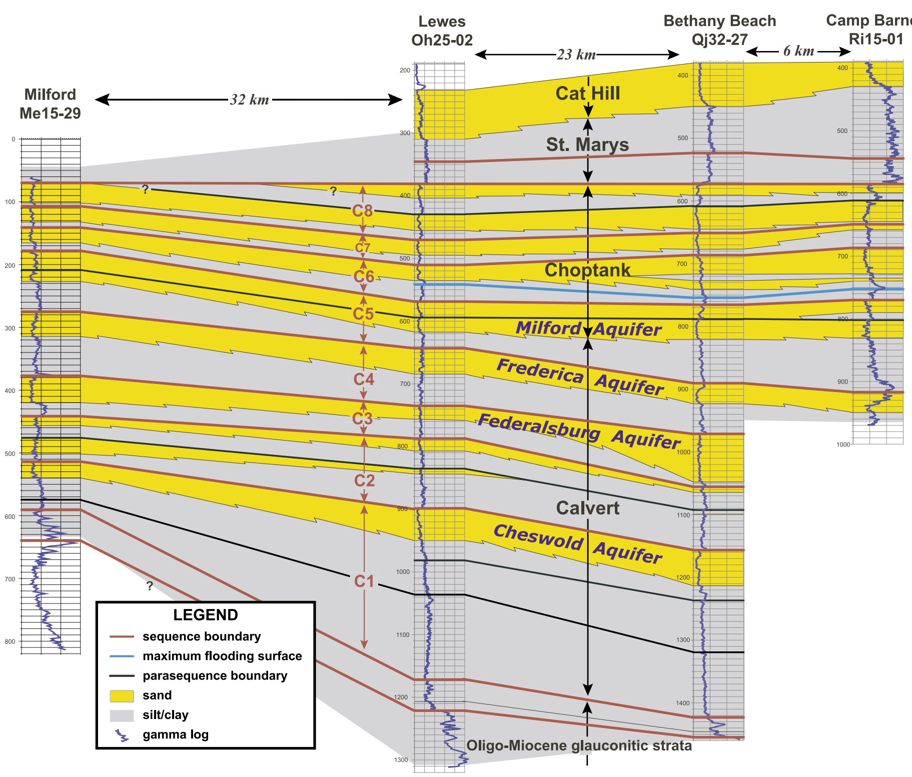
State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 75

STRATIGRAPHY AND CORRELATION OF THE OLIGOCENE TO PLEISTOCENE SECTION AT BETHANY BEACH, DELAWARE



by

Peter P. McLaughlin[1], Kenneth G. Miller[2], James V. Browning[2], Kelvin W. Ramsey[1]
Richard N. Benson[1], Jaime L. Tomlinson[1], and Peter J. Sugarman[3]

University of Delaware
Newark, Delaware
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[2] Rutgers University
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STRATIGRAPHY AND CORRELATION OF THE OLIGOCENE TO PLEISTOCENE SECTION AT BETHANY BEACH, DELAWARE

ABSTRACT

The Bethany Beach borehole (Qj32-27) provides a nearly continuous record of the Oligocene to Pleistocene formations of eastern Sussex County, Delaware. This 1470-ft-deep, continuously cored hole penetrated Oligocene, Miocene, and Pleistocene stratigraphic units that contain important water-bearing intervals. The resulting detailed data on lithology, ages, and environments make this site an important reference section for the subsurface geology of the region.

Dark glauconitic to clayey Oligocene to basal Miocene sediments in the bottom of the hole are overlain by a Miocene section characterized by an overall shallowing-upward succession of shallow- and marginal-marine clastic sediments associated with wave-dominated shorelines. The lower Miocene Calvert Formation is composed of shelfal silts and scattered thick shoreface sands and shell beds. These pass upward into shelly shoreface sands and lesser silts of the lower-to-middle Miocene Choptank Formation. Silts and clays of the middle-to-upper Miocene St. Marys Formation separate the sandy middle Miocene shallow-marine strata from the sandy upper Miocene nearshore to marginal-marine section. The Cat Hill Formation is a coarsening-upward succession, changing from sandy offshore silts at the bottom to cleaner, shallow- or marginal-marine sands at the top. This unit is overlain by an interval of interbedded sands and muds of the upper Miocene Bethany Formation and a predominantly sand section of the upper Miocene (possibly Pliocene) Beaverdam Formation. The Pleistocene strata capping the section include predominantly muddy sediments of the Omar Formation in the lower part and micaceous sands of the Sinepuxent Formation nearest the surface.

Fifteen sequences are recognized in the Oligocene to lowermost upper Miocene marine section. Each is commonly characterized by a thin, deepening-upward transgressive systems tract (sometimes absent) and a thicker shallowing-upward highstand systems tract. In addition, several possible sequences are identified in the upper Miocene (and Pliocene?) shallow-marine to non-marine section, and two sequences are identified in the shallow-subsurface Pleistocene strata.

The findings at this site help delineate the correlation of aquifer-quality sands. Highstand-systems-tract sands in the lower-to-middle Miocene section are stratigraphically equivalent to the Cheswold, Federalsburg, Frederica, and Milford confined aquifers, important ground-water sources further north. Likely uppermost Miocene sands referred to the Manokin and Pocomoke aquifers (undifferentiated) are part of an interfingering complex of nearshore to estuarine deposits and do not appear to be consistently distinct strata in eastern Sussex County. Regional correlation reflects the location of Delaware between the sandy, deltaic Kirkwood-Cohansey system of New Jersey and the shelfal setting Calvert-Choptank succession of Calvert Cliffs, Maryland. The boundary between the Calvert and Choptank Formations appears to be time transgressive, occurring earlier in Delaware than at Calvert Cliffs.

INTRODUCTION

This report summarizes the results of geological investigations conducted on research borehole Qj32-27, drilled at Bethany Beach, Delaware in May and June, 2000 (Figs. 1 and 2). The objective of the project, a cooperative effort of the Delaware Geological Survey, the Rutgers University Department of Geology, and the U.S Geological Survey, was to obtain a continuous cored record of the stratigraphy of coastal Sussex County in order to:

1. improve understanding of the geological history of the area;
2. better characterize the nature of the aquifers of coastal Sussex County;
3. investigate the relationship between global sea level and late Cenozoic stratigraphy of the Coastal Plain of the U.S. Middle Atlantic region.

The drilling operations obtained a nearly complete record of the Oligocene to Pleistocene section (Fig. 3), yielding a wealth of new knowledge about the lithologic characteristics, ages, and history of depositional environments of this area over the last 25 million years. These results have been detailed in a resulting Ocean Drilling Program site report (Miller et al., 2003a).

The purpose of this report is to utilize the results from Bethany Beach to address issues of special interest to studies of Delaware geology and hydrology. Specifically, this report provides:

a. detailed characterization of the formations penetrated in this hole, including lithologies, ages, and environments (updated and condensed from Miller et al., 2003a), to establish Qj32-27 as a reference section for the subsurface geology of eastern Sussex County;
b. documentation of the sequence stratigraphy of the strata in this hole, to provide an understanding of the depositional history of the Oligocene to Pleistocene sediments of eastern Sussex County;
c. analysis of the implications of these findings to local and regional stratigraphic correlations, particularly correlation issues relating to understanding the geologic framework of aquifers in coastal Sussex County.

The scope of this report principally encompasses the geological findings from Qj32-27, summarizing descriptions of stratigraphic units, ages, and paleoenvironmental data from our previous publications (Miller et al., 2003a;

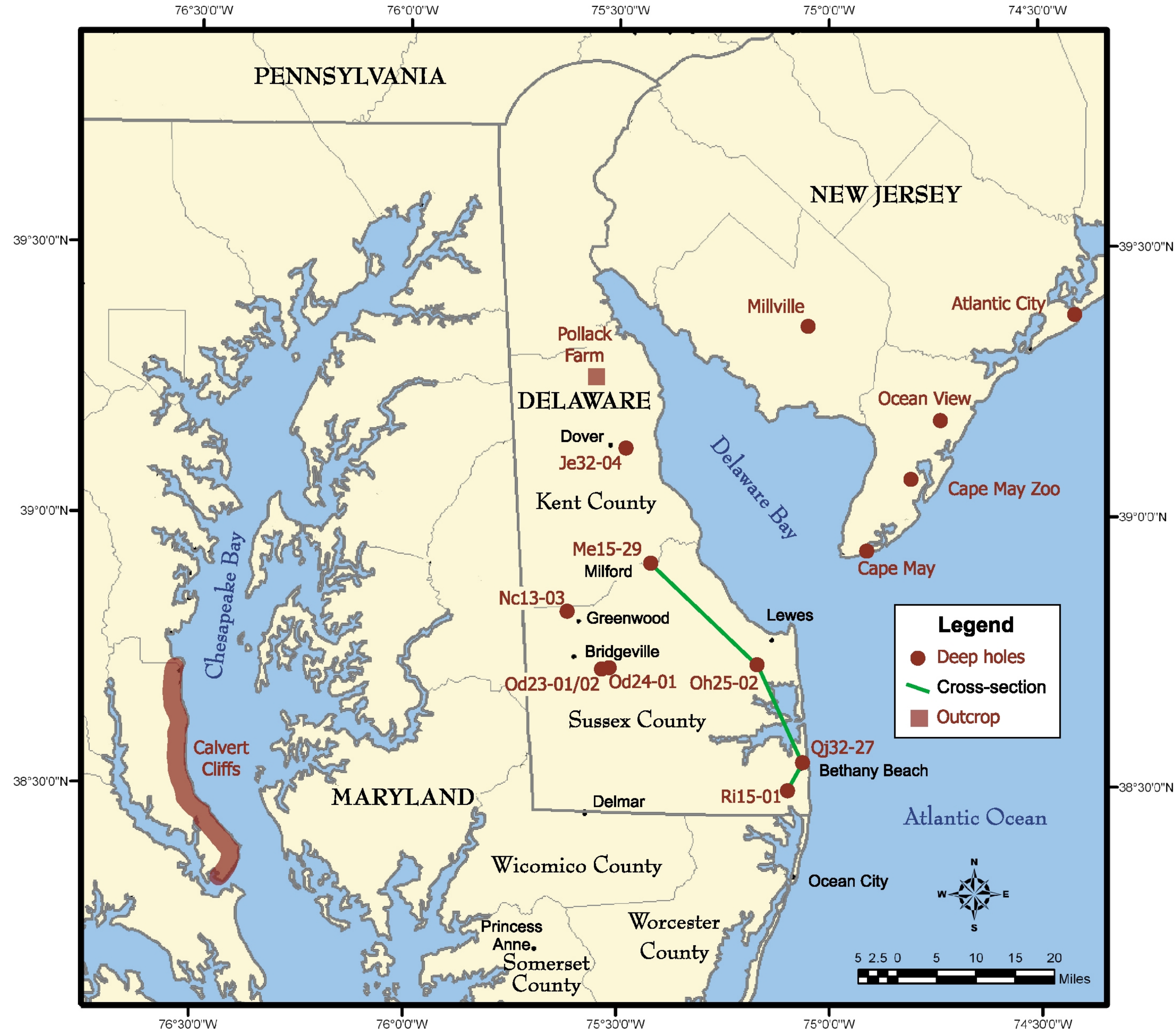

Figure. 1. Regional map of study area with location of Sussex County cross section, including localities discussed in text, deep holes, and line of Sussex County cross section (Fig. 15).

Browning et al., 2006). In addition, we outline correlations of the aquifers between the Bethany Beach borehole (Qj32-27) and other sites in eastern Sussex County, as well as compare the sequence stratigraphy of this site to frameworks published for Maryland and New Jersey.

Previous Work

The foundation for our current understanding of the geology and water resources of southern Delaware was established in several broader-scope studies published between the late 1950s and late 1970s. Rasmussen and Slaughter (1955) was one of first comprehensive reports on the geology and water resources of Delaware and it briefly discussed the geology of Sussex County. Subsequent publications by Rasmussen et al. (1960), Jordan (1962), Sundstrom and Pickett (1969), Cushing et al. (1973), and Owens and Denny (1979) provided additional knowledge of the geologic formations and aquifers of southern Delaware.

Later works treated the upper Miocene deposits of southeastern Delaware in more detail. Hodges (1984) examined the "Manokin, Ocean City, and Pocomoke" aquifers of coastal Sussex County. Andres (1986) used well logs and seismic reflection data to correlate and characterize the geologic formations of eastern Sussex County and nearby offshore areas. This was followed by a detailed analysis of the lithostratigraphy (Andres and Talley, *in* Benson, 1990; Ramsey, *in* Benson, 1990) and chronostratigraphy (Benson, *in* Benson, 1990) of Oligocene to Pleistocene strata penetrated in a research hole at Lewes (Oh25-02). Groot et al. (1990) and Groot and Jordan (1999) used palynology to date

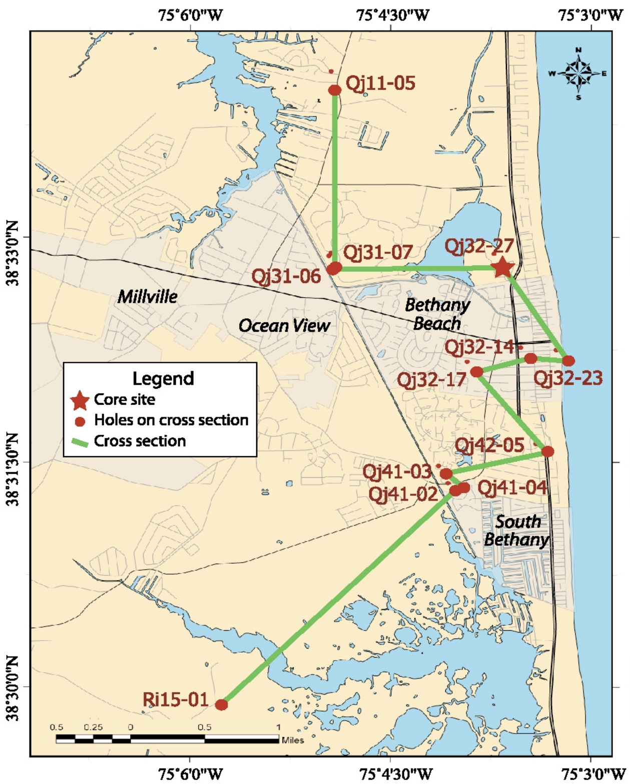

Figure 2. Map of Bethany Beach area with location of local cross section. The site drilled for this study, Qj32-27, and the location of wells used on the local cross-section are shown.

and correlate the Miocene to Quaternary strata in Sussex County. Andres (2004) formally defined two new upper Miocene formations, the Cat Hill and Bethany.

Results of the work on the Bethany Beach cores have been published in an ODP site report (Miller et al., 2003a) that described the core lithologies, chronostratigraphic determinations (from strontium-isotope and biostratigraphic analyses), and sequence stratigraphic interpretations. Browning et al. (2006) further expanded on the sequence stratigraphic interpretations and outlined a regional correlation of these sequences to New Jersey and Maryland.

Acknowledgments

This project was a cooperative effort of research teams from the Delaware Geological Survey (DGS) and Rutgers University (RU) and was led by Peter P. McLaughlin, Jr., (DGS) and Kenneth G. Miller (RU). The findings summarized in this report conform to those detailed in Miller et al. (2003a), with updated nomenclature and added discussion of aquifer relationships and correlation. McLaughlin was responsible for the overall lithostratigraphic framework presented herein. Miller, McLaughlin, Browning, and Sugarman made the lithologic descriptions and sequence stratigraphic interpretations. Ramsey contributed to the lithostratigraphic interpretations, ensuring that the stratigraphy is consistent with the updated framework established in his surficial mapping. Browning and Miller were responsible for the strontium chronology. Micropaleontologic analyses were conducted by Browning (foraminifera), Benson (foraminifera, radiolaria, diatoms), and McLaughlin (foraminifera, palynomorphs). Aquifer interpretations and local correlations were done by

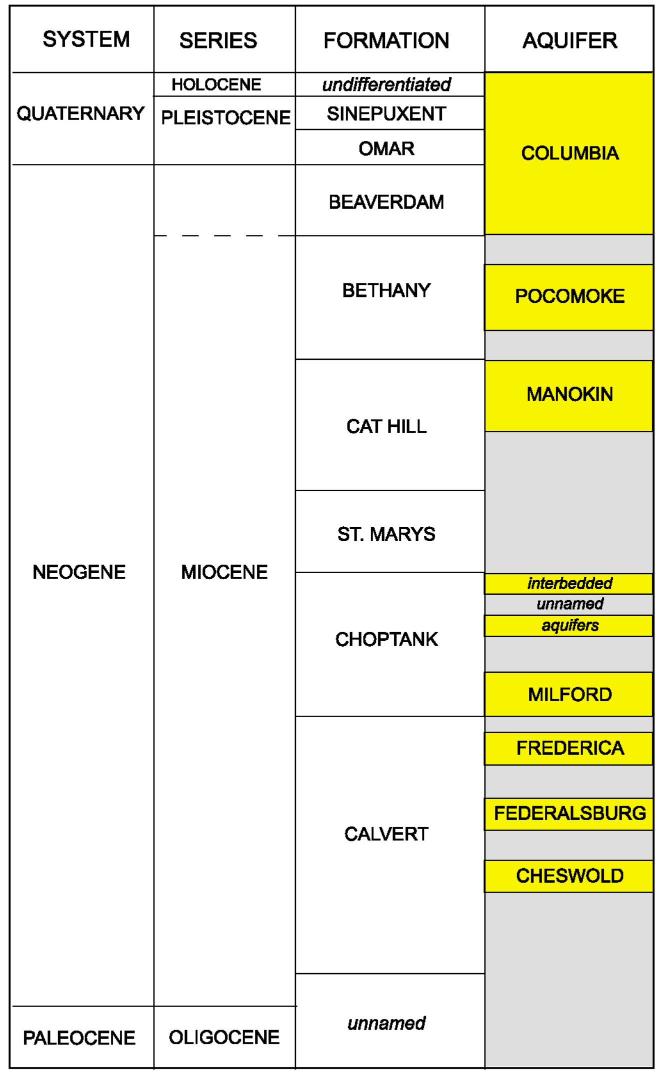

Figure 3. Generalized stratigraphic column for coastal Sussex County. The formation column outlines the relative positions and ages of lithostratigraphic units discussed in this report. The aquifer column is a simplified representation of the hydrostratigraphic names conventionally used in the study area; the actual aquifer stratigraphy is more complicated, with the upper aquifers in contact with each other in places. Yellow represents sandier, aquifer-prone units whereas gray represents muddier, typically confining, units.

McLaughlin and Tomlinson. The regional correlation section was principally written by McLaughlin and incorporates content previously included in Browning et al. (2006).

We gratefully acknowledge M.-P. Aubry for providing nannofossils analysis We also appreciate contributions of numerous members of the Coastal Plain Drilling Project team who participated in the onsite geological operations or post-drilling analytical work (A.S. Andres, S.J. Baxter, B.S. Cramer, S. Curtin, M.D. Feigenson, J. Hernández, M.E. Katz, T.E. McKenna, D. Monteverde, S.F. Pekar, S.A. Strohmeier, and J. Uptegrove). Special thanks are due to U.S. Geological Survey drillers Gene Cobbs and Gene Cobbs III for their hard work and skillful coring. Reviews of the manuscript by Scott Andres, Lucy Edwards, David Andreasen, and Stephen Bell resulted in significant improvements and are gratefully acknowledged.

Drilling operations and laboratory analyses were supported by a National Science Foundation grant (EAR99-09179) awarded to Miller as part of the Middle Atlantic Coastal Plain drilling program, coordinated with the Ocean Drilling Program (ODP). The Delaware Geological Survey supplied materials, personnel, and logging support. Drilling costs were partially supported by the U.S. Geological Survey Eastern Earth Surface Processes Team.

METHODS AND MATERIALS

Drilling, Sampling, and Logging

Borehole Qj32-27 was drilled at the Delaware National Guard training facility at Bethany Beach, Delaware (38N 32' 53", 75W 03' 45"; elevation 4.6 ft) (Figs. 1 and 2). Drilling was conducted by the USGS Eastern Earth Surface Processes Team (Gene Cobbs and Gene Cobbs III) in May and June, 2000, using a hydraulic rotary rig equipped with a wire-line coring system; operations chronology and methods are described in detail in Miller et al. (2003a). The hole was drilled to a depth of 1470 ft, with 1166.5 ft of core recovered of 1465 ft cored (79.62 percent recovery). From the top of the hole to 1077 ft, cores were obtained with a Christensen HQ system with a 4.25-in. bit producing cores of approximately 2.5-inch-diameter. From 1077 ft to the bottom of the hole, core was obtained using a Christensen NQ system with a 3.25-inch drill bit that produces cores of 1.67 to 1.875 inches in diameter. The depth assignment for each core was standardized with the top of each core corresponding to the top of each coring run (rare exceptions noted in Miller et al., 2003a). Each core was assigned a Delaware Geological Survey sample number.

The cores were carefully cleaned to remove drilling mud and any "rind" of ground rock powder. Initial core descriptions were made onsite after each core was cleaned, with careful note made of textures, sedimentary structures, colors, and fossil content (core logs available at http://www-odp.tamu.edu/publications/174AXSIR/VOLUME/CORES/COR_BETH.PDF). When onsite descriptions were complete, the cores were packaged for storage by cutting them into 2-ft sections, placing them in 2-ft long trays of split 3-in diameter PVC pipe, labeling core identifiers and depths on the trays, wrapping them in plastic sheeting, and packing them in labeled 2-ft-long wax-coated boxes.

Wireline geophysical logs were obtained in the hole to provide a continuous digital record of rock and fluid properties. Natural gamma, multipoint electric (simultaneous spontaneous potential, 16- and 64-inch normal resistivity, lateral resistivity, and single-point resistance), and magnetic induction logs were obtained from the ground surface to the bottom of the hole using DGS-owned Century Geophysical Corporation equipment. A full-wave sonic log was obtained to a depth of 200 ft (a deeper log was not obtained due to equipment malfunction). Geophysical log depths may be slightly different than core depths because of depth justification of incomplete cores and slight variations in log depth caused by cable stretching and borehole factors.

The cores were transported to the Rutgers University Department of Geological Sciences in Piscataway, New Jersey, where they are permanently stored as part of the Integrated Ocean Drilling Program core repository (http://geology.rutgers.edu/corerepository.shtml).

Subsample Analysis

Subsamples of the cores were taken for sedimentological, micropaleontological, and geochemical analysis at the Rutgers University core facility.

Sedimentology. Subsamples were taken approximately every 5 ft for grain-size analysis. Percentages of silt and clay, very fine and fine sand, and medium and coarser sand were estimated on the basis of weight percentages of washed sample residues (Miller et al., 2003a). The sand fractions were examined using a microscope, and a visual estimate was made of the relative percentages of different grain types, including quartz, glauconite, carbonate (foraminifera as and other shells), and mica. Cumulative percentage plots of the grain sizes were computed from these data and plotted with the core logs.

Micropaleontology. Several types of micropaleontological analyses were performed for this project (Miller et al., 2003a). Foraminifera were studied in the same 5-ft-subsamples used for grain size analysis. Analysis was made from the >250 µm size fraction using a reflected light binocular microscope; for samples deeper than 1200 ft, specimens were concentrated by floating in tetrachloroethylene. Relative abundances of foraminifera were estimated visually. Benthic foraminifera provided the basis for paleoenvironmental analysis while scattered occurrences of planktic foraminifera provided biostratigraphic criteria for age estimates. Additional subsamples were taken at selected depths for analysis of foraminifera, radiolaria, diatoms, palynomorphs, and calcareous nannofossils. The >63 µm fraction was examined for selected samples using reflected light microscopy to identify foraminifera, radiolaria, diatoms, and planktic foraminifera. Some samples were studied in detail, with relative abundances based on estimated percentages of each species; others were general estimates based on quick scans of samples during and shortly after drilling. Calcareous nannofossil analyses were performed from additional selected samples.

Palynological samples were prepared and analyzed from selected depths with lithologies most likely to yield spores, pollen, or dinocysts. Standard processing techniques were used for demineralization (hydrochloric and hydrofluoric acids), oxidation (dilute nitric acid), and acetolysis (Traverse, 1988); it should be noted that oxidation can lower the recovery of some protoperidinacean dinoflagellates, especially *Brigantedinium* (Hopkins and McCarthy, 2002). Approximately 15 to 30 grams of sediment were weighed and processed. A fixed number of 15 µm polystyrene microspheres suspended in dextran were added to each sample to allow estimation of abundances of specimens per gram of sample. At least 300 grains were identified and counted in 31 samples from selected depths.

Data Analysis

Sedimentary Facies Analysis. The description of each lithostratigraphic unit includes an interpretation of depositional environment based on lithofacies and biofacies, as previously-described in Miller et al. (2003a). The sedimentary facies are predominantly sands and silts that contain common shell material and reflect deposition of most of the sediments in a siliciclastic, wave-dominated, shallow-marine environment. The shallow-marine sediments are characterized using a wave-dominated shoreline model (Bernard et al., 1962; Harms et al., 1975, 1982; McCubbin, 1982). The following facies are recognized in the cores:

1. Fluvial to upper estuarine: dominantly poorly sorted sands; granule-rich or gravelly layers at the base of some beds, likely representing cut-and-fill channels; plant debris common.
2. Lower estuarine: poorly sorted sands admixed with interlaminated thin sands and clays; commonly contains plant debris, woody plant fragments, or pieces of lignite; may be associated with shoreline-type sands.
3. Upper shoreface (proximal) to foreshore: clean, high-energy, shoreline-associated, fine-to- coarse sand, with opaque heavy mineral laminae highlighting cross bedding; in places, may include abundant debris of thick-shelled bivalves; deposited within fair-weather wave base near shoreline (Fig. 5).
4. Upper shoreface (distal): fine-to-medium sands, includes clean sands and slightly silty sands with uncommon silt/clay layers; commonly well bioturbated with poorly preserved lamination; deposited within fair-weather wave base (Fig. 5).
5. Lower shoreface: fine-to-very-fine sand, typically heavily bioturbated; commonly silty and/or slightly clayey due to bioturbation-induced mixing; commonly very shelly with whole shells preserved; shells include more delicate, thinner-shelled forms; deposited below fair-weather wave base but within storm wave base (Fig. 5).
6. Offshore: thinly laminated very fine sands, silts, and clays; deposited below storm wave base, with finer sediments representing deposition further offshore (Fig. 5).

*Foraminiferal Biofacies***.** Benthic foraminiferal assemblages reflect environmental conditions at the time of deposition of marine sediments. In this study, we utilize benthic foraminiferal biofacies to determine approximate water depths (in this report, discussed in standard scientific units of meters). Foraminifera provide useful environmental information from the Oligocene strata at the bottom of the hole to the upper Miocene Cat Hill Formation. As outlined in Miller et al. (1997, 2003a), five benthic biofacies can be identified in the Miocene of the Middle Atlantic region that trace changes in paleo-water depths (PWDs) through the section (Table 1). These biofacies are similar to those identified by Olsson et al. (1987) from the Miocene of the Maryland Coastal Plain.

These biofacies-based paleoenvironmental interpretations are consistent with interpretations of co-occurring sedimentary facies. The upper shoreface/foreshore, distal upper shoreface, and lower shoreface environments all lie within inner neritic depth ranges, whereas the offshore environment encompasses middle neritic and deeper environments.

Table 1. Benthic foraminiferal biofacies.

Biofacies Name	Taxa	Environment
Elphidium	dominated by *Elphidium*	near-shore, including lower estuarine, bay, and innermost neritic environments (10 m or less PWD)
Hanzawaia	includes *Hanzawaia,* notably *H. concentrica; Elphidium* may also be common; *Pseudononion pizarrensis* absent	inner neritic (10-25 m PWD)
Pseudononion	dominated by *Pseudonomion pizarrensis*; *Nonionella miocenica* and *Hanzawaia* common	outer-inner-to-inner-middle neritic (25-50 m PWD)
Bulimina	dominated by *B. elongata*	middle neritic (50-80 m PWD)
Uvigerina	includes *U. subperegrina/auberiana* and *U. calvertensis*	middle neritic (>75 m PWD), associated with maximum flooding surfaces and related carbon enrichment

Strontium Isotope Ages. Strontium isotope analyses of mollusk shell carbonate provide the principal means for age estimates in the Bethany Beach cores. Sixty-eight strontium age determinations are reported in Miller et al. (2003a), covering intervals where shell is present from the Oligocene section near the bottom of the hole to upper Miocene section at around 350 ft. Reported age estimates use the Berggren et al. (1995) time scale and the isotope age regressions of Oslick et al. (1994).

Biostratigraphy. Biostratigraphic analysis of the Bethany Beach section utilizes multiple microfossil groups: planktic foraminifera, radiolaria, diatoms, calcareous nannofossils, dinoflagellates, pollen, and spores (Miller at al., 2003a). Most of these microfossils can be interpreted on the basis of global and regional marine-based zonations; the exceptions are the pollen and spores, for which a local zonation is established herein.

Calcareous microfossils (planktic foraminifera and calcareous nannofossils) provide several key chronostratigraphic picks in these cores (Miller et al., 2003a). However, because these groups generally prefer open ocean habitats, they have limited occurrences in the shallow-marine facies prevalent at this site; they tend to be most useful in the lower part of the section and in the muddy St. Marys Formation. The age significance of these picks is assessed using the zonations of Berggren et al. (1995) and Berggren and Pearson (2005).

Siliceous microfossils (radiolarians and diatoms) occur in foraminiferal sample residues (> 63 microns) between the

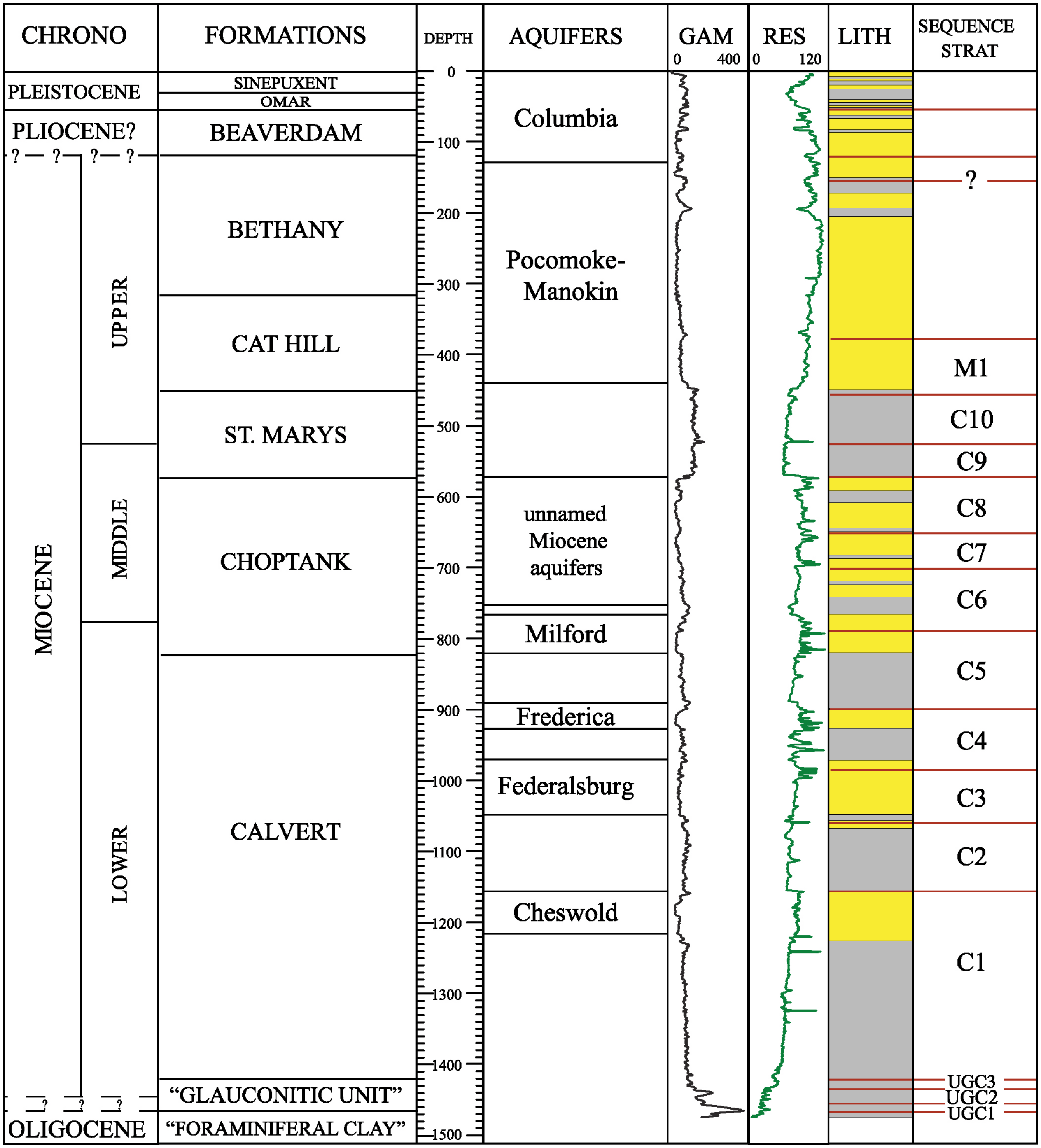

Figure 4. Summary stratigraphic column for hole Qj32-27, Bethany Beach. This figure provides a synthesis chronostratigraphy (CHRONO), formations, geophysical log signatures (GAM = gamma, RES = single-point resistance), aquifers, lithologies (LITH), and sequences recognized in this study. Yellow represents sandier strata whereas gray represents muddier strata.

unnamed glauconitic strata near the bottom of the hole and the base of the St. Marys Formation (Miller et al., 2003a). Groups that favor neritic environments dominate the assemblage. Their stratigraphic significance is assessed using the zonations of Palmer (1986) and Nigrini (1996). A few stratigraphically significant diatom occurrences are assessed using the East Coast Miocene zonations of Abbott (1978) and Andrews (1988).

Dinoflagellates are present in many of the palynological preparations from the unnamed glauconitic sediments to the lower part of the St. Marys Formation. Occurrences are interpreted in the context of the eastern U.S. Miocene zonation of de Verteuil and Norris (1996) and of similar age assemblages from the region discussed in de Verteuil and Norris (1996) and de Verteuil (1997).

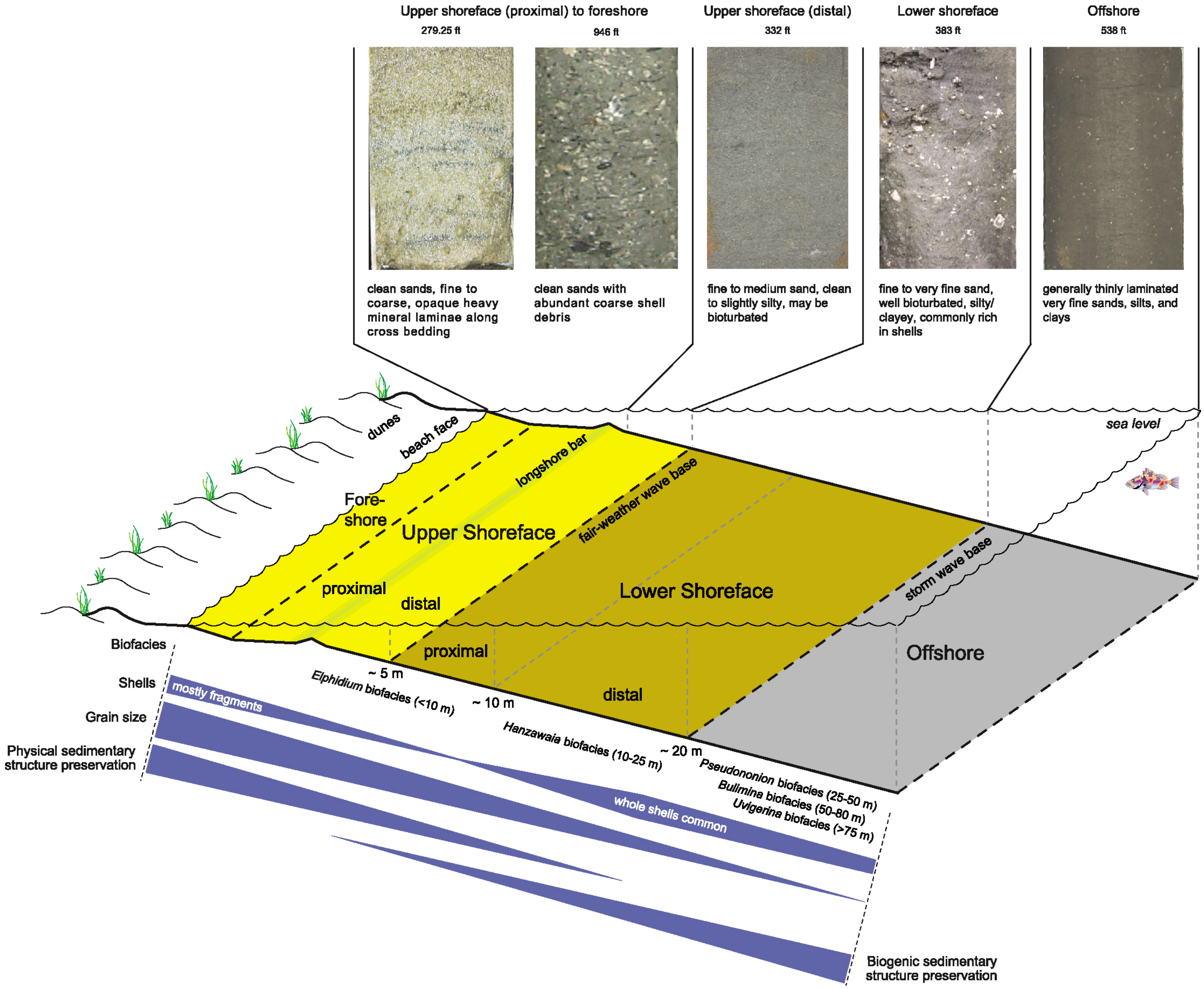

Figure 5. Wave-dominated shoreline facies model, summarizing the general lithofacies and biofacies schemes used to interpret the sediments found in cores from Qj32-27 (after Miller et al., 2003a and Browning et al., 2006). Core photographs for each lithofacies are from Qj32-27 at the depths indicated above the photographs. Yellow represents sandier sediments, brown represents muddy sand and/or silt, and gray represents muddier sediments.

Pollen and spores were used to subdivide the stratigraphic section at Bethany Beach. Because they are derived from land plants and easily transported by water and air, they are generally abundant in the shallow-marine and marginal-marine sediments sampled in these cores. The stratigraphic variations in proportions of different taxa reflect changes in vegetation through time. The assemblages are generally dominated by varying abundances of Quercus (oak), Carya (hickory), and Pinus (pine). The pre-Pleistocene sediments also commonly contain "exotic" taxa that do not live in the area in modern times. Because no established pollen zonation exists for the Miocene of this region, we defined a preliminary zonation for the hole through a stratigraphically-constrained cluster analysis of percentage data for 25 species with abundances >1 percent in at least one of the samples. The approach utilized the software CLUSTER (J. van Huissteden, Amsterdam) with the Furthest-Neighbor (Complete Linkage) Method and the chord distance coefficient. Four Miocene (to Pliocene?) pollen zones and two Pleistocene zones can be tentatively identified and characterized by composition of assemblages (Fig. 6; Table 2).

STRATIGRAPHIC FRAMEWORK

General Framework

Overview of Stratigraphy. The Bethany Beach borehole (Qj32-27) penetrated a section extending from the Oligocene to Pleistocene (Fig. 4). These strata were described in Miller et al. (2003a), but the lithostratigraphy of some of these strata has since been updated and they are, therefore, described in this report with a few differences.

Table 2. Pollen zonation established in Qj32-27 cores.

Zone	Palynological characteristics
Zone 6	Assemblage: Dominated by *Quercus* (typically >50%, in places > 80%) • subzone a) common *Pinus* and *Carya* • subzone b) common TCT (Taxodiaceae/Cupressaceae/Taxaceae) Exotics: *Engelhardia*-type >10% in places; common *Pterocarya*; rare *Podocarpus* Stratigraphy: Unnamed Glauconitic Unit, Calvert Formation, and lower Choptank Formation
Zone 5	Assemblage: Abundant *Quercus*, increased *Pinus* (frequently > 70%), *Carya* slightly more common than below • subzone a) more *Quercus* • subzone b) abundant *Pinus* Exotics: *Engelhardia*-type most common (decreases upward), some *Podocarpus* and *Symplocos* Stratigraphy: Upper Choptank Formation to lower St. Marys Formation
Zone 4	Assemblage: Abundant *Quercus*, more frequent than below • subzone a) more abundant *Carya* • subzone b) more abundant non-aboreal pollen and charcoal Exotics: *Pterocarya* fairly consistent Stratigraphy: Upper St. Marys Formation and Cat Hill Formation
Zone 3	Assemblage: *Quercus* and *Carya* most abundant, *Pinus* common, *Fagus*, *Liquidambar*, and polypodiacean fern spores more common than below Exotics: less common than below, include *Pterocarya* and *Engelhardia*-type pollen Stratigraphy: Bethany Formation
Zone 2	Assemblage: *Quercus* most abundant; *Pinus, Fagus, Liquidambar,* and polypodiacean fern spores common; significantly decreased *Carya* Exotics: none Stratigraphy: Omar Formation
Zone 1	Assemblage: *Pinus, Picea,* and *Betula* increase sharply, *Fagus* and *Liquidambar* less abundant than below Exotics: none Stratigraphy: Sinepuxent Formation

The strata at the bottom of the hole are dark foraminifera-rich clays of Oligocene age that comprise an unnamed unit (Fig. 4). These are overlain by a thick lower to middle Miocene section of interbedded silts, clays, and intervening sand beds. Above a basal, unnamed glauconitic unit, the lower part of this interval contains more mud than sand and is assigned to the Calvert Formation; the upper part, which is sandier and more shell-rich, is assigned to the Choptank Formation. At the top of the middle Miocene section is an interval of relatively uniform silt and clays assigned to the St. Marys Formation. Above that section, the formations are again sandier, with the upward-coarsening section of the Cat Hill Formation (upper Miocene) passing into interbedded sands and muds of the Bethany Formation (upper Miocene?) and, in turn, into sandy strata of the Beaverdam Formation (Pliocene?). The top of the section is composed of Pleistocene strata, consisting of predominantly muddy sediments of the Omar Formation in the lower part and micaceous sands of the Sinepuxent Formation nearest the surface.

Unnamed Foraminiferal Clay (1467.95-1465.7 ft)

Nomenclature. Not previously formally recognized.

Lithologic Description. This unit consists of dark olive gray, thinly laminated, slightly micaceous, slightly glauconitic foraminiferal clay (Figs. 7 and 8). The top of the unit is marked by a sharp, heavily burrowed contact. Glauconite-filled burrows are abundant in the upper 0.3 ft, and some extend as far as 1.2 ft below the contact.

Log Signature. This interval is at the very bottom of the logging runs and did not produce a clear log signature.

Age. This unit is considered Oligocene based on biostratigraphy and a single strontium age determination. Browning et al. (2006) reported a strontium age of 28.0 Ma at 1467.2 ft, which places it near the top of the lower Oligocene (Fig. 9). Biostratigraphic indicators also point to an Oligocene age (Miller et al., 2003a) but differ slightly from the strontium age. The occurrences at 1467.2 ft of a *Paragloborotalia opima* form transitional between *Pg. opima opima* and *Pg. opima nana*, as well as *Pg. opima nana* and *Paragloborotalia mayeri*, suggest this sample lies in upper Oligocene Zone O6, which ranges from 27.1 to 23.8 Ma (Berggren and Pearson, 2005).

Depositional Environment. Benthic foraminifera are suggestive of an offshore, outer neritic paleoenvironment at around 80 m PWD (Miller et al., 2003a) (Fig. 8). The fauna includes the uvigerinids *Tiptonina nodifera, Uvigerina tumeyensis,* and *?U. glabrans*. Other forms present include *Frondicularia, Guttulina, Gyroidina scalata, Lenticulina spp., Bolivina paula, Bulimina elongata,* and *Eponides ?cocoaensis*. Palynological preparations are rich in algal amorphous kerogen, also suggesting an offshore environment.

Unnamed Glauconitic Unit (1465.7 to 1420.0 ft)

Nomenclature. An interval characterized by couplets of glauconite sand and clay between 1465.7 and 1420.0 ft is herein referred to as the Unnamed Glauconitic Unit. It likely corresponds to a lower Miocene “unnamed glauconitic sand unit” described by Andres and Talley (*in* Benson, 1990) in Oh25-02 near Lewes, and likely to at least part of the underlying "unnamed glauconitic silt" considered by Benson (*in* Benson, 1990) to span the Oligocene-Miocene boundary. It may be referable to the Newport News Unit of the Calvert Formation (lower Miocene) of Powars and Bruce (1999), or to the Old Church Formation (Oligocene to lower Miocene) of Ward (1984), which are similar in lithology and age to these beds; additional age or biostratigraphic control will be required to evaluate the appropriate stratigraphic assignment.

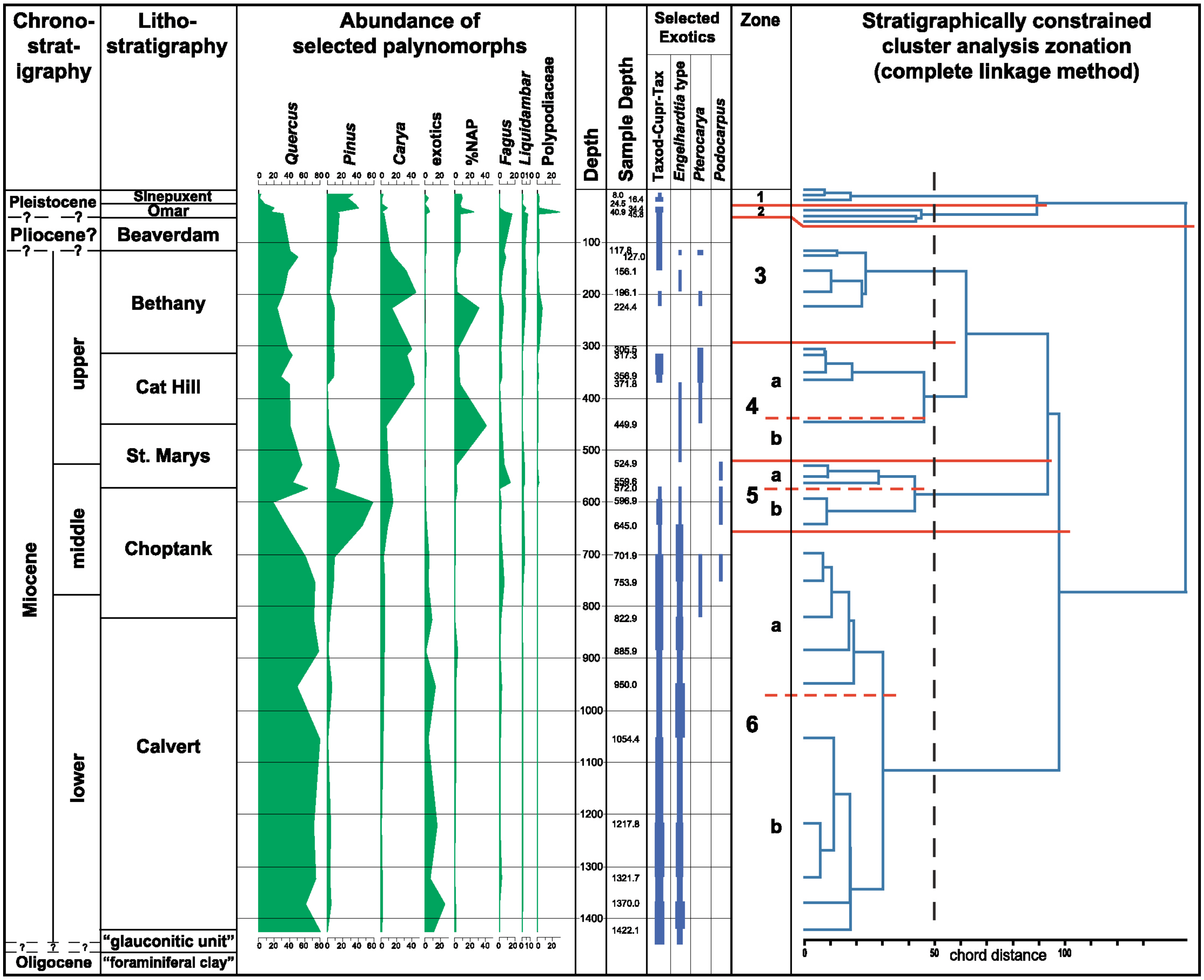

Figure 6. Pollen zonation established on the basis of cluster analysis of samples from Qj32-27. The positions of pollen zones 1 through 6 are shown relative to the lithostratigraphy and chronostratigraphy of Qj32-27. The cluster analysis dendrogram used to defines these zones is shown on the right, with zone and subzone boundaries demarcated by red lines and red dashed lines, respectively. The abundance (percentages) of key palynomorphs is indicated by width of the sawtooth graphs in green, showing the variations of major taxa and groups that characterize these zones (NAP = non-arboreal pollen). The range of exotic, warm-climate taxa is indicated by blue bars, with bar widths representing generalized relative abundances of these overall rare taxa.

Lithologic Description. The Unnamed Glauconitic Unit is characterized by an alternation between hard clays and glauconite sands and punctuated by extensively burrowed surfaces at the base of each glauconite sand interval (Fig. 8). Four such burrowed surfaces occur in this unit: at the base at 1465.7 ft, at 1454.5 ft, at 1430.5 ft, and near the top at 1421.1 ft.

At the base, clayey, fine to medium grained, glauconite sand (1465.7-1457.9 ft) lies on a burrowed contact with underlying foraminiferal clays. The sand passes upward into slightly glauconitic, dark brown clay with scattered small shell fragments and a trace of mica (1457.9-1454.5 ft), with glauconite-sand-filled burrows in the upper 0.5 ft extending down from the burrowed surface at 1454.5 ft. The glauconite sand changes upward from mostly black grains (below 1461.8 ft) to a mixture of green, black, and rusty-brown grains.

Between the burrowed surfaces at 1454.5 and 1430.5 ft, clayey glauconitic sands (1454.5-1453 ft) grade upward into hard, laminated clayey silts and silty clays with disseminated shells (1453-1431.25 ft) capped by an extensively burrowed, lithified zone (1431.25-1430.5 ft).

The package between the surfaces at 1430.5 ft and 1421.1 ft includes indurated, clayey, burrowed glauconitic sand (1430.5-1429.0 ft) that passes upward into faintly laminated clay (1428.3-1421.1 ft). The glauconitic sand contains clay-filled burrows in the bottom 0.7 ft; the upper 1.0 ft includes burrows filled with glauconitic clay from the overlying unit.

The top of the Unnamed Glauconitic Unit is a 1.1-ft-thick bed (1421.1-1420 ft) of glauconitic, heavily bioturbated silt that represents the highest strongly glauconitic interval in the bottom of the hole. It is composed of up to 50 percent glauconite sand at the base and is clayier (< 20 percent glauconite) at the top.

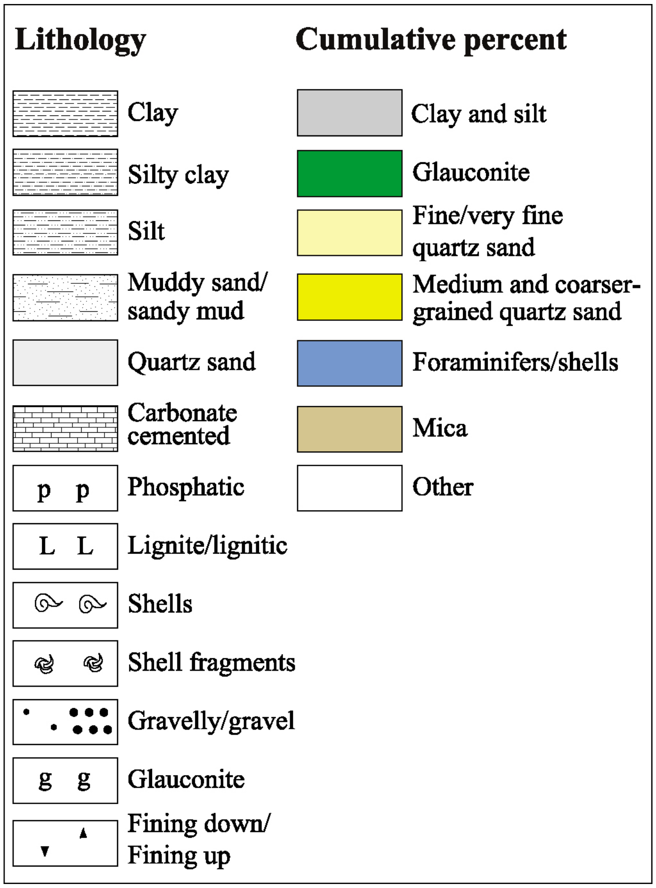

Figure 7. Key to summary stratigraphic sections for Qj32-27.

Log Signature. The Unnamed Glauconitic Unit exhibits some of the highest high gamma log values in the hole, reflecting high glauconite content (Fig. 8). High gamma values correspond to the highest glauconite content, such as from 1465.7 to 1453 ft and from around 1436 to just above 1430 ft. Resistivities are fairly low and conductivities are fairly high throughout this unit; single-point resistance is relatively high in the thin sandy zones, whereas short-and long-normal resistivities do not show these thin beds as well.

Age. Strontium-age data and biostratigraphy are available only from the upper part of the unnamed glauconitic unit (above 1446.6 ft) and place it in the lower Miocene (Miller et al., 2003a). The lower part of the unit (below 1446.6 ft) may be considered Oligocene or basal Miocene on the basis of overlying and underlying chronostratigraphic control.

A single strontium analysis at 1430.8 ft yields an age of 21.0 Ma (Fig. 9). The planktic foraminifer *Globorotalia kugleri* was identified at 1446.6 ft, indicating basal Miocene Zone M1, between 23.8 and 21.5 Ma (Berggren et al., 1995). Calcareous nannofossils at 1426 ft are suggestive of lowermost Zone NN2 (Miller et al., 2003a), which covers this same age range. Diverse and stratigraphically significant radiolarians at 1446.6 ft are indicative of lowermost Miocene *Cyrtocapsella tetrapera* Zone (RN1), including: *C. tetrapera,* the first-appearance datum (FAD) of which marks the base of the RN1; *Calocycletta virginis,* with a FAD near the base of RN1 (Sanfilippo and Nigrini, 1998); and *Cyrtocapsella cornuta*, with a FAD in RN1 (Sanfilippo and Nigrini, 1998).

Palynological analysis yielded observations of the dinoflagellate *Cousteadinium aubryae* at 1435.0 and 1446.6 ft, placing this interval between the base of Zone DN2 (22.2 Ma) and the top of Zone DN4 (15.2 Ma). Samples in this unit are characterized by abundant clumpy algal amorphous matter that obscures many of the palynomorphs. Terrestrial pollen and spores from this unit are grouped into subzone b of Zone 6 (Fig. 6) and include abundant *Quercus*, frequent *Carya*, and common *Pinus. Alnus, Tilia,* TCT (Taxodiaceael/Cupressaceae/Taxaceae), and *Ulmus* also occur in this interval.

Depositional Environment. The Unnamed Glauconitic Unit was deposited in an offshore setting (Fig. 8), but probably at shallower depths than the underlying Unnamed Foraminiferal Clay. Sedimentology and foraminifera trace a shoaling trend within the unit punctuated by a hiatus and marine-flooding event at each of the four heavily burrowed horizons. Foraminifera in the eight samples examined from the middle of the unit (1454.5-1430.5 ft) represent a *Bulimina*-biofacies indicative of deposition at middle neritic depths (50-80 m); however, it has a shallower aspect than does the assemblage in the underlying Oligocene clay, with lower abundance of uvigerinids and greater importance of *Pseudononion.* The upper part of the unit (1430.0 to 1421.1 ft) represents slightly shallower offshore environments, with foraminifera near the top (1422.0 ft) suggestive of shallow middle neritic environments (50 m PWD). The assemblage, which includes *P. pizarrensis, B. elongata, B. curta, U. subperegrina/auberiana*, and the highest occurrence of *Transversigerina transversa*, can be referred to the *Pseudononion* biofacies with some deeper aspects of the *B. gracilis* and *Uvigerina* biofacies.

Calvert Formation (1420 to 819.9 ft)

Nomenclature. The Calvert Formation was defined by Shattuck (1902, 1904) in Maryland as a division of the Chesapeake Group based on lithology and fossil content. The name Calvert Formation was first applied in Delaware by Miller (1906) for Miocene beds on the Dover sheet of the USGS Geologic Atlas (Ward, 1998), and first used in Sussex County in a water resources report by Rasmussen et al. (1960). As currently used in Delaware, the Calvert Formation is an interval of interbedded silt, sand, and clay with common shells (Andres and Talley *in* Benson, 1990; Ramsey, 1997). It is finer-grained and less shelly than the overlying Choptank Formation; in contrast with the underlying unnamed glauconitic unit, it has more common intervals of quartz sand and minor amounts of glauconite.

Lithologic Description. The Calvert Formation is, at this site, characterized by interbedded zones of silt and sand that are arranged in overall coarsening-upward packages. At the base of the formation (1420 ft), clayey silt of the lower Calvert Formation overlies glauconitic sandy silt of the underlying Unnamed Glauconitic Unit. The abundance of glauconite is much reduced (a few percent). The Calvert Formation can be subdivided into seven units (three sandy intervals alternating with four muddier intervals) at Bethany Beach:

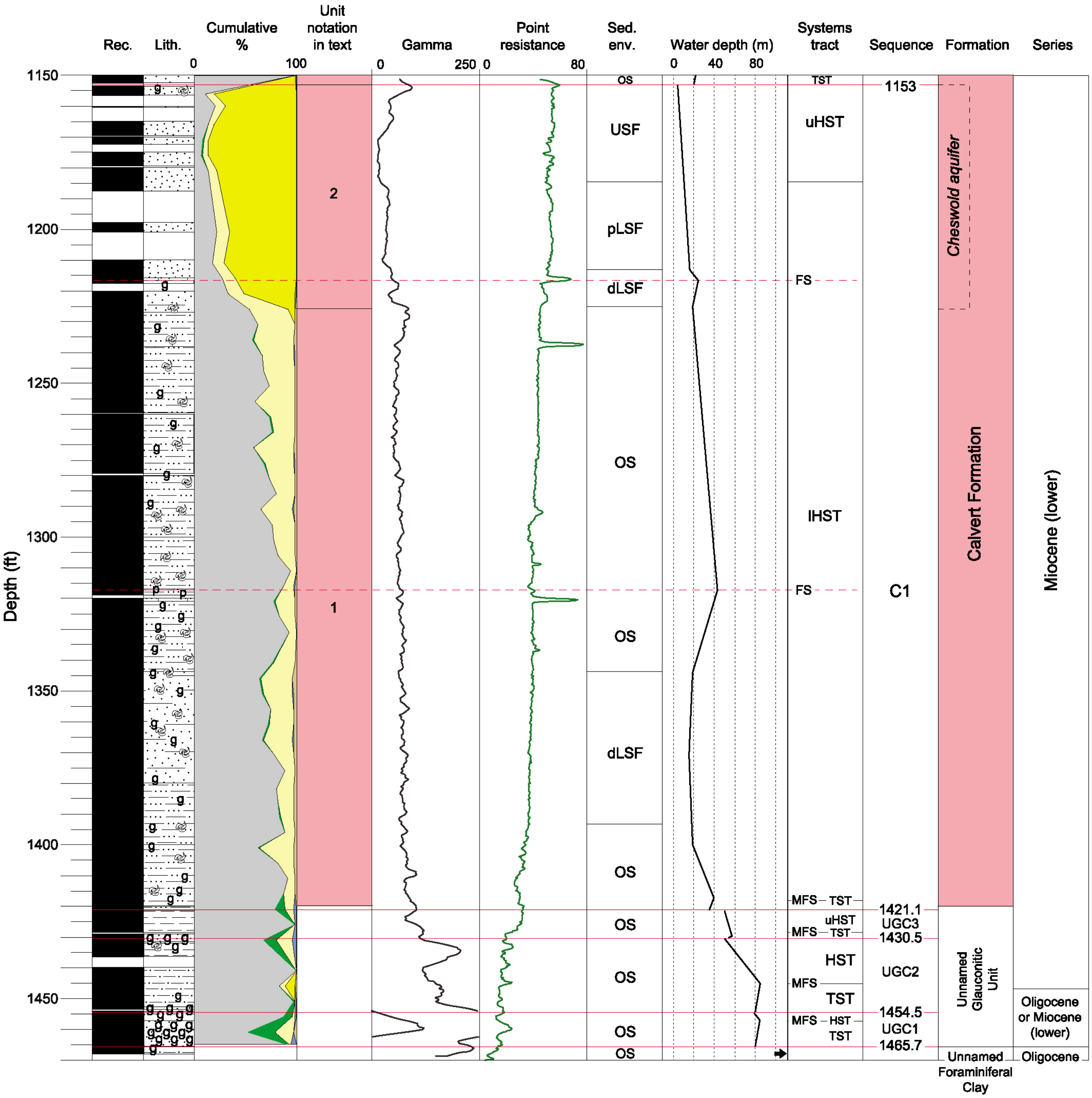

Figure 8. Summary stratigraphic section for unnamed foraminiferal clay, unnamed glauconitic unit, and lower part of the Calvert Formation in Qj32-27. Figure includes core recovery (in black; abbreviated as Rec.), lithology types (Lith.) and cumulative percent, unit notation used in text, gamma-ray and single-point-resistance logs, sedimentary environments (Sed. env.), inferred paleo-water depths, systems tracts sequence, formation, and series (after Miller et al., 2003a and Browning et al., 2006). See Figure 7 for key to lithology symbols. HST-Highstand Systems Tract; uHST-Upper Highstand Systems Tract; lHST-Lower Highstand Systems Tract; TST-Transgressive Systems Tract; LST-Lowstand Systems Tract; FS-Flooding Surface; MFS-Maximum Flooding Surface; SB-Sequence Boundary; FL-Fluvial; Est-Estuarine; LEst-Lower Estuarine; USF-Upper Shoreface; pUSF-Proximal Upper Shoreface; dUSF-Distal Upper Shoreface; LSF-Lower Shoreface; pLSF-Proximal Lower Shoreface; dLSF-Distal Lower Shoreface; OS-Offshore.

(1) A thick lower silty interval from 1420 to 1225.7 ft comprises approximately one third of the Calvert Formation (Fig. 8). The lowest 10 feet (1420-1410 ft) is silt with common glauconite-filled burrows and clay laminae and less common sandy laminae. This coarsens upward into sandier silts (1410-1225.7 ft), some laminated (in places cross laminated), some bioturbated and homogenous with sparse shells, with a few sandy, shelly, and indurated siltstone beds. A significant contact is evident at 1317.45 ft (core depth, registers slightly lower on log) where a heavily bioturbated, irregularly indurated sandy silt bed is overlain by a thin cemented sand layer (1317.45-1317.3 ft) and a zone of abundant shells and extensive burrows (1317.35-1316.4 ft). Glauconite content generally decreases upward.

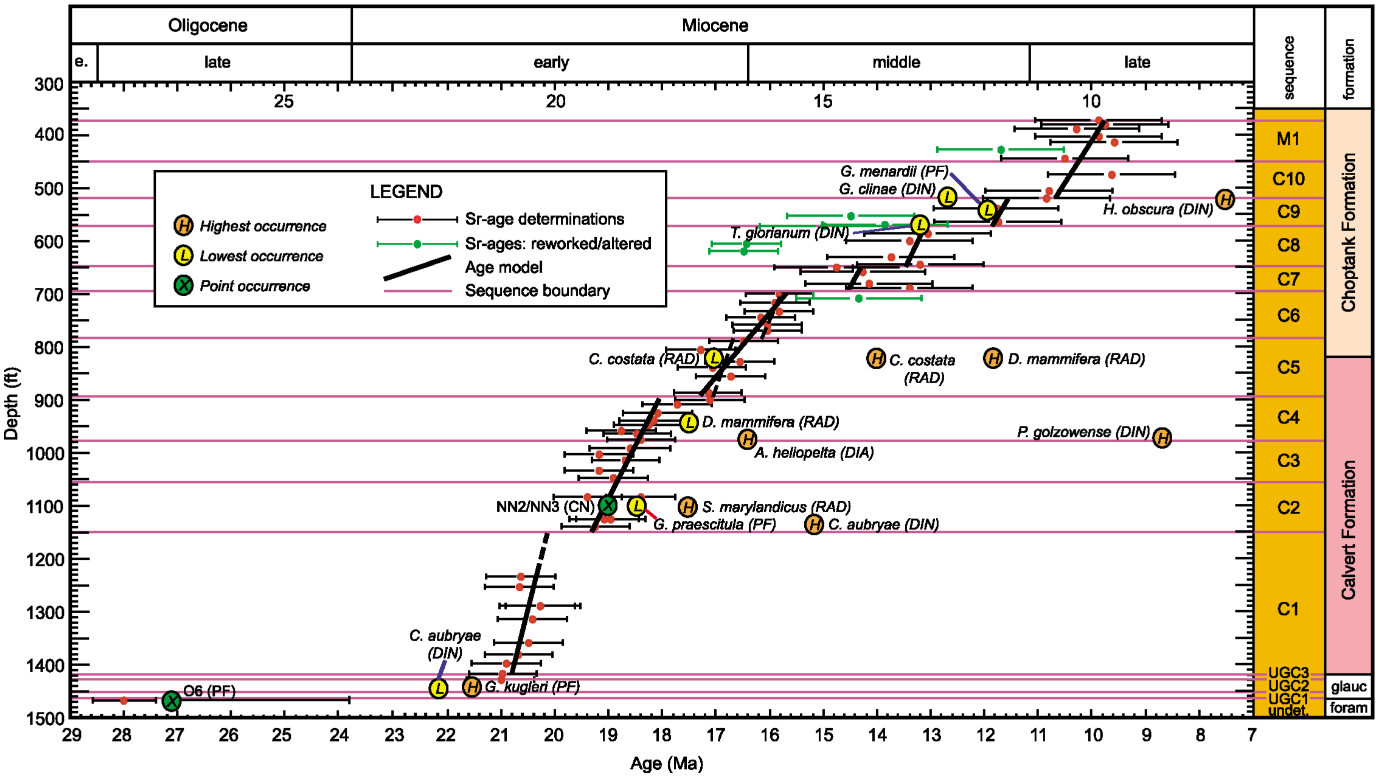

Figure 9. Age-depth plot for the Oligocene to Miocene section in Qj32-27 (after Miller et al., 2003a and Browning et al., 2006). Strontium isotope age estimates are the basis for the age-depth lines; primary age model is indicated by a solid line and alternate model by a dashed line. Temporal distribution of sequences and formations is shown in columns on the right. Biostratigraphic events are included on the basis of stratigraphic position and estimated ages as discussed in the text. Abbreviations are: foram. – unnamed foraminiferal clay; glauc. – unnamed glauconitic unit; undet. – undetermined; PF – planktic foraminifera; DIN – dinoflagellate; RAD – radiolarian; DIA – diatom; CN – calcareous nannofossil; NN number – calcareous nannofossil zone; O6 – planktic foraminiferal zone.

(2) A lower sandy interval between 1225.7 and 1153.5 ft (Fig. 8) represents the top of the coarsening-upward trend evident in unit 1. We consider this to be correlative with the Cheswold aquifer, which is an important ground-water resource in Kent County. The lower part (1225.7-1184.9 ft) coarsens upward from very muddy sand to interbedded muddy and clean sands, with a thin indurated bed (1217.0-1216.5 ft) near the bottom. The upper part (1184.9-1153.5 ft) continues the coarsening, with progressively cleaner bioturbated quartz sand capped by a thin bed (0.5 ft) of coarse sand with granules, glauconite, and large, broken shell fragments.

(3) A middle silty interval from 1152.55 (above a coring gap) to 1047.2 ft represents a shift back to finer-grained sediments (Fig. 10). Above a thin, basal glauconitic, shelly, silty sand (1152.55-1152 ft), this interval coarsens upward from laminated clayey, increasingly sandy silt with scattered shell fragments (1152-1070 ft) to burrowed, silty, very fine to fine sand (1065.2-1057.95 ft). A heavily bioturbated surface at 1057.95 ft represents a notable lithologic break and is overlain by an alternation of hard sands and silts (1057.95-1050.6 ft) capped by softer clayey silts (1050.6-1047.5 ft).

(4) A middle sandy interval between 1047.2 and 970 ft traces a continuation of upward coarsening from unit 3 (Fig. 10). We consider this sand to be equivalent to a sand interval designated the Federalsburg aquifer in Kent County. Silty, shelly, fine to very fine sand (1047.2-1007 ft) passes upward into well-sorted, cleaner, medium to fine sand with shell fragments (1007-1000 ft) to an alternation of sands and cemented shelly sand and shell hash facies (996.5-980 ft). The lithology becomes finer at the top (977.4-970 ft), where very fine to fine, muddy, bioturbated sand occurs.

(5) An interval of variably muddy sand occurs from 970 to 926.6 ft (Fig. 10). It is composed of irregularly alternating intervals of sandy silt to silty sand with numerous shelly and/or calcite-cemented beds in the upper half (956.25-926.6 ft).

(6) The highest sandy interval in the Calvert Formation occurs from 926.6 to 887.7 ft (Figs. 10 and 11). This sand interval can be correlated to the Frederica aquifer, an important ground-water source for central and southern Kent County. Most of it (926.6-897.7 ft) is composed of clean, well-sorted, medium-grained sand with shells and shell fragments, alternating between more shell-rich cemented bedsand unconsolidated beds. Above a heavily burrowed surface at 897.7 ft, the sand becomes finer, siltier, and bioturbated and fines upward, with a burrowed upper contact at 887.7 ft (Fig. 11).

(7) An upper silty interval between 887.7 and 819.9 ft caps the Calvert Formation (Fig. 11). It is characterized by sandy, clayey, laminated-to-bioturbated silt with scattered-to -rare shells. The amount of sand increases upward from approximately 10 percent at 880 ft to 40 percent at the top, with an indurated zone at 851.65 to 853.75 ft. The boundary between the Calvert Formation and the overlying Choptank Formation is marked by a shift from predominantly silty lithology to sandy lithology at 819.9 ft.

Log Signature. Geophysical logs through the Calvert Formation reflect the alternation between silty and sandy zones evident in the cores (Figs. 8, 10, and 11). High gamma-log values at the base of the formation (1420-1418 ft) reflect high clay and glauconite content (Fig. 8). Intermediate gamma values and moderately low resistivity/resistance values in the lower silty zone are punctuated by spikes on the single-point-resistance log that indicate thin cemented beds at approximately 1317 ft and 1237 ft. Above that, the log character reflects the alternation between sandy zones (low gamma and higher resistivity/resistance) and intervening muddier zones (moderate gamma and low resistivity/resistance). The sandy intervals at 1225.7 to 1152 ft (unit 2, Cheswold-aquifer equivalent), 1047.2 to 970 ft (unit 4, Federalsburg-aquifer equivalent), and 926.6 to 888.7 ft (unit 6, Frederica-aquifer equivalent) are clearly delineated on the logs. The single-point-resistance log reveals increasingly abundant thin limestone or calcite-cemented sand higher in the formation (above 992 ft), especially in the sandy intervals. However, these sands have lower resistivity and resistance values than stratigraphically higher fresh-water sands in the Cat Hill Formation (Manokin aquifer), suggesting that chloride concentrations may be higher and the potability of the water questionable in the Calvert Formation in this part of Sussex County.

Age. Shells from the Calvert Formation yielded thirty-one strontium age dates that indicate an early Miocene age (Miller et al., 2003a). The age-depth plot for these data (Fig. 9) reveals three groups of ages that appear to be separated by two unconformities that occur at the tops of significant sand intervals. The first group encompasses the lower silty part of the Calvert Formation (unit 1) through the top of the lowest sand interval (unit 2, Cheswold-aquifer equivalent). The best-fit line through these data yields early Miocene ages from 20.8 to 20.2 Ma. The line through the second group of ages, between 1153 and 897.7 ft (unit 3 through unit 6, Frederica-sand equivalent) indicates an age range from 19.3 to 18.1 Ma (Fig. 9). The break in ages between these two groups suggests a hiatus of as much as 1 m.y. The uppermost, muddy part of the Calvert (unit 7, above 887.7 ft), comprises a third group of ages around 17.0 Ma, placing this interval in the uppermost part of the lower Miocene. The gap in ages between these two groups suggests a hiatus of as much as 1 m.y.

Biostratigraphy is generally consistent with these strontium ages. Most of the lowest occurrences conform reasonably well to the strontium age trends; highest occurrences appear to be much less useful, probably because the overall shallowing trend in this section creates less favorable environmental conditions through time, causing taxa to disappear before their true extinction (Fig. 9). The planktic foraminifer *Globorotalia praescitula* was noted at 1103 ft, suggesting an age no older than 18.5 Ma, slightly younger than the strontium ages. Calcareous nannofossils place the lower and middle parts of the Calvert Formation in the lower Miocene (Miller et al., 2003a): lower Zone NN2 at 1311 ft; Zone NN2 at 1136 ft; upper NN2 at 1116 ft; and possible NN3 assignments at 1091 and 1071 ft. The radiolarian *Spongasteriscus marylandicus* occurs in the middle silty interval (unit 3) at 1103.0 ft, indicating an age no younger than the LAD of this species in the lower Miocene *Stichocorys wolffi* Zone (RN3). The occurrence of *Calocycletta costata* near the base of the upper silty interval (unit 7) 822.8 ft puts the uppermost part of the Calvert Formation in the lower-to-middle Miocene *Calocycletta costata* Zone (RN4) or higher. Intervening samples at 948.9 and 888.0 ft are assigned to this RN3 based on the presence of *Didymocyrtis mammifera* (FAD in RN3) and absence of *C. costata.*

The dinoflagellate *Cousteadinium aubryae* has multiple occurrences from the base of the formation up to 1135 ft, placing these samples between the base of dinoflagellate Zone DN2 (lower Miocene, 22.2 Ma) and the top of Zone DN4 (middle Miocene, 15.2 Ma).

Terrestrial pollen and spores from the Calvert Formation, along with one sample from the unnamed glauconitic unit and a few samples from the overlying Choptank Formation, are grouped by cluster analysis into Zone 6 (Fig. 6). Arboreal forms are most abundant, with *Quercus* dominant and the exotic taxon *Engelhardia* common in most samples. Samples studied between 1370 and 1054.4 ft are placed in subzone b; samples from 950 to 822.9 ft are placed in subzone a and characterized by more common *Pinus* and *Carya*. These are consistent with assemblages reported from the Calvert Formation in central Delaware by Groot (1993).

Depositional Environment. Facies analysis indicates that the Calvert Formation represents a succession of shallow-marine environments. The formation shoals upward in a step-wise fashion, reflecting rises and falls in sea level. At Bethany Beach, this is recorded as a series of four overall shoaling-upward packages in which muddy offshore or lower shoreface facies gradually prograde upward to sandy upper shoreface facies, punctuated by abrupt deepening events with thin transgressive packages (Figs. 8, 10, and 11).

The thick lower silty zone, unit 1, represents offshore and distal lower shoreface environments (Fig. 8). Foraminifera are typical of the *Pseudononion* biofacies (outer inner to inner middle neritic, 25-50 m PWD). Subtle environmental shifts are evident in variations between muddier offshore facies and sandier distal lower shoreface facies. The cemented sand with shells and phosphatized burrows in the middle of unit 1 (1317.45 to 1315.8 ft) may reflect a marine-flooding event. Taylor et al. (2000) noted that the low-sedimentation rates associated with marine-flooding events allow for longer residence of bottom sediments in early diagenetic zones, producing laterally extensive thin carbonate-cemented beds beneath marine-flooding surfaces.

The coarsening into the lower sandy interval, unit 2, reflects an overall shoaling trend (Fig. 8). The muddier sands in the lowermost part are distal lower shoreface deposits and include foraminifera of the *Pseudononion* biofacies (25-50 m PWD). The cleaner sands that comprise most of this unit reflect shoaling to proximal lower shoreface and upper shoreface environments.

The middle silty interval, unit 3, reflects deeper-water environments (Fig. 10). A shelly bed at the base represents a condensed section formed during marine transgression. It

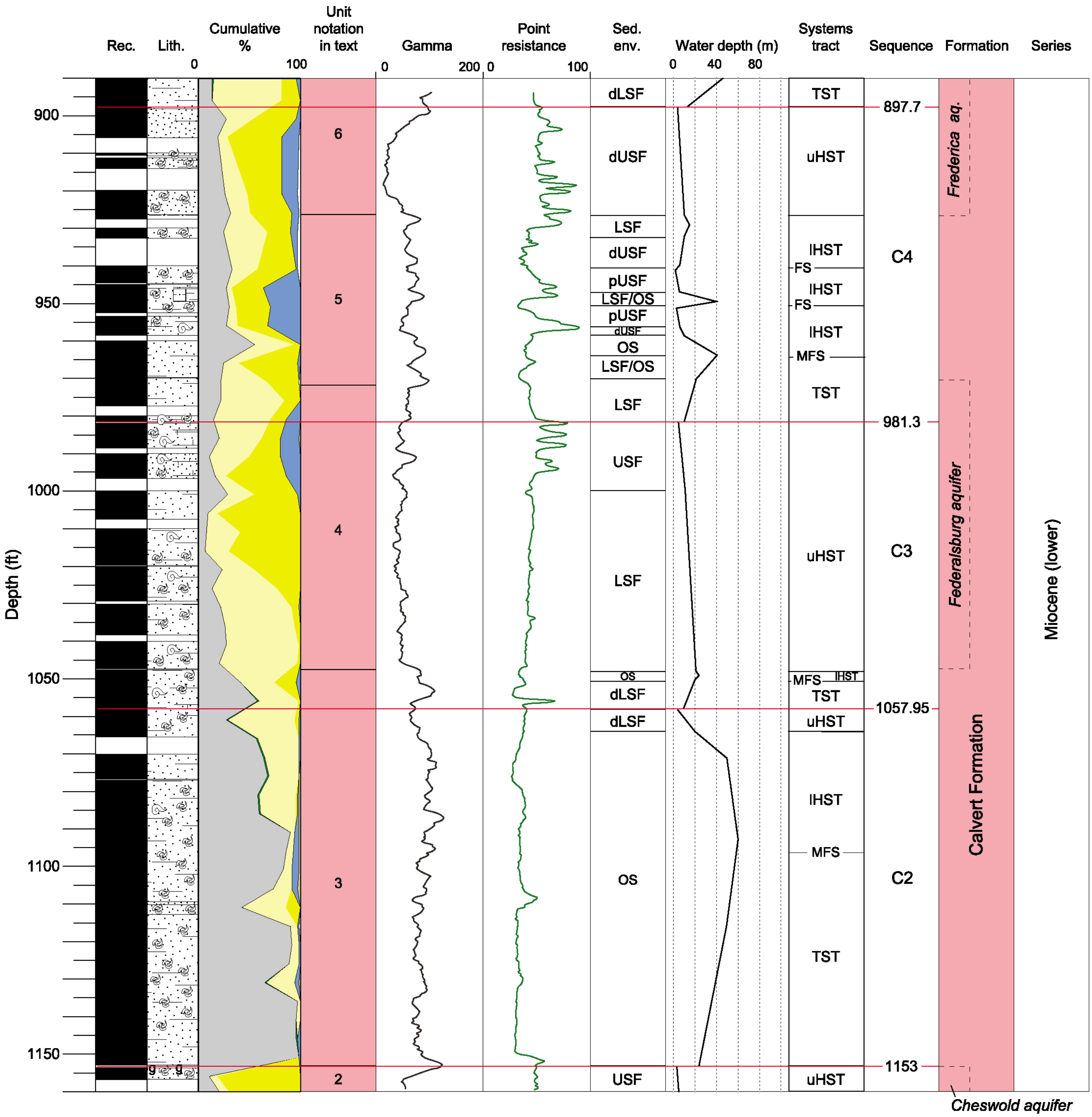

Figure 10. Summary stratigraphic section for the middle part of the Calvert Formation in Qj32-27. See Fig. 7 for key to lithology symbols and Figure 8 for explanation. HST-Highstand Systems Tract; uHST-Upper Highstand Systems Tract; lHST-Lower Highstand Systems Tract; TST-Transgressive Systems Tract; LST-Lowstand Systems Tract; FS-Flooding Surface; MFS-Maximum Flooding Surface; SB-Sequence Boundary; FL-Fluvial; Est-Estuarine; LEst-Lower Estuarine; USF-Upper Shoreface; pUSF-Proximal Upper Shoreface; dUSF-Distal Upper Shoreface; LSF-Lower Shoreface; pLSF-Proximal Lower Shoreface; dLSF-Distal Lower Shoreface; OS-Offshore.

is overlain by muddy offshore deposits characterized by *Pseudononion* foraminiferal biofacies mostly indicative of inner-to-middle neritic environments; a relatively diverse assemblage with deeper-water taxa suggests peak water depths (50-80 m) in the middle of this interval. Subsequent shallowing to a lower shoreface environment is traced by an increase in sand content. The uppermost part of this unit reflects deepening with a heavily bioturbated marine-flooding surface (1057.95 ft) overlain by lower shoreface sands and bioturbated offshore silt.

The middle sand, unit 4, traces another shoaling episode (Fig. 10). Environments change upward from lower shoreface, with inner neritic foraminifera of the *Pseudononion* biofacies to upper shoreface. The top of this sand reflects a transgression where the upper shoreface gives way to muddier lower shoreface environments.

The interval of variably muddy sands, unit 5, records a series of small transgressions and regression (Fig. 10). The lower part consists of silty offshore strata, reflecting deepening above the shoreface sands of unit 4. The middle and upper parts record shoaling to shoreface environments punctuated by two flooding surfaces (950.5 and 940.9 ft).

Unit 6 reflects another period of shoaling, the shell- and shell-fragment-rich sands representing deposition in an upper shoreface environment (Fig. 10). The uppermost portion of this sand represents a distinct transgression (Fig. 11), from upper shoreface sands to distal lower shoreface sands to offshore silts that mark the base of unit 7. Unit 7 represents the fine-grained, uppermost package in the Calvert Formation. An upward increase in sand content of the silts trace a gradual shallowing (Fig. 11). This shallowing is also reflected in the foraminifera, with the *Pseudononion* biofacies (25-50 m PWD) gaining elements of the shallower *Hanzawaia* biofacies upsection.

Pollen analysis suggests that the Calvert Formation was deposited during a time of climatic warmth. A number of plant species are represented in the pollen assemblage that no longer live in the region but are extant in warmer climates, including common *Engelhardia* (Fig. 6) in most samples and *Podocarpus* (in a reconnaissance sample from 985.7 ft). These pollen findings are consistent with those reported from the Calvert Formation in central Delaware by Groot (1992), who concluded that these assemblages reflect an environment similar to the modern Atlantic coastal plain of Georgia or Florida.

Choptank Formation (819.9-570.23 ft)

Nomenclature. Like the Calvert Formation, the Choptank Formation was defined by Shattuck (1902, 1904) in Maryland as a division of the Chesapeake Group based on lithology and fossil content. Rasmussen et al. (1960) first applied the name Choptank Formation in Delaware to the part of the Miocene that includes important aquifers near the town of Milford. It is characterized as interbedded fine to coarse sand, shell, silt, and some clay (Andres and Talley in Benson, 1990). In current use in Delaware, it is a sandier unit than both the overlying St. Marys Formation and the underlying Calvert Formation (Ramsey, 1997).

Lithologic Description. In the Bethany Beach borehole, the Choptank Formation is composed of shelly sand and some silt (Miller et al., 2003a), with the silt less common than in the underlying Calvert Formation. Seven, mostly coarsening-upward, packages can be recognized in the cores and on geophysical logs (Figs. 11 and 12).

Sand characterizes the lowest package in the formation, from 819.9 to 787.1 ft (Fig. 11). Between 819.9 and 805 ft, core recovery was limited to bits of shelly calcareous sandstone and unconsolidated fine-to-medium quartz sand with shell debris. Well-sorted, fine-to-medium sands from 804.55 to 787.1 ft have scattered silt and heavy mineral laminae (some cross laminae) and some indurated calcareous sandstone beds.

The next interval (unit 2), from 787.1 to 750.3 ft, fines upward from sand to silt (Fig. 11). The sandy lower part consists of silty, rubbly, shelly sand at the base (787.1-785.3 ft), with fragments of cemented sandstone and sand steinkerns, that passes into silty sand with some shell and cemented zones (785.3-780.0 ft) and shelly, bioturbated, sand and silt (779.1-765.0 ft). Together with the sands of underlying unit 1, these sands comprise a basal-Choptank sand package that appears to be equivalent to the Milford aquifer. The finer lithologies in the upper part of unit 2 are composed of the bioturbated, slightly clayey silt (765.0-750.3 ft), the top of which (751.5-750.3 ft) has abundant burrows filled with sand from the overlying unit.

Above this silt, the Choptank Formation coarsens upward overall, with a few thin fining intervals. Sandy lithologies (unit 3) from 750.3 to 700 ft (Fig. 11) change upward from fine to very fine, silty, slightly shelly, burrowed sand (750.3-720.0 ft) to less bioturbated fine sand (719.45-710 ft) to shelly, heavily bioturbated, medium to fine silty sand (703.2-700 ft).

Above a coring gap are two similar, overall coarsening-upward packages, from 694.1 to approximately 649 ft (unit 4) and from 648.3 to 606.75 ft (unit 5) (Fig. 11). Both have a thin (less than 10-ft-thick) basal fining-upward interval in which a shelly sand bed fines upward to silt (unit 4) or silty sand (unit 5). Above the finest lithologies, both intervals show coarsening from interlaminated silts and sands to progressively cleaner and coarser sand with more abundant shell material and some indurated intervals (such as 662.5-649 ft in unit 4).

The next package, from 606.75 to 580 ft (unit 6), also coarsens upward overall (Fig. 11 and 12). The base is marked by abrupt fining to heavily bioturbated, slightly muddy sand (606.75-593 ft). The remainder of the package coarsens from variably cemented, shelly sand with minor sandy silt (593-584 ft) to gravelly silty sand (584-581 ft), with a thin, slightly finer cap of fine- to medium-grained sand (581-580 ft).

The uppermost part of the Choptank Formation (unit 7) is thin, fining-upward package only partially recovered as core (Fig. 11). Shelly, poorly sorted sand (575.2-572.6 ft), its lower part cemented, transitions upward into muddy sand with progressively more common bioturbation (572.6-570.23 ft). This interval was placed in the St. Marys Formation in Miller et al. (2003a) but is here included in the Choptank Formation because of its sandy lithology.

Log Signature. The geophysical log character of the Choptank Formation in Qj32-27 helps separate it from the underlying Calvert Formation (Fig. 11). Sandy lithologies characterized by low gamma values, negative SP shifts, and relatively high resistivities/resistance predominate, with abundant single-point resistance spikes corresponding to cemented beds. Intervening muddier intervals with lower resistivities and slightly higher gamma values are less common; gamma values are not particularly high, reflecting the generally sandy character of even the muddier lithologies.

The Milford-aquifer-equivalent sand at the base of the formation from 819.9 to 765 ft has fairly low gamma values and higher resistivities/resistance, indicating it is a clean,

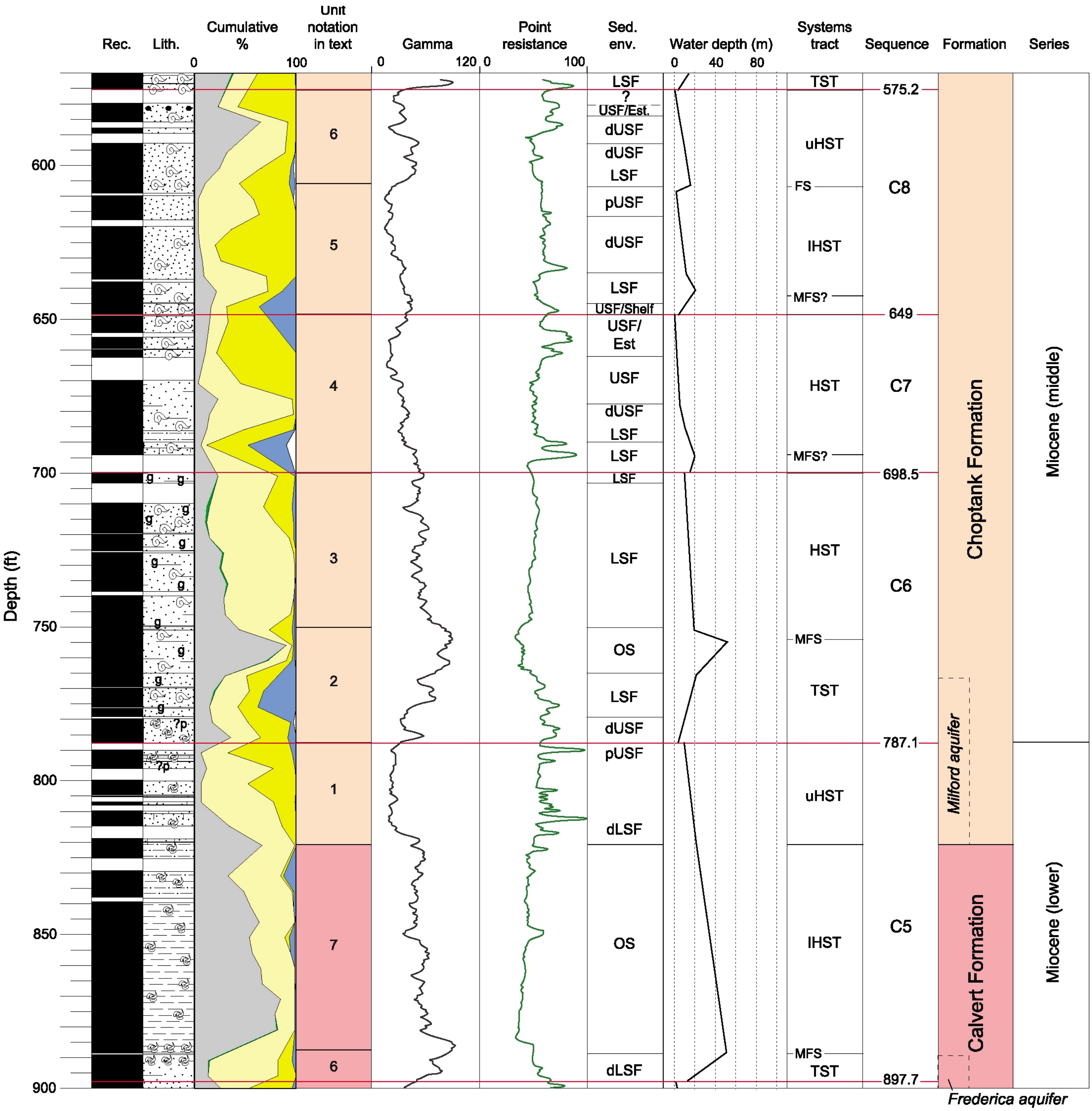

Figure 11. Summary stratigraphic section for the upper part of the Calvert Formation and for the Choptank Formation in Qj32-27. See Figure 7 for key to lithology symbols and Figure 8 for explanation. HST-Highstand Systems Tract; uHST-Upper Highstand Systems Tract; lHST-Lower Highstand Systems Tract; TST-Transgressive Systems Tract; LST-Lowstand Systems Tract; FS-Flooding Surface; MFS-Maximum Flooding Surface; SB-Sequence Boundary; FL-Fluvial; Est-Estuarine; LEst-Lower Estuarine; USF-Upper Shoreface; pUSF-Proximal Upper Shoreface; dUSF-Distal Upper Shoreface; LSF-Lower Shoreface; pLSF-Proximal Lower Shoreface; dLSF-Distal Lower Shoreface; OS-Offshore.

water-bearing sand (Fig. 11). Three other clean sands (low gamma, high resistivity) with cemented zones (single-point-resistance spikes) are evident on the logs in the upper part of the formation: at 670 to 649 (top of unit 4), 635.5 to 606.75 (top of unit 5), and 590 to 575 ft (top of unit 6) (these register about 3-4 ft above core depth). The log signatures suggest that these are aquifer-quality sands but, like the aquifer-quality sands in the Calvert Formation, have lower resistivities/resistance than the Manokin fresh-water sands above, possibly reflecting more elevated chloride levels. Stratigraphically equivalent sands in test well Oh25-02 near Lewes showed this same log character and produced

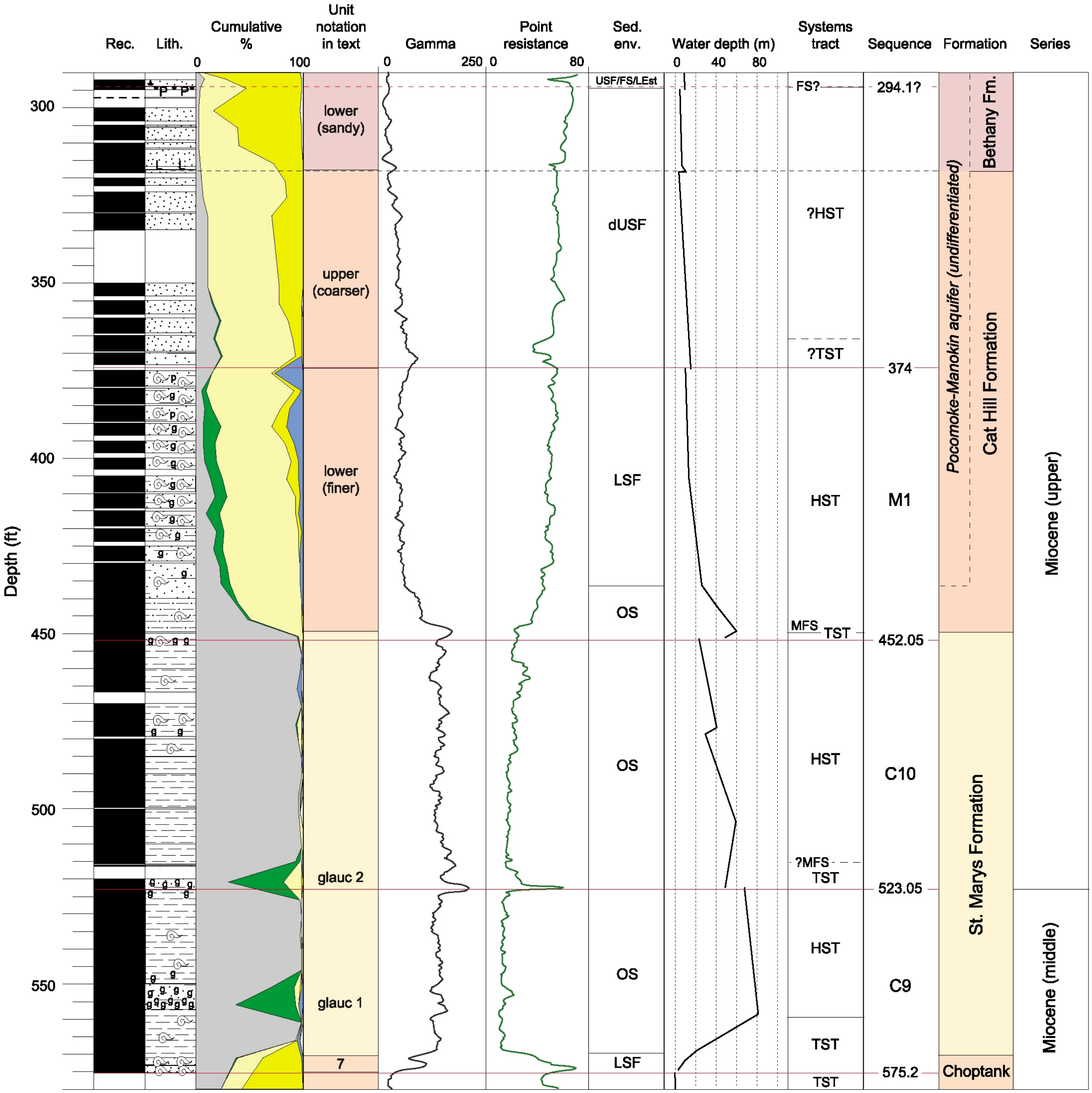

Figure 12. Summary stratigraphic section for the uppermost Choptank Formation, St. Marys Formation, Cat Hill Formation, and basal Bethany Formation in Qj32-27. See Figure 7 for key to lithology symbols and Figure 8 for explanation. HST-Highstand Systems Tract; uHST-Upper Highstand Systems Tract; lHST-Lower Highstand Systems Tract; TST-Transgressive Systems Tract; LST-Lowstand Systems Tract; FS-Flooding Surface; MFS-Maximum Flooding Surface; SB-Sequence Boundary; FL-Fluvial; Est-Estuarine; LEst-Lower Estuarine; USF-Upper Shoreface; pUSF-Proximal Upper Shoreface; dUSF-Distal Upper Shoreface; LSF-Lower Shoreface; pLSF-Proximal Lower Shoreface; dLSF-Distal Lower Shoreface; OS-Offshore.

ground water with chloride content of 600 mg/L (Talley *in* Benson, 1990). It is also worth noting that the greater abundance of cemented zones in the upper parts of the Choptank Formation is thought by some workers to negatively impact the quantity of water yielded by Choptank sands above the Milford aquifer (Talley *in* Benson, 1990; A.S. Andres, written communication, 2008). The Choptank sands in Qj32-27 are likely correlative with unnamed (or misnamed) upper Choptank fresh-water-bearing sands that are used for ground water where they occur at shallower depths in areas of Sussex County to the west and north.

Age. Shells in the cores from the Choptank Formation yielded 21 strontium ages, indicating this formation extends from near the top of the lower Miocene into the middle Miocene (Miller at al., 2003a). The age-depth plot for these data (Fig. 9) reveal a clear cluster of ages in the lower part of the formation and more scattered age-depth relationships in the upper part. The lower group of data points (below 700 ft) appear to date to between 17 and 16 Ma. Within this interval, the surface at the top of the Milford-equivalent sand (787.1 ft) appears to represent an unconformity, possibly only a minor age break or possibly a hiatus of as much as 0.5 m.y., depending on how best-fit lines are applied to the data.

The age data from the sandier higher part of the formation (above 700 ft) exhibit much more scatter and are generally between 15 and 13 Ma. The greater scatter and age uncertainty are expected because of the lower rate of change of sea-water strontium isotopes younger than 15 Ma (Oslick et al., 1994). Because this group of ages is notably younger than those in the lower part of the Choptank Formation, a hiatus of more than 1.m.y. is interpreted at around 700 ft. In addition, there appear to be two subgroups of strontium ages in this group, one older and one younger than 14 Ma; this suggests the presence of another significant unconformity at around 649 ft.

No stratigraphically significant planktic foraminifera, calcareous nannofossils, radiolaria, or diatoms were noted in the Choptank Formation samples examined. Dinoflagellates provide very broad stratigraphic constraints. *Polysphaeridium zoharyi* is the most common taxon, and its abundance just below occurrences of *Hystrichosphaeropsis obscura* and *Geonettia clinae* in the overlying St. Marys Formation was noted in the lower part of Zone DN8 (lower part of upper Miocene) in the Cape May, New Jersey, core hole (de Verteuil, 1997). A poor specimen resembling *Trinovantedinium glorianum*, which appears in mid-Zone DN7, occurs in the uppermost Choptank Formation at 520.0 ft, suggesting an age no older than approximately 12.4 Ma (Fig. 9).

Terrestrial pollen and spores in the Choptank Formation represent pollen Zones 5 and 6 (Fig. 6). The lower two samples (701.9 and 753.9 ft) are included Zone 6 (subzone a) and are dominated by *Quercus*, with common *Pinus* and *Carya*. Two upper samples (596.9 and 645 ft) reflect a different assemblage, designated Zone 5 (subzone b), dominated by *Pinus*, with abundant *Quercus* and common *Carya*. The change in pollen zones defined by cluster analysis is consistent with the unconformity suggested by strontium ages at around 700 ft. A single sample in the very top part of the Choptank Formation (572.0 ft) has a slightly different pollen assemblage, similar to overlying samples from the St. Marys Formation, and is grouped with them into subzone a of Zone 5 (Fig. 6). The presence of exotic taxa in these zones supports a middle Miocene age. Pazzaglia (1993) compared the flora of the Bryn Mawr Formation of Maryland closely to that of the Choptank Formation, especially the similar significant abundance of *Engelhardia*-type pollen, as a basis for suggesting that the Bryn Mawr Formation is the proximal, up-dip equivalent of the Choptank Formation.

Depositional Environment. The Choptank Formation was deposited in nearshore shallow marine environments. Analysis of paleoenvironments reveals a succession of smaller, gently shoaling-upward packages punctuated by minor deepening events or thin transgressive packages (Fig. 11). Scattered occurrences of foraminifera in the finer-grained lithologies suggest water depths were mostly no more than approximately 25 m.

The sandy interval that overlies the base of the formation, unit 1, was deposited in a high energy upper shoreface environment. The overlying fining-upward unit 2 reflects a transgressive succession from distal upper shoreface environments in the lower sandy part deepening to offshore environments in the upper muddy part. Foraminifera indicate that depths increase from shallow inner neritic, with *Hanzawaia* biofacies, to a peak of shallow middle neritic (~50 m PWD) where *Pseudononion* biofacies types occur with some deeper elements such as *Uvigerina*.

Sandier lithologies of units 3 and 4 trace a shallowing trend. The siltier finer sands of unit 3 reflect progressively shallower lower shoreface environments, whereas the mostly coarser, cleaner sands of unit 4 trace a transition to lower shoreface to upper shoreface and possibly estuarine environments. Foraminifera in the siltier beds in the upper part of this package (681-671 ft) are typical of the inner neritic *Hanzawaia* biofacies (10-25 m PWD). The increase in gamma-log values and decrease in resistivity- and resistance-log values suggest the presence of a minor marine-flooding surface in the coring gap between units 3 and 4.

The uppermost part of the Choptank Formation, consisting of units 5 and 6, is characterized by packages with a thin basal transgressive interval and a thicker upper regressive interval (Fig. 11). Deepening from coarser upper shoreface to finer lower shoreface is evident just above the base of unit 5, followed by a thicker shallowing-upward interval in which inner neritic (*Hanzawaia* biofacies, 10-25 m PWD) lower shoreface environments give way to proximal upper shoreface environments. The base of unit 6 is a marine flooding surface where the facies deepen to muddy, burrowed lower shoreface sands (basal unit 6). The section shallows upward from this point, transitioning from lower shoreface to upper shoreface or estuarine environments (at the top of unit 6). Unit 7 is a transgressive package that represents the uppermost part of the Choptank Formation, tracing deepening from upper shoreface to lower shoreface environments.

Pollen analysis suggests that the Choptank Formation, like the Calvert Formation, was deposited under a warm-temperate climate with forested areas dominating the nearby land masses. Arboreal types dominate, but there are a few occurrences of non-arboreal pollen, including Compositae (sunflower family) and Poaceace (grass family). Exotic, warm-climate taxa that are no longer present in or around Delaware occur in the Choptank Formation but are not as abundant as in the Calvert Formation (Fig. 6). *Engelhardia*-type pollen are significantly more abundant in the lower two-thirds of the formation (645.0 ft and lower) than in higher strata but are less abundant than in the Calvert Formation. *Pterocarya* and *Podocarpus* are also present in most Choptank samples, and *Symplocos* and possible *Manilkara* pollen are present in a few samples. Together, these occurrences suggest a warm-temperate climate, consistent with that reported for the Choptank Formation in Delaware by Groot (1997).

St. Marys Formation (570.23-449.4 ft)

Nomenclature. The St. Marys Formation was established in Maryland by Shattuck (1902) and first recognized in Delaware by Rasmussen (1960) as an important Miocene confining unit in Sussex County. It is characterized by glauconitic, laminated to burrowed, sandy and silty clays (Andres, 1986; Ramsey, 1997) and is finer-grained than the over- and underlying formations. In many places, it appears to gradually coarsen upward into the Cat Hill Formation (Andres, 1986, 2004).

Lithologic Description. The St. Marys Formation is an overall fine-grained interval with some glauconite-sand-bearing zones in the Bethany Beach borehole (Miller et al., 2003a) (Fig. 12). Most of the formation consists of grayish, laminated, slightly micaceous, slightly glauconitic silty clay and clayey silt with scattered shells. High-spired (*Turritella*) gastropods are typical of the St. Marys Formation at this site, especially higher in the unit; pyritic concretions are associated with burrows in the upper part of the formation.

The base of the formation is marked by a shift from sandy sediments of the underlying Choptank Formation to muddy sediments of the St. Marys Formation. The thin, fining-upward sandy interval between 575.2 and 570.23 ft is here included in the Choptank Formation, a change from its previous (Miller et al., 2003a; Browning et al., 2006) placement in the St. Marys Formation.

Two glauconite-rich intervals stand out in this overall mud-dominated unit (Fig. 12). The lowest is associated with a heavily burrowed contact at 557.5 ft. It is overlain by extensively burrowed, slightly shelly glauconite sand from 557.5 to 553.5 ft, with large glauconite-sand-filled burrows extending more than a foot below the base of the bed. The upper one is associated with a heavily burrowed contact in the core at 523.05 ft. Cemented siltstone underlies this surface (523.8-523.05 ft core depth, slightly higher on log), with glauconite-sand-filled burrows extending as much as 3 ft downward. Above it is silty glauconite sand (523.05-520.0 ft) with a few large shells (522-522.7 ft) and (above a coring gap) carbonate concretions with glauconite and scattered phosphate grains (516.2-515.5 ft).

The uppermost part of the St. Marys Formation is marked by two conspicuous, closely spaced, burrowed surfaces. One occurs at 452.45 ft, separating brown clay below from slightly silty, slightly glauconitic shelly clay above. The second, at 449.4 ft, marks the top of the formation, a lithologic change from muds of the St. Marys Formation below to sandy silt of the basal Cat Hill Formation above.

Log Signature. The St. Marys Formation contrasts with other Miocene formations by its generally high gamma values and low resistivities that reflect the fine-grained nature of the formation (Fig. 12). The base of the formation is characterized by an abrupt shift at around 570 ft from the lower gamma, higher resistivity sands of the underlying Choptank Formation. The top of the formation is evident just above 450 ft where the logs show an upward increase in resistivity and decrease in gamma values marking the boundary with the Cat Hill Formation.

The wireline logs highlight several important surfaces noted in the cores. An interval of slightly higher resistivity and gamma values is evident around 550 ft, reflecting the occurrence of glauconite sand above the 557.5-ft-surface. Around 520 ft, a pronounced gamma spike (521 ft) and single-point-resistance spike (520 ft) occur. These are associated with the burrowed contact noted at 523.05 ft, with the gamma reflecting the concentration of glauconite and the single-point-resistance highlighting the thin carbonate-cemented zone. An interval of higher gamma near the top of the formation (450 ft) reflects the abundance of glauconite-filled burrows just below the top of the formation.

Age. Shell material from the St. Marys Formation yielded six strontium ages that span the middle-upper Miocene boundary (Miller at al., 2003a). These fall into two groups on the age-depth plot (Fig. 9). A trend through the data in the lower group, between the base of the formation and the surface at 523.05 ft, suggests an age from 11.9 to 11.6 Ma (latest middle Miocene). The strontium ages from the upper part of the formation (above 523.05 ft) form an age-depth trend that continues into the overlying Cat Hill Formation; the age of the upper St. Marys is estimated as 10.6 to 10.2 Ma (earliest late Miocene) on this basis.

Age-significant planktic foraminifera are consistent with the strontium ages. Two species in the lower part of the St. Marys Formation (540-550 ft) suggest placement between the FAD of one, *Globorotalia menardii* (one juvenile specimen), in the middle part of the middle Miocene (~12 Ma) and the LAD of the other, *Globoquadrina dehiscens* (rare), near the top of the Miocene (5.8 Ma). At 506 ft, a single specimen resembling *Globorotalia pseudomiocenica* suggests this mid-St Marys sample is in the upper part of the upper Miocene (based on the species range reported in Bolli and Saunders, 1985), which would be 8.3 Ma or younger using the time scale of Berggren et al. (1995). If correct, this would suggest an age slightly younger than strontium isotope determinations.

The sample from 524.9 ft contains the highest stratigraphically significant dinoflagellates identified, which suggest upper Miocene Zone DN8 (~8.6-11.2 Ma). *Hystrichosphaeropsis obscura* limits it to a position below the top of upper Miocene Zone DN9. *Geonettia clinae* is common, a form that is restricted to Zone DN8 in the Cape May borehole, although it ranges overall from upper middle Miocene to near the top of the Miocene (de Verteuil and Norris, 1996; de Verteuil, 1997).

Terrestrial pollen and spores in the St. Marys Formation are characterized by a decrease in the abundance of exotic taxa and a corresponding increase in the abundance of non-arboreal pollen (NAP, including Compositae, Poaceae, Umbelliferae). This is likely the local manifestation of the late Miocene “modernization” of North American vegetation described by Graham (1999). Cluster analysis places the St. Marys samples in Pollen Zones 5 and 4 (Fig. 6). The lower two samples, from 524.9 and 477.0 ft, are grouped with the highest Choptank Formation sample into subzone a of Zone 5. The upper sample, from 449.9 ft, is grouped with samples from the overlying Cat Hill Formation in Zone 4, but is separated as subzone b, reflecting lower abundance of *Carya.* The transition from pollen Zone 4 to Zone 5, which occurs in the upper part of the St. Marys Formation, does not appear to represent an unconformity; strontium isotope ages instead suggest a hiatus occurs at 523.5 ft, in the middle of the formation (Fig. 9). Interestingly, another change in the pollen assemblages, the decrease in abundance of exotic taxa, appears to be associated with the unconformity rather than the zone boundary; for example, *Symplocos* and *Podocarpus* are absent, or nearly so, in the samples above the unconformity (477.0 and 449.9 ft).

Depositional Environment. The St. Marys Formation at Bethany Beach represents deposition in low-energy, shelfal environments in the deep-inner-neritic-to-middle-neritic depth zones (25-75 m). The predominantly fine-grained deposits in this formation generally reflect deeper-water conditions than those of the underlying Choptank Formation.

Two paleoenvironmental cycles are evident, each with slight deepening at the base followed by shoaling. The lowest package (570.23-523.05 ft) has a thin basal transgressive interval where offshore silts with foraminifera suggestive of PWDs around 75 m (diverse *Uvigerina* biofacies assemblage) are capped by glauconite sand (557.5 ft) representing sediment starvation at the peak of transgression (Fig. 12). In the silts above this, foraminifera suggest a degree of shoaling (*Pseudononion* biofacies).

The upper package (523.05-452.45 ft) exhibits a similar succession, but in slightly shallower environments. Environments deepen in the lower part where glauconite sand passes upward to clay with PWDs of at least 50 m at around 500 ft (diverse deep *Pseudononion-type* biofacies). This is followed by gradual shoaling to inner neritic environments with PWDs of around 25 m (less diverse shallow *Pseudononion* biofacies). A heavily burrowed contact (452.45 ft) near the top of the formation marks an abrupt deepening to offshore clays reflecting PWDs of more than 50 m.

The pollen assemblage appears to represent a warm-temperate climate. Exotic, warm-climate taxa are present but overall not as common as in underlying formations; these include *Engelhardia, Pterocarya, Podocarpus*, and *Symplocos*. However, the first significant incursion of non-arboreal pollen (NAP, Fig. 6) in the hole is noted in the St. Marys Formation, suggesting a change in environmental conditions. Although tree pollen (arboreal pollen, AP) are most abundant, including *Quercus* (oak), *Pinus* (pine), and *Carya* (hickory), non-arboreal pollen include abundant Compositae (sunflower family) as well as some Poaceae (grasses) and Umbelliferae (carrot family). The increase of NAP likely reflects the greater abundance of open areas that favor growth of grasses and herbaceous plants, possibly related to cooler and/or drier climatic conditions. Similar St. Marys assemblages were reported in southern Delaware by Groot (1997).

Cat Hill Formation (449.4 - 318.35 ft)

Nomenclature. The Cat Hill Formation is characterized by gray sand with some beds of gravel and local clayey/silty, lignitic, and shelly beds (Andres, 2004). It typically coarsens upward, is sandier overall than the underlying St. Marys Formation, and generally lacks the significant thicknesses of fine-grained interbeds characteristic of the overlying Bethany Formation. The Manokin aquifer is commonly identified in this unit and, as a result, it was for a time informally referred to as the Manokin formation (Andres, 1986). In this report, the stratigraphic extent of the Cat Hill Formation differs slightly from that of the Manokin formation in Miller et al. (2003a).

Lithologic Description. The Cat Hill Formation exhibits a clear coarsening-upward succession in the Bethany Beach borehole (Fig. 12). It can be divided into two parts: a lower finer-grained, slightly glauconitic part (449.4-375 ft) and an upper coarser-grained part (373.15-318.35 ft).

The base of the formation is a burrowed contact (449.4 ft) marked by a shift to sandy sediments above the muddy strata of the underlying St. Marys Formation (Fig. 12). The lower, finer part of the formation changes upward from sandy silt (449.4-445 ft), to silty sand with an increasing amount of sand and decreasing amount of silt (445-438 ft), to fine-grained sand (438-375 ft), with an upward increasing component of medium-grained sand (above 415 ft) and granules (403.3-375 ft). Above 415 ft, the section includes more abundant, thicker, larger shells; they are especially abundant above 380 ft, with shell content ranging from large, whole clams (*Mercenaria*) to coarse shell hash. Phosphate pebbles occur between 390 and 375 ft. Glauconite is generally common through this interval, the highest pre-Pleistocene occurrences of more than 1 percent in washed sand residues.

The upper part of the Cat Hill Formation is slightly coarser grained and bioturbated (Fig. 12). It includes a thin basal bed of slightly silty fine sand (373.15-370 ft) that coarsens upward into generally well-sorted, fine to medium sand (369.3-318.35 ft). These sands have conspicuous fine disseminated plant debris, mica, and scattered phosphatic pebbles. Glauconite is present in only trace amounts and shell material is mostly absent. The top of the formation is marked by a shift from sand to a thin muddy bed at 318.35 ft.

Log Signature. The Cat Hill Formation has a distinctive coarsening-upward character on geophysical logs, reflected in an overall steady decrease in gamma and increase in resistivity/resistance (Fig. 12). These log trends reflect the increasingly clean, coarser-grained, permeable character of the sands higher in the unit. However, it also may partially reflect an upward change in ground-water chemistry from slightly saline to fresh, as has been noted in other wells in the Bethany Beach area (Talley and Andres, 1987).

One gamma spike occurs within the unit, a minor peak around 374 ft where phosphate pebbles occur. A slight increase in gamma and slight decrease on the single-point-resistance and short-normal resistivity logs at around 317 ft marks the occurrence of multiple thin-beds of clay and silt that defines the base of the overlying Bethany Formation.

Age. Strontium isotopic age estimates in the Cat Hill Formation are limited to the lower part of the unit, where suitable shell material occurs (Miller at al., 2003a). Samples from seven beds between 448.4 and 376.25 ft yield ages that range from 11.7 to 9.6 Ma, though they cluster from 10.5 to 9.6 Ma (Fig. 9). On this basis, the Cat Hill Formation is considered upper Miocene.

Although the sandy lithology of this unit is not optimal for palynology, two samples (413.9 and 356.9 ft) yielded assemblages dominated by abundant *Quercus* and *Carya.* Cluster analysis places them (along with two higher samples from the lowermost Bethany Formation) in Zone 4, subzone a (Fig. 6). The trend of decreasing abundance of exotic taxa noted in underlying units continues, consistent with expectations for a late Miocene assemblage. *Pterocarya* occurs in most of the samples; *Engelhardia*-type pollen and *Podocarpus* have rare occurrences.

Depositional Environment. The Cat Hill Formation represents a shallowing-upward succession of shelfal to nearshore sediments. The lower portion of the formation (449.4-375 ft) becomes sandier upward, paralleled by a change from richer *Pseudononion* biofacies (~50 m PWD) to less diverse, lower abundance *Pseudononion* biofacies (~25 m PWD). These facies changes reflect shoaling from offshore to lower shoreface environments (Fig. 12).

The upper part of the formation (373.15-318.35 ft) appears to be shallower nearshore deposits (Fig. 12). The silty sand bed at the base (373.15-370 ft) represents a minor marine-flooding event, shoaling above to cross-bedded upper shoreface sands. Foraminifera, and all shell material, are absent in the upper part of the Cat Hill Formation. This may be a result of the paleoenvironments but, given the interpreted marine nature of these strata, is more likely due to dissolution by ground water flowing through these very permeable sandy lithologies.

Palynomorphs indicate deposition in a warm temperate climate. Exotic subtropical to tropical taxa are present but rare and less common than in the underlying St. Marys Formation (Fig. 6). *Pterocarya* occurs in most of the samples. *Engelhardia-type* pollen (356.9 ft) and *Podocarpus* pollen (413.9 ft) each occur in a sample. Non-arboreal taxa are notable, as in the St. Marys Formation, suggesting some open space in the nearby land areas. Umbelliferae (carrot family) is a common component of the flora, and *Ambrosia*-group composites (ragweed), Caryophyllaceae, Chenopodiaceae-Amaranthaceae, and Poaceae (grasses) are also present.

Bethany Formation (318.35-117.5 ft)

Nomenclature. The Bethany Formation is a lithologically heterogeneous unit of clayey and silty beds with discontinuous lenses of sand (Andres, 1986, 2004; Ramsey, 2003). Plant debris, mica, and heavy mineral laminae are common; granule and pebble layers occur in places. This unit is restricted to the subsurface and includes the Pocomoke aquifer, which is a prolific producer of ground water in coastal Sussex County.

The Bethany Formation was first informally established in Andres (1986) and formally described (along with the Cat Hill Formation) in Andres (2004). It is generally differentiated from the underlying Cat Hill Formation and overlying Beaverdam Formation by the abundance of muddy lithologies and its "saw-tooth" gamma log pattern. However, because it includes significant but scattered sand packages, its formation boundaries can in places be marked by a sand-on-sand contact and, thus, difficult to identify with certainty. This difficulty is compounded by significant lateral and vertical facies changes that can make the boundary clear in one location but unclear less than a mile away. With this understanding, the boundary between the Bethany Formation and the underlying Cat Hill Formation is defined differently in this report than it isin Miller et al. (2003a).

Lithologic Description. In Qj32-27, the Bethany Formation is composed of a predominantly sandy lower portion (318.35-197.6 ft) and an upper portion characterized by intercalated sandy and muddy strata (197.6-117.5 ft) (Figs. 12 and 13). The predominance of sand in the lower part of the formation at this site is somewhat atypical, lacking the interbedded muds typical of this interval in most borehole records from coastal Sussex County.

The lower part of the Bethany Formation in Qj32-27 (318.35-197.6 ft) is superficially similar to the underlying Cat Hill Formation but differs in its distinctly coarser grain size; medium-grained and coarser quartz sand constitutes more than 50 percent of the sediment in most samples examined, in contrast with predominantly fine and very fine quartz sand in the Cat Hill samples (Fig. 12). The formation boundary is placed at the base of the lowest (318.35-318.0 ft) of several thin beds of silty, organic-rich clays (also at 317.55-317.25 ft and 305.65-305.5 ft). Between 318 and 205.1 ft, the sands are generally homogenous, bioturbated, and predominantly medium-grained (Figs. 12 and 13). Although core recovery was incomplete, cores and wireline logs suggest fining-upward successions of several feet thickness are common in the sandy zones. A notable bedding contact occurs at 294.0 ft where thin clay (294.1-294.0 ft) is overlain by gravelly sand (294.0-293.8 ft). Cross bedding, highlighted by concentrations of opaque heavy minerals on bedding surfaces, is more common above 294.0 ft. Disseminated plant debris is more abundant above 232 ft. From 205.1-197.6 ft, the sands become fine grained, silty, and heavily bioturbated (Fig. 13).

The upper part of the Bethany Formation, above 197.6 ft, is characterized by an alternation between muddy and sandy lithologies (Fig. 13) typical of this unit. A muddy interval from 197.6 to 185.6 ft includes white clay (197.6-197.4 ft) capped by an irregular surface, overlain by sandy silty clay (197.4-193.5 ft), sandy clayey silt (193.5-188.5 ft), and silty sand with plant fragments and silt laminae (188.5-185.6 ft). A fining-upward package occurs from 185.6 to 150.5 ft; a thin layer of gravelly sand (185.6-185.4 ft) passes into well-sorted sands with heavy mineral laminae (185.4-173.0 ft), silty, bioturbated fine to medium sands (173.0-162.25 ft), and heavily bioturbated, muddy, fine to medium sands with scattered clayey laminae (162.25-150.6 ft). This fining-upward pattern is repeated, with coarser grain sizes, from 150.6 to 117.5 ft. Above a sharp, irregular, burrowed contact at 150.6 ft are

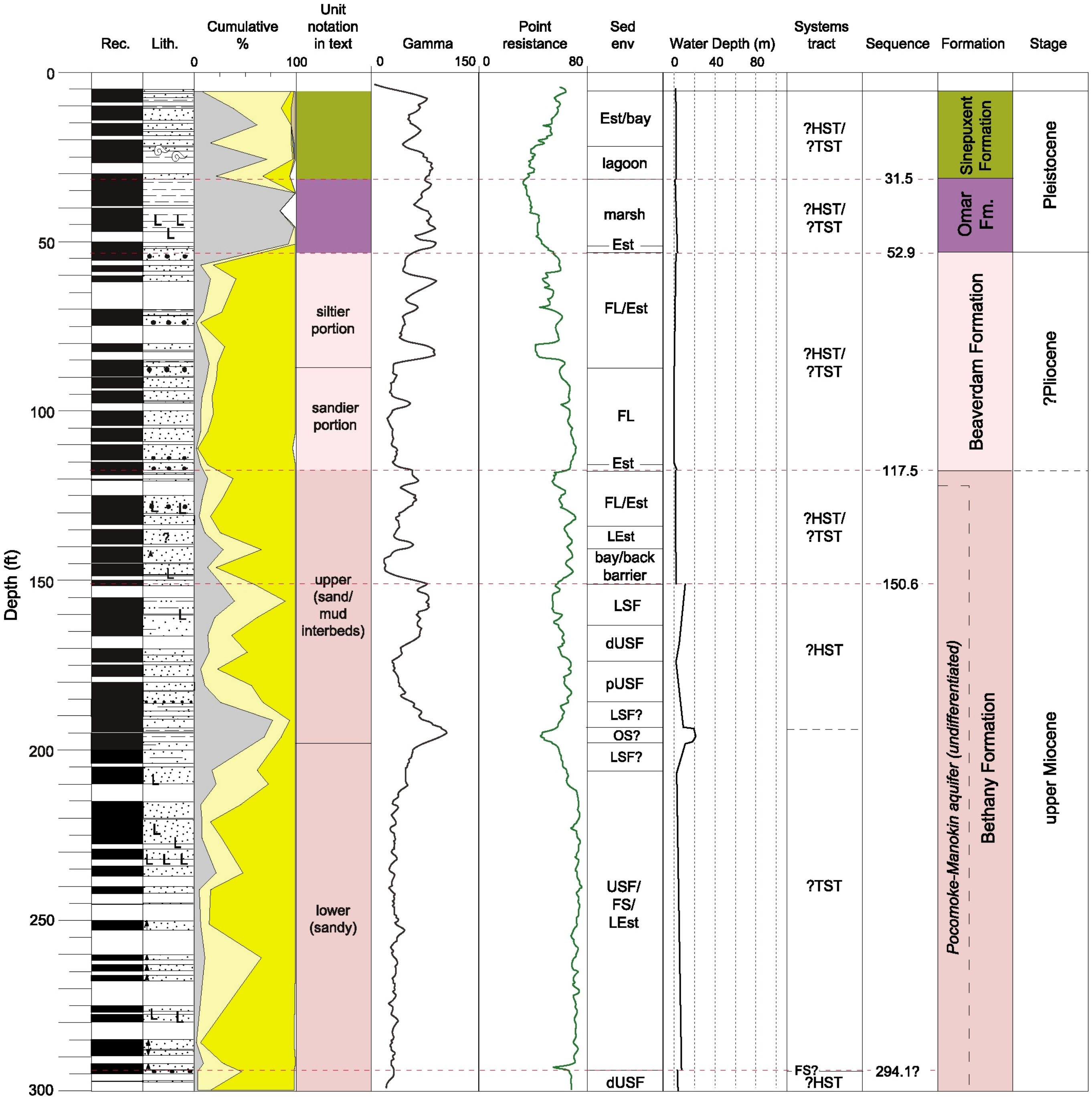

Figure 13. Summary stratigraphic section for the Bethany Formation, Beaverdam Formation, Omar Formation, and Sinepuxent Formation in Qj32-27. See Figure 7 for key to lithology symbols and Figure 8 for explanation. HST-Highstand Systems Tract; uHST-Upper Highstand Systems Tract; lHST-Lower Highstand Systems Tract; TST-Transgressive Systems Tract; LST-Lowstand Systems Tract; FS-Flooding Surface; MFS-Maximum Flooding Surface; SB-Sequence Boundary; FL-Fluvial; Est-Estuarine; LEst-Lower Estuarine; USF-Upper Shoreface; pUSF-Proximal Upper Shoreface; dUSF-Distal Upper Shoreface; LSF-Lower Shoreface; pLSF-Proximal Lower Shoreface; dLSF-Distal Lower Shoreface; OS-Offshore.

medium to coarse sands (150.6-135.0 ft), coarser and more granule-rich near the bottom, passing upward into poorly sorted, granule- and pebble-bearing muddy sands (133.3-117.85 ft), capped by thin, finely laminated, olive-gray clay with plant debris and lignite fragments (117.85-117.5 ft). This highest fining-upward package is here designated as the uppermost part of the Bethany Formation. It could potentially be included in the Beaverdam Formation based on the coarseness of the sediments, but the greater abundance of plant debris, the presence of marine indicators (dinoflagellates), and the correlation to other nearby wells suggest it is better included in the Bethany Formation.

Log Signature. The Bethany Formation exhibits in Qj32-27 the “saw-tooth” geophysical log pattern described as characteristic of this unit by Andres (1986). Above the thick lower sandy zone, logs trace an alternation between sandy intervals, which have lower gamma and higher resistivity/resistance values, and clay/silt intervals, which have higher gamma and lower resistivity/resistance values (Figs. 12 and 13). The sand packages mostly exhibit fining-upward patterns on these logs, paralleling the fining-upward lithologies noted in the cores.

The low-gamma, high-resistivity/resistance interval in the lower part of the Bethany Formation makes up a thick unit of clean, permeable, fresh-water-bearing sands. The thinner high-resistivity/resistance, low gamma, sand zones in the upper part of the Bethany Formation also appear to be capable of producing water. Sands in this interval are commonly referred to the Pocomoke aquifer.

Age. Age control is generally lacking in the Bethany Formation. No shell material was recovered for strontium isotope dating and no calcareous microfossils were noted. Only palynological analysis provides insights into the age of this unit (Fig. 6). The lower Bethany Formation samples (317.3 and 305.5 ft) yielded *Quercus*- and *Carya*-dominated assemblages similar to the two Cat Hill Formation samples; they are placed, with them, into pollen Zone 4, subzone a. The five samples yielding palynomorphs in the upper part of the Bethany Formation (224.4, 196.1, 156.1, 127.0, 117.8 ft) constitute the cluster defining Zone 3. These have assemblages dominated by *Carya* and *Quercus*, but differ from Zone 4 in more abundant *Fagus, Liquidambar*, and polypodiacean fern spores. Rare grains of *Pterocarya* and *Engelhardia*-type pollen, both exotic types, are present in all Bethany Formation samples studied and have their highest occurrences at 117.8 ft. Groot et al. (1990) treated the presence of exotic taxa as indicative of a pre-Pleistocene age. In addition, a single specimen of an exotic form possibly attributable to *Dacrydium* (Huon Pine) was noted at 156.1 ft; this conifer is currently restricted to Asia, Australasia, and western South America, but its pollen was recently noted in the Pliocene of Florida by Hansen et al. (2001). Together these occurrences suggest that the Bethany Formation was deposited during late Miocene or Pliocene times.

Depositional Environment. The Bethany Formation was deposited in shallow-marine to estuarine environments. Sedimentary facies reflect an overall shallowing of environments with a few deepening events (Figs. 12 and 13).

Facies in the thick sandy lower portion of the Bethany Formation (318.35-197.6 ft) suggest nearshore marine environments. Environments are interpreted to shallow overall from distal upper shoreface (318.35-294.1 ft) to upper shoreface and estuarine facies (294.0-205.1 ft) as cross-laminations and plant debris become more frequent. A thin clay bed (294.1-294.0 ft) is interpreted to represent a minor marine-flooding event. The increase in mud and burrowing at the top of this sandy interval (205.1-197.6 ft) suggests deepening to a lower shoreface environment.

The lithologically more heterogeneous upper part of the Bethany Formation, (197.6-117.5 ft), reflects greater variation of coastal environments (Fig. 13). This part of the formation can be subdivided into two packages: a lower marine-influenced package (197.6-150.6 ft) and an upper more estuarine-influenced interval (150.6-117.5 ft). The base of this package is marked by a thin bed of white clay (197.6-197.4 ft) that visually resembles kaolinite and, if so, may reflect a period of subaerial exposure and weathering. This possible exposure surface is immediately overlain by darker silty clay that appears to be a marine deposit (197.4-185.6 ft), reflecting a marine-flooding event followed by gradual shoaling from offshore clay to lower shoreface sands and then abruptly to sandy foreshore/upper shoreface facies (185.6-173.0 ft). The top of this marine package exhibits deepening from upper shoreface to muddier lower shoreface environments (173.0-150.6 ft). The more estuarine package at the top of the formation begins at a sharp, irregular, burrowed contact (150.6 ft). Above this surface, facies reflect shoaling from coarse-grained, plant-debris-rich estuarine or tidal channel deposits (150.6-135.0 ft) to marginal-marine interbedded coarse sands and muds (133.3-117.5 ft).

The pollen of the Bethany Formation suggests deposition under warm climatic conditions, like the underlying Cat Hill Formation. The consistent presence of exotic pollen such as *Pterocarya* and *Engelhardia*-type suggests a warmer climate than at present (Fig. 6). Although the assemblage is dominated by arboreal pollen (especially *Carya* and *Quercus*), nearby land areas likely had some open spaces based on the common occurrences of non-arboreal taxa (NAP including Poaceae, Chenopodiaceae-Amaranthaceae, *Ambrosia*-group composites).

Beaverdam Formation (117.5-52.9 ft)

Nomenclature. The Beaverdam Formation consists primarily of white to buff to greenish-gray quartz sand with notable potassium feldspar, some gravelly sand, and lesser light gray to greenish-gray silty clay, deposited in fluvial and estuarine environments (Groot et al., 1990). It was originally described in Maryland (Rasmussen and Slaughter, 1955) and later recognized in Sussex County by Rasmussen at al. (1960) and Jordan (1962). Groot et al. (1990), Andres and Ramsey (1996), and Andres and Klingbeil (2006) described a general upward decrease in grain size in the Beaverdam Formation in Sussex County, the lower part characterized by coarser and more gravel-rich sediments and the upper part by less coarse sand with more common occurrence of thin mud beds and a whitish silty matrix in the sand beds. On the basis of pollen, Groot and Jordan (1999) considered this unit to be Pliocene.

Lithologic Description. At Bethany Beach, the Beaverdam Formation is differentiated from the underlying Bethany Formation and overlying Omar Formation by its overall sandier nature. The formation exhibits an overall upward decrease in grain size and a corresponding increase in silt and clay (Fig. 13). Sand grain sizes are variable.

The bottom of the formation is moderately well-sorted fine to medium sand (117.5-115 ft) with granules and pebbles at the base. Above this, the lower part of the formation is more poorly sorted, fine to coarse granular sand with some zones of very coarse sand, granules, and scattered pebbles (108.7-86.85 ft). A notable mud bed occurs from 86.85 to 86.3 ft, above which the formation becomes a bit finer grained.

The upper part of the formation is also generally coarse sand, more poorly sorted, and has a slightly more silty matrix. It includes interbedded, thin, light-colored clay/silt beds (85.55-85.0 and 70.6-70.15 ft), scattered cross laminae rich in plant debris, and scattered small pieces of clay (possibly rip-up clasts). Orange-tinted possible feldspar grains, noted by Ramsey (*in* Benson, 1990) and Andres and Ramsey (1996) as typical of the Beaverdam Formation, are more common in the upper part of the formation in Qj32-27.

Log Signature. The Beaverdam Formation is an overall low-gamma, high resistivity/resistance unit on geophysical logs at Bethany Beach, reflecting the prevalence of permeable sands (Fig. 13). The lower part of the formation exhibits a very blocky log character (117.5-85 ft), with a relatively sharp base and top. Resistivity and resistance are fairly high, but not as high as in the underlying aquifer intervals. A thin clay bed occurs at 85 ft and registers clearly on most of the logs. Above that, the upper part of the formation has an overall gentle increase in gamma with a more irregular, spiky log pattern, representing sandy, permeable lithologies with scattered thin clay beds and muddy matrix in some of the sand beds. In Sussex County, the sands of the Beaverdam Formation make up, volumetrically, most of the Columbia aquifer, which is typically an unconfined aquifer (Andres and Klingbeil, 2006). However, in Qj32-27, the water-bearing sands of the Beaverdam Formation are at least locally confined by the overlying clays of the Omar Formation.

Age. No data are available from Qj32-27 to constrain the age of the Beaverdam Formation. All samples examined for palynomorphs had very poor recovery or were barren. No shell material was found. Previous work suggests a possible Pliocene age based on the presence of exotic taxa at other locations that have been placed in the Beaverdam Formation by other workers (Groot et al., 1990; Owens and Denny, 1979; Groot and Jordan, 1999); however, these are not definitive.

Depositional Environment. The Beaverdam Formation in Qj32-27 appears to record an overall upward trend from fluvial to estuarine conditions (Fig. 13). The granule- to pebble-bearing, cross-bedded sand in the lower part of the formation (117.5-87 ft) indicates fluvial environments. The increase in mud in the upper part (86.85-52.9 ft) suggests estuarine influence. Although no marine microfossils were found in the Beaverdam in this borehole, rare dinoflagellates have been reported in the Beaverdam Formation elsewhere in Sussex County (Groot et al., 1990; Groot and Jordan, 1999), suggesting marine influence in places. The presence of exotic pollen types such as *Pterocarya* reflect a warmer climate than today.

Omar Formation (52.9-31.5 ft)

Nomenclature. The Omar Formation was established by Jordan (1962) as a heterogeneous unit of gray quartz sands interbedded with clayey silts and silty clays that commonly contain abundant plant debris. In places, it contains shell beds dominated by *Crassostrea* and *Mercenaria* (Groot et al., 1990). The formation appears to represent a complex of nearshore, lagoonal, and salt-marsh environments. It has been recognized in eastern Sussex County and nearby areas of southeastern Maryland. Most previous age data indicate the Omar Formation is Pleistocene; a few samples referred to the Omar Formation (Groot et al., 1990; Groot and Jordan, 1999) have been suggested to be Pliocene.

Lithologic Description. The predominantly muddy interval from 52.9 to 31.5 ft in Qj32-27 is placed in the Omar Formation (Fig. 13). The bottom of the formation is an abrupt contact marked by slightly sandy greenish gray clay (52.9-50.65 ft) resting on the sands of the underlying Beaverdam Formation. At the top of this clay is an abrupt and irregular surface (50.65 ft) with a distinct color change just below it. Above it (50.65-31.5 ft) the section is a thick interval of laminated, dark, predominantly organic-rich, clay. Plant debris is abundant and commonly aligned with laminations; a clayey peat occurs at 41.0 to 40.7 ft. The clays are generally dark gray-olive, the color varying slightly, with lighter and darker laminae. Rare fine fragments of thin shells are present in places. The top of the formation is marked by a sharp lithologic change from sticky, plastic Omar clay to soft, slightly muddy sand of the overlying Sinepuxent Formation.

Log Signature. Geophysical logs reflect a shift to fine-grained sediments at the base of the Omar Formation. Generally, gamma values are moderately high and resistivity/resistance generally low in this unit, with minor variations in the logs reflecting the interbedding of clay, plant-debris-rich clay, and muddy sands.

Age. The pollen in Omar Formation samples examined from Qj32-27 (34.4, 40.9, 45.8 ft) constitute a warm-climate pollen assemblage consistent with the previously published Pleistocene ages for this unit (Owens and Denny, 1979; Groot et al., 1990; Groot and Jordan, 1999). On the basis of cluster analysis, they form a separate group of samples, herein designated Zone 2 (Fig. 6). They reflect a distinct change from underlying strata and are distinct from the cooler-climate assemblage of the overlying Sinepuxent Formation. *Pinus* (pine) and *Quercus* (oak) are the most abundant, with *Pinus* increasing upward somewhat as *Fagus* (beech) becomes less abundant. No pre-Pleistocene exotic taxa were noted.

The Pleistocene age interpretation is consistent with amino acid racemization ages in Aminozone IIc (200,000-250,000 yrs BP) or IId (400,000-600,000 yrs BP) for samples from eastern Sussex County and nearby Maryland cited in Groot et al. (1990). Radiocarbon accelerator mass spectrometer dates of $>48.0 \pm 10.5$ ka at 40.9 to 40.95 ft and 47.1 $\pm$ 1.2 ka at 50.4 to 50.5 ft cited in Miller at al. (2003a) likely reflect low residual 14C in radioactively "dead" carbon and are therefore not age diagnostic.

Depositional Environment. The Omar Formation in Qj32-27 represents marginal marine deposits; pollen data suggest this unit was laid down during a period of warm climate. The bottom of the formation is interpreted as an unconformity at the base of an incised valley. The thin green clay above it (52.9-50.65 ft) is interpreted as a low-energy estuarine (lagoonal) deposit representing incised-valley fill. The irregular nature and color change at the top of the green clay suggests subaerial exposure and a depositional break within the Omar Formation (Fig. 13). The overlying dark gray to black clays (50.65-31.5 ft) that comprise most of the Omar Formation are very rich in terrigenous plant material but also contain dinoflagellates, supporting the interpretation of estuarine or marine-influenced conditions. Therefore, we consider it likely that these dark clays were deposited in salt-marsh environments or estuarine environments adjacent to marshes. The lithologic break at the top of the formation is considered to represent a hiatus between Pleistocene warm-climate deposits of the Omar Formation and younger Pleistocene cool-climate deposits of the Sinepuxent Formation.

Sinepuxent Formation (31.5-5.0 ft)

Nomenclature. The Sinepuxent Formation was defined by Owens and Denny (1979) as micaceous sand with beds of black clay and peat in drill holes at Sinepuxent Neck, approximately 20 miles south of Bethany Beach in Worcester County, Maryland. Conspicuous mica content is a distinguishing characteristic. Owens and Denny (1979) and, more recently, Andres and Klingbeil (2006) have recognized this unit in coastal southern Delaware, including in the Bethany Beach area.

Lithologic Description. In Qj32-27, the Sinepuxent Formation encompasses the uppermost sub-soil deposits cored and is composed of interbedded sand and clay extending from 31.5 to 5.0 ft (Fig. 13). It is similar to the underlying Omar sediments but is sandier and contains several percent mica in most washed residues. The lower contact is marked by a basal poorly sorted sand (31.5-30.0 ft) resting on clay of the underlying Omar Formation. This is overlain by an interval of slightly micaceous silt and clay with abundant shells and a few beds of sand (26.3-21.8 ft); a zone of very fine, micaceous sand with common plant debris aligned with laminations (21.8-10.7 ft); and, at the top (10.7-5.0 ft), interbedded silty, micaceous, laminated clay and loose, watery sand.

Log Signature. Geophysical logs reflect the coarsening of the section above the underlying Omar Formation. This coarsening is manifested by lower gamma-log and significantly increased resistivity- and resistance-log values, the latter reflecting the fresh-water content of these permeable near-surface sediments (Fig. 13).

Age. The pollen assemblages of three samples studied (8.0, 16.4, 24.5, ft) are a cool-climate flora and reflect a distinct change from the underlying Omar Formation. These samples are dominated by *Pinus* (pine) and *Picea* (spruce); other common constituents include *Betula* (birch), *Carya* (hickory), *Quercus* (oak), *Sphagnum* (moss), *Lycopodium* (clubmoss), Polypodiaceae (polypod fern family), Poaceae (grass family), and Cyperaceae (sedge family). These samples are distinctly different from any other samples in the core, and are grouped as Zone 1 on the basis of the cluster analysis (Fig. 6). On the basis of the pollen and stratigraphic position, we interpret this unit as being deposited in a cool part of the late Pleistocene, consistent with the pollen results reported by Owens and Denny (1979).

An amino acid racemization age of 100,000 +/- 25,000 (youngest Aminozone IIa) was reported by McDonald (1981) from a sample assignable to the Sinepuxent Formation in nearby hole Qj22-06 (-24.5 to -21.2 ft msl), about the same elevation as the shell-bearing Sinepuxent interval (26.3-21.8 ft depth) in this hole. An age of 1 ± 0.35 Ma cited by Miller at al. (2003a) from strontium isotope analysis of a shell at 24.6 ft in Qj32-27 is not consistent with other age data from this unit.

Depositional Environment. The Sinepuxent Formation at Bethany Beach is composed of deposits likely laid down in a marginal marine setting (Fig. 13). The base of the formation represents an unconformity between older, warm-climate Pleistocene deposits of the Omar Formation and cool-climate Sinepuxent deposits. Interbedded shelly sands and clays between 31.5 and 21.8 ft are likely back-barrier lagoonal or estuarine deposits. They include the bivalve *Mulinia*, a form common in estuarine environments on the east coast of North America. The sandier section above that from 21.8 to 5.0 ft likely represents estuarine deposition, with dispersed plant debris (probably from nearby marshes) abundant in both the sands and the clays. A cool-temperate climate is indicated by the palynomorphs, as also reported in Owens and Denny (1979). The presence of dinoflagellates in samples from Qj32-27 supports our interpretation of marine-influenced deposition.

Sequence Stratigraphic Interpretation

Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition or their correlative conformities. In Qj32-27, we utilize sequence stratigraphy to subdivide the sedimentary section and correlate it to other boreholes in Delaware and neighboring states. The sequence stratigraphy of Qj32-27 has previously been described in Miller et al. (2003a) and Browning et al. (2006). In this report, we discuss these sequences as a genetic frame of reference for the formations and aquifers of southern Delaware, a context that sheds additional light on the distribution and connectivity of lithologies that control the movement of ground water. The interpretations are based on integration of detailed examination of the cores, geophysical logs, microfossils, and strontium-isotope age determinations.

In the lower part of Qj32-27, the Oligocene to lowermost Miocene offshore deposits encountered are characterized by thin sequences interrupted by conspicuous unconformities (Fig. 8). Above that, the lower-to-middle-Miocene section (Calvert and Choptank Formations) is characterized, overall, by a stack of nearshore-highstand systems-tract (HST) deposits, with some transgressive-systems-tract (TST) intervals, punctuated by multiple unconformities. The HSTs are predominantly upward-coarsening successions that shallow upwards from offshore to shoreface facies (Fig. 14A). These are commonly separated by thin, fining- and deepening-upward, intervals comprising TSTs. Sequence boundaries (SB) are unconformities marked by a hiatus and subsequent-marine-flooding event and, as such, reflect a merged sequence-boundary and transgressive surface (TS/SB). Typically, the sequence boundary intervals exhibit the following succession:

- clean, shelly sand leading up to the SB, representing nearshore deposition in the upper HST;
- silty, bioturbated sand with shell fragments immediately under the SB, produced by bioturbation of pre-hiatus sediments during the post-hiatus transgression when sedimentation rates are low;
- finer-grained deposits above the TS/SB, which may be either a thin, fining-upward sand interval laid down during the post-SB transgression, and thus a thin TST, or a zone of laminated, glauconitic silt that represents deposition at the base of another upward-coarsening and upward-shoaling HST.

We did not recognize any lowstand-systems-tract (LST) deposits in the cores. The absence of LST deposits is probably a result of the location of this site, which is relatively high on the continental margin. As a result, transgressive surfaces are merged with the sequence boundaries.

The sequence stratigraphy of the upper Miocene (to Pliocene?) section is more complex, characterized by a heterogeneous mix of estuarine, non-marine, and shoreface deposits with significant facies changes and/or cut-and-fill features (Fig. 14B). Placement of sequence boundaries is not always unequivocal in such facies where cut-and-fill relationships are common. We identify SBs where there appears to be evidence for an unconformity and for subaerial exposure, followed by marine flooding, in a facies succession where this would not be otherwise expected. One example of such a succession is shown in Fig. 14B:

- clean sand above the SB, composed of facies associated with a shoreline complex, deposited as TST;
- variable sandy and muddy lithologies, representing shallower marine and estuarine environments, constituting the HST;
- an erosive and/or bioturbated contact, in some instances with evidence of exposure and soil-forming processes, at the SB;
- marine flooding, as reflected in another interval of clean sand associated with a shoreline complex of the next TST.

On the basis of these criteria, fifteen Oligocene to lowermost upper Miocene shallow-marine sequences are discussed here, consistent with those previously defined in Miller et al. (2003a) and Browning et al. (2006) (Fig. 4). These sequences can be related to the global sea-level curve of Miller et al. (2005). They are, in summary:

- part of one undetermined Oligocene sequence;
- three thin (10-25 ft) glauconitic Oligocene to lowermost Miocene sequences (UGC1-UGC3);
- one very thick (~270 ft) predominantly lower Miocene silty sequence (C1);
- four moderately thick (90-160 ft) silty-to-sandy shallow-marine lower Miocene (Calvert) sequences (C2-C5);
- three thinner (50-90 ft) middle Miocene sand- and shell-rich nearshore sequences (C6-C8);
- two glauconitic muddy shelf sequences across the middle-to-upper Miocene transition (C9-C10);
- one sequence in the coarsening-upward, upper Miocene Cat Hill Formation (M1).

In addition, several sequences are tentatively identified in the upper Miocene (and Pliocene?) shallow-marine to non-marine section and in the Pleistocene formations in the uppermost part of the borehole.

Undetermined Oligocene Sequence (1467.95-1465.7 ft). The thin interval of foraminifera-rich clay at the bottom of the hole represents part of an Oligocene sequence of unknown thickness (Fig. 8). The top is marked by a prominent unconformity that probably represents a significant hiatus; glauconite-filled burrows extend nearly a foot below this sequence boundary. Based on a single strontium date of 28.0 Ma, and planktic foraminifera indicative of Zone O6, this sequence appears be upper Oligocene (Fig. 9), possibly correlative to the Sewell Point Formation of New Jersey and sequence O4 (27.9-27.2 Ma) of Pekar et al. (2003).

Sequence UGC1 (1465.7-1454.5 ft). Sequence UGC1 represents the thin basal sequence in the Unnamed Glauconitic Unit (Fig. 8). Its expression is typical of these lower, glauconitic sequences (UGC1-UGC3): glauconitic sands (TST) passing upward into clayey sediments (HST). The sequence is bounded by prominent, burrowed unconformities at the base and the top. Environments deepen up to the MFS (1457.9 ft), where foraminifera indicate middle neritic (up to 80 m PWD) environments, and then shoal into the thin HST clay (~50 m PWD). The age of UGC1 is uncertain; it may be upper Oligocene or lower Miocene, between the upper Oligocene sequence below and lower Miocene planktic foraminifera and strontium ages above.

Sequence UGC2 (1454.5-1430.5 ft). Sequence UGC2 spans most of the Unnamed Glauconitic Unit (Fig. 8). The heavily burrowed basal sequence boundary is associated with a major gamma log peak. The lithology passes upward from glauconitic sand (TST) to shelly clays and clayey silts (HST) with a heavily burrowed lithified zone at the top. The deepest-marine environments (80-100 m) occur around the gamma log peak marking the MFS at 1445 ft. A single strontium-isotope age of 21.0 Ma was obtained near the top of this sequence, corroborating biostratigraphy that places it in the lower Miocene (Fig. 9).

Sequence UGC3 (1430.5-1421.1 ft). At the base of Sequence UGC3, a heavily burrowed SB is overlain by glauconitic sand (TST) (Fig. 8). A MFS is interpreted at around 1429 ft where the sand passes into clay (HST) and foraminifera suggest deposition at approximately 50 m PWD. Calcareous nannofossils in this sequence (NN2) and strontium ages in under- and overlying sequences place this sequence in the lower part of the lower Miocene.

*Sequence C1 (1421.1-1153 ft)***.** Sequence C1 is the thickest sequence in Qj32-27 (Fig. 8). The TS/SB at the base is a heavily burrowed, irregular unconformity and is overlain by a

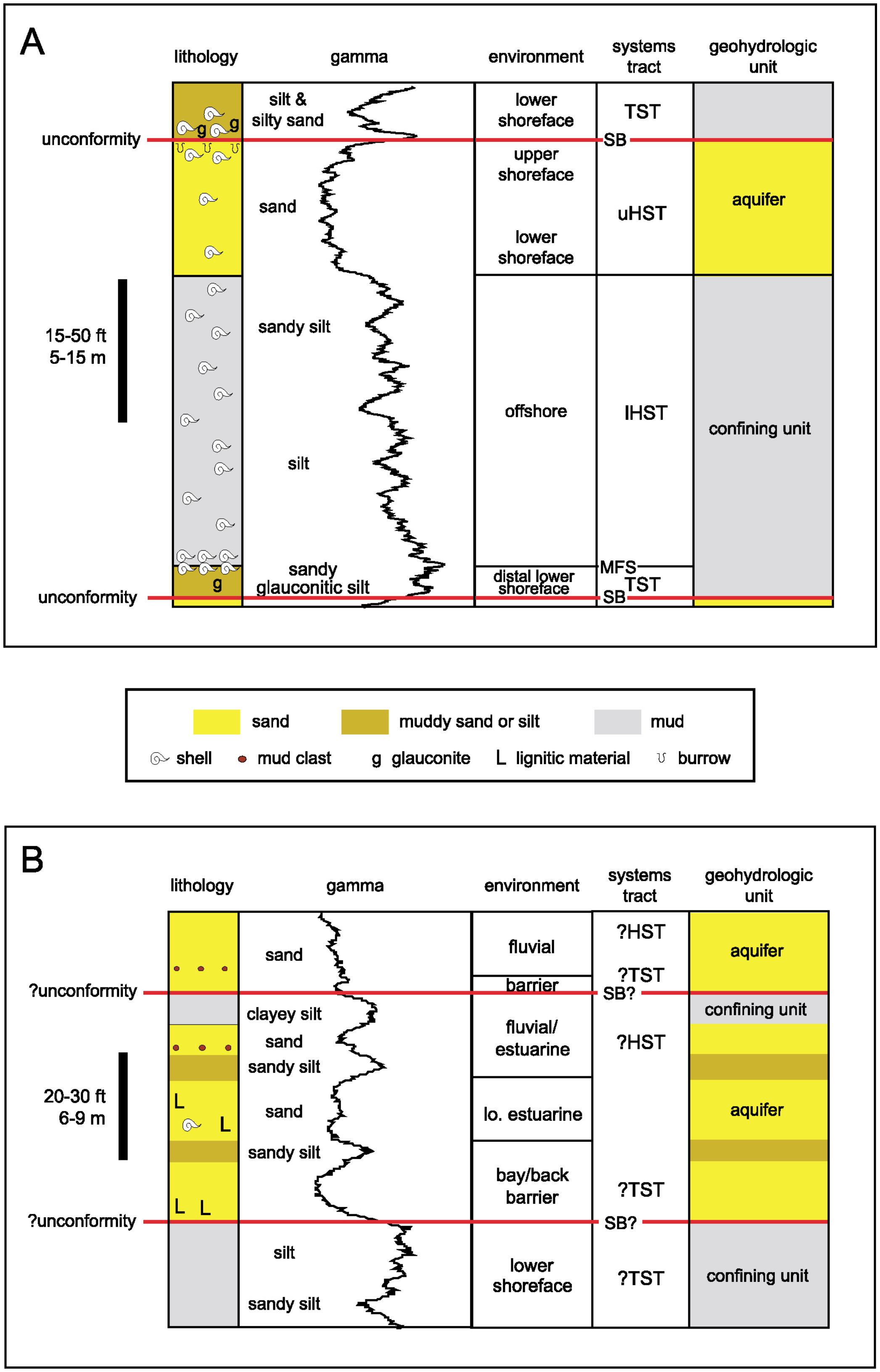

Figure 14. Idealized expression of sequences in the Miocene section of Qj32-27. A. Sequence expression in the overall shallow-marine lower-to-middle Miocene section. B. Sequence expression in the shallow- to marginal-marine upper Miocene section.

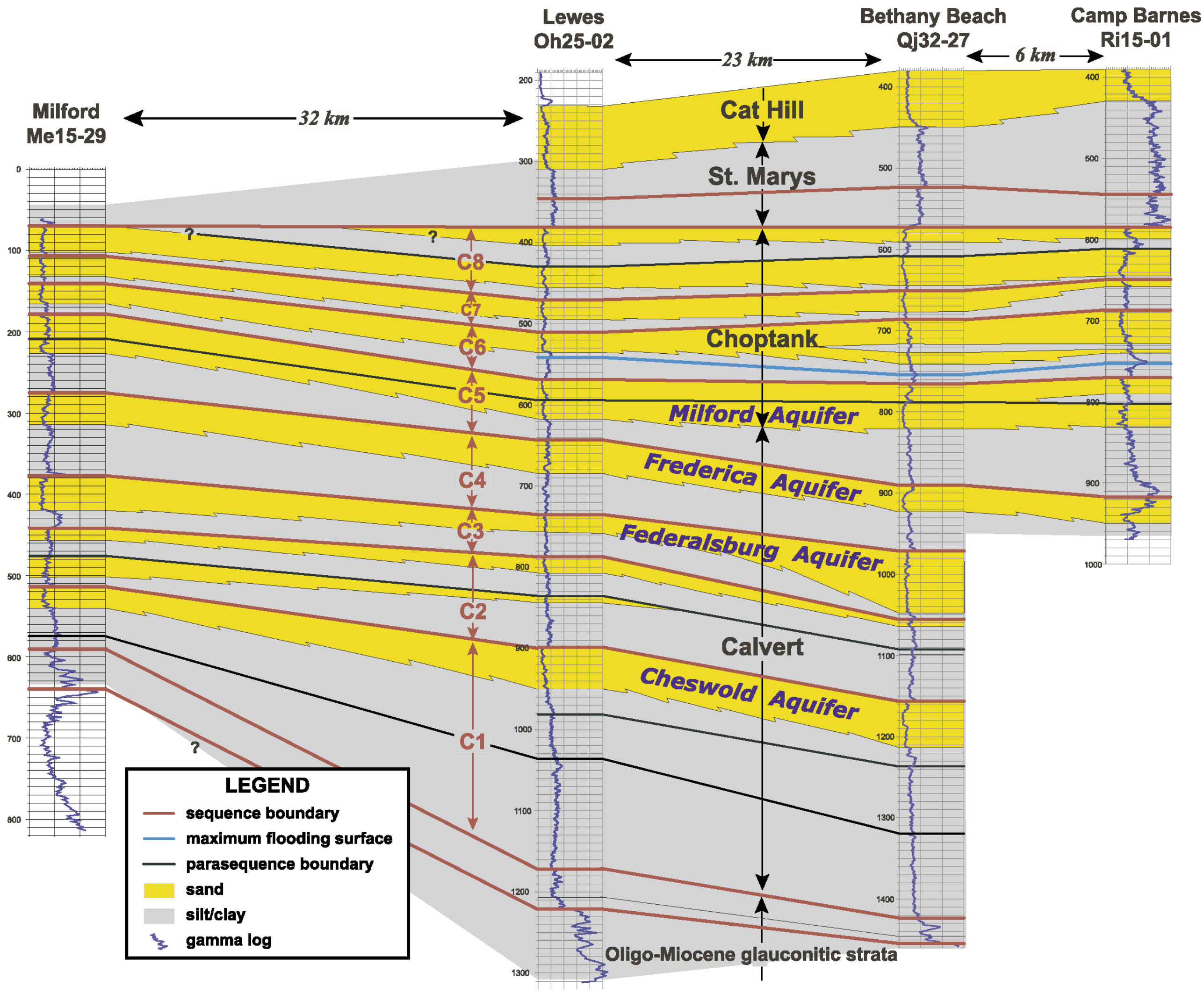

Figure 15. Sussex County deep-hole wireline log geologic cross section, Milford to Lewes to Bethany Beach to Camp Barnes. The cross-section shows correlation of selected stratigraphic surfaces and stratigraphic units for the Oligocene to lowermost upper Miocene section in a northwest to southeast direction across Sussex County (see Figure 1 for location map). The section is constructed on a datum at boundary between the Choptank and St Marys Formations. Aquifer sands are labeled with blue text; formations are indicated by black text and arrows; sequences are indicated by red text and arrows; distances between holes are indicated in kilometers (following DGS use of UTM coordinate system in meters).

thin TST comprising the uppermost beds of the Unnamed Glauconitic Unit. The thick HST traces a gradual overall coarsening and shoaling, extending from the thick lower silty zone of the Calvert Formation (Calvert unit 1), representing the lower HST, to the lowest thick sand interval in the Calvert Formation (Calvert unit 2), representing the upper HST. We consider the upper HST sand of this sequence to be equivalent to the Cheswold aquifer. Two parasequence boundaries are noted: at 1317.45 ft, where a cemented zone is overlain by a minor gamma peak with slight deepening (up to 50 m); and at 1216.5 ft, where a slight deepening in shoreface deposits is noted. Linear fit of strontium-isotope age-depth plot data (Fig. 9) yields an age estimate of 20.8 to 20.2 Ma for this sequence.

Sequence C2 (1153-1057.95 ft). Whereas most sequences in the Calvert and Choptank Formations are composed of a thin TST and a thick, increasingly sandy HST, the predominantly silty Sequence C2 differs in having a thicker, silt-dominated TST (1153-1096 ft) and a thin HST characterized by muddy very fine sand (1096-1057.95 ft) (Fig. 10). The basal TS/SB is inferred at a significant gamma-ray log increase. The MFS is placed at around 1096 ft where high gamma log values coincide with maximum benthic foraminiferal PWDs (50-80 m). The upper sequence boundary is picked at a heavily bioturbated contact between muddy sands and an indurated sandstone that marks the base of the next sequence. Strontium isotope data in this sequence yield a best-fit age estimate of 19.3 to 18.8 Ma, assuming constant sedimentation rates (Fig. 9), suggesting a hiatus of approximately 1 m.y. duration at the base.

Sequence C3 (1057.95-981.3 ft). The thin TST (1057.95-1050.6 ft) of Sequence C3 overlies a heavily bioturbated TS/SB, with indurated sandstone at the base deepening upward to lower shoreface and offshore facies, culminating at a MFS (1050.6 ft) (Fig. 10). The thicker HST (1050.6-981.3 ft) coarsens upward, with clayey offshore silt passing to muddy lower shoreface sand and ultimately to coarser, cleaner, upper shoreface sand with a capping cemented horizon. The clean sand in the upper HST encompasses Calvert unit 4, which we consider equivalent to the Federalsburg aquifer. Strontium isotope data yield age estimates that range from 19.2 to 18.6 Ma, with a best-fit estimate of 18.8 to 18.4 Ma (Fig. 9). Based on the age-depth plot, the unconformity at the base of C3 appears to represent no more than a brief hiatus, probably approximately 0.1 m.y.

Sequence C4 (981.3-897.7 ft). The TS/SB at the base of Sequence C4 is marked by silty lower shoreface sand lying on a cemented sand bed that caps the underlying sequence (Fig. 10). The TST (981.3-964 ft) fines from muddy sand to higher-gamma, deeper-water mud. The HST (964-897.7 ft) is composed of three parasequences separated by marine-flooding surfaces at 950.5 and 940.9 ft. These form a composite package that coarsens overall from muddy sand at the base to coarser, clean upper shoreface sand at the top (Calvert unit 6); the clean sand is equivalent to the Frederica aquifer. The SB at the top is picked where the clean nearshore sands are overlain by silty lower shoreface sands. Based on a best fit line through the data, the age of this sequence is estimated between 18.4 and 18.0 Ma (Fig. 9), indicating only a minor hiatus at the TS/SB at the base of C4.

Sequence C5 (897.7-787.1 ft). The basal TS/SB is a burrowed contact (897.7 ft) marked by a gamma increase where silty lower shoreface sands overlie upper shoreface sands of Sequence C4 (Fig. 11). Deepening marks the thin TST (897.7-887.7 ft), with the basal silty sands fining upward into offshore sandy silts, culminating at a burrowed surface with high gamma values representing the MFS. Above this, the thicker HST (887.7-787.1 ft) coarsens upward, tracing shallowing from a muddy offshore inner neritic setting (as much as 50 m PWD) to a sandy upper shoreface environment. The clean shoreface sands in the upper HST marks the bottom of the Choptank Formation (unit 1) and correspond to the Milford aquifer.

Strontium isotopes ages in this sequence range from 17.3 to 16.5 Ma (Fig. 9). Depending on how the age-depth plot is interpreted, the boundary between Sequences C5 and C6 could be viewed as either a hiatus or as a relatively continuous record. We have chosen an age-depth line (Fig. 9) that makes the top of Sequence C5 a hiatus. On this basis, we interpret the age of this sequence as of 17.1 to 16.7 Ma with a hiatus of approximately 0.7 m.y. at the base and as much as 0.5 m.y. at the top.

Sequence C6 (787.1-698.5 ft). The SB at the base of Sequence C6 (787.1 ft) is not a pronounced surface, as are some of the other SBs; instead, it is a shift from clean sand below to partly cemented shelly sand above. This coincides with a sharp gamma-log increase and a change in the facies stacking pattern from progradational to retrogradational. The TST (787.1-753.9 ft) fines upward from distal upper shoreface and lower shoreface sand to offshore clayey silt. The MFS (753.9 ft) is picked at a gamma-log peak in the clayey silt that has a diverse benthic foraminiferal assemblage indicative of offshore, middle neritic environments (~50 m PWD). The HST section (753.9-698.5 ft) coarsens upward from there, with silt transitioning to sand; however, it is notable that the sand at the top of this sequence is not the same type of clean, aquifer-quality sand present at the top of most of the underlying sequences. On the basis of strontium ages, and an age-depth line fit that places a 0.5 m.y. hiatus at the C5-C6 boundary, the age of Sequence C6 is estimated as 16.2 to 15.8 Ma (Fig. 9).

Sequence C7 (698.5-649 ft). The basal TS/SB of Sequence C7 is interpreted at a thin zone of high gamma ray log values (698.5 ft) in a core gap (700-694.1 ft). Although a very thin MFS may occur in the core gap based on geophysical logs, nearly all of the sequence is a predominantly sandy HST succession, with lower shoreface sand and lesser silt coarsening overall to an unnamed, potentially aquifer-quality sand that is coarse-grained and rich in shell debris. The strontium-age data have more scatter in this sequence than most of the other lower-to-middle Miocene sequences at this site. Assuming similar sedimentation rates as found in other sequences in this section, we estimate an age estimate of 14.5 to 14.2 Ma for this sequence (Fig. 9). The major shift in strontium ages relative to Sequence C6 corroborates the placement of the basal sequence boundary around 698.5 ft, indicating a hiatus of more than 1 m.y.

Sequence C8 (649-575.2 ft). This sequence is mostly composed of sandy, shelly HST deposits consisting of two coarsening-upward packages separated by a parasequence boundary (marine-flooding surface) at 606.75 ft (Fig. 11). Like the sands in Sequence C7, these sands represent unnamed, potentially aquifer-quality beds. The TS/SB at the base is marked by a shift from granule-bearing silty sand below to a shell bed with phosphate grains above. The MFS is associated with the finest lithologies and higher gamma zone around 645 ft. Based on a straight line fit on the age-depth plot, the age of this sequence is estimated as 13.5 to 13.1 Ma (Fig. 9), with a hiatus of approximately 0.7 m.y. at the basal TS/SB.

Sequence C9 (575.2-523.05 ft). The basal TS/SB is marked by the base of a cemented, quartz sandstone associated with a sharp gamma-ray peak (Fig. 12). This SB is followed by significant deepening in the TST (575.2-557.5 ft), with a fining-upward sand (top Choptank Formation) overlain by progressively deeper-water silts and clays (St. Marys Formation), culminating at an extensively burrowed MFS at 557.5 ft where glauconite sand lies on silt. The HST (557.5-523.05 ft) passes from the glauconite sand back to silt, with foraminifera indicating shoaling from around 75 m to 50 m. The HST is a capped by a heavily burrowed siltstone, with abundant glauconite-sand-filled burrows below the top-bounding SB. The age of Sequence C9 is estimated as 11.9 to 11.6 Ma, assuming reasonably constant sedimentation rates through the St. Marys Formation and excluding strontium ages of 14 to 15 Ma as outliers (Fig. 9). On this basis, the basal TS/SB appears to represent a hiatus of approximately 1.3 m.y.

Sequence C10 (523.05-452.05 ft). The basal SB occurs in the middle part of the St. Marys Formation (523.05 ft); it is an extensively burrowed surface at the top of an indurated zone that coincides with gamma-log peak (Fig. 12). The TST is thin, with silty glauconite sand (523.05-520.0 ft) fining upward to silt deposited in middle neritic environments. The MFS is probably around 515.5 ft where concretions and phosphatic grains occur. This is overlain by a thicker, silty clay HST (515.5-452.05 ft) in which environments generally shoal from middle neritic to inner neritic. The most reasonable line on the strontium age-depth plot yields an age estimate of 10.6 to 10.2 Ma for Sequence C10 (Fig. 9). Thus, the TS/SB at the base appears to represent a hiatus on the order of 1.0 m.y.

Sequence M1 (452.05-374 ft). Sequence M1 begins at a TS/SB that is recognized at a highly burrowed surface with a gamma-log peak (452.05 ft). The TST is a thin interval of glauconitic clays (452.05-449.4 ft) encompassing the uppermost part of the St. Marys Formation (Fig. 12). The MFS is placed at a highly burrowed surface 449.4 ft, across which the lithology becomes sandier, marking the base of the Cat Hill Formation. The muddy sands of the lower part of the Cat Hill Formation become cleaner upsection, reflecting progradation and shallowing of environments in the HST (449.4-374 ft). The top of M1 is tentatively placed at 374 ft at the break between the progradational sand package and overlying silty sand with higher gamma-log values. Sequence M1 contains the stratigraphically highest strontium-isotopic age determinations in the Miocene section, with an estimated age of 10.2 to 9.8 Ma (Fig. 9). Because the age-depth trend appears reasonably continuous from the underlying sequence, the basal SB does not appear to represent a significant hiatus.

Higher sequences (Above 374 ft). Because of the prevalence of shallow- to marginal-marine facies from the upper part of the Cat Hill Formation upward, sequences can be difficult to pick precisely with confidence. In addition, this interval lacks strontium age data and precise biostratigraphic determinations to constrain the ages of sequences and sequence boundaries. Therefore, we here focus on several notable stratigraphic surfaces that appear to be sequence boundaries and may provide areally significant horizons for correlation.

- *150.6 ft.* This surface represents a significant shift in depositional environments in the Bethany Formation (Fig. 13). The strata below this level are interpreted as predominantly shallow-marine, shoreface deposits and commonly include interbedded muds. The strata above are generally coarser grained and interpreted as predominantly estuarine strata. We interpret this as a SB with a significant basinward shift in facies.
- *117.5 ft.* This horizon marks the boundary between the Bethany Formation and the Beaverdam Formation (Fig. 13). Like the surface at 150.6 ft, it is interpreted as a basinward shift in facies marking a SB. Grain sizes are overall coarser than below this SB and environments are overall less marine influenced, principally estuarine and fluvial. An unconformity at this level is consistent with the recognition by Ramsey (2007) of a regional unconformity at the base of the Beaverdam Formation in southern and central Delaware.
- *52.9 ft.* The base of the Omar Formation represents a major unconformity in this section, separating the Pleistocene lagoonal deposits that constitute this unit from sandy fluvial-estuarine deposits of the underlying (presumably upper Miocene or Pliocene) Beaverdam Formation (Fig. 13). This unconformity is known to have significant relief in the Atlantic coastal area of Delaware and likely represents at least 1 m.y. of time.
- *31.5 ft.* The base of the Sinepuxent Formation is an intra-Pleistocene unconformity, separating younger Pleistocene Sinepuxent strata from older Pleistocene Omar deposits below (Fig. 13). This SB appears to represent a hiatus formed during a late Pleistocene lowstand that was followed by estuarine deposition.

Local Correlation and Implications for Aquifers

The Bethany Beach core hole (Qj32-27) provides a useful reference section for the Oligocene and younger stratigraphic units of southern and central Delaware. The availability of a nearly continuous core record and a suite of wireline geophysical logs allows calibration of log character to lithology, establishing relationships that can be extended to other holes with geophysical logs in the local area. The local correlations discussed below reflect an overall south-to-southeasterly dip of geologic units that is approximately paralleled by downdip facies changes toward deeper water depositional environments (Fig. 15).

Oligocene

Recognition and correlation of Oligocene strata in Delaware can be difficult. The only definite Oligocene-age strata in Delaware occur under a basal Miocene unconformity in Sussex County. However, this unconformity cuts into progressively older strata in an updip direction, removing Oligocene sediments and placing lower Miocene strata on top of Eocene in central Delaware (McLaughlin and Velez, 2006). However, the details of the regional stratigraphic relationships above (onlap) and below (truncation) this unconformity are yet to be established.

In Qj32-27, planktic foraminifera and strontium ages place the thin Oligocene section near the lower/upper Oligocene boundary. This determination is consistent with prior determinations for Oligocene strata at Oh25-02, near Lewes, for which Benson (*in* Benson, 1990) identified "mid" Oligocene planktic foraminifera in glauconitic silts in the bottom (1337-1218 ft) of that hole (Fig. 15). Oligocene sediments at Bethany Beach and Lewes are, therefore, muds that would act as confining units.

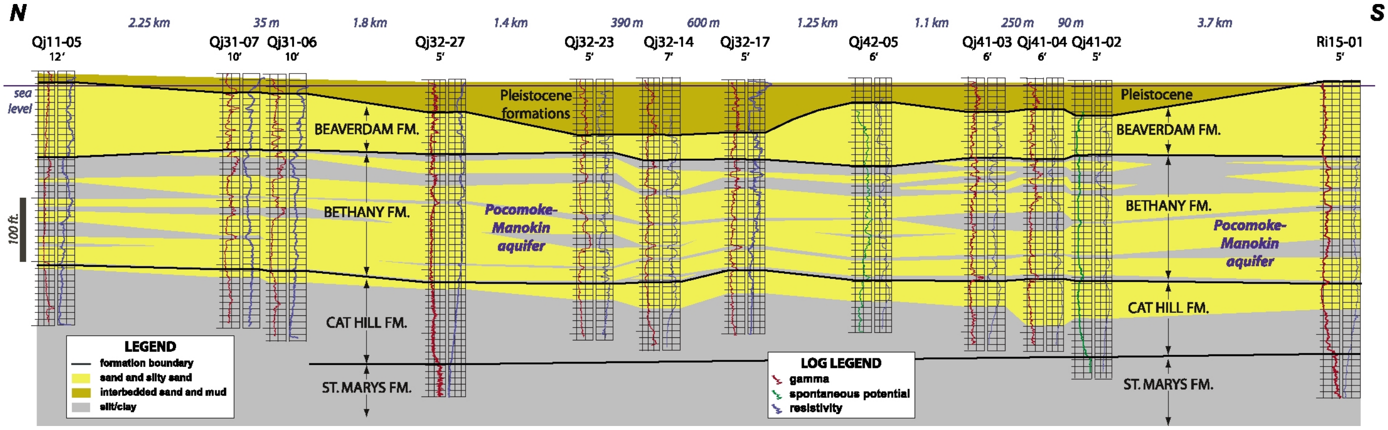

Figure 16. Local wireline log geologic cross section, Bethany Beach area. The cross-section shows correlation of important stratigraphic surfaces and stratigraphic units for the upper Miocene to Pleistocene section in a north to south direction through the Bethany Beach area (see Figure 2 for location map). The section is constructed on a sea-level datum; well elevations are given in feet. Aquifer sands are labeled with blue text; formations are indicated by black text and arrows; distances between holes are indicated in kilometers or meters.

However, strata referred to as Oligocene in previous studies in other parts of southern Delaware include sandy, potential aquifer facies. In well Me15-29 at Milford, in glauconitic sands below 650 ft, some of the same stratigraphically significant benthic foraminifera were noted by Benson (*in* Benson, 1990) that occur in the Oligocene sediments of Qj32-27 and Oh25-02. In addition, based on the similarity of log signatures, Benson (*in* Benson, 1990) identified Oligocene sands in wells in the Bridgeville area (below 700 ft in Od23-01, Od23-02, and Od24-01; Fig. 1). On this basis, there appears to be a change in the Oligocene depositional system across southern Delaware from muddier sediments in southeastern Sussex County to glauconitic sand in the northern part of the county. Further study is needed, though, to establish a complete understanding of the nature of the Oligocene section and its relationship to overlying Miocene and underlying Eocene strata.

Lower-to-middle Miocene section and aquifer sands

Four sandy intervals in lower and middle Miocene strata of Qj32-27 are here interpreted as correlative to important aquifers of central Delaware (Fig. 15): the Cheswold, Federalsburg, and Frederica aquifers, which are in the Calvert Formation, and the Milford aquifer, which is in the Choptank Formation (McLaughlin and Velez, 2006). These sands are not commonly used for ground water in coastal Sussex County. They occur at greater depths than more easily drilled younger aquifers. In addition, elevated chloride levels appear to be a problem. Geophysical logs from Qj32-27 show a decrease in resistivity and resistance values is evident below the freshwater sands of the Manokin aquifer; this log shift is consistent with an increase in chlorides in the ground water. In test hole Oh25-02, near Lewes, where this same trend was evident, water produced from the upper part of the Choptank Formation has relatively high values (600 mg/L) of chlorides (Talley *in* Benson, 1990). Although these characteristics make the lower-middle Miocene sands generally unfavorable as a source of ground water, stratigraphically equivalent sands potentially may be usable aquifers in further north and west in Sussex County where they occur at shallower depths and more likely contain fresh water. In this report, where these sands are not used for ground water, we have referred to them as stratigraphically equivalent to those aquifers, not as the aquifers themselves.

The Calvert and Choptank Formations both show a clear overall trend of increasing thickness in a downdip (south to southeast) direction (Fig. 15). Within this interval, each aquifer-sand unit reflects deposition by a prograding shoreline that advanced across Sussex County during a period of high, but relatively static, sea level when sedimentation rate exceeded the combined effects of sea-level rise and subsidence. Each sand is a shallowing-upward package of shoreline sediments capped by an unconformity (sequence boundary) that can be traced across central and southern Delaware. In the test holes shown on this cross section, the coarsest-grained sands tend to be in the upper part of the sand units, making these potentially good to excellent aquifer lithologies if not cemented. A similar relationship between sequences and aquifers was noted by Sugarman et al. (2005) in the Kirkwood Formation of southern New Jersey.

The Cheswold aquifer-equivalent sand (sequence C1) is a good example of these characteristics. Geophysical logs at Bethany Beach, Lewes, and Milford indicate that the sand becomes cleaner and to coarser upward, with a gamma log shift and resistivity spike near the top. The gamma spike probably reflects a concentration of authigenic minerals in the sediment-starved interval just above the surface we interpret as a sequence boundary; glauconite is present in core and phosphate might also be expected at such a surface. The single-point-resistance peak reflects the higher concentration of carbonate produced by the concentration of shells at and just below the surface. Because the processes producing thse lithologies would be expected from a global sea-level fall (exposure/shell dissolution/carbonate reprecipitation) followed by a global marine transgression (authigenic minerals/carbonate reprecipitation), the associated sequence (C1) and its boundary can be correlated between these wells and to other sites in the region.

The Federalsburg-, Frederica-, and Milford-aquifer-equivalent sands exhibit the same relationships to sequence stratigraphy as the Cheswold-aquifer-equivalent sand. Clean sands comprising these aquifers occur at the tops of Sequences C3, C4, and C5, respectively (Fig. 15), commonly having gamma peaks (authigenic minerals) and/or single-point-resistance spikes (carbonate) associated with the sequence boundary that caps each. In general, each successive sequence represents slightly shallower environments as a result of the overall progradation of shoreline depositional systems through the Miocene; as a result, equivalent environments occur slightly further to the southeast in each sequence. At Bethany Beach, and most other locations in coastal Sussex County (e.g., Fig. 15), the shallowing-upward trend gives each of these sands a coarsening-upward character. However, in updip (north to northwesterly) locations of these sands – for example the Milford aquifer at Me15-29 (in Milford) – the shallowing upward trend may be expressed as a sharp-based, blocky to fining-upward pattern log pattern, with the coarsest grained shallow-marine sands lower in the interval and environments shallowing upward to finer-grained estuarine-influenced sediments at the top. This change in facies stacking patterns from downdip to updip locations was previously noted in McLaughlin and Velez (2006) in Kent County.

There are also several clean sandy zones in the Choptank Formation above the Milford aquifer-equivalent sand that appear to be aquifer-quality facies. In Qj32-27, three coarsening upward sequences (C6, C7, and C8) are developed in this interval, with the sandy upper part of each capped by a sequence boundary. Sequences C7 and C8 contain generally coarse clean sand; Sequence C6 has slightly finer and muddier sand. At Bethany Beach, these sands, like the four lower Calvert/Choptank sands, occur at greater depths than commonly used for water wells in Sussex County and appear to contain somewhat brackish water. In a test hole drilled at Lewes (Oh25-02), the sand at the top of the Choptank Formation was reported to contain high chloride levels (600 mg/L). In addition, the greater abundance of cemented beds in the Choptank Formation above the stratigraphic level of the Milford aquifer may reduce aquifer quality of these sands (Talley *in* Benson, 1990; A.S. Andres, written communication, 2008). However, the sands in this interval appear to be correlative with unnamed (or misnamed) Choptank sands used as aquifers further north and west in Sussex County (for example; the "Frederica" aquifer in the Seaford area) where they occur at shallower depths and yield fresh water to wells.

Upper Miocene (to Pliocene?) section and aquifer sands

The cores and geophysical logs obtained from Qj32-27 help to better delineate the boundaries between the three formations that make up the Miocene (to possibly Pliocene) section in coastal Sussex County: the Cat Hill, Bethany, and Beaverdam Formations. They also shed light on the complexity of the stratigraphic relationships of the two important aquifers that occur in this interval, the Manokin and Pocomoke.

The Cat Hill Formation displays a clear, coarsening-upward, shallow-marine succession in Qj32-27. This pattern is typical of the unit (Andres, 2004) and can be readily correlated locally (Fig. 16). The overlying Bethany Formation is more heterogeneous, with interbedded sands and muds that reflect a coastal/estuarine environment of deposition. This heterogeneity complicates correlation (Fig. 16) and can make the lower and upper formation boundaries difficult to confidently identify.

In this report, for the Bethany Beach area, we follow Andres (2004) in recognizing the base of the Bethany Formation at the bottom of the lowest fine-grained bed that occurs above the coarsening-upward succession of the Cat Hill Formation. This boundary can be readily recognized and correlated where muddy strata characterize the lower part of the Bethany Formation. However, the boundary is difficult to recognize where the lower part of the Bethany Formation is sandy and no clear lithologic contrast exists (Andres, 1986, 2004; Andres and Klingbell, 2006). The section at Qj32-27 is a good example; the fine-grained bed marking the boundary is difficult to recognize on geophysical logs (and would not be recognized in cuttings) and was only readily identified in core.

The top of the Bethany Formation is marked by an unconformable contact with the overlying Beaverdam Formation. Recent geologic mapping by Ramsey (2007) indicates that the base of the Beaverdam Formation represents a significant regional unconformity that extends across Sussex County and northward into Kent County, cutting into successively older stratigraphic units in a north-northwestward direction. In the Qj32-27 cores and logs, the Beaverdam Formation has its typical expression, with a basal unconformity marked by a shift to more abundant coarse clastic material followed by an overall upward increase in silt content. However, the boundary between these two formations can be difficult to define in some locations (Andres, 1986, 2004; Andres and Klingbell, 2006). One difficulty is presented where the uppermost part of the Bethany Formation includes coarse lithologies similar to those of the Beaverdam Formation, as is evident in Qj32-27 (Fig. 13). Alternatively, the lower part of the Beaverdam Formation can include thin muddy beds that may be suggestive of the Bethany Formation. Where such ambiguity exists in coastal Sussex County, we suggest that the differentiation between these units could be based on:

a. sand lithologies, where sands of the Beaverdam Formation have more feldspars or orange- to pink-stained grains; or,

b. mud lithologies, where darker gray to brown mud beds with plant debris are considered part of the Bethany Formation versus more oxidized, lighter-colored muds of the Beaverdam Formation that contain little to no plant debris; or,

c. gamma-log values, where sands tend to have slightly higher values in the Beaverdam Formation than in the

Bethany Formation (Andres, 2004; Andres and Klingbeil, 2006).

The complexity of stratigraphic relationships between these formations is also manifested in the stratigraphic relationships of the aquifers. The Manokin and Pocomoke aquifer names have long been applied to the confined aquifers above the St. Marys Formation and below the Columbia (water-table) aquifer in southern Delaware (Rasmussen et al., 1960) and nearby areas of Maryland (Rasmussen and Slaughter, 1955). The Manokin aquifer was established by Rasmussen and Slaughter (1955) for the lowest water-producing sand above the St. Marys Formation. For a time, the name "Manokin formation" (Andres, 1986) was applied to the geologic unit more recently designated as the Cat Hill Formation (Andres, 2004), including both the aquifer-quality beds in the upper part and associated, non-aquifer facies in the lower part.

The Pocomoke aquifer was defined by Rasmussen and Slaughter (1955) as the confined water-producing sand above the Manokin aquifer and below the water-table aquifer. In Delaware, it occurs in the Bethany Formation, as that formation was first defined (informally) by Andres (1986). Where more than one aquifer sand occurs in this interval, the name "Ocean City aquifer" has in the past been used for the lower of the sands (Weigle, 1974; Hodges, 1984; Andres, 1986); this unit is more commonly differentiated in Maryland than in Delaware (Hansen, 1981; Achmad and Wilson, 1993).

Aquifer-quality sands occur consistently in the upper part of the Cat Hill Formation in the Bethany Beach area (Fig. 16). Therefore, we consider the Manokin aquifer an areally persistent hydrologic unit in this area, consistent with Andres (1986). In contrast, sand occurrences are less predictable in the Bethany Formation. Because of this, as previously recognized by Andres (1986), the Pocomoke aquifer does not represent a simple, discrete, uniform sheet of sand; instead, it is better characterized as a network of sandy, water-bearing facies within a geometrically complex set of heterogeneous lithologies (Fig. 16). In places, this leaves Bethany (Pocomoke) sands in direct stratigraphic contact with underlying Cat Hill (Manokin) sands, making differentiation between these aquifers difficult. This suggests that the Pocomoke and Manokin aquifers may be in hydrologic communication in some areas. Previous studies have arrived at differing conclusions about the connectivity of these aquifers; for example, analysis by Hodges (1984) suggested these behave as a single hydrologic unit regionally; Achmad and Wilson (1993) concluded that they are essentially individual aquifers in a local study in the Ocean City area. Because of this uncertainty, in this report we group these two aquifers as undifferentiated Pocomoke-Manokin aquifers in the Bethany Beach area. The hydrologic relationship between these aquifers should be examined in future studies using hydrologic head data.

The sands of the Beaverdam Formation also provide a potential aquifer resource. Most of the volume of the Columbia aquifer in Sussex County occurs in the Beaverdam Formation. The Columbia aquifer is normally defined as an unconfined aquifer in Delaware. However, in Qj32-27, the aquifer-quality sands of the Beaverdam Formation are, at least locally, confined by the overlying clays of the Omar Formation. Because these sands occur above the Pocomoke-Manokin aquifer system, they may be regarded as "confined Columbia" aquifer sands. Further complicating aquifer definition is the recognition, from the geology (Fig. 16) and previous hydrogeology studies (Andres and Klingbeil, 2006), that an effective confining unit is not everywhere present between the Pocomoke-Manokin sands and the Beaverdam ("Columbia") sands. This relationship also warrants further study using hydrologic data.

Pleistocene section and unconfined aquifers

The Bethany Beach core hole was drilled in an area in which a fairly thick Pleistocene section occurs. The Omar Formation, which is the lowest of the Pleistocene units, occurs as an incised valley fill in coastal southern Delaware where an erosive topography created by Pleistocene sea level fall was later filled by estuarine sediments. Ramsey (1999) interpreted significant relief on the basal unconformity; the formation is absent in some areas and more than 100 ft thick in others, with some of its thicker occurrences near Bethany Beach. Some of the strata previously considered part of the Omar Formation in Qj32-27 (Miller et al., 2003a) are in this report reassigned to a younger Pleistocene unit, the Sinepuxent Formation. It is distinguished from the Omar Formation by is greater mica content. Andres and Klingbeil (2006) also recognized the Sinepuxent Formation in eastern Sussex County, indicating it is separated from the underlying Omar at an erosional scarp occurring between land surface elevations of 15 to 20 ft. Because local subsurface correlation of these units has not been resolved in detail, our cross section (Fig. 16) groups the Omar and Sinepuxent Formations together in one package referred to as "Pleistocene formations."

As recently documented by Andres and Klingbeil (2006), the unconfined surficial aquifer, known as the Columbia aquifer, may occur in one or more of several geologic units in Sussex County. In the area around this study site north and west of Bethany Beach, the Sinepuxent Formation appears to provide a potentially locally useful thin, unconfined aquifer, as mapped by Andres and Klingbeil (2006) and indicated by the stratigraphic record from Qj32-27.

Regional Correlation

Lower-to-middle Miocene

As demonstrated by Browning et al. (2006), the lower-to -middle Miocene strata at Bethany Beach, Calvert Cliffs (Maryland), and the southern New Jersey Coastal Plain (Miller et al., 2003b) share a generally similar sequence record. In much of this interval, a comparable number of sequences of similar ages can be identified (Fig. 17), likely reflecting the control of global sea-level changes on depositional systems across the region.

One major difference occurs in the lower Miocene in Maryland. The six lowermost Miocene (older than ca. 18 Ma) sequences present at Bethany Beach (UGC1-3, C1-C3) correspond to a hiatus in the Calvert Cliffs outcrops examined in Browning et al. (2006). In contrast, approximately age-equivalent sequences can be correlated between Bethany Beach and southern New Jersey in this same interval. A few

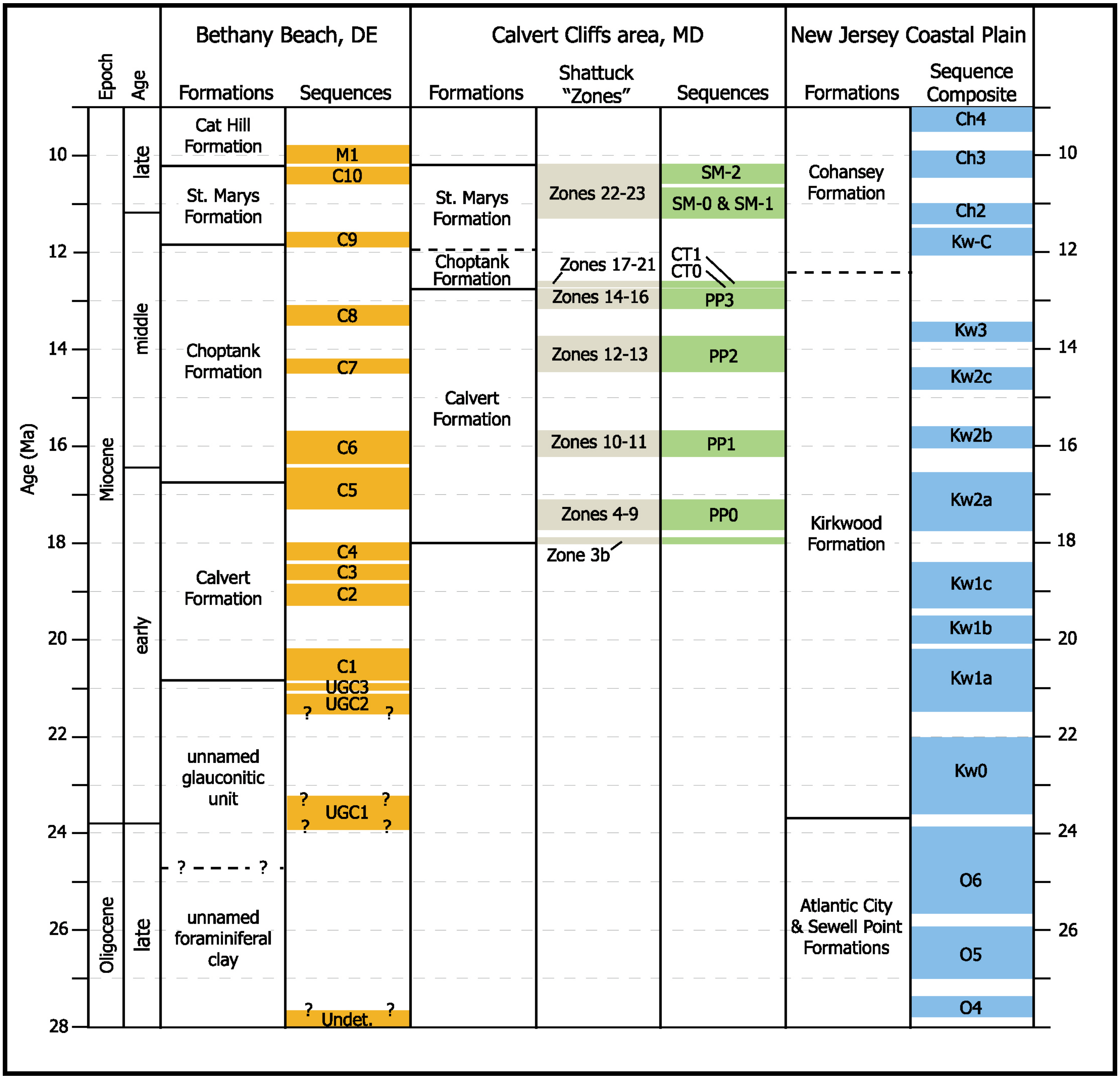

Figure 17. Regional correlation of sequences and formations, Delaware, New Jersey, and Maryland. Ages and nomenclature of the Delaware Oligocene to Miocene sequences are as discussed in this report. New Jersey sequence nomenclature and ages are from the New Jersey sequence composites of Browning et al. (2006) and Miller et al. (2003a) for the Kirkwood, Sugarman et al. (2005) for the Cohansey, and Pekar et al. (2003) for the Oligocene. Calvert Cliffs, Maryland sequence and "Shattuck zone" nomenclature are as given in Kidwell (1988, 1997) and de Verteuil and Norris (1996); ages are from Browning et al. (2006).

minor differences are evident: 1) the lowermost Miocene (UGC) sequences in Delaware are overall thinner than their New Jersey equivalents; 2) strata equivalent to the New Jersey Kw1b sequence (ca. 19.5-20 Ma) are absent in Qj32-27 and instead are represented by an unconformity between sequences C1 and C2; 3) two sequences, C2 and C3, are present in Qj32-27 in an interval equivalent to sequence Kw1b in New Jersey; and 4) Sequence C4 occurs in Qj32-27 in an interval that is represented by a hiatus between Kw1c and Kw2a in the New Jersey sites. This regional pattern may reflect a difference in early Miocene subsidence/uplift and/or sediment supply in the Calvert Cliffs area compared to areas further northeast in Delaware and Maryland.

Another pattern evident in previous sequence stratigraphic studies of these Atlantic Coastal Plain localities (Browning et al., 2006; Miller et al., 2003a, 2003b; Kidwell, 1988, 1997; Ward and Blackwelder, 1980) is the prevalence of highstand systems tract (HST) deposits. At Bethany Beach, the southern New Jersey core sites, and the Calvert Cliff outcrops, the lower-to-middle Miocene sequences are dominated by HSTs, with finer-grained lower HSTs and sandier upper HSTs; transgressive systems tracts (TSTs) are generally thin fining-upward packages where present; and lowstand deposits are mostly absent. This is an especially useful pattern to understand for ground-water studies, as the best aquifer facies are in most places developed in the sandiest upper portions of the HST deposits.

However, while HST deposits make up the majority of these lower-to-middle Miocene Coastal Plain strata, the type of depositional systems that produced them appear to differ across the region. The Bethany Beach section is predominantly sandy and silty shoreface and nearshore sediments that appear to have been deposited along wave dominated coastlines (Miller et al., 2003a). In contrast, sequences at the New Jersey sites examined in Browning et al. (2006) are characterized by deltaic sands and muds interfingering with shelfal muds, with the fluvio-deltaic influence reflected in dirtier sequences that contain more mica, terrigenous plant debris, and clay (Owens and Sohl, 1969; Owens et al., 1988, Sugarman et al., 1993, 1995, 2005; Sugarman and Miller, 1997). The age-equivalent lower and middle Miocene sequences at Calvert Cliffs have been characterized by Kidwell (1988, 1997) as open shelf deposits, some shallower, some deeper; like the Bethany Beach section, these are reflective of deposition along a wave-dominated shoreline rather than a deltaic coastline.

Lithostratigraphy of the Miocene section of this region presents an interesting issue that we feel can be significantly clarified by strontium ages and sequence stratigraphy (Fig. 17). Different formation names are used across the region, with one set of names originating in New Jersey and another in Maryland, as previously summarized by Ward (1998). These names largely reflect the contrast between the predominantly deltaic deposits in New Jersey and the predominantly shelfal deposits in Maryland. The Maryland units, the Calvert and Choptank Formations, were first described by Shattuck (1902, 1904) for shell-rich Miocene sands and muds occurring in the Chesapeake Bay region. The name Kirkwood Formation was established by Knapp (1904) in New Jersey for age-equivalent Miocene strata.

The position of Delaware between these two areas has made the choice of formations names an issue of contention for some workers. The name Calvert Formation was first used by Miller (1906) for Miocene beds on the Dover sheet of the USGS Geologic Atlas, soon after the formation was established in Maryland by Shattuck (1902, 1904). It was probably first put into general use in the Sussex County ground water study authored by Rasmussen et al. (1960). However, the Kirkwood name has also been applied to Miocene strata in Delaware by some authors, including Richards (1945) and Ward (1998).

In current usage in Delaware (Andres and Talley *in* Benson, 1990; Ramsey, 1997), lower-to-middle Miocene strata use the Maryland names. The Calvert Formation encompasses the finer-grained strata (interbedded clays, silts, and sands) of the lower part of this interval and the Choptank Formation the coarser grained strata (predominantly sand and silt) in the upper part. In Qj32-27, the formation boundary was chosen where the section changes from subequal sand and mud below to majority sand above, a change that appears to be correlatable across most of Sussex County (Fig. 15).

However, though the same formation names are used in Delaware and Maryland, the units are not exactly the same age. In Qj32-27, the boundary between the Calvert and Choptank Formations is approximately 16.7 Ma, in the upper part of sequence C5 near the top of the lower Miocene (Fig. 17). This is approximately age-equivalent to unconformity PP1 (base of sequence PP1) at Calvert Cliffs, a level fairly low in the Calvert Formation in that area. At Calvert Cliffs, the Calvert-Choptank boundary is significantly younger, in the middle Miocene (Fig. 17). On the basis of dinoflagellate studies, de Verteuil and Norris (1996) placed the boundary between approximately 13.5 and 13.0 Ma. Similarly, a recent revaluation of strontium ages from Calvert Cliffs by Browning et al. (2006) places the age of the boundary at around 13 Ma. This is approximately the same age as the unconformity between sequences C8 and C9 in Qj32-27, which is near the top of the Choptank Formation.

The difference in the age of the Calvert-Choptank boundary between these areas can probably be attributed to two factors. One factor is the way the formations are defined. As described at Calvert Cliffs, the formations and their constituent beds were defined on the basis of lithology and fossil mollusk faunas, with the formation boundary interpreted as an unconformity. However, as Gernant (1970) notes, the definition of this formational boundary is problematic even in the Calvert Cliffs area and that "(a)way from the area of the Calvert cliffs, where the boundary is defined, it becomes more difficult to locate." This difficulty is reflected in the reassignment of Bed 16 of Shattuck (1904), later named the Calvert Beach Member by Gernant (1970), from its original placement in the Choptank Formation to the Calvert Formation in more recent works (Ward, 1984; Ward and Powars, 2004). Despite these issues, outcrop descriptions fairly consistently describe the Calvert Formation as finer grained, bluish sands and sandy clays and the Choptank Formation as more fossiliferous yellow sands and bluish silts (Cleaves et al., 1968; Kidwell, 1984). This general contrast between a finer Calvert Formation and a shellier, sandier Choptank Formation was also noted by Ward and Stickland (1985) and has been extended into the subsurface in studies of the southern part of Maryland's Eastern Shore, where fossil mollusk data do not factor into the recognition of the units (Anderson, 1948; Rasmussen and Slaughter, 1955; Olsson et al., 1987; Achmad and Wilson, 1993). Therefore, a lithology-based approach to recognizing these formations in Delaware seems appropriate.

The second factor is that the progradation of coastal clastic depositional systems causes the formation boundary to be time transgressive. The Calvert-Choptank succession represents an overall shallowing- and coarsening-upward trend that reflects the gradual progradation of a coastal clastic depositional system through the early and middle Miocene. The fact that the sandy facies that characterize the Choptank Formation occur in older strata in Delaware than at Calvert Cliffs appears to reflect the progradation of clastic systems from the north. So, while deposition in southern

Delaware was dominated by nearshore sands (Choptank Formation) between 16.7 and 13 Ma, the environments at Calvert Cliffs were at the same time muddier and lower energy (Calvert Formation), only increasing in sandiness (to Choptank facies) after around 13 Ma (Fig. 17). The contrast between southern Delaware and Calvert Cliffs suggests a northeast to southwest migration of sandier shoreline environments into the Salisbury Embayment during the early and middle Miocene; if so, this migration should be traceable in locations in between on the eastern shore of Maryland, as well.

This trend appears to be consistent looking north to New Jersey. Indeed, several authors have noted a southward (Isphording, 1970) or seaward (Owens et al., 1988) decrease in sandiness in equivalent levels of the Calvert-equivalent Kirkwood Formation in New Jersey. This same trend is noted in younger formations, with Choptank-equivalent strata in New Jersey composed of very shallow- to marginal-marine sandy strata of the uppermost Kirkwood Formation or Cohansey Formation (Fig. 17). These observations support the idea of north to south progradation of sandy depositional systems across the region through the early and middle Miocene. This progradation seems consistent with the opinion of Poag and Ward (1993) that the thick lower Miocene (Berkeley Alloformation) and middle Miocene (Phoenix Canyon Alloformation) accumulations off New Jersey suggest sediment sources from the north.

This southward progradation of environments, with Delaware in an intermediate position between New Jersey and Maryland, explains the opinion of some authors that the name Kirkwood Formation may be appropriate in places in Delaware. DeVerteuil and Norris (1996) were of the opinion that the lower Miocene of central Delaware had characteristics in common with both the Calvert and Kirkwood Formations, and considered that these units probably interfinger in Delaware. Ward (1998) also suggested that these formations interfinger in Delaware, describing the deposits in both Kent County and the type area of the Kirkwood Formation in New Jersey as deltaic, with the sands prograding and pinching out southwestward in a transition to finer sediments of the more classic Calvert Formation facies. Ward (1998) also noted a strong relationship in molluscan assemblages between those at the Pollack Farm site in central Delaware and New Jersey localities of the Kirkwood Formation. We are in agreement with Ward's characterization of the lower Miocene of Delaware being intermediate in lithology, especially in regards to sandiness, between New Jersey and Calvert Cliffs; however, we differ in that we see little evidence in Delaware for the significant deltaic influence on sand deposition that is characteristic of the Kirkwood Formation, and consider these more wave-dominated shoreline sands (as especially well shown in Qj32-27) to be more like the Calvert Formation. Therefore, because of the facies differences between the Delaware strata and the Kirkwood of New Jersey, and the long-standing use of the Calvert name in the Delaware section, we choose to retain the name Calvert Formation for the lower Miocene sand and mud section in Delaware.

Uppermost middle Miocene to upper Miocene (to Pliocene?)

Regional correlation of uppermost middle Miocene to upper Miocene (and possible Pliocene) strata from Delaware to Maryland and New Jersey is more complicated than the correlation in the older Miocene section. The lowest unit in this interval in Delaware and Maryland, the fine-grained St. Marys Formation, appears to be regionally extensive. Strontium age data from Qj32-27 indicate that the St. Marys Formation lies in and just below the lower part of the upper Miocene (11.9 to 10.2 Ma; Miller et al., 2003a) in Delaware (Fig. 17). This is reasonably close to the estimated ages derived from dinoflagellate biostratigraphy at Calvert Cliffs (ca. 10.5 to 7.5 Ma; de Verteuil and Norris, 1996). To the north in New Jersey, more marginal-marine, sandy strata of the Cohansey Formation appear above the sandy uppermost Kirkwood Formation. Although precise age controls are lacking, the upper Kirkwood/lower Cohansey sequences can be approximately correlated to the St. Marys sequences on the basis of their stratigraphic position (Fig. 17) (Browning et al., 2006).

The facies expression of these sequences varies from New Jersey to Delaware to Maryland, likely reflecting differing positions in the Salisbury Embayment. The New Jersey sequences are developed in higher-sedimentation-rate, shallower-water environments at the north end of the embayment, closer to likely sources of significant sediment input. In Delaware and Maryland, the facies in this interval are more marine and predominantly fine-grained. At Bethany Beach, the deepest environments in sequences C9 and C10 at Qj32-27 occur just above the sequence boundaries (Fig. 12). The sequences are interpreted as having a thin, basal, deeper-shelfal, glauconitic, transgressive systems tract (TST) and a thicker fine-grained shallow-shelfal highstand systems tract (HST). In contrast, at Calvert Cliffs (Kidwell, 1988, 1997), each sequence in the St. Marys Formation exhibits a deepening-upward trend, with fining-upward sand to mud successions representing TSTs deposited in a paralic environment. Kidwell (1988, 1997) suggested that the HSTs are absent because they were "shaved" from the top of the sequence by the next sea-level fall. The difference in sequence expression between these two areas can probably be attributed to the location of Calvert Cliffs in a more landward, paralic part of a fine-grained depositional system, where TSTs are thicker (higher sedimentation rates) and HSTs are eroded, and the location of Bethany Beach in a more basinward part of the system, where the TSTs are thin (lower sedimentation rates) and HSTs are preserved.

Above the St. Marys Formation, shallower-marine and marginal-marine environments prevail in southern Delaware and Maryland; facies relationships become increasingly complex and age control less precise, making these strata more difficult to correlate regionally. Although the lithostratigraphy for the Delaware section above the St. Marys Formation has recently been revised and formalized by Andres (2004) to consist of the Cat Hill and Bethany Formations, the nomenclature for equivalent Maryland strata is less well defined. The interval that includes the Manokin and Pocomoke aquifers has been referred to as undifferentiated "Yorktown and Cohansey

(?) Formations" in several early works (Rasmussen and Slaughter, 1955; Owens and Denny, 1979; Hansen, 1981). Two of these works (Owens and Denny, 1979: Hansen, 1981) cited mollusk and pollen data they considered suggestive of a late Miocene age, older than the Yorktown Formation in Virginia. Weigle (1974) and Achmad and Wilson (1993) recognized three aquifers in this interval in the Ocean City area: the Manokin, Ocean City, and Pocomoke. Achmad and Wilson (1993) followed Andres (1986) by referring to the lower part of this interval as the "Manokin formation," but, citing uncertainty in correlation to the "Bethany formation" of Andres (1986), used the nomenclature "Pocomoke beds" and "Ocean City beds" in lieu of a formation name.

The environments of deposition of these units merit some comment. Andres (1986) and Achmad and Wilson (1993) referred to the Manokin-to-Pocomoke interval (now Cat Hill and Bethany Formations) as deltaic deposits. Although these sediments have some of the characteristics of deltaic deposits, particularly the progradational nature of the succession, we believe a shoreface model is more applicable. The sedimentary facies of deltaic deposits should reflect the fluvial source, with abundant terrestrial organic matter and clay and evidence of high turbidity and variable salinity (Galloway and Hobday, 1996; Elliott, 1986). However, though plant debris is abundant in places in the Cat Hill and Bethany Formations in Qj32-27, it is not a ubiquitous feature. Areal distribution of sedimentary packages and environments also supports a shoreface interpretation over delta. A deltaic model implies a constructional coastal morphology with thickened isopachs around a depocenter produced where fluvial sedimentation interacts with the sea (Galloway and Hobday, 1996). In contrast, a shoreface model reflects processes related to marine inundation and reworking that produce facies and thickness patterns that generally trend parallel to the coast (Galloway and Hobday, 1996). The isopach maps and cross-sections for these units in Andres (1986) and Achmad and Wilson (1993) do not clearly exhibit areas of local thickening or seaward protrusion of the coastline that would indicate fluvial input to a depocenter along the shoreline; instead, the clearest trend appears to be an overall thickening of the section toward the east to southeast. For these reasons we interpret the Cat Hill and Bethany Formations to be a shallowing-upward succession produced by a prograding wave-dominated shoreline complex capped by interfingering tidal channels, tidal bars/deltas, and estuarine muds.

In summary, the stratigraphy of the upper Miocene section in this region becomes an increasingly complicated upsection as a result of shallowing paleoenvironments. Recent work in southern Delaware (Andres, 2004 and this study) has resolved significant issues of formation nomenclature and correlation in this interval. However, significant questions on aquifer stratigraphy remain. Separate Pocomoke, Ocean City, and Manokin aquifers do not appear to be consistently recognizable in the southern Delaware and eastern Maryland region as shown by our correlations in the Bethany Beach area (Fig. 16). Additional detailed work needs to be done to understand the distribution and geometry of these aquifer sands as well as the correlation of formations and aquifers between coastal Sussex County and nearby areas of southeastern Maryland.

CONCLUSIONS

Borehole Qj32-27 provides a nearly complete stratigraphic record of the mid-Oligocene to the Pleistocene section at Bethany Beach. Cores and wireline geophysical logs were obtained from unnamed Oligocene and lowermost Miocene strata at the bottom of the hole, as well as the Calvert, Choptank, St. Marys, Cat Hill, Bethany, Beaverdam, Omar, and Sinepuxent Formations. The high-quality record of lithology, ages, and environments yielded from this study establish Qj32-27 as an important reference section for the subsurface geology of eastern Sussex County.

Detailed lithologic descriptions of cores allow accurate characterization of the formations encountered at the site. Age control derived from strontium-isotope analyses and biostratigraphy yield the most precise chronostratigraphic framework available for these sedimentary units in Delaware. On the basis of core sedimentology and microfossils, paleoenvironmental interpretations through this section reveal an overall progradation of the shoreline from the Oligocene to the Pleistocene, with higher frequency transgressions and regressions reflecting global sea-level change.

Examination of key stratigraphic surfaces, combined with delineation of the finer-scale trends in paleoenvironments, allows a sequence stratigraphic framework to be established for these strata. In most of the Miocene section, sequence boundaries can be located based on changes in facies stacking patterns and commonly show evidence of exposure or non-deposition at an unconformity, such as cementation or enrichment of authigenic minerals like glauconite or phosphate. Sequences most commonly are composed of a thin, deepening-upward transgressive systems tract (sometimes absent) and a thicker shallowing-upward highstand systems tract. Fourteen sequences are recognized in the Oligocene to lowermost upper Miocene marine section. Sequence definition is less clear in higher strata; several sequences are tentatively delineated in the upper Miocene (and Pliocene?) shallow-marine to non-marine section and two sequences are identified in the Pleistocene section in the top of the borehole.

The results of this study help to better understand the depositional history and distribution of a number of aquifer sands important to southern Delaware. Sand units are identified in the deep part of the hole that correspond to the Cheswold, Federalsburg, Frederica, and Milford confined aquifers, all of which are important ground-water sources further north in northern Sussex County and Kent County. These clean sands occur in the highstand systems tracts of lower-to-middle Miocene sequences. In the upper Miocene section, sand units are identified that are locally referred to as the Manokin and Pocomoke aquifers. Stratigraphic correlation of the cored section at this site with other holes in the area suggests that the Manokin and Pocomoke aquifers are sands that occur within an interfingering complex of nearshore to estuarine deposits and, geologically, do not appear to be consistently definable as distinct sand bodies in eastern Sussex County. In Qj32-27, these are referred to a single undifferentiated Pocomoke-Manokin aquifer interval.

Comparing the stratigraphy at the Bethany Beach site to other Miocene sections in the region indicates that the

Delaware section has characteristics that reflect its position intermediate between the systems that deposited the sandy, deltaic Kirkwood and Cohansey Formations in New Jersey and the shelfal setting of the Calvert and Choptank Formations of Calvert Cliffs, Maryland. The boundary between the Calvert and Choptank Formations appears to be time transgressive between Delaware and Calvert Cliffs, with sandier, Choptank-type deposition occurring earlier in Delaware. Fine-grained sedimentation that characterizes the St. Marys Formation appears to have occurred at approximately the same time in both areas, but is expressed slightly differently in the more seaward location at Bethany Beach. Regional correlation of the nearshore and estuarine deposits of the upper part of the upper Miocene section is more problematic.

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