with previous studies. The Waste Gate Formation was assigned to pre–Zone I in the wells discussed below based on pollen (Hansen and Doyle 1982). Ages of these zones were assigned by correlations with better-dated marine sections in England and Portugal (Brenner 1963; Doyle and Robbins 1977; Sugarman et al. 2005b), with the most recent revision by Hochuli et al. (2006) (Fig. 4). These pollen zones are loosely calibrated to the Geological Time Scale (Gradstein et al. 2012) and are long in duration (3 zones in $\sim$ 30 Myr; Fig. 4).

Following the division of the Potomac Formation into pollen Zones I, II, and III, Owens et al. (1998) suggested that there were three cycles in the Potomac Formation in New Jersey. In New Jersey, only Unit III occurs in outcrop, where it "…consists of abruptly lensing clay, sand, and less commonly gravel"; the older Units II and I are restricted to the subsurface in New Jersey. Each Potomac unit corresponds to a distinct pollen zone (Fig. 4) that spans the Barremian to lowermost Cenomanian (ca. 126–98 Ma). Ages are updated in the Results section.

In Delaware, Potomac units C, B, and A (from oldest to youngest) were established by Benson (2006) based on well-logs and pollen. Benson's (2006) units do not correspond exactly to Units I through III in New Jersey. On the basis of pollen biostratigraphy, Potomac C likely corresponds to Unit I and the lower part of Unit II, Potomac B to the upper part of Unit II, and Potomac A to Unit III (Peter McLaughlin, written communication, 2016).

In Maryland, the Patapsco, Arundel, and Patuxent formations crop out, and the deeper Waste Gate Formation is found only downdip in the subsurface (Hansen and Doyle 1982; Hansen 1984). In the updip section of Maryland's Coastal Plain, primarily areas west of Chesapeake Bay, the Patuxent and Patapsco formations were deposited in a depositional basin by high-energy, braided river systems producing typically blocky, stacked sand bodies that are generally coarse-grained and laterally extensive (Hansen and Doyle 1982; Hansen 1984). The axis of the river system was oriented northwest–southeast and located in the vicinity of present-day Baltimore. To the southwest of that area, in southern Maryland, meandering river systems dominated, producing lensoidal channel and point-bar deposits interbedded with fine-grained overbank and floodplain deposits (Hansen 1969, 1972). The Arundel Formation, dividing the Patuxent and Patapsco formations, was deposited during a prolonged period dominated by fine-grained overbank and floodplain deposits, in which channel and point-bar sand deposits were quite rare.

The Patuxent, Arundel, and Patapsco formations have been mapped extensively in updip areas in Maryland based on geophysical log (electric and gamma-ray logs) signatures, clay–sand content, lithological data, and pollen biostratigraphy (Hansen 1968, 1972). Much of the work in mapping the Potomac Group has been done for hydrogeological investigations. In updip areas, the sand content of the Patuxent and Patapsco formations ranges from less than 20 percent to more than 50 percent (Hansen 1968, 1969; Otton and Mandle 1984; Staley 2015). While individual sands are typically local in extent, zones of sands are broadly correlative over distances exceeding 20 miles (32 km) (Hansen 1968). Likewise, the Arundel Formation, typically a massive low-permeability clay, is present over much of the updip portions of the Maryland Coastal Plain, becoming difficult to identify northeast of Baltimore and in southern Maryland, where the Patuxent and Patapsco formations become increasingly clayey (Andreasen et al. 2013; Drummond and Blomquist 1993; Owens 1969; Staley 2015).

The lateral continuity of Potomac Group sand zones has long been established in updip sections in Maryland through the correlation of groundwater levels and pumpage (Staley et al. 2016), trends in long-term groundwater levels (Achmad and Hansen 2001; Soeder et al. 2007), numerical groundwater-flow modeling (Andreasen 2007; Drummond 2007), and hydrogeochemical facies (Back 1966). Continuity of layers into the deeper, downdip section is less well established, due to the limited well control. The Patuxent and Patapsco formations form major aquifer systems in Maryland (Andreasen et al. 2013). In many updip areas, the Patuxent and Lower Patapsco aquifer systems are effectively separated hydraulically by the confining unit of the Arundel Formation (Andreasen 1999, 2007; Drummond 2007); however, where the Arundel Formation has thinned, the hydraulic separation may be less pronounced.

Most prior lithologic data on the Potomac were derived from wells (generally cuttings) and geophysical wire-line logs in updip sections in New Jersey (Sugarman et al. 2011), Maryland (Andreasen et al. 2013), and Delaware (Benson 2006). Three updip cores provide ground truth to the wells and well-logs (Fig. 5): Summit Marina, Delaware (Thornburg 2016), Fort Mott, New Jersey (Sugarman et al. 2004), and Medford, New Jersey (Sugarman et al. 2010). No deep wells (with total depths below 800 m) are available in Delaware, but eight deep wells with logs in New Jersey (four wells) and Maryland (four wells) penetrated deep reservoirs (Fig. 1) (Hansen and Doyle 1982; Andreasen et al. 2013; Sugarman et al. 2011). We use well-logs and pollen data from these rotary wells to correlate the Waste Gate and Potomac sequences between New Jersey and Maryland.

METHODS

We focus on compiling log and pollen data from downdip wells ($>$ 800 m total depth) to develop a stratigraphic framework for the Potomac Formation/Group and Waste Gate Formation in the New Jersey and Maryland coastal plains. Pollen zones for the sections evaluated here were taken from the following references: Fort Mott cores (G. Brenner and P. McLaughlin in Sugarman et al. 2004) (Fig. 2), Medford cores (G. Brenner and P. McLaughlin in Sugarman et al. 2010), Summit Marina cores

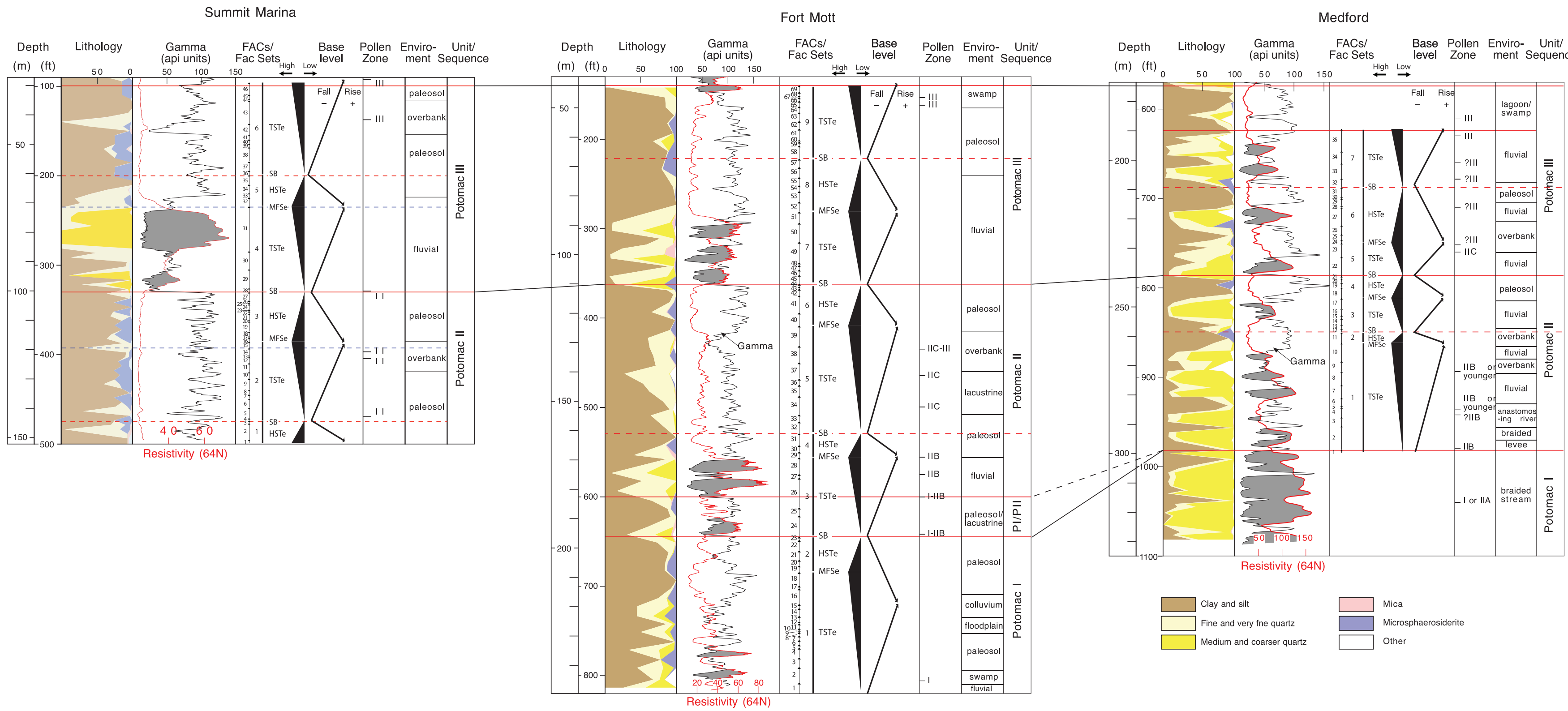

FIG. 5.—Correlation of lithology, logs, and depositional environments for Summit Marina, Fort Mott, and Medford. Black arrows point in direction of increasing accommodation based on FSAC set stacking pattern. Maximum flooding surface equivalents (MFSe) are placed at convergent arrows, and sequence boundaries (red lines) at divergent arrows. Note that the previously identified sequence boundaries are supported by the accommodation arrows (at levels with minimal accommodation) and two higher-order sequences have been identified (dashed red lines). Modified after Thornburg (2016). TSTe, transgressive-systems-tract equivalent placed between sequence boundaries and MFSe. HSTe, highstand-systems-tract equivalent placed between MFSe and the overlying sequence boundary.

(Thornburg 2016; see supplemental Table 1), New Jersey wells (complied from unpublished pollen zones primarily from G. Brenner by Sugarman et al. 2011 for the AD#1, Butler Place, Ragovin, Warren Grove/Oxly, and New Brooklyn Park wells) (Figs. 3, 6–8; Zones given in supplemental Table 2), and Maryland (Robbins et al. 1975; Hansen and Doyle 1982; Trapp et al. 1984).

Because there are only four deep (> 800 m) wells in New Jersey and four in Maryland (all consisting of well-logs and cuttings), we constructed an updip strike cross section in New Jersey (Figs. 3, 6) using three coreholes (Summit Marina, Fort Mott, Medford; Fig. 5) and other wells with geophysical logs. The cores provide lithostratigraphic and paleoenvironmental ground truth to the gamma logs (Fig. 5) that can be extended along strike and downdip to wells having only logs and cuttings. Lithology for the cores (Fig. 5) was determined by quantitatively measuring weight percent mud (< 63 μm), very fine to fine sand (63–125 μm), and medium to coarse sand (> 125 μm) in washed samples at ~ 1.5 m intervals. We semiquantitatively estimated the abundance of glauconite, shells, and mica in the sand fraction (> 63 μm) by splitting samples into aliquots and visually estimating percentages on a picking tray. The semiquantitative and quantitative percent data were combined and presented as "lithology"; these lithologic data exhibit distinct trends with grain size (Fig. 5). We display gamma log and resistivity logs, lithology, pollen zones, and environment of deposition as previously reported (Browning et al. 2008; Sugarman et al. 2004; Sugarman et al. 2010; Thornburg 2016).

We updated previous studies of Fort Mott and Medford (Sugarman et al. 2004; Sugarman et al. 2010) by adding fluvial aggradation cycles (FACs; Fig. 5). FACs and FAC sets identified in the three updip cores (Thornburg 2016) allow us to objectively identify sequence boundaries and systems tracts based on stacking patterns. The smallest units, known as FACs, are recognized as typically fining-upward sediment packages, usually with paleosols at the upper boundary (Atchley et al. 2004; Atchley et al. 2013). At larger scales, FACs are components in decameter-scale FAC sets that record fluvial stability and avulsion. FAC sets are recognized as a stacking of individual FACs that generally fine upward; FAC sets demonstrate a gradual upward increase in paleosol maturity and drainage or an upward increase to decrease in paleosol maturity with associated good to poor drainage (Atchley et al. 2004). As base-level rise slows and begins to fall, accommodation is reduced and alluvial aggradation gives way to more mature paleosols associated with enhanced drainage and thinner individual FACs. Sequence boundaries can thus be placed above the mature paleosols with the best drainage before base-level rise begins to again increase the frequency of avulsions and flooding events. These sequence boundaries are typically associated with an upsection change from thinning FACs to thickening FACs, and by extension the maximum flooding surface (MFS) equivalent is placed at the upsection change from thickening FACs to thinning FACs (Fig. 5; Atchley et al. 2004; Atchley et al. 2013). FACs were assigned after a detailed grain-size analysis revealed distinct fining-upward successions, usually capped with a paleosol deposit (Fig. 5; Thornburg 2016). Ultimately the stacking pattern of these FACs allows the placement of the MFS and sequence boundaries. We provide examples of placement of stratal boundaries in the Results section; detailed discussion of FACs is the subject of a future contribution.

Analysis of New Jersey Coastal Plain rotary wells is updated from Sugarman et al. (2011). The New Jersey Geological and Water Survey compiled 56 southern New Jersey Coastal Plain well logs, digitized into LAS standard format (including deep wells at US Geological Survey [USGS] Island Beach, Dorothy/Ragovin, Warren Grove/Oxly, and AD#1). Geophysical logs including gamma, spontaneous potential (SP), resistivity, long and short normal and induction generally constitute the suite used for groundwater studies. Here, we focused on gamma logs (Figs. 6–8), except for the AD#1 well which has only spontaneous potential (SP) (Fig. 7). Sugarman et al. (2011) selected 25 well logs to construct four well-log cross sections; we update these and present one updip strike section (section A–A′; Fig. 6) and two dip sections (B–B′ to AD#1 and C–C′ to Island Beach) (Figs. 7, 8). The strike section is based entirely on gamma logs, with low values (sands) shaded. The dip sections are also all gamma logs except AD#1, where we shaded low values of SP logs. Since Sugarman et al. (2011) determined that only the Potomac and older formations were suitable for storage, we focus on these units (Fig 6). In general, we used gamma logs to correlate units and used the limited pollen data to support our correlations. In the rare instances where pollen data appear uncertain or even contradict correlations (e.g., Butler Place, discussed below), we favored the log interpretations. For example, at Medford (Fig. 5), there is a possible identification of Zone IIC at 761.1–762.2 ft (231.98–232.32 m) above the sequence boundary, yet we place this in sequence III (Brenner assigned this level to undifferentiated Zone III–IIC and McLaughlin to Zone IIC, both in Sugarman et al. 2010).

The well data were used to construct structural contour maps for New Jersey (Fig. 9). Using ESRI ArcMap 9.x., point files were created for each well that contained depth to selected surfaces. Point data were converted to a 2-D surface (raster) using ArcMap's 3-D analyst module. These surfaces were contoured using a kriging with a spherical semi-variogram model. Contours were connected to surface contacts defined by mapping exposures of the different units. Structural contour maps were compared with previous efforts (Zapecza 1989; Kulpecz et al. 2008); these studies had greater number of updip wells but lacked the deepest wells that place constraints on the Potomac Formation. They were used to check contouring of the updip locations. The structural contour maps confirm that only the Potomac and Waste Gate sands reach sufficient burial depth for sequestration (> 800 m) onshore.

We revisit correlations in Maryland originally made by Hansen and Doyle (1982) and Owens and Gohn (1985) and correlate the AD#1 well to Maryland by projecting it along pre-Mesozoic basement contours (Benson 1984) (Fig. 1). This regional "jump" correlation is supported by pollen data (see below). Pollen data and published age interpretations (Brown et al. 1972; Hansen and Doyle 1982; McLaughlin in Benson 2006) were used to guide the correlations as discussed below. The downhole logs from Maryland (Fig. 10) consist of SP logs at the Ohio Hammond, AD#1, Mobil Bethards, and Ocean City Esso wells. We added the gamma log for the updip Crisfield Airport well (Andreasen et al. 2013) and correlated the Maryland wells to the AD#1 (Fig. 10). All log data were averaged over a 1.8 m vertical interval. In the supplementary material, we display the deep downhole logs for SP, resistivity, and, where available, gamma logs for the five wells (Crisfield Airport, Ohio Hammond, AD#1, Mobile Bethards, and Ocean City Esso) along with the updip Cambridge well (Dorchester County, Maryland).

RESULTS

Age Correlation of Units

We update previous chronostratigraphic charts (Sugarman et al. 2005b; Sugarman et al. 2011; Thornburg 2016) and show correlations of units in Maryland, Delaware, and New Jersey (Fig. 4). The units we examined are primarily Lower Cretaceous, though they extend into the lowermost Upper Cretaceous (lower Cenomanian). The long durations of the palynology zones do not allow firm determination of hiatuses, though they can be inferred in association with sequence boundaries and the truncation of units updip (Fig. 4).

The Waste Gate Formation is lower Lower Cretaceous. It was assigned to pre-Zone I at the Ohio Hammond, Mobil Bethards, and Chrisfield wells in Maryland (Fig. 1; Robbins et al. 1975; Hansen and Doyle 1982), and correlated with the Berriasian to Hauterivian Stages (Fig. 4; Habib 1977; Hansen and Doyle 1982). Brenner (1981) reported early angiosperms in the Ohio Hammond well, suggesting that the Waste Gate reaches into the early Barremian. The ages of the Potomac Unit I and the underlying Waste

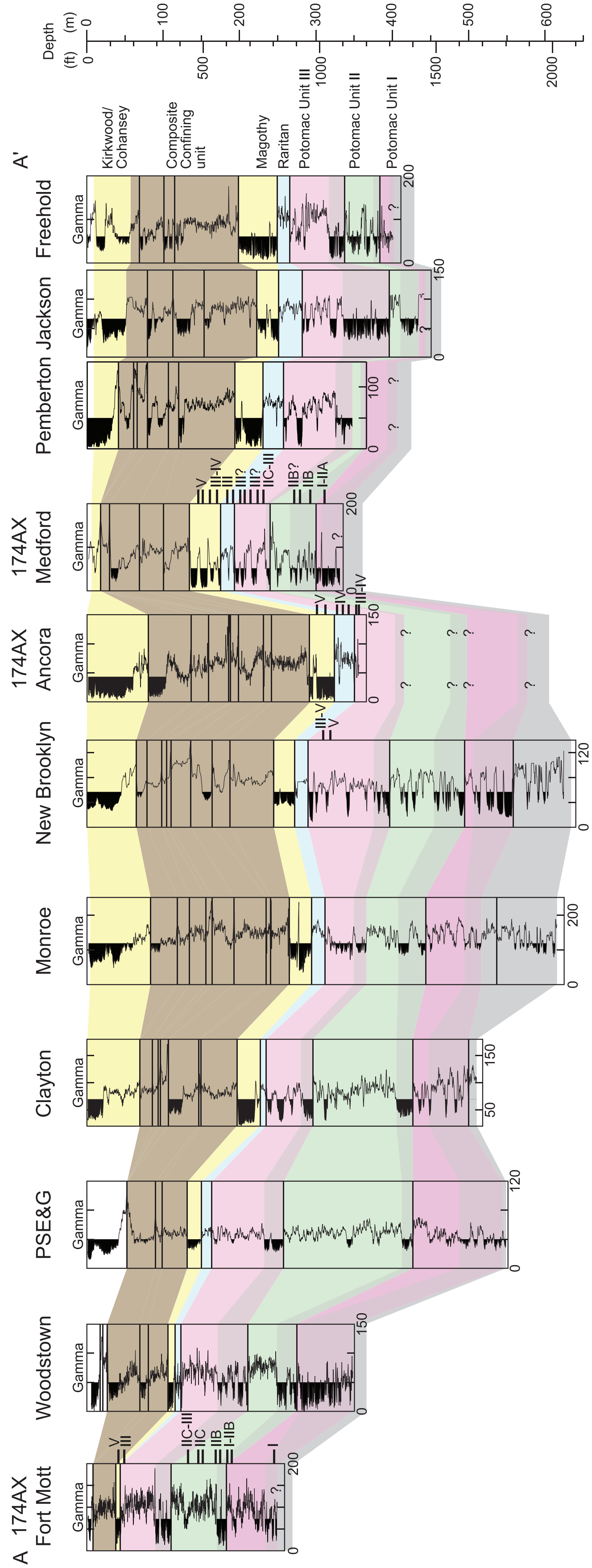

FIG. 6.—Gamma-log strike correlation A–A′ (Fig. 3) from Fort Mott to Freehold, New Jersey. Low gamma-log values are shaded. Modified after Sugarman et al. (2011).

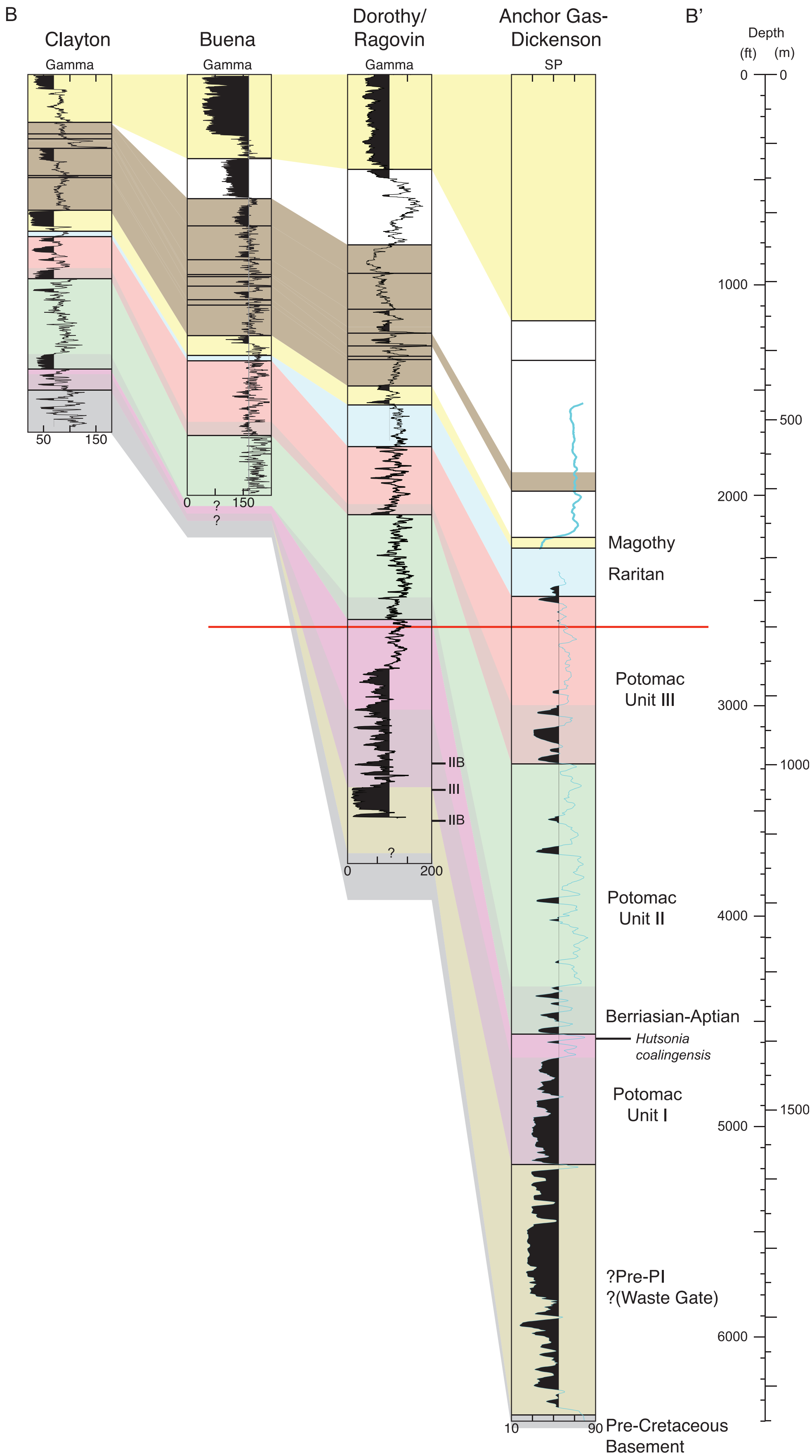

FIG. 7.—Well-log cross section B–B′, modified after Sugarman et al. (2011). Thick red line shows 800 m depth of supercritical storage. SP, spontaneous potential. Low log values are shaded

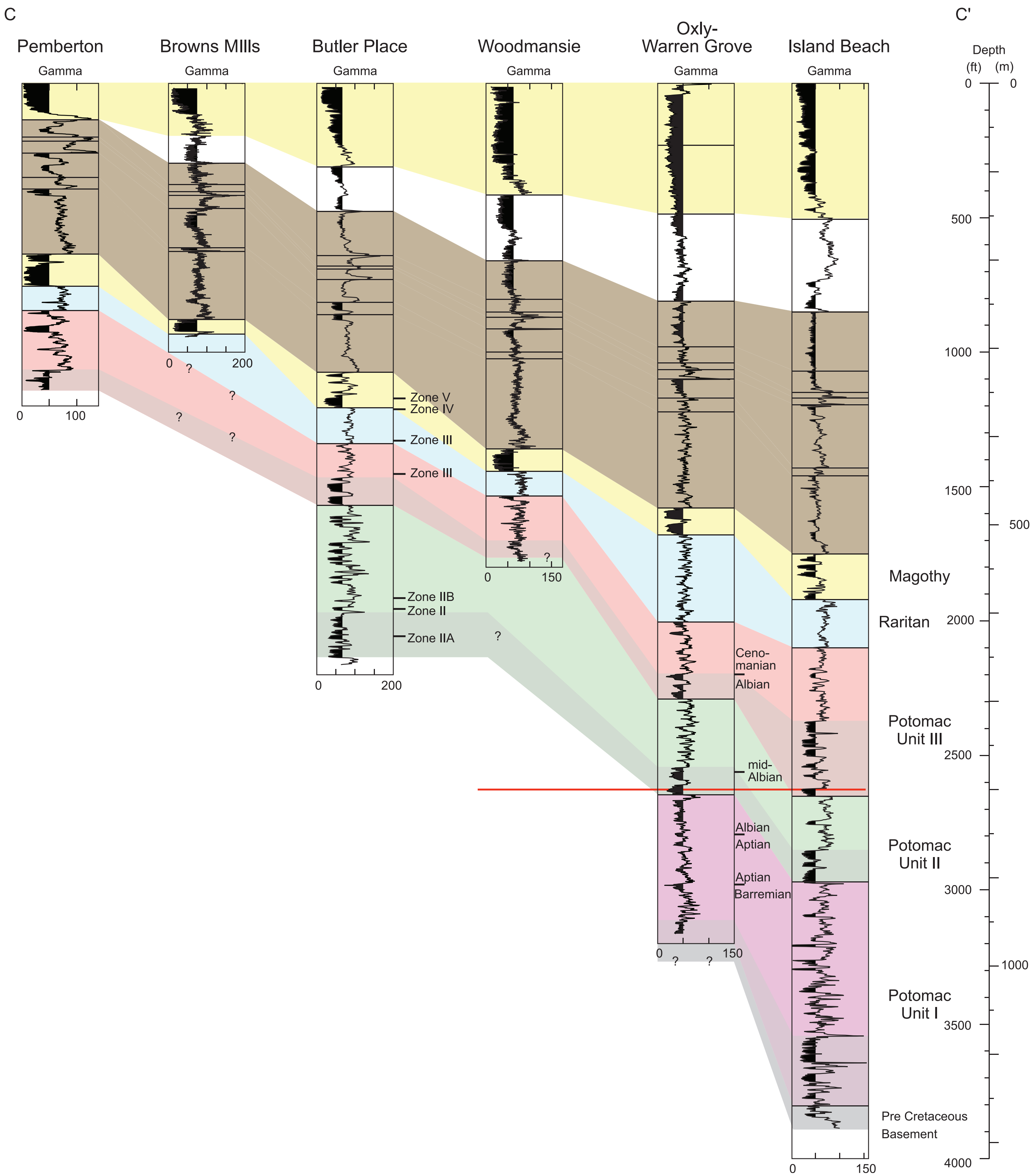

FIG. 8.—Well-log cross section C–C′, modified after Sugarman et al. (2011). Thick red line shows 800 m depth of supercritical storage. SP, spontaneous potential.

Gate Formation at this AD#1, NJ well (Fig. 7) are loosely constrained; Brown et al. (1972) assigned the top of Potomac I sands at the AD#1 well to Berriasian–Aptian, and the underlying Waste Gate Formation may be as old as uppermost Jurassic (Olsson et al. 1988).

Potomac Units I to III are ?Barremian to early Cenomanian (Fig. 4). Unit I was assigned to pollen Zone I and correlated to the Aptian (Hochuli et al. 2006), though it may extend to the Barremian (Doyle and Robbins 1977), with an age of ~ 111–126 Ma (Gradstein et al. 2012). Global

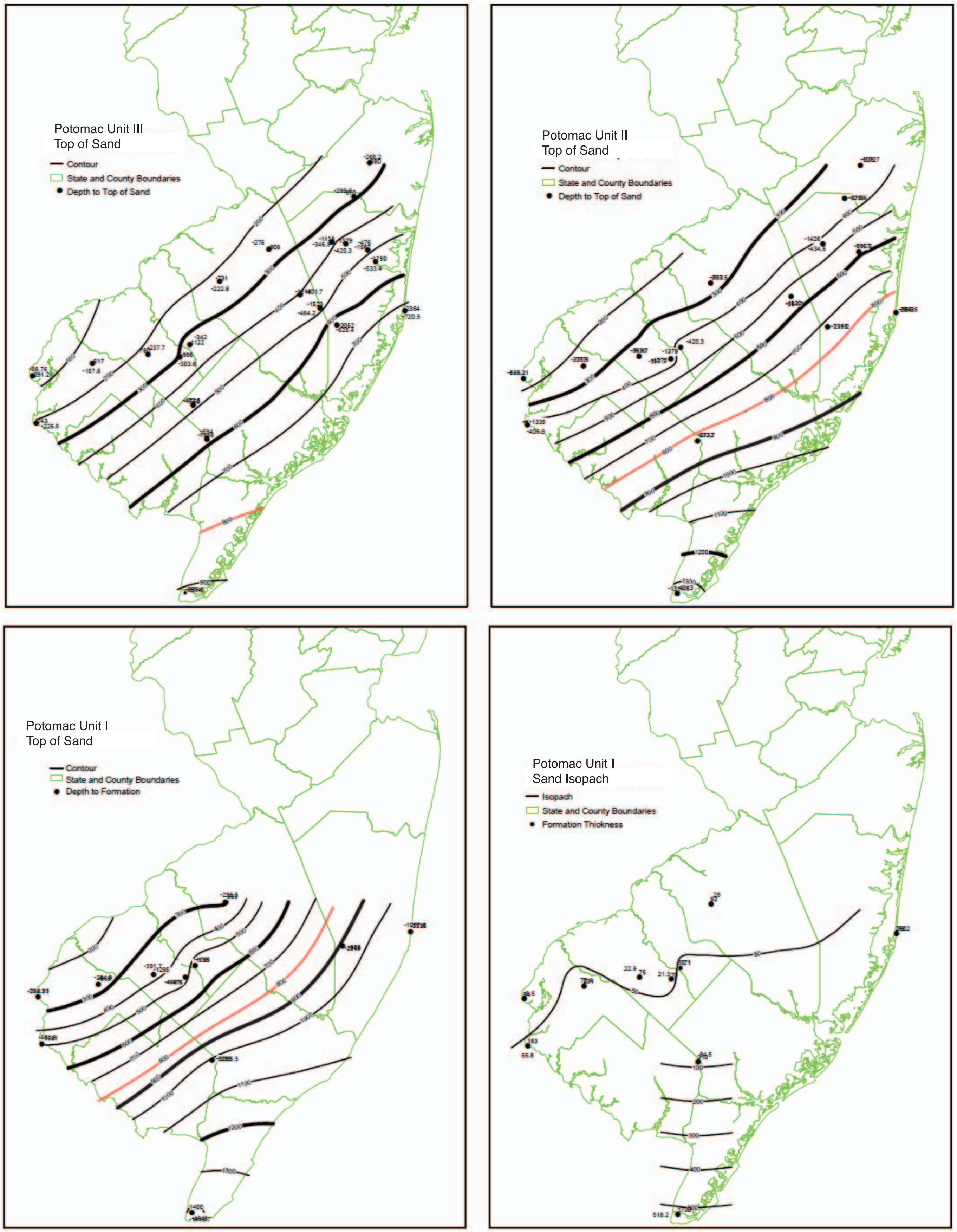

FIG. 9.—Structural contour maps to the top of the Potomac Unit I, II, and III sands and the isopach of the Potomac Unit I sands. Thick red line shows 800 m depth of supercritical storage. Modified after Sugarman et al. (2011).

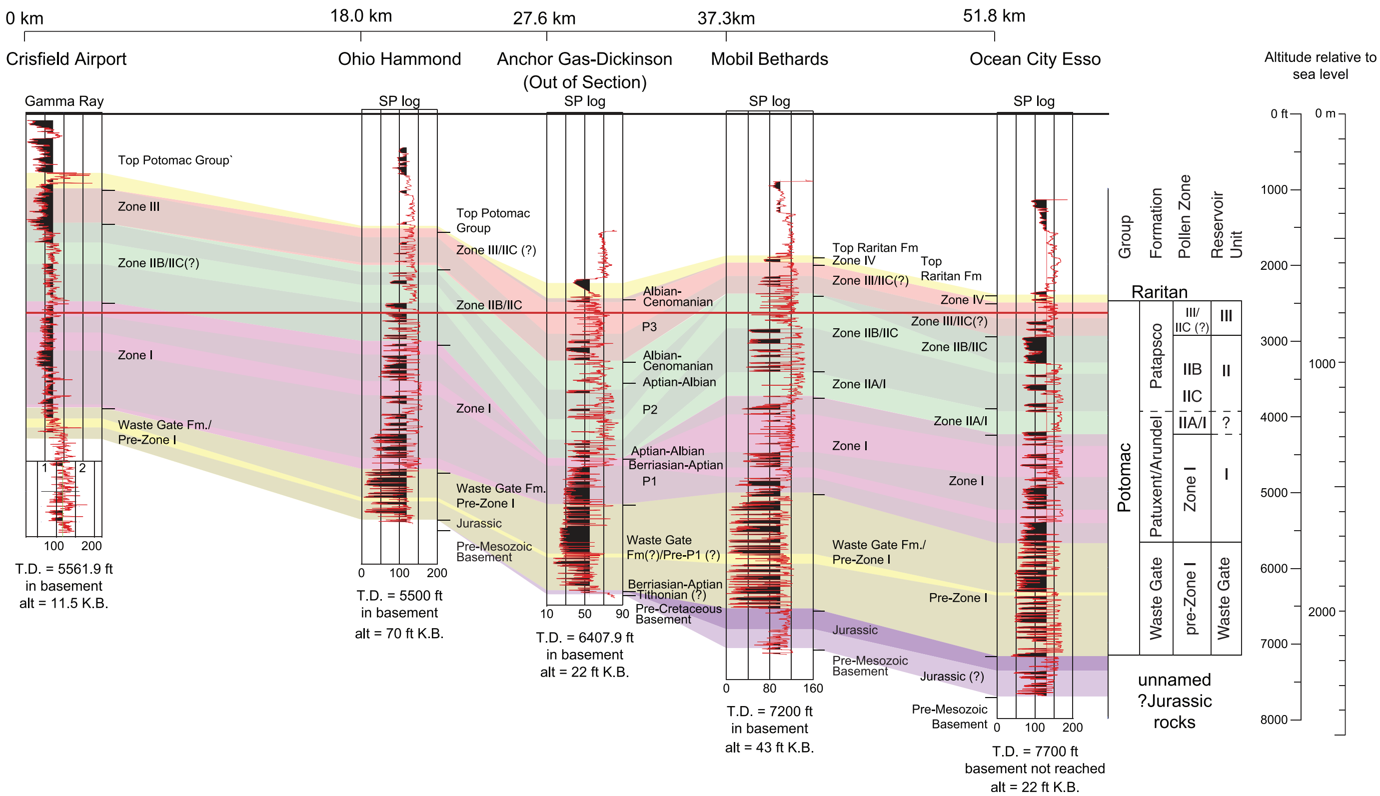

FIG. 10.—Simplified well-log correlation of AD#1 (AD) Cape May with Maryland. AD#1 was projected along basement contours of Benson (1984). See supplemental Figure 1 for full version including pollen zones, other available logs, and the updip Cambridge, Dorchester well. Thick red line shows 800 m depth of supercritical storage.

correlations of this unit are limited, although it appears to correlate with the Mississauga Formation sands found beneath the present-day continental shelf (Monteverde et al. 2011). We tentatively show an inferred hiatus for the much of the Barremian based on the Waste Gate extending into the early Barremian and the interpretation that Zone I may extend into the Barremian but is primarily Aptian. Unit II is assigned to pollen Zone II and correlated to the middle to late Albian to the earliest Cenomanian (Doyle and Robbins 1977; Hochuli et al. 2006), with an age of $\sim$ 100–111 Ma (Gradstein et al. 2012). Potomac Units I and II are not represented updip in New Jersey due to erosion (Owens et al. 1998), but they are represented downdip in the subsurface (Fig. 4). In Delaware, well-log correlations (Benson 2006; McLaughlin, written communication, 2017) indicate that Unit I thins and disappears in an updip direction, with Unit II lying on basement in the most updip areas; in Maryland Unit I lies on basement updip. Unit III is assigned to pollen Zone III and correlated to the early Cenomanian (Doyle and Robbins 1977; Hochuli et al. 2006) with an age of $\sim$ 98–100 Ma (Gradstein et al. 2012). In the Ancora, New Jersey, core, the Potomac Formation is unconformably overlain by the Bass River Formation, assigned to lower Cenomanian nannofossil Zone CC9 (Miller et al. 2004), indicating that the Potomac Formation barely extends into the earliest Late Cretaceous. Potomac Unit III appears to correlate with the offshore Logan Canyon sands, another potential CO_2 sequestration target (Monteverde et al. 2011; Lombardi et al. 2015).

Sequence Stratigraphy of Cores

Continuous cores at three updip sites (Fig. 5; Fort Mott, Medford, New Jersey, and Summit Marina Delaware) provide insight into sequence stratigraphy, sediment architecture, and facies stacking patterns of the Potomac and verify that Units I to III are distinct and correlatable sequences (Fig. 5). Data from the Fort Mott core provide the most complete stratigraphic record, because Unit I was not sampled at Summit Marina and is largely coarse sands lacking pollen at Medford. In the Fort Mott core, Potomac Unit II and Unit III have medium sands at their bases, overlain by thick silty clay confining beds (Fig. 5). These sand bodies can be correlated among the three sites (Fig. 5), as well as across New Jersey from Fort Mott to Freehold using well-log correlations (Figs. 3, 6), though it is likely that individual beds are discontinuous. Based on the widespread continuity of the units, Sugarman et al. (2005b, 2010) suggested that Potomac Units II and III (and possibly Unit I) are regionally significant depositional sequences.

Coring at the three updip sites (Fig. 5) has also shed light on the depositional environments of the Potomac Formation (Browning et al. 2008). Early studies noted that the Potomac was deposited in fluvial (Glaser 1969) and fluvial–deltaic (Owens and Gohn 1985) environments in a warm subtropical climate with intense weathering (Wolfe and Upchurch 1987) and abundant sediment supply from the Appalachian Mountains. The Potomac has generally been assigned to delta-plain environments in New Jersey (Owens and Gohn 1985; Owens et al. 1998) that are divided into two distinct subenvironments: the upper delta plain (deposited above higher high tide, containing fresh-water deposits and distinguished by greater soil development) and the lower delta plain (affected by fluvial and/or tidal processes, containing brackish-water deposits). Studies of the updip cores suggest deposition on the upper delta plain for the upper silty clays and lower delta plain and perhaps delta front for the sands. The exception is the Potomac I at Medford, which is interpreted as braided-river deposits (Sugarman et al. 2010).

Most of the silty clay facies of the Potomac have been interpreted as being deposited in an anastomosing river system on a low-gradient upper delta plain (Sugarman et al. 2005b; Browning et al. 2008). Anastomosing river systems (e.g., the modern Orinoco) have bars separating channels similar to braided systems, but differ because channel and bar stability prevents the river from reworking organic-rich sediments. As such, anastomosing systems are dominated by silty clay floodplain deposits with common soils and organic-rich sediments (Makaske 2001). Studies of the paleosols in the three updip cores show that they consist of: 1) weakly developed, immature soils formed under poor drainage conditions; 2) moderately developed soils formed under alternating wet/dry conditions; and 3) well-developed, mature soils formed under well-drained conditions (Thornburg 2016).

An analysis of FAC stacking patterns reveals sequence boundaries and systems tracts (Fig. 5) at three updip sites using the methodology proposed by Atchley et al. (2004, 2013) and Thornburg (2016). Sequence boundaries, MFSs, and inferred systems tracts are revealed by the stacking pattern of FACs. Our analysis strongly suggests that the Potomac II and III are distinct depositional sequences (Fig. 3) and the identification of unit boundaries as sequence boundaries. Firmly establishing that these lithologic and pollen units are sequences provides greater confidence in the regional correlations. In addition, we provide evidence for higher-order sequences within the major units. For example, candidate sequence boundaries occur within Units III and II at all three sites (dashed red lines, Fig. 5), suggesting that they are associated with regional base-level lowerings.

For example, at Fort Mott, there are 9 FACs above the base of Unit III (363.6 ft, 110.8 m) that thicken upsection, with most capped by thin, weakly developed paleosols. Above this level, (281.5 ft; 85.8 m) there are 6 FACs that begin to generally thin upsection. This shift in stacking pattern is interpreted as a MFS. The 6 thinning-upward FACs are capped with paleosols of increasing maturity and drainage, with an abrupt shift (223.8 ft, 68.2 m) to thickening upward with decreased paleosol maturity and drainage. This shift in stacking pattern is interpreted as a higher-order sequence boundary (223.8 ft, 68.2 m) within Unit III (Fig. 5).

Well-Log Cross Sections

New Jersey Potomac Unit III.—In the updip Summit Marina and Fort Mott coreholes, Potomac Unit III has a distinct lower fluvial–deltaic sand subunit and an upper paleosol clay subunit (Fig. 5). This pattern appears to typify sequences in the nonmarine sections of the coastal plain. The lower sands show a progressive thickening of FACs upsection, interpreted as the transgressive-systems tract equivalent (Thornburg 2016). The contact between the sands and the overlying paleosol clays is interpreted as the maximum-flooding surface equivalent (MFSe), and the paleosols are interpreted as the highstand systems tract equivalent (HSTe; Thornburg 2016).

Our updip well-log cross section shows the continuity of the Unit III sand-prone interval (Fig. 6). The lower sand–upper clay pattern can be traced through Salem, Gloucester, and Camden counties (Fig. 6); north of this, the upper clay subunit becomes locally sandy in its upper part (e.g., at Medford; Figs. 5, 6). Along strike (Fig. 5), the Unit III lower sands thicken to over 60 m and then thin to $\sim$ 15 m on the South Jersey High, and can be traced from northern Delaware to Monmouth County, New Jersey. The continuity of the sand subunit over such a wide region documents that this is an extensive sand body ($>$ 100 km scale); such sand bodies typically develop in delta-front environments, though firm evidence for marine deposition is lacking. The sand zones in the lower Potomac Unit III sequence are laterally continuous across long distances; however, individual sands may be local in extent (Benson 2006). Stacking patterns of logs tied to core lithology show that the Unit III sands consist of three coarsening-upward parasequences at Summit Marina (Fig. 5); the basal parasequence above the basal Unit III sequence boundary at Fort Mott (363.6 ft, 110.83 m; Fig. 5) also coarsens up. Such log parasequences are typical of classic river or wave-dominated deltaic stacking (Van Wagoner et al. 1990), in which the sands thicken upward, percent sands increases upward, and there are sharp upper contacts with abrupt shifts to finer-grained facies at flooding surfaces (parasequence boundaries).

The fact that the Unit III sand–clay package is a sequence provides confidence in its integrity as a reservoir and its confinement by the HSTe clays. Tracing Potomac Unit III sands downdip (Figs. 7, 8) shows that they thicken to over 75 m at the AD#1 well. Though the sands attain similar thickness at Island Beach (Fig. 8), they attain burial depths greater than 800 m only in the southern portion of Cape May County (Fig. 8, 9). Thus, Unit III is potentially suitable for carbon storage only in the Cape May Peninsula (Fig. 9).

New Jersey Potomac Unit II.—The Albian to lowermost Cenomanian Potomac Unit II has been mapped throughout the New Jersey Coastal Plain (Sugarman et al. 2011). The lower sand–upper clay pattern is well represented at the Fort Mott corehole (Fig. 5). Sugarman et al. (2005b, 2011) noted that placement of the lower sequence boundary at this site was uncertain, either at the base of sands at 182.9 m or 196.3 m (Fig. 5). Analysis of FACs suggests that the sequence boundary is at the base of the lower sands at 196.3 m (Fig. 5). The upper part of the Potomac Unit II sands were recovered at Summit Marina, but the base of the sands was not penetrated. In the updip strike section (Fig. 6), the Potomac II sands appear continuous in our study area, although the geophysical well-log character varies from one distinct blocky sand body (e.g., with a boxcar shape as at Clayton, New Jersey; Fig. 6) to numerous sand bodies at other sites (Fig. 6). At the ODP Leg 174AX Medford site, core and log data show at least six to seven sand bodies in the Potomac Unit II sequence; the upper clays are thinner and interrupted by sands (Fig. 5). This variability is attributable to deposition of the Potomac II sands and clays in a fluvial, anastomosing-river environment.

The Potomac II sands thicken and thin downdip. On Section C–C′ (Fig. 7), the basal Potomac II sands thicken downdip from Clayton (23 m) to AD#1 well (84 m). There is one distinct blocky sand with a boxcar log pattern at Clayton, but the basal sands at downdip AD#1 are separated by three clay units (Fig. 7). On dip section C–C′ from Browns Mills to Island Beach (Fig. 8), Unit II sands are 58 m thick at Butler Place (but too shallow for carbon storage) and thin at Oxley (33 m), where they are interrupted by one clay, and Island Beach (35 m), where they are interrupted by two clays.

Though the stacking pattern of FACs indicates that the Potomac II is a distinct sequence, there is a higher-order sequence within it at all three coreholes (Fig. 5). The Potomac II sequence appears to have thick confining beds above it both updip along strike and downdip. However, compared to the Potomac III and Potomac I, the sands appear to be thinner, more discontinuous, and less suitable for carbon storage.

New Jersey Potomac Unit I and Waste Gate.—Thick, confined Potomac Unit I and Waste Gate sands provide reservoirs in the New Jersey Coastal Plain. In updip wells, the Potomac I exhibits considerable lateral variability. At Fort Mott, Potomac I consists of the usual package of a lower fluvial sand subunit, with interbedded clays deposited in paleosols on floodplains and swamps (Fig. 5), and an upper subunit consisting of predominantly thick clays deposited as paleosols. At Medford, Unit I has a blocky gamma-log pattern and consists of thick, pebbly coarse sands with interbedded light gray coarse–medium sands with dark laminae and gravelly sands interpreted as braided-river deposits. The variability continues along strike, with similar blocky gamma-log patterns at New Brooklyn and Woodstown (Fig. 5). In contrast, the Monroe, Clayton, and PSE&G wells have lower gamma-log values in the lower subunit, indicating less sand. Again, this variability suggests multiple fluvial sources with both braided and anastomosing river systems, and suggests that fine-scale continuity may be in question.

Like the overlying units, Potomac Unit I generally thickens downdip, but there are only four deep ($>$ 800 m) downdip wells in New Jersey, so constraints on its age and paleoenvironment are limited. At Island Beach, Unit I sands are 79 m thick and buried by more than 1 km of sediment; on gamma logs they consist of several blocky sands separated by thinner clays (Fig. 8). They appear to be a suitable target for carbon storage. However, the Unit I sand thins and becomes finer grained ~ 11.5 km updip at the Warren Grove/Oxly well (Fig. 8). At the AD#1 well, the Unit I sands are 125 m thick and appear to be continuous with the Waste Gate Formation sands (Fig. 7).

The Waste Gate-Unit I sands comprise a reservoir that is nearly 500 m thick in the downdip sections in New Jersey (AD#1) and Maryland (Ocean City). The Unit I-Waste Gate at AD#1 has 8–12 thick blocky log units separated by comparatively thin mud units (Fig. 7). Updip, differentiation of Unit II, Unit I, and the Waste Gate Formation is difficult at the Dorothy/Ragovin well (Fig. 7) because of contradictory pollen data. Pollen data suggest an anomalously thick Potomac Unit II, but these data are likely compromised by cavings (Sugarman et al. 2011) and the correlations shown (Fig. 7) are based on log interpretations. There is a blocky sand at the base of the Dorothy/Ragovin well that appears, based on the finding of similar signature downdip, to be the Waste Gate; the overlying Potomac Unit I section from 883 to 1036 m at Dorothy/Ragovin appears to be sandy overall and potentially suitable for carbon storage (Fig. 7). Though the blocky sand zones of Unit I and the Waste Gate Formation appear in similar positions in widely spaced wells, individual sand beds are likely discontinuous as observed in updip studies (Benson 2006). At all four downdip holes, the reservoir sands are confined by the thick Unit I clays and overlying confining units.

With the possible exception of the AD#1 well (Olsson et al. 1988), the Waste Gate Formation had not been previously identified in New Jersey. We note that blocky sands, tentatively identified as Waste Gate Formation, in the Dorothy/Ragovin well are separated from the Potomac Unit I at AD#1 by a thin (6 m) clay. From a reservoir point of view, we lump Potomac Unit I and the Waste Gate Formation in our volume calculations (see Discussion, Carbon Storage Potential volumetric estimates).

Correlations to Maryland Well-Log Cross Sections

We display four deep (> 1.5 km) downhole logs in Maryland (Crisfield Airport, Ohio Hammond, Mobile Bethards, and Ocean City Esso) and correlate them to the AD #1 well in Cape May, New Jersey (Fig. 10). We also include the updip Cambridge, Maryland, well and details of pollen biostratigraphy (see Supplemental Material, Fig. 1). The regional "jump" of correlation to New Jersey by projecting AD#1 along pre-Mesozoic basement contours (Benson 1984) (Fig. 1) is supported by pollen zonation in the Maryland and New Jersey wells.

The total thickness of Potomac Unit III in Maryland ranges from ~ 125 m at Mobile Bethards to ~ 195 m at Cambridge (Fig. 10; Table 2). However, total sand content in the unit ranges significantly from ~ 15 to 139 m thick (~ 50 m average thickness); in contrast, at the along-strike AD#1 well in New Jersey, total sand thickness is ~ 70 m. Sand percentages range from ~ 12% of the total unit thickness at Mobile Bethards to 100% at Crisfield Airport in Maryland, and ~ 27% at AD#1 in New Jersey.

In the Potomac Unit III, sand layers are confined by an upper Unit III clayey zone (confining bed) that increases in thickness somewhat downdip from ~ 35 m at Ohio Hammond, ~ 55 m at Mobile Bethards, and ~ 60 m at Ocean City Esso (Fig. 10; Table 2). Updip, the upper confining bed is absent updip of Crisfield Airport (supplemental Fig. 1), where sands of Unit III are in direct contact with sands of the overlying Magothy Formation. Confining beds reappear in Unit III farther updip at Cambridge, with a thickness of ~ 45–105 m; the range in confining-bed thickness is attributed to discrepancies between geophysical-log and lithologic-log clay content. The confining bed is much thicker at AD#1 (~ 140 m) than at Mobile Bethards (~ 55 m). Potomac Unit III is also confined by overlying Cretaceous to Paleogene muds–mudstones in New Jersey (composite confining unit; CCU) (Zapecza 1989) and Eocene–Late Cretaceous silts

TABLE 1.—*Thickness (in meters) of the sand units in New Jersey (modified from Sugarman et al. 2011).*

	Section A–A'											Section B–B'				Section C–C'					
Depth to Unit in meters	Fort Mott 174AX	Woodstown	PSEG	Clayton	Monroe	New Brooklyn	Ancora 174AX	Medford	Pemberton	Jackson	Freehold	Anchor Dickinson	Dorothy/ Ragovin	Buena	Clayton	Pemberton	Browns Mills	Butler Place	Woodmansie	Warren Grove/Oxly	Island Beach
Base of composite confining unit	41	106	132	197	265	244	292	134	194	223	199	671	451	378	197	194	268	328	415	482	533
Base Magothy	44	116	150	227	294	272	324	175	230	251	249	686	479	407	227	230	285	368	440	512	585
base Raritan		123	163	235	312	290	350	190	257	282	266	756	538	415	235	257	x	408	468	611	640
Top PIII (top sand)	90	171	233	280	349	376	x	235	325	335	317	913	628	503	280	325	x	447	520	670	724
Base PIII (base sand)	111	211	258	296	366	397	x	240	x	396	338	998	639	523	296	x	x	479	x	698	808
Top PII (top sand)	170	249	413	405	433	454	x	265	x	410	376	1321	860	x	405	x	x	600	x	776	870
Base PII (base sand)	183	275	428	427	443	495	x	300	x	434	387	1390	1067	x	427	x	x	x	x	807	907
Top PI (top sand)	234	279	488	448	511	572	x	307	x	x	x	1423	1091	x	434	x	x	x	x	949	1081
Top Pre-PI (Waste Gate)							x					1579	x	x	x	x	x	x	x	x	x
Base PI (basement)	?253	349	544	457	536	592	x	x	x	x	x	1942	1100	x	457	x	x	x	x	x	1160
Bottom of log	250	349	549	512	616	634	357	332	347	440	402	1951	1132	610	511	347	287	658	543	964	1204
Elevation (m)	1.2	12.2	3.0	42.7	45.1	33.8	31.7	11.9	46.9	39.3	48.8	6.7	27.7	30.5	42.7	46.9	31.7	45.7	55.5	40.8	1.5

x = unit below total depth of hole

TABLE 2.—*Thickness and number of sands in the Potomac and Waste Gate units in Maryland.*

	Reservoir Units															
	Unit III				Unit II				Unit I				Waste Gate			
Well	Total Unit Thickness (m)	# of Sand Layers	Total Sand Thickness (m)	Sand %	Total Unit Thickness (m)	# of Sand Layers	Total Sand Thickness (m)	Sand %	Total Unit Thickness (m)	# of Sand Layers	Total Sand Thickness (m)	Sand %	Total Unit Thickness (m)	# of Sand Layers	Total Sand Thickness (m)	Sand %
Cambridge[1]	195	8	52 (148)	27 (76)	171	7	36 (110)	21 (64)	283	10	88 (132)	31 (47)	0	–	–	–
Crisfield Airport	139	1	139	100	312	8	100	32	429	13	137	32	94	6	81	86
Ohio Hammond	149	6	20	14	305	11	85	28	515	21	223	43	204	12	168	82
AD#1	251	13	69	27	390	13	67	17	186	9	125	67	363	14	287	79
Mobile Bethards	125	3	15	12	411	14	84	20	387	16	135	35	466	25	282	61
Ocean City Esso	134	4	26	19	396	7	166	42	439	16	216	49	451	29	288	64
Average total sand thickness in MD, m			50				94				160				204	

[1] Numbers in parentheses are based on lithologic descriptions of drill cuttings described primarily as sand (Trapp et al. 1984).

and clays in Maryland (Andreasen et al. 2013). The overlying CCU is much thicker in New Jersey (~ 500 m thick) than in Maryland (~ 225 m thick). The thick CCU in New Jersey also provides stratigraphic continuity and integrity as a seal updip. This is less true in Maryland, where the fine-grained Paleogene section is much thinner than in New Jersey (and thins updip) and the Miocene sands are thicker (see supplemental Fig. 1 illustrating this at the updip Cambridge well).

The total thickness of Potomac Unit II in Maryland ranges from ~ 171 m at Cambridge to ~ 411 m at Mobile Bethards (Fig. 10; Table 2). Total sand thickness within the unit ranges from ~ 36 to 166 m (~ 94 m average thickness); at the along-strike AD#1 well in New Jersey, total sand thickness is ~ 67 m. Sand percentages range from ~ 20% of the total unit thickness at Mobile Bethards to ~ 42% at Ocean City Esso in Maryland, and ~ 17% at AD#1 in New Jersey.

Potomac Unit II sands show considerable variability, and there are ambiguities in their precise correlation. At AD#1 in New Jersey, lower Potomac Unit II sands occur as five to six thin sand bodies separated by thin clays from 1310 to 1390 m and are underlain by clays assigned to pollen Zone I. At Mobile Bethards in Maryland, the Unit II sands consist of seven bodies separated by thin clays from 875 to 1050 m and are underlain by thick (~ 90 m) clays, assigned to pollen Zone II–I (Hansen and Doyle 1982), that are part of the Arundel Clay confining unit (Andreasen et al. 2013). Downdip at Ocean City Esso, there are sand bodies throughout Unit II; three to four thin sand bodies are present from 1060 to 1200 m in the lower part of Unit II and a thick, blocky sand occurs in the upper part (900–1000 m). There are three possible correlations of Potomac Unit II from New Jersey to Maryland:

1. Pollen Zone I–II clays in Maryland below the lower Unit II sands are, in fact, Zone II and these clays pinchout or transition into sandy facies in New Jersey; this is the interpretation presented based on current data (Fig. 10).
2. The lower Unit II sands in New Jersey pinch out or transition into clayey facies into Maryland and the sands in Maryland are younger than in New Jersey.
3. The clays below the lower Unit II sands in Maryland are actually Zone I and thus older than Unit II; further pollen studies are needed to test this hypothesis.

Though any of the sand bodies in Unit II could have carbon-storage potential, they are generally thin (< 25 m), except for the thick (100 m), blocky upper Potomac Unit II sand at Ocean City Esso in Maryland. The number of sand bodies seems to vary, and as in the updip studies in Delaware (see below), it appears that these sands are not continuous, but discontinuous and blebby. The Unit II sands at both Bethards and Ocean City approach the updip depth limit for supercritical storage (875 and 900 m for their tops, respectively).

The uppermost confining bed in Unit II varies in thickness from ~ 33 m at Ohio Hammond to ~ 140 m at Mobile Bethards (Fig. 10; Table 2). The confining unit is absent at Ocean City Esso, where upper sands of Unit II are overlain by ~ 20 m of clay at the base of Unit III. At Crisfield Airport, the uppermost confining bed is also absent and sands of Units II and III are in direct contact. Updip at Cambridge, ~ 30 m of clay confines Unit II sands. Approximately 116 m of clay confines the sands in Unit II at AD#1.

The total thickness of Potomac Unit I in Maryland ranges from ~ 283 m at Cambridge to ~ 515 m at Ohio Hammond (Fig. 10; Table 2). Total sand content within the unit ranges from ~ 88 to 223 m thick (~ 160 m average thickness); at the along-strike AD#1 well in New Jersey, total sand thickness is ~ 125 m. Sand percentages range from ~ 31% of the total unit thickness at Cambridge to ~ 49% at Ocean City Esso in Maryland, and ~ 67% at AD#1 in New Jersey. The Unit I sands at AD#1 are blocky and have only thin (< 7 m) interbedded clay layers; in contrast, Mobile Bethards and Ocean City Esso have more numerous, thicker (up to 15 m) interbedded clay layers.

Potomac Unit I sands are confined at the top by clayey zones at the base of Unit II at Mobile Bethards (~ 98-m-thick clayey zone) and Ocean City Esso (~ 80-m-thick clayey zone) (Fig. 10; Table 2). Those clayey zones were previously mapped as the Arundel Clay confining unit (Andreasen et al. 2013), which, as defined in that study, may include overlying clay of the Patapsco Formation as well as clay of the underlying Patuxent Formation. Pollen data suggest that part of the clay layer at the base of Unit II may be younger (Zone II) than the Arundel Formation (Zone I) (Hansen and Doyle 1982). Below the uppermost sands at Mobile Bethards and Ocean City Esso are relatively thick clayey zones (~ 150 m and ~ 82 m, respectively) that confine deeper Unit I sands. Updip, at Ohio Hammond, Crisfield Airport, and Cambridge, Unit I is confined at the top by ~ 44 m, ~ 64 m, and ~ 88 m, respectively, of Unit I clays (Arundel Clay confining unit) (Trapp et al. 1984; Andreasen et al. 2013). In contrast to Mobile Bethards, the upper confining unit at AD#1 is ~ 30 m thick. Potomac Unit I sands can be traced updip to Cambridge, where they are confined by Unit I clays that are over 100 m thick (supplemental Fig. 1). The continuity of the confining beds on the Potomac I in Maryland is less certain updip of Cambridge, and further studies are warranted.

The total thickness of the Waste Gate Unit in Maryland ranges from ~ 94 m at Crisfield Airport to ~ 466 m at Mobile Bethards (Fig. 10; Table

2). Total sand thickness in the unit ranges from ~ 81 to 288 m (~ 204 m average thickness); at the along-strike AD#1 well in New Jersey, total sand thickness is ~ 287 m. Sand percentages range from ~ 61% of the total unit thickness at Mobile Bethards to ~ 86% at Crisfield Airport in Maryland, and ~ 79% at AD#1 in New Jersey.

The Waste Gate sands pinch out updip between Crisfield Airport and Cambridge (supplemental Fig. 1). The Waste Gate Unit sands appear to be hydraulically continuous with Potomac Unit I sands at most downdip sites in Maryland and along strike at AD#1. Thus, although the Waste Gate pinches out updip, the sands of Unit I continue updip, and the Waste Gate reservoir may not be confined. The greatest separation between the units occurs at Ohio Hammond with a total of ~ 40 m of clay–shale.

The ?Jurassic sections below the Waste Gate Unit also contain sands. There is a thin (6 m) confining unit near the base of the Waste Gate Unit at AD#1 that overlies thin (15 m) ?Tithonian sands (Brown et al. 1972) on top of pre-Mesozoic basement rock. Further modern pollen studies are needed to verify the presence of Jurassic strata in the New Jersey Coastal Plain. There is a thick confining unit at the top of the ?Jurassic section at Mobile Bethards that overlies discontinuous ?Jurassic sands that total ~ 33 m in thickness. There is a 55-m-thick confining unit at the top of the ?Jurassic section at the Ocean City Esso well, but the underlying sands thicken slightly to ~ 50 m of total thickness over pre-Mesozoic metamorphic basement rock. The depth (> 1,900 m) and relative thinness of these sands makes them less desirable than the Waste Gate-Potomac Unit I sands.

Correlations to Delaware

The Potomac Formation has been sampled extensively in updip Delaware wells (Benson 2006; Thornburg 2016). Benson (2006) traced fairly extensive (10–15 km along strike) and continuous sands that appear to correlate with our Unit III sands. Correlation of the sands to New Jersey is supported by three pollen assignments to Zone III (Fig. 5); this unit is bracketed in Delaware by sequence boundaries as it in New Jersey (Fig. 5). Sands are concentrated in the lower part of the sequence with clays in the upper part as observed at Summit Marina and Fort Mott (Fig. 5). The systems-tract interpretation is TSTe, as they are in New Jersey (Fig. 5). In contrast, the sands assigned to pollen Zone II (and likely equivalent to our Potomac Unit II) are discontinuous in Delaware (Benson 2006), as they are discontinuous in New Jersey updip (Fig. 6) and downdip (Figs. 7, 8).

There are no deep (> 800 m) wells or coreholes in Delaware. However, a prediction of the suitability of deep sands and confining units in southern Delaware can be based on interpolating between the four deep holes in New Jersey (Figs. 1–3, 8) and the four deep holes in Maryland (Fig. 9). The Waste Gate-Potomac I, Unit II, and Unit III may be present at sufficient depths for carbon storage in the southern part of Delaware (e.g., seaward of the 800-m contour, Fig. 1).

DISCUSSION

Tectonostratigraphy and Regional Correlations

A seesaw pattern of thickening and thinning of strata occurred from the Late Jurassic to present, with thickening differentially shifting from the south to the north and back (Fig. 2). The Jurassic strata and Waste Gate Formation appear to follow basement, with greatest thickness in the Salisbury Embayment and thinning on the Norfolk Arch and South Jersey High (Fig. 2). Both Unit I and II generally thicken to the south from New Jersey to Maryland (Fig. 2), whereas Unit III thickens toward Cape May (Fig. 10). This pattern continues, with the overlying Raritan and Bass River formations (Zone IV; Fig. 2) thickening to the north and the overlying Magothy Formation thickening dramatically to Long Island (Fig. 2; see Perry et al. 1975; Brown et al. 1972). The rest of the Upper Cretaceous and Paleogene strata thicken north of Delaware, whereas the Miocene and younger thicken toward Maryland. This seesaw pattern has perplexed geologists for decades (Brown et al. 1972) and has been dubbed "rolling basins" (Owens et al. 1997). Though the changes may be partly due to sediment sources, such variations cannot explain large changes in accommodation. A likely mechanism explaining this pattern is changes in mantle dynamic topography (Moucha et al. 2008; Rowley et al. 2013).

Our analysis of updip sections, particularly those with continuous cores (Figs. 5, 6), inform our predictions for the stratigraphic continuity and paleoenvironmental interpretation for downdip sites where continuous cores are lacking. Updip, our studies show that the Unit III sand zones are laterally continuous, although individual sand beds may not be (Figs. 5, 6); similar continuity downdip leads us to suggest that these are laterally continuous sand zones deposited on a delta front (Figs. 7, 8, 10). The discontinuous sands of Unit II were deposited in anastomosing-river environments updip, as indicated by ground truth at Fort Mott, Medford, and Summit Marina (Fig. 5); they appear to be similar downdip. Finally, the blocky sands of Unit I updip also appear to be primarily braided deposits, as indicated by ground truth at Medford, where cores indicate braided deposits are associated with blocky sands.

Estimates of Potential Carbon-Storage Volume

Many studies have provided qualitative estimates (e.g., high/low) of porosity and permeability for the Potomac and, to a lesser extent, the Waste Gate Formation (e.g., Brown et al. 1972; Leahy and Martin 1993; Zapecza 1989) based on logs (mostly SP-Resistivity kick outs; summary of Hovorka et al. 2000). Quantitative porosity estimates were taken from previous hydrostratigraphic studies of the Waste Gate Formation in Maryland using graphical methods applied to the resistivity logs (Hansen and Doyle 1982). At the Hammond well, Waste Gate Formation sands–sandstones have porosities of 23–27%; at the Ocean City and Bethards wells, porosities were slightly lower (19–24%). We used a conservative porosity of 20% in our calculations for the Waste Gate-Potomac I reservoir. Permeabilities of the Waste Gate Formation were estimated based on pumping tests at the Crisfield well, where they ranged from 75 to 118 mD (Hansen and Doyle 1982). Though these baseline studies demonstrate good porosities and permeabilities, further studies of porosities on core material and permeabilities from laboratory and pumping tests are warranted.

We calculated the storage capacity of the Waste Gate-Potomac I target unit using the Capacity Calculator (Wickstrom et al. 2005), following procedures recommended by National Energy Technology Laboratory (DOE/NETL 2010). Following Wickstrom et al. (2005), the Capacity Calculator gives:

$$GCO_2 = A_t H_g \phi_t \rho_{CO2res} E_{saline} \tag{1}$$

Where GCO_2 is the mass of CO_2 storage resource, ρ_{CO2res} is the density of CO_2 under reservoir conditions, ϕ is formation total porosity, A_t is the total area of the formation, and H_g is the gross thickness of the prospective formation. E_{saline} is the storage efficiency factor which represents the percentage of the total formation fluid that will actually be displaced by CO_2. The calculation of ρ_{CO2res} requires the mean reservoir temperature and pressure, both a function of reservoir depth. The parameters and results are shown in Table 3. We considered the low (1%), intermediate (2.5%), and high (4%) values for E_{saline} reported in Appendix 1 of the Carbon Sequestration Atlas of the United States and Canada (DOE/NETL 2010). These values reflect the wide range of combinations of formation characteristics and their statistical distributions.

We estimate the storage capacity of the Waste Gate-Potomac I sand package with the following constraints. We estimated the mean thickness of each unit and multiplied it by the unit's areal extent to estimate volumes. The mean reservoir depths are ~ 1500 m (Figs. 8, 10; Tables 1, 2). This depth is used to determine the mean temperature, based on the reading at 1950 m depth (50.5°C) at the AD#1 site, giving a temperature of 40°C at 1500 m. This is consistent with the 23°C/km geothermal gradient at the

TABLE 3.—*Volume estimates for the combined Waste Gate-Potomac I in the Mid-Atlantic region for area seaward of red 800 m contour using the assumption of effective porosity value of 20% (Fig. 1).*

Reservoir Depth (m)	Reservoir Temperature (°F)	Reservoir Pressure		Reservoir Thickness (m)	Reservoir Area (sqkm)	CO_2 Mass Storage Capacity (Gt)		
		psi	entered in calculator			displace 1%	displace 2.5%	displace 4%
1524	100	2000	1600	213	6795388	8.4	21	33.5

Crisfield well (Hansen and Doyle 1982). Reservoir hydrostatic pressure is calculated from the pressure–depth relation of Schlumberger (2017); at 1500 m depth, it is roughly 13.8 Mpa. At this pressure, CO_2 is at its maximum density of 705 kg/m^3 and does not respond to further pressure increases. Finally, an effective porosity value of 20% is assumed as discussed above.

The resulting estimates for the storage potential of the Waste Gate-Potomac I target unit are 8.4, 21.0, and 33.5 Gt CO_2 for the three displacement values of 1, 2.5, and 4%, respectively (Table 3). We apportion this by area (Table 4) to the states of New Jersey (1.1, 2.9, and 4.6 Gt, respectively) and Maryland (2.5, 6.2, and 9.9 Gt, respectively). We note that estimates in these states are constrained by four deep wells in each state. Estimates for Delaware (1.5, 3.8, and 6.1 Gt) are unconstrained by data except by interpolation between New Jersey and Maryland, and Virginia (3.2, 8.1, and 12.9 Gt, respectively) is constrained by only one deep hole (Fig. 1). Nevertheless, despite uncertainties in porosity and areal distributions in Delaware and Virginia, it appears likely that the Waste Gate-Potomac I reservoirs may contain relatively high storage volumes for potential carbon storage.

Our volume estimates provide firmer constraints than previously available for storage in the Waste Gate-Potomac I target unit. Hovorka et al. (2000) reported on similar thickness of Waste Sands and Potomac sands that they lumped as Potomac Group, but they did not provide volume estimates. Volume estimates for this region done as part of a U.S. assessment (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team 2013) were lower (14 Gt) in part because of regional screening criteria; they also noted concerns with confinement (W.H. Craddock, written communication 2017). As noted above, we echo concerns about the updip confinement in Maryland, though the confinement in New Jersey appears more certain. Also, although our studies use the DOE/NETL method for volume estimates, recent studies have examined the complexities of storage in detail, and future work should include modeling efforts incorporating evaluation of the role of pressure and time effects on storage efficiency of brine reservoirs (Bachu 2015).

Carbon-Storage Potential in the Mid-Atlantic Coastal Plain

Our analysis indicates that there is potential for storage of large volumes of CO_2 (8.4 to 33.5 Gt CO_2) in the Waste Gate-Potomac I in the subsurface of the Mid-Atlantic Coastal Plain. The large volume potentially could provide sufficient storage space for multiple CO_2 point sources (power plants). For example, a 500-megawatt coal-fired power plant generates $\sim$ 3 billion kWh/yr of electricity and emits $\sim$ 3 Mt CO_2/yr (Koomey et al. 2010). Assuming a CO_2 capture rate of 90%, approximately 100 Mt of CO_2 storage would be stored over the estimated 40-year lifespan of a 500 MW coal-CCS power plant. Substituting natural gas for coal would reduce the storage requirement to about 55 Mt CO_2 storage, while substituting agricultural byproducts would increase the storage requirement to about 120 Mt CO_2 storage (U.S. Environmental Protection Agency (2014). Thus, the Waste Gate-Potomac I reservoir unit appears adequate to store CO_2 captured from 24–95 GW of natural gas generation for a century, or equivalently, to store an amount of CO_2 equal to 0.6–2.4 years of current U.S. emissions (U.S. Environmental Protection Agency 2014). Detailed studies are needed to confirm the porosity estimates used here, previously reported permeability estimates, and to test the ability to store large volumes of CO_2.

TABLE 4.—*Volume estimates apportioned by state for area seaward of red 800 m basement contour (Fig. 1).*

State	Reservoir Area (sqkm)	CO_2 Mass Storage Capacity (billion ton, Gt)		
		displace 1%	displace 2.5%	displace 4%
NJ	3750	1.1	2.9	4.6
DE	5000	1.5	3.8	6.1
MD	8125	2.5	6.2	9.9
VA	10625	3.2	8.1	12.9
Total	27500	8.4	21	33.5

Any location for carbon storage should ideally be located near large CO_2 point sources. We mapped point sources for CO_2 using data extracted from the Environmental Protection Agency's (EPA) FLIGHT Tool (U.S. Environmental Protection Agency, 2014). There are currently only two intermediate-size point sources that are sufficiently downdip of the line of supercritical storage, emitting between 0.1 and 1 Mt CO_2/yr: the BL England power plant in Beesley Point, New Jersey, and the Indian River power plant in Millsboro, Delaware (Fig. 11; Table 5). Both are power plants using old coal-fired or oil boilers. These plants could potentially be replaced with newer facilities using the Waste Gate-Potomac I sands for CO_2 storage. Millsboro, Delaware (Fig. 1) is along strike of the Hammond well (Fig. 10), where the Waste Gate-Potomac I sands are 427 m thick (Fig. 10) and would require no significant lateral piping of captured gas. The BL England site (Fig. 1) projects along strike to a position between the AD#1 and Dorothy/Ragovin wells (Fig. 7), with a projected Waste Gate-Potomac Unit I sand thickness of 350–400 m. While construction of new coal plants, with or without CCS, remains unlikely, natural gas with carbon capture and storage could be part of the solution as New Jersey seeks low-carbon replacements for the Oyster Creek nuclear plant, scheduled to close in 2019 (New Jersey Department of Environmental Protection 2010).

The CO_2 storage resource assessment of the Waste Gate-Potomac I reservoir unit presented in this paper is a broad, initial estimate based on limited, average borehole and well data. Detailed geologic and hydraulic studies are needed to better constrain porosity, sand volumes, and reservoir pressures and temperatures, as well as permeability, sand connectivity, and the competency of confining units and their efficacy as seals. As we have show here, the geological potential exists for carbon storage in the Mid-Atlantic Coastal Plain, and geologic and engineering studies are needed to further test the suitability of the Potomac-Waste Gate reservoirs for carbon storage. Stratigraphic test coreholes in Maryland (e.g., Ocean City) and, especially, New Jersey (e.g., Beesley Point) and Delaware (e.g., Millsboro) given their proximity to existing CO_2 point sources, could provide valuable geological and engineering information. It would also yield a wealth of geological information on the tectonics, sea level, and Earth history of the region (e.g., Miller et al. 2005) from its most expanded sections.

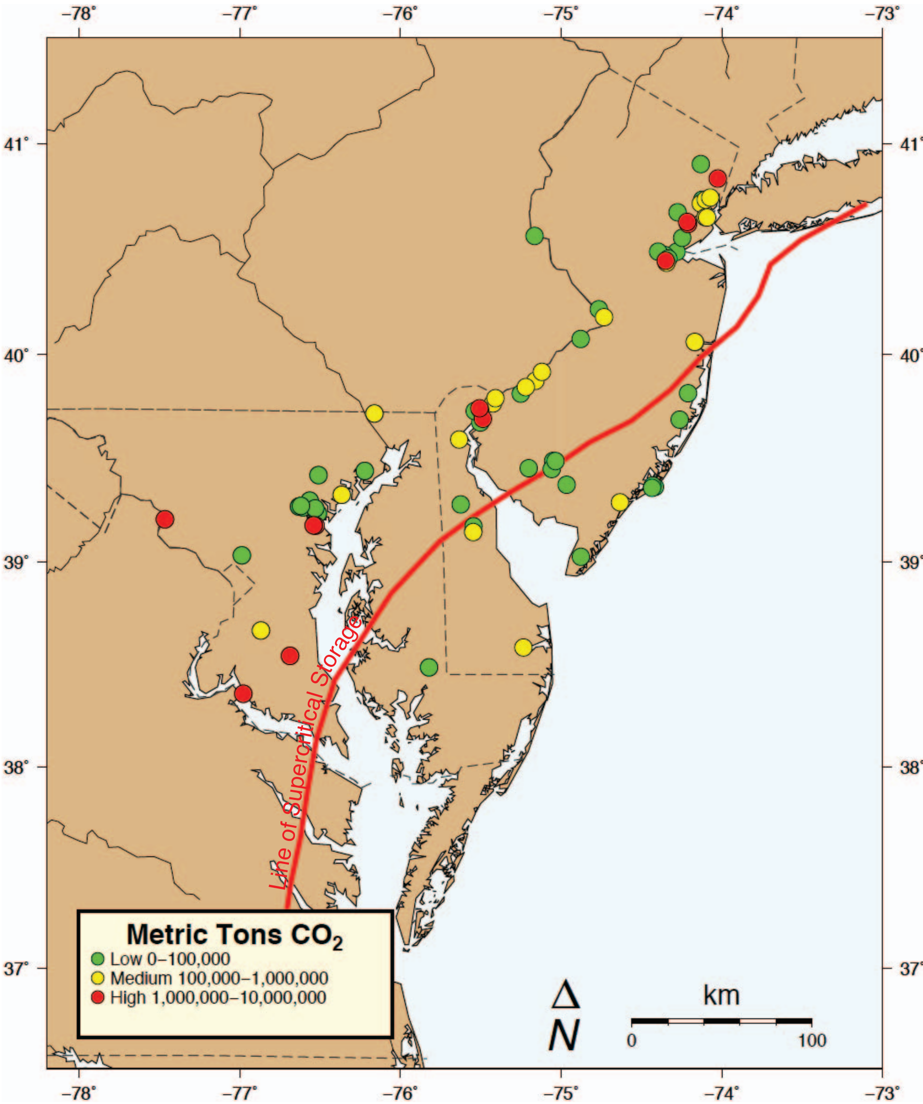

FIG. 11.—Map of point sources of CO_2 from data extracted from the Environmental Protection Agency's (EPA) FLIGHT Tool (http://ghgdata.epa.gov/ghgp). The data are reported to EPA by facilities as of 08/16/2015. All emissions data are presented in units of metric tons of CO_2. Red line is the 800-m structural contour; supercritical carbon sequestration in coastal-plain strata is possible only seaward of this contour.

TABLE 5.—*CO_2 point sources seaward of the 800 m basement contour (Fig. 1).*

Operator	Plant Type			2014 CO_2 Emissions (Metric Tons CO_2)
Vienna	Petroleum liquids			20800
Indian River	Petroleum liquids	Conventional steam coal		797333
McKee Run			Natural gas	22787
Van Sant			Natural gas	1614
NRG Energy Center Dover			Natural gas	104553
Middle Energy Center			Natural gas	2445
Cumberland Energy Center			Natural gas	62629
B L England		Coal	Natural gas	250366
Marina Thermal Facility			Natural gas	45146
Inlet District Energy Center			Natural gas	31170
Mid-Town Thermal Center		Data not available		47596
Sherman Avenue			Natural gas	21637
Howard M Down			Natural gas	39281
West Station	Petroleum liquids			2701
Cedar Energy Station			Natural gas	4945
Forked River			Natural gas	5323

CONCLUSIONS

Sequence stratigraphy integrated with lithostratigraphy, biostratigraphy, and paleoenvironmental reconstructions can be used to better predict the continuity of potential CO_2 storage targets and confining (clay–shale) units. We evaluate the Lower Cretaceous Waste Gate Formation and mid-Cretaceous Potomac Formation/Group in New Jersey and Maryland, which we divide into three major reservoirs (Waste Gate-Potomac Unit I, Potomac Unit II, and Potomac Unit III) based on regional log correlations, sequence stratigraphic stacking patterns, and pollen biostratigraphy. Our assessment indicates that sand zones in the lower Potomac Unit III sequence are laterally continuous across long distances ($>$ 60 km), though individual sands may be local in extent. Cenomanian Potomac Unit III sands are suitable for storage in the lower part of Cape May County, New Jersey, though near the updip limit for supercritical storage (800 m). Also, even if carbon is injected into these strata, the updip migration above the depth of supercritical storage may occur. The Potomac Unit III sands thin into Maryland, where they are less suitable for carbon storage. Potomac Unit II sands (Albian pollen Zone II) are generally thin and discontinuous across the region. Waste Gate-Potomac Unit I sands are thick in Maryland and New Jersey and confined in New Jersey; the confinement updip in Maryland is uncertain. Like Unit III, the Waste Gate-Unit I sand zones appear similar at widely spaced wells, suggesting correlatable sand zones, though individual sand beds may be laterally discontinuous. Potentially, large volumes of CO_2 ($\sim$ 8–34 Gt) could be stored in the Waste Gate-Potomac I reservoir; however, more information is needed to refine the geologic structure (sand connectivity, storage volumes, and confining-unit competency) and hydraulic characteristics (porosity, permeability, and pressures).

SUPPLEMENTAL MATERIAL

Supplemental files, Tables 1 and 2 and Figure 1, are available from JSR's Data Archive: http://sepm.org/pages.aspx?pageid=229.

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