Stratigraphy of Miocene through Lower Pleistocene Strata of the United States Central Atlantic Coastal Plain

Thomas G. Gibson

ABSTRACT

Miocene, Pliocene, and Pleistocene strata were deposited in two embayments in the central Atlantic Coastal Plain, the Salisbury to the north and Albermarle to the south. Both embayments underwent local tectonics, and no single area within either has a continuous section.

Deposition in both embayments began in early Miocene time. In the Salisbury embayment, the early deposits were largely biogenic (Fairhaven Member of the Calvert Formation), and the center of deposition was located in Maryland. Relatively continuous clastic deposition commenced in the late early Miocene and continued through the middle Miocene (Plum Point Marl Member of the Calvert Formation and the Choptank and St. Marys formations). Deltaic deposition began in the northern part of the embayment, as seen in the Calvert and Kirkwood formations and influenced environments west of the delta lobe. The center of deposition in the Salisbury embayment shifted southward into Virginia during late Miocene time ("Virginia St. Marys" beds) and continued there through the early and middle(?) Pliocene (Yorktown Formation); only the southeastern part of the embayment received sediments in the late Pliocene and early Pleistocene (uppermost part of the "Yorktown" Formation). Environments throughout this time were largely inner shelf (less than 60-m depths), and some marginal-marine to nonmarine intervals.

The Albemarle embayment in North Carolina received largely biogenic and biochemical deposition during the early and early middle Miocene (Pungo River Formation). This was followed by uplift in the late middle and late Miocene. Clastic sedimentation started near the Miocene-Pliocene boundary and continued with minor hiatuses throughout much of the Pliocene and into early Pleistocene (Yorktown, uppermost part of the "Yorktown," Duplin, Croatan, and Waccamaw formations). Some Pungo River strata formed in middle-shelf environments as deep as 100 m; most younger strata were deposited in inner-shelf environments (less than 60-m depth), but some in marginal-marine intervals.

Introduction

The Lee Creek Mine in eastern North Carolina exposes Miocene, Pliocene, and Pleistocene strata, which in most of this area are otherwise available only in subsurface borings. This paper presents the general geologic setting of the strata in the mine and related strata from southern New Jersey to southern North Carolina and provides an interpretation of depositional environments. These strata represent extensive Cenozoic transgressions. They rest upon strata ranging in age from Cretaceous to late Oligocene in various parts of New Jersey, Maryland, Virginia, and North Carolina. In some areas, the strata transgress sufficiently westward to rest upon Piedmont crystalline rocks.

The central Atlantic Coastal Plain contains two adjacent major embayments, the Salisbury and Albemarle, in which structural activity and

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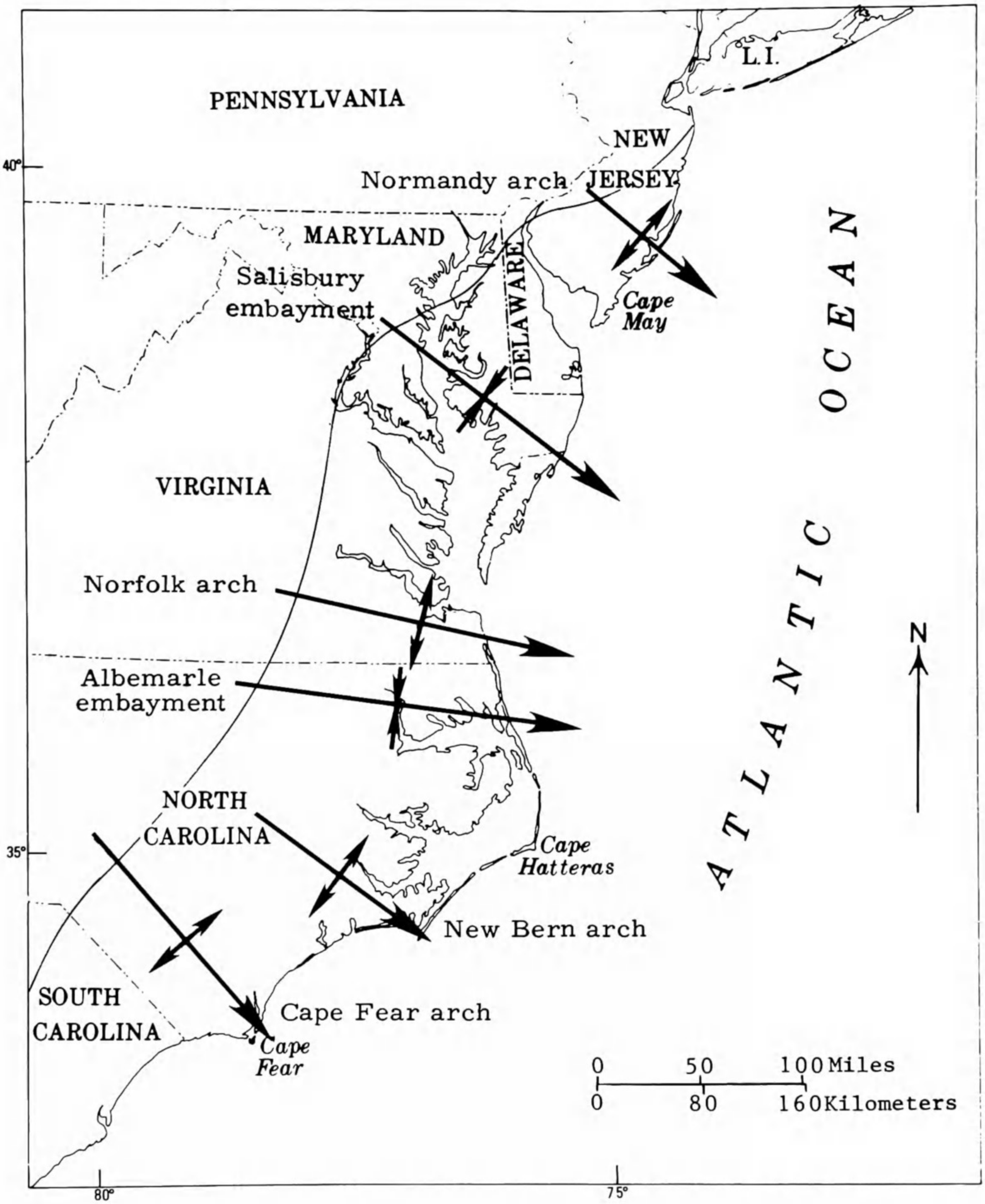

FIGURE 1.—Map showing major embayments and arches of the middle Atlantic Coastal Plain during the Miocene and Pliocene (from Gibson, 1967; Brown, Miller, and Swain, 1972). Line shows present westward limit of Miocene, Pliocene, and lower Pleistocene strata.

sedimentary patterns sometimes coincided. The embayments are separated by the Norfolk arch (Figure 1), which affected sedimentary patterns and thicknesses during Miocene and Pliocene time. The embayments are shoreward extensions of the Baltimore Canyon Trough (Poag, 1978:262).

Part of the lithologic data is from surface outcrops; these are correlated by use of mollusks (particularly the pectens), ostracodes, and foraminifers. The rest is from subsurface cuttings and cores that are correlated by foraminifers, lithologic character, and stratigraphic position. The basis for the age assignments of the formations is discussed on pages 356–367. Figure 2 is a correlation chart of the late Oligocene through early Pleistocene strata in this area.

The paleoenvironments are reconstructed from lithologies (both individual localities and regional patterns) and faunal data. The faunal interpretations are based largely upon modern benthic foraminiferal ecology (upon the known environmental tolerances of individual species and groups of species); in Miocene strata, where species that have living representatives are less numerous, assemblage characteristics (e.g., species diversity and abundance of planktonic specimens) were used. (See Phleger, 1960; Walton, 1964; Gibson, 1968; Gibson and Buzas, 1973; J.W. Murray, 1973, and Boltovskoy and Wright, 1976, for discussions and further references.) Some environmental interpretations are made from the molluscan assemblages following Gernant (1970) and Bailey (1973).

The lithologic and paleoenvironmental patterns that are evident onshore, in conjunction with the biostratigraphic data presented by Gibson (pp. 368–402), will permit more detailed correlations of equivalent strata found in offshore borings (Poag, 1978).

ACKNOWLEDGMENTS.—Philip M. Brown, formerly of the U.S. Geological Survey, graciously provided access to the well materials examined in this study and aided in much of the field work. Robert E. Gernant of the University of Wisconsin, Milwaukee, helped in the description and stratigraphy of the Baltimore Gas and Electric Company core hole at Calvert Cliffs and gave useful advice concerning field problems in Maryland. Jeffrey Lund and Elinor Stromberg did the illustrations. George W. Andrews, Philip M. Brown, C. Wylie Poag, and Frank C. Whitmore, Jr., of the U.S. Geological Survey, Robert E. Gernant of the University of Wisconsin, Milwaukee, and Druid Wilson of the Smithsonian Institution critically read the manuscript and made numerous helpful suggestions.

Previous Work

Comprehensive works on the Miocene and Pliocene strata of Maryland (Clark, Shattuck, and Dall, 1904), Virginia (Clark and Miller, 1912), and North Carolina (Clark et al., 1912) were published within a short time span in the early part of the 20th century. Later references include Mansfield (1943), Richards (1945), Spangler (1950), Spangler and Peterson (1950), G.E. Murray (1961), Maher (1965, 1971), Gernant (1970), Glaser (1971), Brown, Miller, and Swain (1972), Teifke (1973), and Weaver and Beck (1977).

The structural framework affecting the distribution of Coastal Plain strata generally has been considered to be controlled by warping in the basement rocks. These warps influenced the locations of the sedimentary basins as indicated by Stephenson (1928) and Mansfield (1929, 1937). Cederstrom (1945) and Ferenczi (1959) concluded that some of the positive and negative structures are fault controlled, thus accounting for the rapid lateral changes in thickness in some units. Subsurface control, however, is sparse along the possible fault zones, and the fault traces have not been detected in the exposed strata. Brown et al. (1977) presented evidence of a wrench fault in North Carolina, but no direct evidence of fault planes in the Miocene and Pliocene strata yet has been published. In the present investigation, the positive geologic structures are called arches, without distinguishing the mechanism by which they were formed. Figure 1 shows the location of

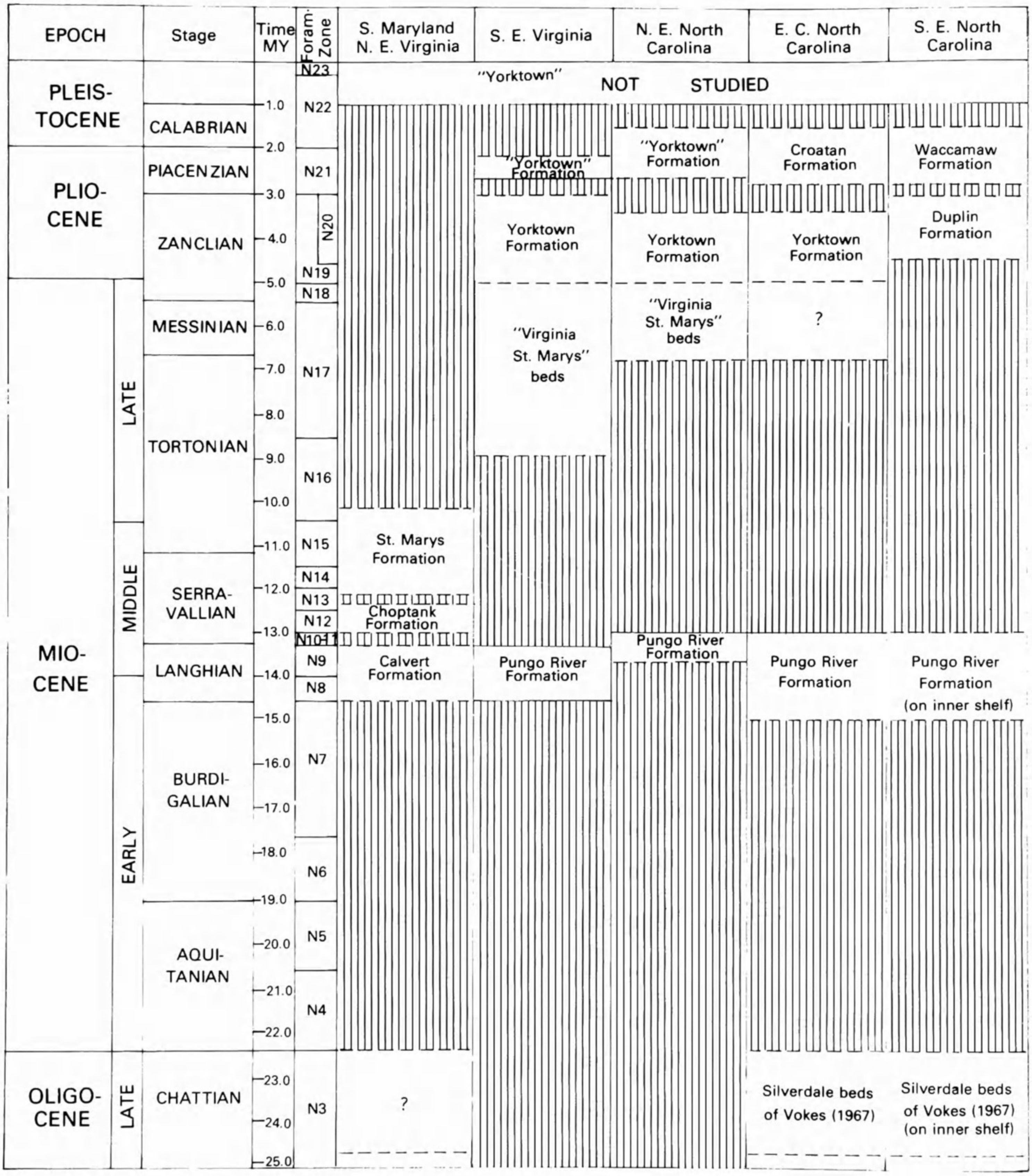

FIGURE 2.—Correlation chart for strata of late Oligocene through early Pleistocene age in the central Atlantic Coastal Plain. Stages, time scale, and planktonic foraminiferal zones are from Berggren and Van Couvering (1974). Solid lines at formational boundaries indicate well-documented time limits; dashed lines indicate limits that are incompletely known.

proposed structures in the Coastal Plain taken from Gibson (1967) and Brown, Miller, and Swain (1972).

The complex positive or negative movements of one of these structures is seen in the New Bern area of North Carolina. The Miocene and Pliocene formations are strongly influenced by a positive feature, the New Bern arch (Figure 1). For example, the Pungo River Formation is composed of strata that were deposited in middle-shelf environments in much of the Albemarle embayment (Gibson, 1967); the formation thins southward from the Lee Creek Mine toward the New Bern arch and the strata are of shallower water origin. At New Bern, on top of the feature, the formation is entirely absent (Figure 3). Similar southward thinning of strata and appearance of shallower water facies toward the arch is shown in the Yorktown Formation (Gibson, 1970). An opposing distributional pattern is seen in the uppermost Oligocene strata, such as those found at Silverdale, Pollocksville, Belgrade, along the Trent River, and in the New Bern quarry of Superior Stone Company. Although these Oligocene strata are well represented over the New Bern arch, indicating a depositional low, they are absent throughout most of the Albemarle embayment to the north. This change in environment in the Albemarle embayment, from a largely nondepositional or erosional area in the late Oligocene to probably the most persistent and deepest basin in the Miocene and Pliocene, suggests that features such as the New Bern arch may be fault controlled rather than a simple upwarp.

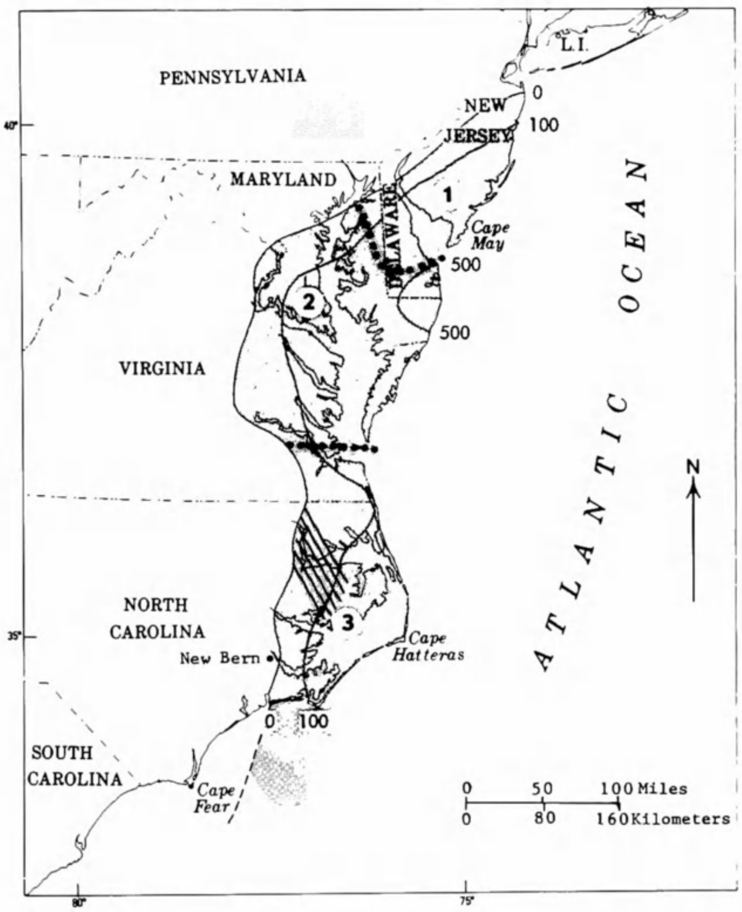

FIGURE 3.—Isopachous map of upper lower and lower middle Miocene strata. 1 = Kirkwood Formation, 2 = Calvert Formation, 3 = Pungo River Formation; contours are in feet, the dotted lines show the approximate location of the facies changes between the formations; the diagonal-lined area in North Carolina is the known location of the youngest, planktonic zone N11 strata of the Pungo River Formation (modified from Gibson, 1970).

Another anomalous distribution of strata, which apparently resulted from structural movement, is seen in the Paleocene and Eocene strata of Maryland and Virginia. Shifflett (1948) described the relatively thick sections of Aquia Formation (lower and upper Paleocene) and Nanjemoy Formation (lower and middle Eocene) in Maryland west of Chesapeake Bay and pointed out that strata of these ages are largely or completely absent on the Eastern Shore of Maryland, even though the Eastern Shore commonly was considered a down-dip area where one could expect thicker sections. A similar pattern is found in Virginia where the Aquia and Nanjemoy formations are found in most of the central and inner Coastal Plain, but are absent to the east in the subsurface of Norfolk (Brown, Miller, and Swain, 1972:46–47).

To understand the complex structural and stratigraphic patterns, Brown, Miller, and Swain (1972) examined Mesozoic and Cenozoic strata in more than 2200 wells from Long Island to South Carolina. They described the structural architecture of the Atlantic Coastal Plain as being dominated by lateral and vertical movements along a system of intersecting hinge zones. The stratigraphic intervals used by them in the Miocene included rocks of middle Miocene age (equals the Calvert, Choptank, and St. Marys formations) and a unit of rocks of late Miocene age (equals the St. Marys Formation of Virginia of Mansfield (1943) and the Yorktown Formation, units subsequently considered to be of late Miocene and Pliocene age). They presented a combined isopach, lithofacies, and permeability distribution map for each of these units. Some of the units, such as the rocks of middle Miocene age, were considered to have depositional alignments and thickening trends accordant with the present-day configuration of the underlying basement surface. Other units, the upper Miocene, for example, were considered to have depositional alignments and thickening trends independent of the present-day basement configuration.

Stratigraphy

The Miocene, Pliocene, and lower Pleistocene formations are discussed from oldest to youngest in the following sections. For each formation, the lithology and thickness in the type area are described, followed by a discussion of the areal distribution and paleoenvironments. Facies changes and times of deposition are emphasized, especially to contrast the Salisbury and Albemarle embayments. The locations of important outcrop and well sections specifically mentioned here are shown in Figure 4.

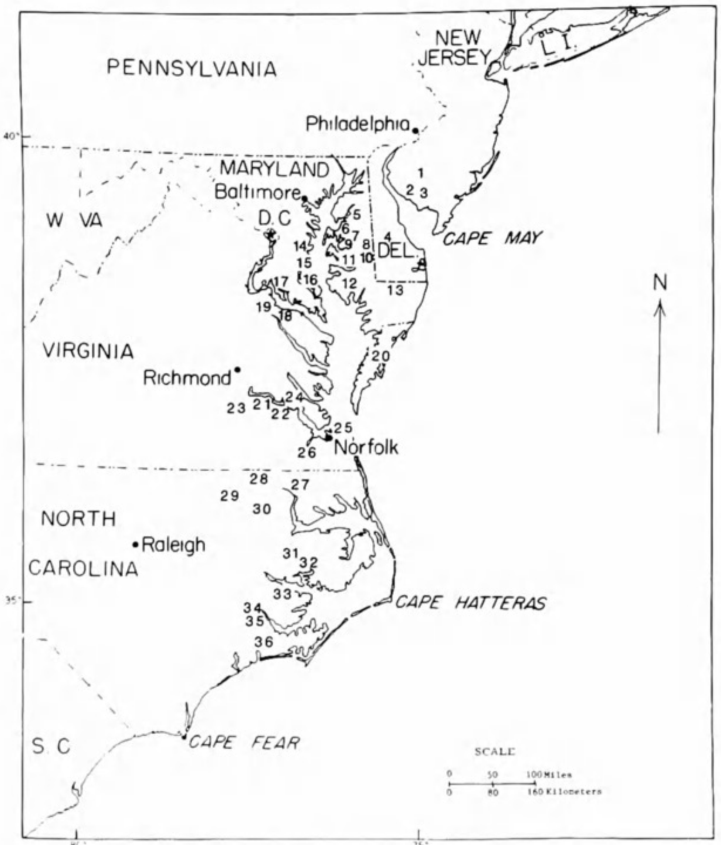

FIGURE 4.—Localities of outcrops and well sections mentioned in text: 1 = Well NJ2, 2 = Well NJ3 and Shiloh, 3 = Well NJ1, 4 = Greenwood Well, 5 = Well 231, 6 = Well 229, 7 = Well 228, 8 = Well 225, 9 = Well 227, 10 = Well 224, 11 = Well 226, 12 = Well 220, 13 = Hammond Well, 14 = Fairhaven, 15 = BG&E Well, 16 = Calvert Cliffs, 17 = Popes Creek, 18 = Nomini Cliffs, 19 = Oak Grove core hole, 20 = Accomack Well, 21 = Well 217, 22 = Claremont, 23 = Petersburg and Lieutenant Run, 24 = Jamestown, 25 = Moores Bridge Well, 26 = Well 209, 27 = Gatesville, 28 = Murfreesboro, 29 = Halifax, 30 = Palmyra, 31 = Terra Ceia, 32 = Belhaven, 33 = Lee Creek Mine and AU-1-GRL core hole, 34 = New Bern, 35 = James City, 36 = Great Lake Well 181.

Calvert Formation

The Calvert Formation was named by Shattuck (1902) from well-developed exposures in the Calvert Cliffs along the western shore of Chesapeake Bay in Calvert County, Maryland (Figure 4: loc. 16). An outcrop thickness of 150 to 170 feet (46 to 52 m) for the formation was determined by the superposition of discontinuous sections (Shattuck, 1904, pl. 5). This thickness in the type area is supported by a continuous core hole drilled in 1968 at the Calvert Cliffs site of the Baltimore Gas and Electric Company's (BG&E) nuclear power plant near St. Leonards, Maryland (Figure 4: loc. 15). At this location, slightly down-dip from the type outcrops, the Calvert Formation is 200 feet (61 m) thick (Figure 5). The thickest known section onshore is in the Hammond Well on the Eastern Shore of Maryland (Figure 6), where 500 feet (152 m) of section was assigned to the Calvert by Anderson (1948:18).

Two relatively distinctive lithologies were recognized in the Calvert Formation in Maryland by Shattuck (1904) and given member status. The lower, Fairhaven Diatomaceous Earth Member, contained basal pebbly sands overlain by highly diatomaceous clay to fine sand intervals. This member is largely olive-gray to olive-green,

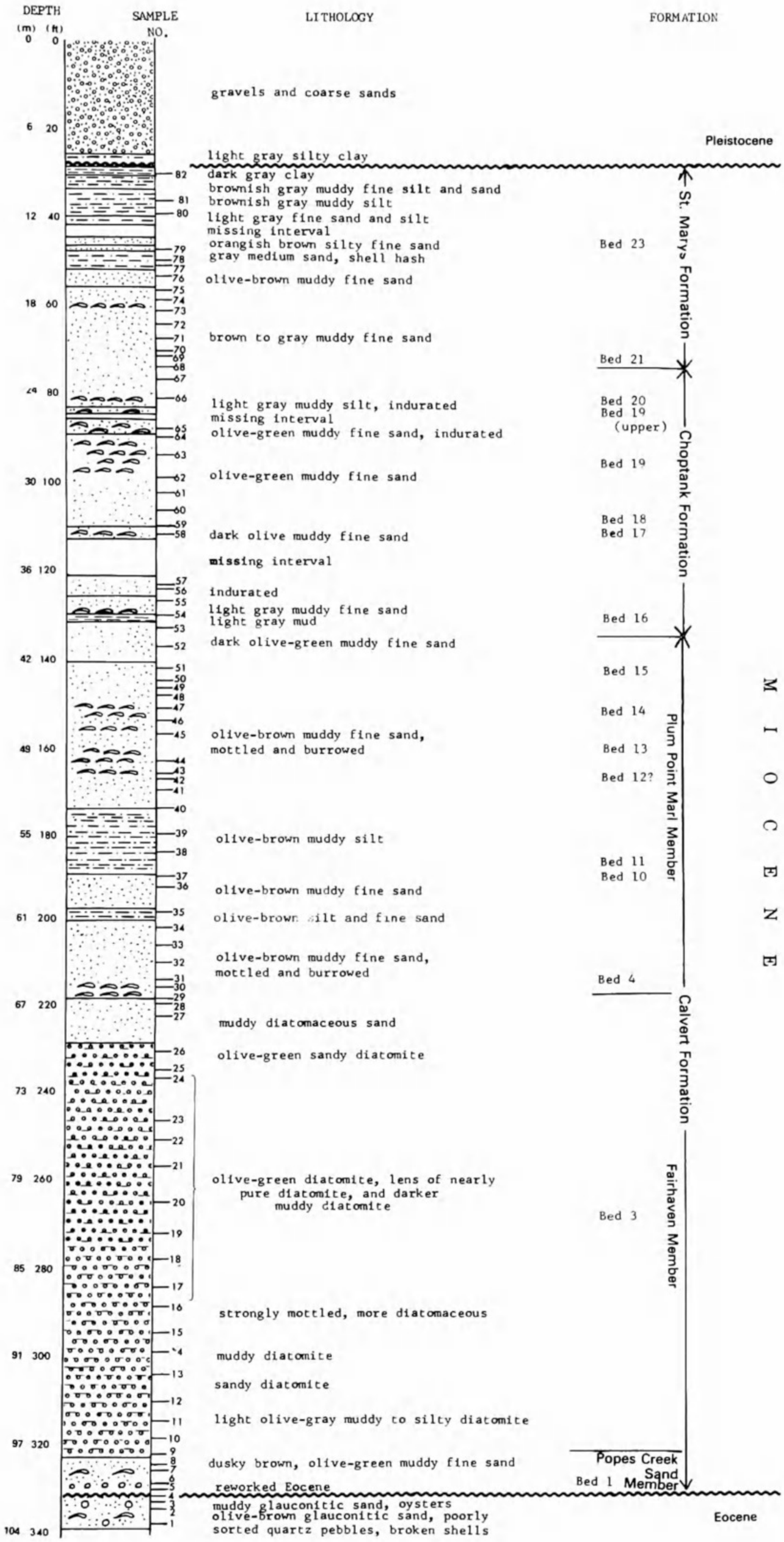

FIGURE 5.—Geologic column for Baltimore Gas and Electric Company Well (BG&E) at nuclear power plant site at Calvert Cliffs, southeast of St. Leonards, Calvert County, Maryland.

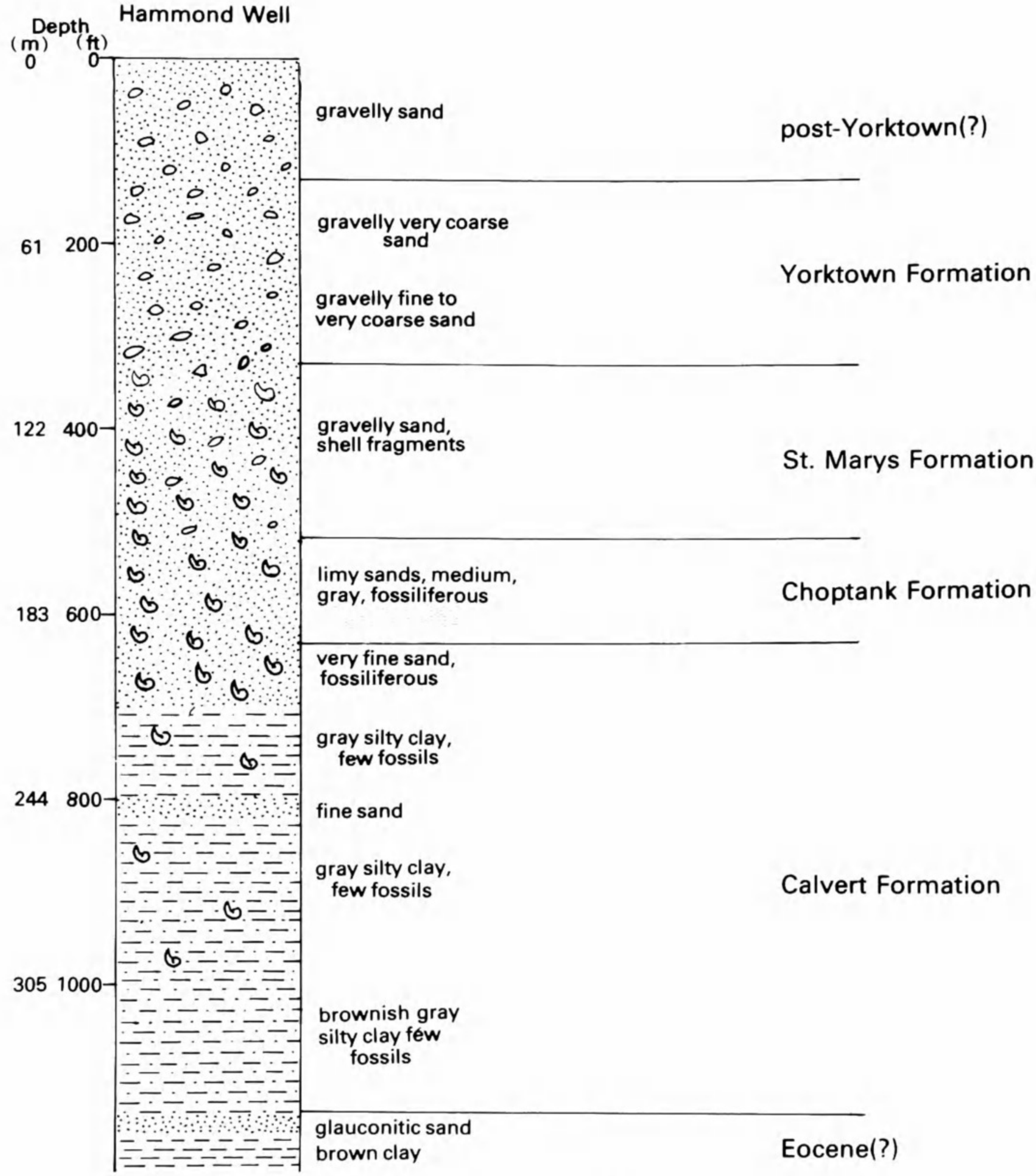

FIGURE 6.—Geologic column for Larry G. Hammond Well, Dorchester County, Maryland, showing inner-shelf facies in Calvert and Choptank formations and delta front to topset delta conditions in St. Marys and Yorktown formations.

and varies from relatively pure diatomite (as much as 65 percent of the sediment (Glaser, 1971:41)) to sandy and muddy diatomite (Figure 5). The member is 60 to 70 feet (18 to 21 m) thick in outcrop (Shattuck, 1904, pl. 5) and thickens down-dip to about 100 feet (30 m) in the BG&E Well (Figure 5). West of Chesapeake Bay, the top of the Fairhaven is marked by a distinct discontinuity indicated by an undulating surface that is overlain by a thin oyster bed of the Plum Point Marl Member (Dryden, 1936). Calcareous fossils are scarce in the diatomaceous beds in outcrop

(Gibson et al., 1980), but Foraminifera are present in the uppermost, more sandy and less diatomaceous part, and Mollusca are found in the basal sand. Foraminifera are found throughout the diatomite beds in the BG&E core, although they are lacking in the diatomaceous intervals in many other subsurface sections.

The lower beds of quartz sand in the Fairhaven Member are characterized by olive-brown, olive-green, to light greenish white fine to medium sand, muddy in places, that may contain coarse sand to fine gravel pebbles of quartz, phosphate, and glauconite. A thin layer of quartz and phosphate pebbles, bone fragments, and phosphatized mollusk shells is often found at the base. Cylindrical burrows are common in the sands. These sands crop out in Maryland west of Chesapeake Bay from near Fairhaven southward to Popes Creek, a tributary of the Potomac River, and extend into Virginia where they are muddier and thinner, such as those in the Oak Grove core (Reinhardt, Newell, and Mixon, 1980). The equivalents of zones 1 and 2 can be traced in the subsurface of the Eastern Shore of Maryland, where basal sands containing *Pecten humphreysii* are found in Well 220 (Figures 4: loc. 12; and 7), and into Delaware, where Valia, Khalifa, and Cameron (1977) described the basal unit as pebbly glauconitic and quartzitic sands containing typical Calvert Foraminifera. Poag (1978) reported conspicuous glauconite in the lower few meters of the probable Calvert Formation equivalent in core holes in the Norfolk Canyon area east of the Delmarva Peninsula, extending the distribution even beyond the edge of the present-day shelf. Because of the wide distribution of these distinctive sands (which represent the basal transgressive unit of the rapidly subsiding Salisbury embayment) and because of their lithologic distinction from the remainder of the Fairhaven Member, I herein classify them as the Popes Creek Sand Member of the Calvert Formation (Figure 9). The type section is the outcrop 100 yards (91 m) southeast of the mouth of Popes Creek, Charles County, Maryland, on the north bank of the Potomac River (Figure 8). Glauconite is rare (Glaser, 1971:46) in the western outcrop exposures, but increases to significant proportions eastward. Valia, Khalifa, and Cameron (1977) showed that beds, which I consider a part of this member, consist of 20 to 50 feet (6 to 15 m) of pebbly glauconitic sand in the subsurface of Delaware.

The thickest part of the outcropping Fairhaven (zone 3 of Shattuck, 1904) is retained as the Fairhaven Member. This member comprises the sandy and muddy diatomaceous strata above the Popes Creek Sand Member and below the shelly sand of the Plum Point Marl Member.

The Plum Point Marl Member consists of beds of olive-green to olive-brown silty and clayey fine sand that generally contain scattered to highly abundant molluscan shells, a considerable number of marine mammal bones, and other vertebrate remains. Zones 4 to 15 of Shattuck (1904) compose this member, which reaches a thickness of 90 to 100 feet (27 to 30 m) in outcrop along the Calvert Cliffs.

AREAL RELATIONSHIPS.—Very little change is found in the Calvert Formation from the Calvert Cliffs area (Figure 5) eastward to Well 220 near Bucktown (Figures 4: loc. 12; and 7) on the Eastern Shore of Maryland. Well 220 is 20 miles (32 km) obliquely down-dip from the BG&E Well, and the similar thickness and lithology is somewhat surprising. The Calvert in Well 220 is only slightly thicker than at the outcrop (~220 ft, 67 m), and the facies are similar to those in the BG&E core. The Popes Creek Sand Member is slightly thicker in Well 220 (25 ft, 7.6 m) and is more glauconitic in the lower part. The Fairhaven Member is almost identical in the two wells as Well 220 has 110 feet (34 m) of green diatomaceous clay. The Plum Point Marl Member also is similar; Well 220 has 85 feet (26 m) of sand and sandy clays generally containing scattered shells, but abundant shells in some places.

About 30 miles (48 km) to the east of Well 220, the Ohio Oil Company's Larry G. Hammond Well (Figure 4: loc. 13) penetrated 500 feet (152 m) of Calvert (Anderson, 1948). Here the entire Calvert consists of brownish gray to gray silty

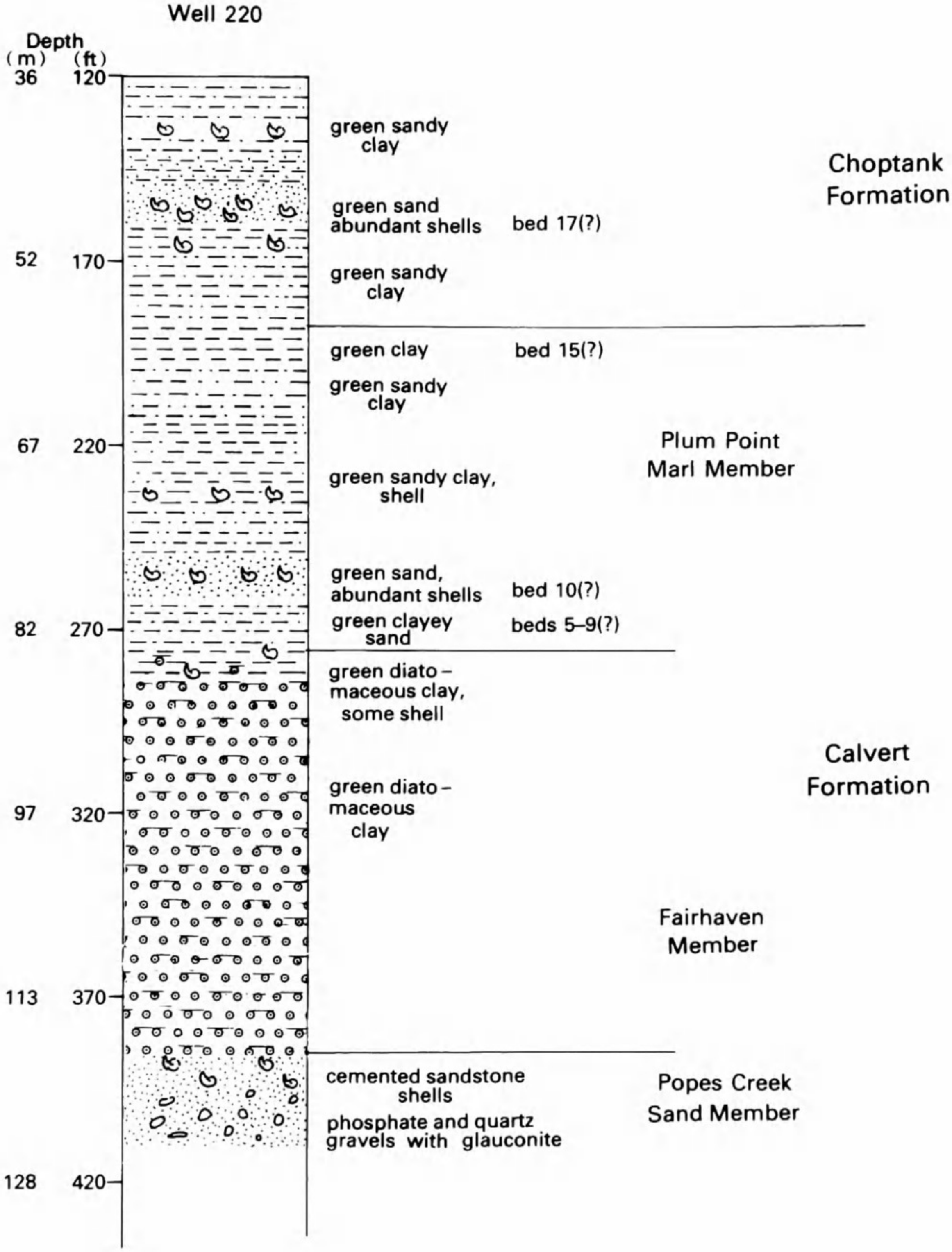

FIGURE 7.—Geologic column for Well 220, near Bucktown, Dorchester County, Maryland, showing inner-shelf facies of Calvert and Choptank formations with well-developed basal member of Calvert.

clay and very fine sand containing mollusk shells and rare to moderate amounts of glauconite scattered throughout (Figure 6). The three members of the Calvert, so characteristic to the west, are no longer recognizable. These changes in the Calvert Formation are shown in Figures 5–7.

Lithologies similar to those of the lower and upper parts of the Calvert in the type area are

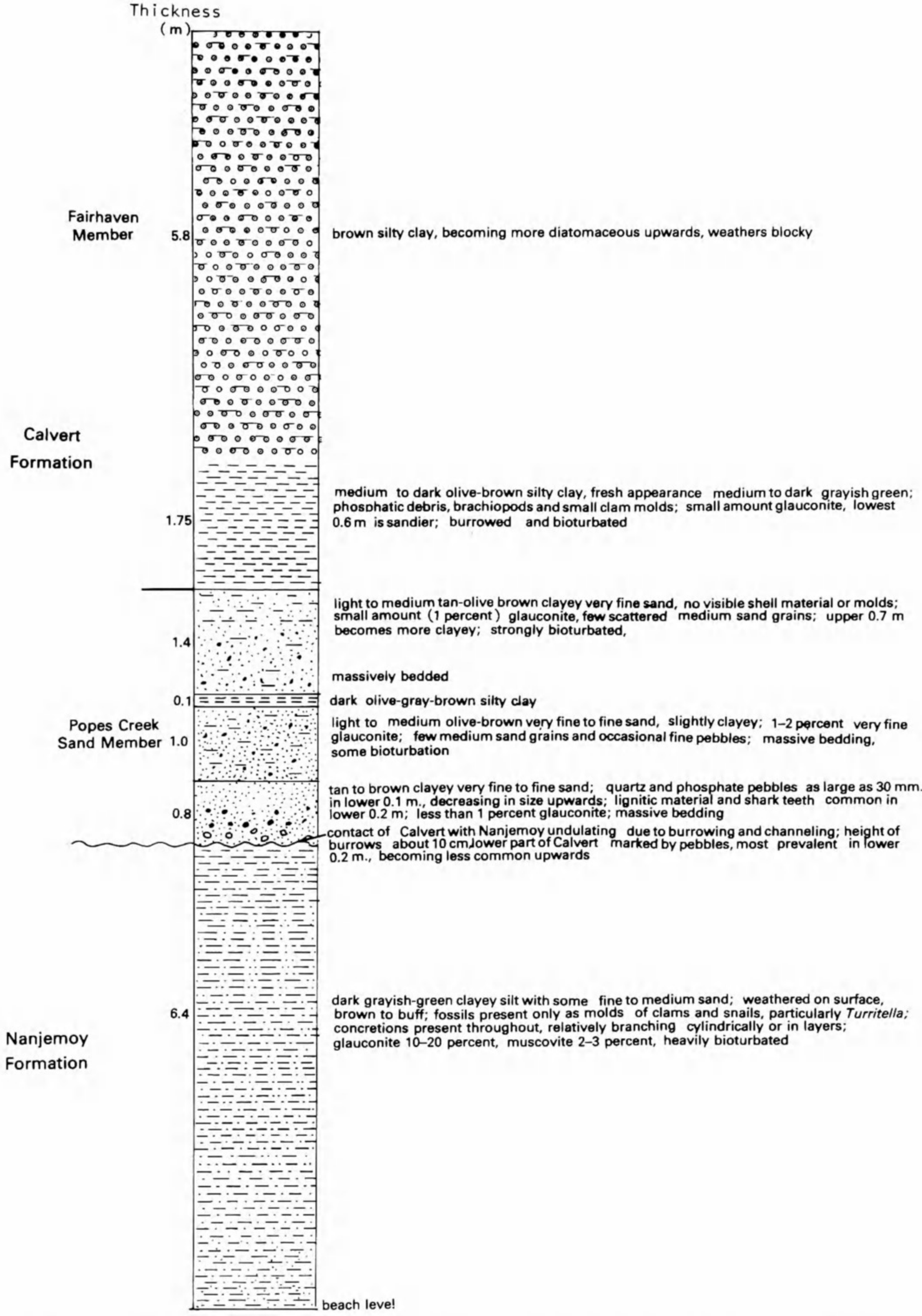

FIGURE 8.—Geologic section on north bank of Potomac River, 100 yards (91 m) southeast of the mouth of Popes Creek, Charles County, Maryland. This outcrop is the type section of the Popes Creek Sand Member of the Calvert Formation.

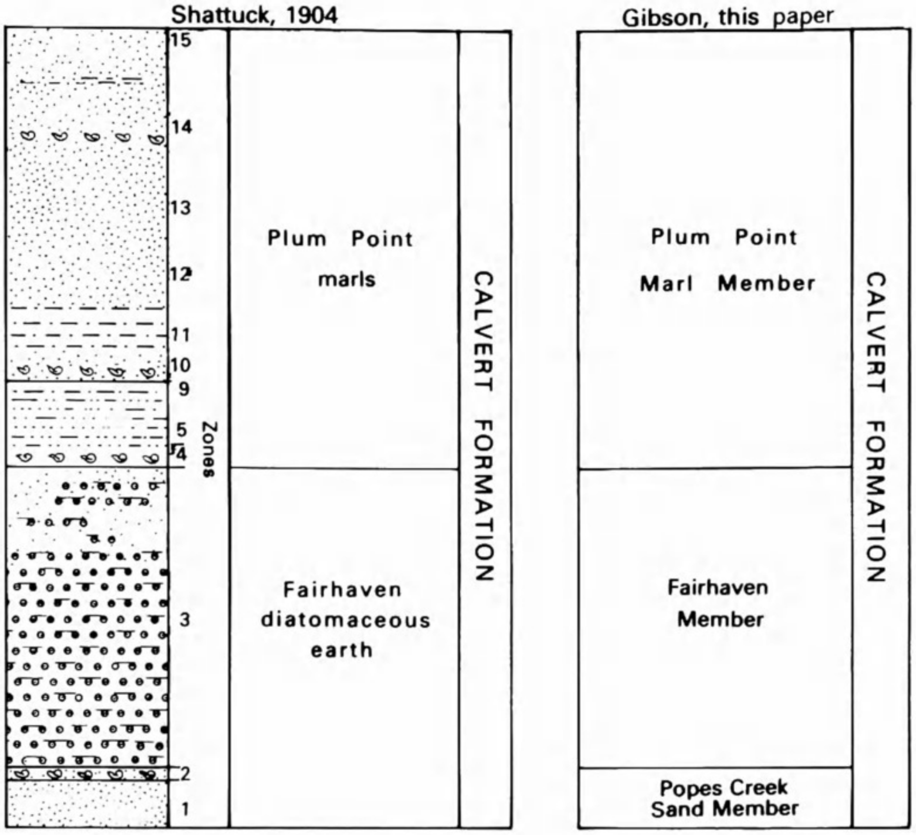

FIGURE 9.—Chart showing beds 1–15 and members of the Calvert Formation according to Shattuck (1904) and as treated in this paper.

found on the Eastern Shore north of Well 220. But there, the middle part of the Calvert is divisible into two facies as seen in wells 224 through 231 (Figures 10–16). The Popes Creek Sand Member continues across the area as a 10 to 20 foot (3 to 6 m) glauconitic sand and gravel, containing quartz and phosphatic pebbles as much as 2 inches (5 cm) in diameter. The Fairhaven Member generally is similar to the beds west of Chesapeake Bay. However, the strata in some of the easternmost wells are less diatomaceous and are composed mostly of green clay and sandy clay. These are interbedded with green and brown clays in the farthest northeast well, 231 (Figures 4: loc. 5, and 10). A significant change is seen in the lower part of the Plum Point Marl Member (equivalent to beds 3 through 9 west of the Bay). Nearest the Bay (to the west, southwest, and northwest of Easton; wells 226, 227, 229 (Figures 4: loc. 11, 9, 6; and 11–13), the beds of green sandy clay containing scattered shells are still present. But in wells to the east of a roughly north-south line through Easton, this interval consists of brown clay and silty clay and gray sand interbeds. The interbedded clay and sand are from ¼ to 2 inches (0.6 to 5 cm) thick, and the thicker sand beds appear to be crossbedded in the cores. Between the brown clay intervals, which may be 30 to 40 feet (9 to 12 m) thick, are intervals of green clayey sand containing scattered shells. This sequence is well developed in Well 224 located approximately 6 miles (9.7 km) southeast of Easton (Figures 4: loc. 10; and 14). The brown clay facies continues northeastward and eastward of Easton (wells 231, 225, and 228; Figures 4: loc. 5, 8, 7; and 10, 15, 16), and appears to be equivalent to the brown clay of the Alloway Clay Member of the Kirkwood Formation of New Jersey as mapped by Isphording (1970).

The upper part of the Plum Point Marl Member (beds 10 to 15 of Shattuck, 1904) is similar over the entire area to the equivalent strata in the

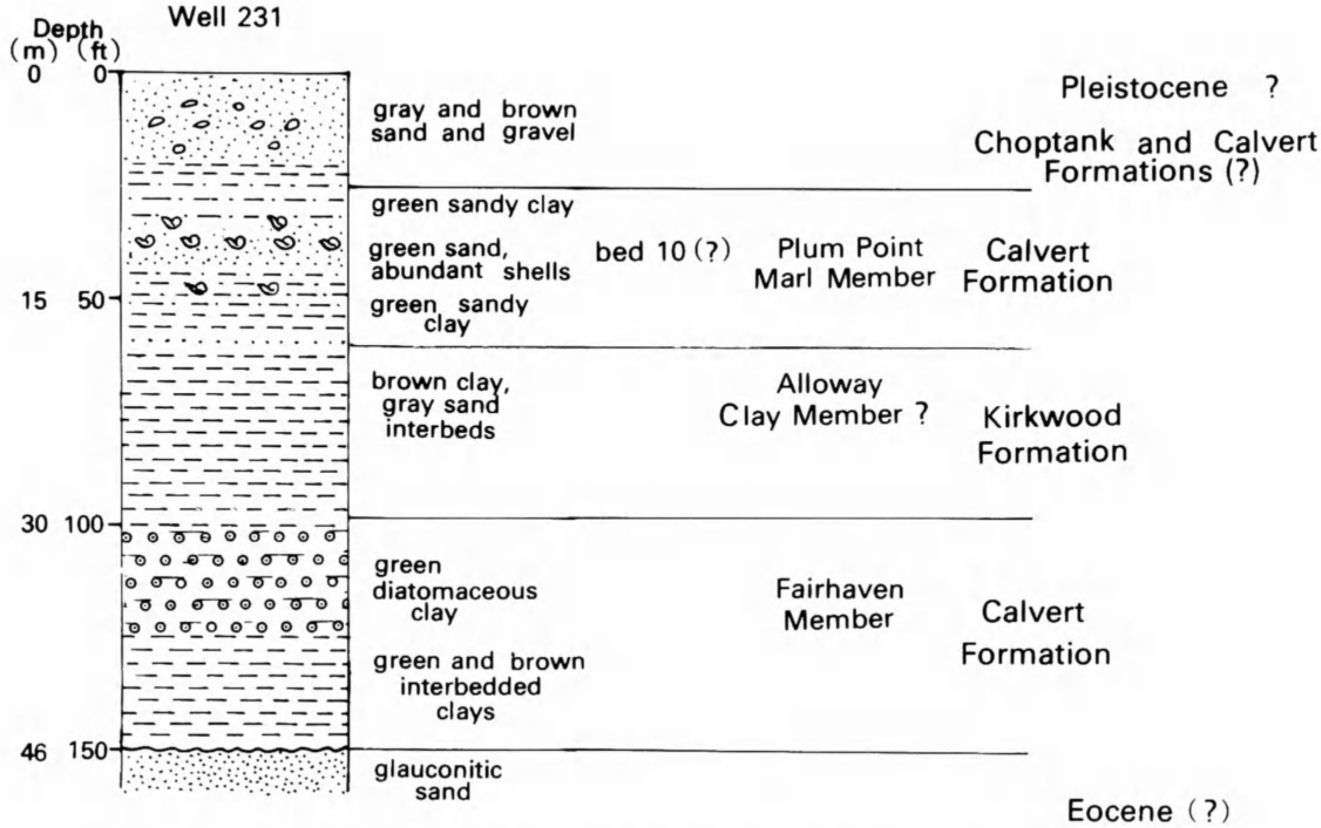

FIGURE 10.—Geologic column for Well 231, near Sudlersville, Queen Annes County, Maryland, showing interfingering of deltaic beds provisionally assigned to Alloway Clay Member of the Kirkwood Formation with inner-shelf sediments of the Plum Point Marl Member of the Calvert.

Calvert Cliffs (beds of green clayey sand and clay and a basal sandy shell bed overlain by intervals of scattered to abundant shells).

Farther east, Talley (1975) described the strata in a well at Greenwood, Delaware (Figure 4; loc. 4), but did not divide the Chesapeake Group into formations. The lower part of the section in this well consists of shelly, glauconitic sand, which Valia, Khalifa, and Cameron (1977) placed in the basal part of the Calvert. I consider the strata to be an eastward extension of the Popes Creek Sand Member. These strata are overlain by dark gray silty clay, probably equivalent to the Fairhaven Member, and then by brown to gray, commonly shelly silt and sand, probably equivalent to the Plum Point Marl Member.

In southwestern New Jersey, Miocene strata of the time-equivalent part of the Kirkwood Formation (Richards and Harbison, 1942), in wells such as NJ1–NJ3 (Figures 4: loc. 1–3; and 17–19), consist of a basal sand overlain by green silty clay, and then by brown clay with thin interbeds of gray sand. The brown clay contains carbonaceous fragments (as long as 5 cm) and generally lacks shells. Above the brown clay sequence, silt and medium sand containing abundant shells crop out near Shiloh (Figure 4: loc. 2) and have been penetrated by the NJ1 well near Cedarville (Figure 4: loc. 3). The stratigraphic sequence is similar to that found in the northeastern part of the Eastern Shore of Maryland. The strata in southwestern New Jersey belong in the Alloway Clay Member as used by Isphording (1970). To the northeast in New Jersey, Isphording reported that the clay grades into his Grenloch Sand Member (herein adopted), which in turn grades northeastward into finely laminated, organic-rich, silty sand of his Asbury Park Member (also herein adopted; former Asbury Clay of Kümmel and Knapp, 1904).

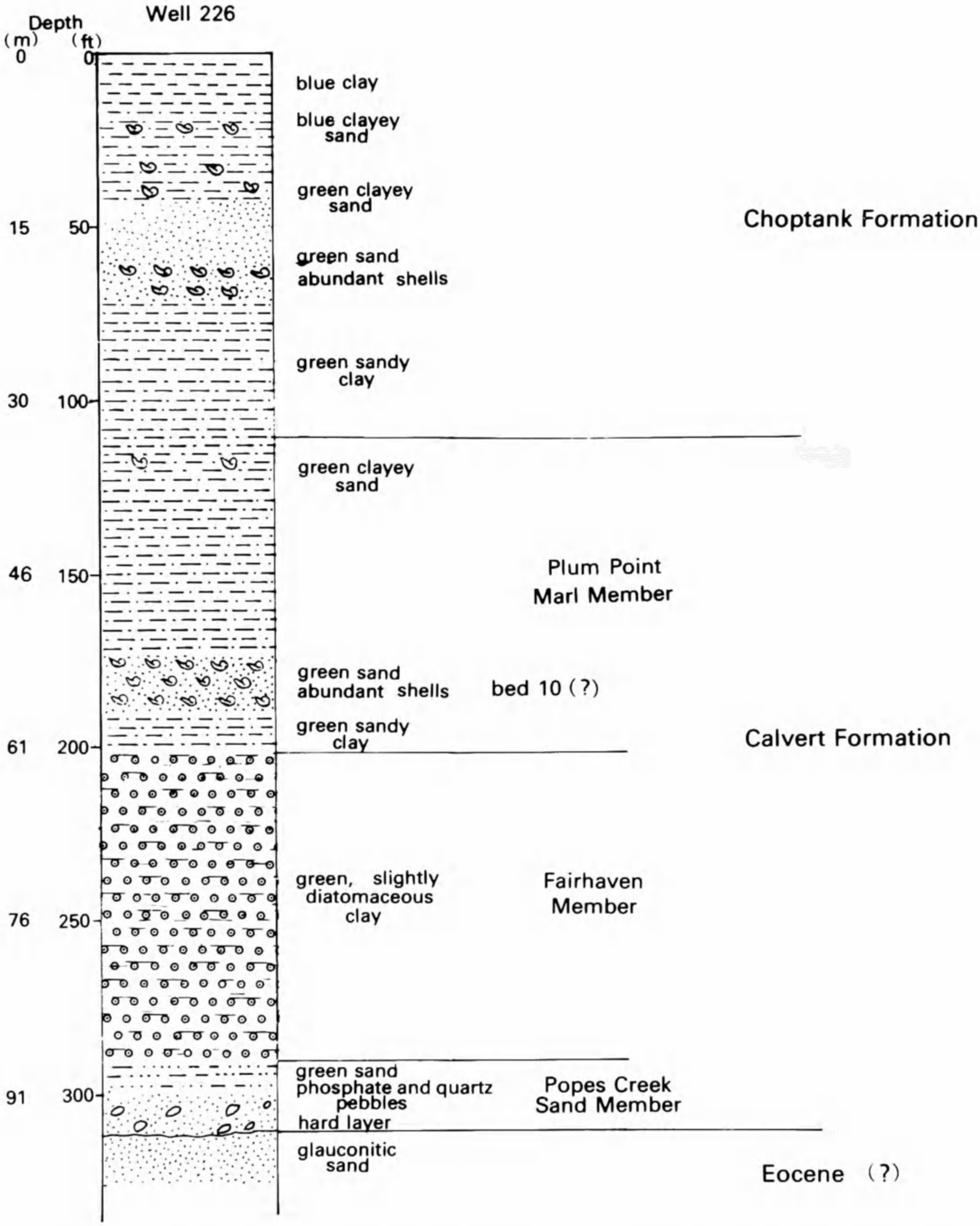

FIGURE 11.—Geologic column for Well 226, near Trappe Creek, Talbot County, Maryland, showing inner-shelf environments in Choptank and Calvert formations.

South of the Calvert Cliffs, the Calvert Formation thins to 110 feet (34 m) in the Oak Grove core hole in northeastern Virginia (Figure 4: loc 19). Here, the basal unit in the Calvert is a 9-foot (2.7-m) pebbly coarse sand to clayey sand containing phosphatized shell fragments. It is overlain by 9 feet (2.7 m) of diatomaceous clay, and above that is 82 feet (25 m) of clayey to silty very

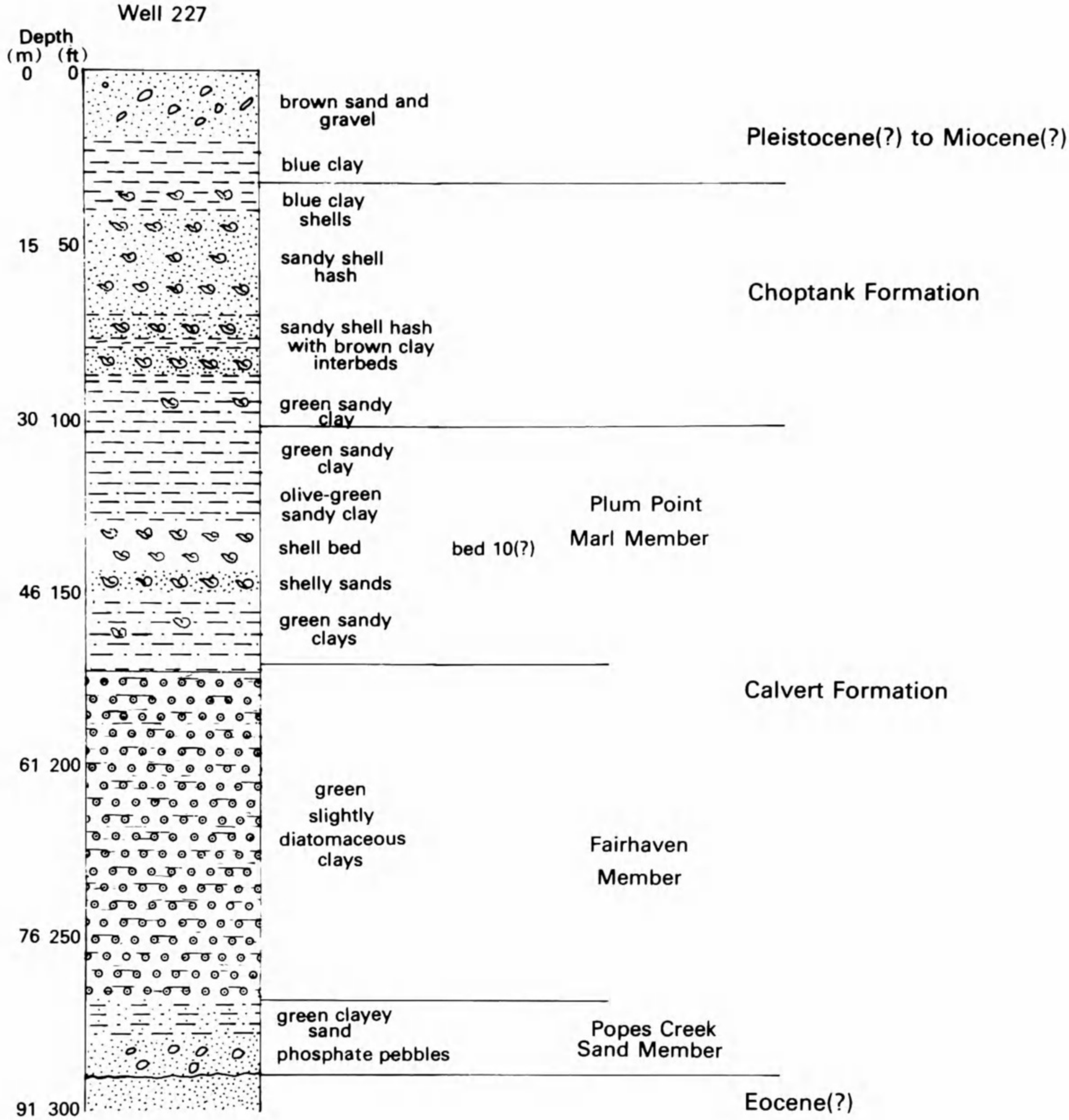

FIGURE 12.—Geologic column for Well 227, near Easton, Talbot County, Maryland, showing basal sands of Popes Creek Sand Member overlain by sediments of inner-shelf environments in remainder of Calvert Formation and small amount of deltaic to prodelta influence in Choptank Formation.

fine sand (Reinhardt, Newell, and Mixon, 1980). The lower sand is considered the equivalent of the Popes Creek Sand Member; the diatomaceous clay, the equivalent of the Fairhaven Member, and the upper 82 feet (25 m), the equivalent of the Plum Point Marl Member. A diatomaceous interval in the upper part of the upper sand contains diatoms equivalent to those of beds 14 and 15 in the Calvert Cliffs (Gibson et al., 1980). Whether the equivalent of the entire Plum Point

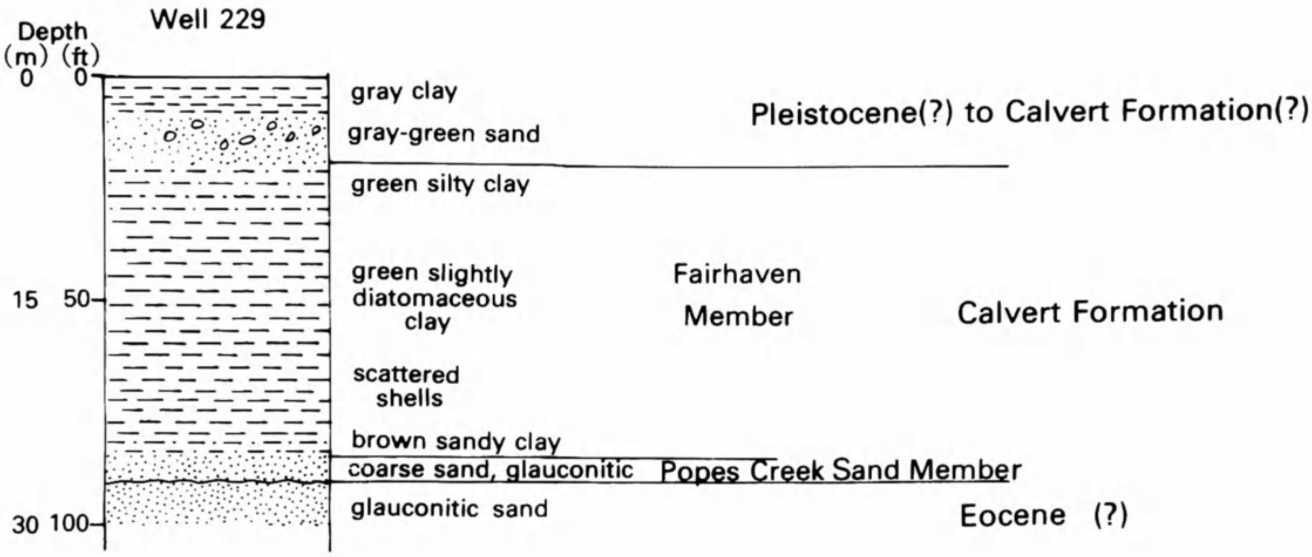

FIGURE 13.—Geologic column for Well 229, near Queenston, Queen Annes County, Maryland, showing coarse sand of Popes Creek Sand Member overlain by diatomaceous facies of Fairhaven Member.

Marl Member is present here is unknown because biostratigraphic control is lacking. However, equivalents of at least part of each member are found. Although marine diatoms and dinoflagellates are present in the Calvert of the Oak Grove core, calcareous fossils are absent here and in most up-dip sections in Virginia. The absence of shells prevents lithologic recognition of the Plum Point Marl Member, although strata of equivalent age are present as determined from the diatoms (Gibson et al., 1980). Lithologically similar sections of the Calvert Formation are found in other parts of the Virginia outcrop belt toward the western edge of the Coastal Plain. Typically, as along the Mattaponi River, the strata contain a basal sand and gravel bed characterized by quartz and phosphatic pebbles and shark teeth and other vertebrate fossils. This is overlain by diatomaceous clay and then by silty clay (Clark and Miller, 1912:126, 135).

In down-dip subsurface sections to the east and southeast in Virginia, such as at Jamestown (Figure 4: loc. 24), green sand and clay containing faunas indicative of open marine to partially restricted marine conditions are found. The Calvert Formation and equivalents are not found on the western part of the Norfolk arch (Figures 1, 3), but are found on or near the arch toward the coast, as in the Moores Bridge Well at Norfolk (Figure 4: loc. 25). Here the upper part of the Calvert section comprises beds of fossiliferous green silty clay characteristic of the formation, but the lowermost 11 feet (3.4 m) is an olive clayey phosphatic sand, similar to that of the Pungo River Formation to the south. Thus, the Norfolk area contains the transition from terrigenous clastic deposition in the Salisbury embayment to largely chemical and bioclastic deposition in the Albemarle embayment to the south.

ENVIRONMENT OF DEPOSITION.—The BG&E Well is the key section for paleoenvironmental interpretation of the Calvert Formation, because it contains the most detailed information in a single continuous section. From this focal point, the regional patterns for each of the members are discussed. Figure 20 shows sand percentage, species diversity of benthic Foraminifera, and percentage of planktonic Foraminifera.

The lowermost strata of the Calvert (Popes Creek Sand Member) accumulated during the transgression of the Calvert sea into the Salisbury embayment. Prior to this, the embayment received widespread glauconitic clay and sand during much of the early and middle Eocene and more restrictively in the late Eocene. In addition, Oligocene seas invaded part of this embayment

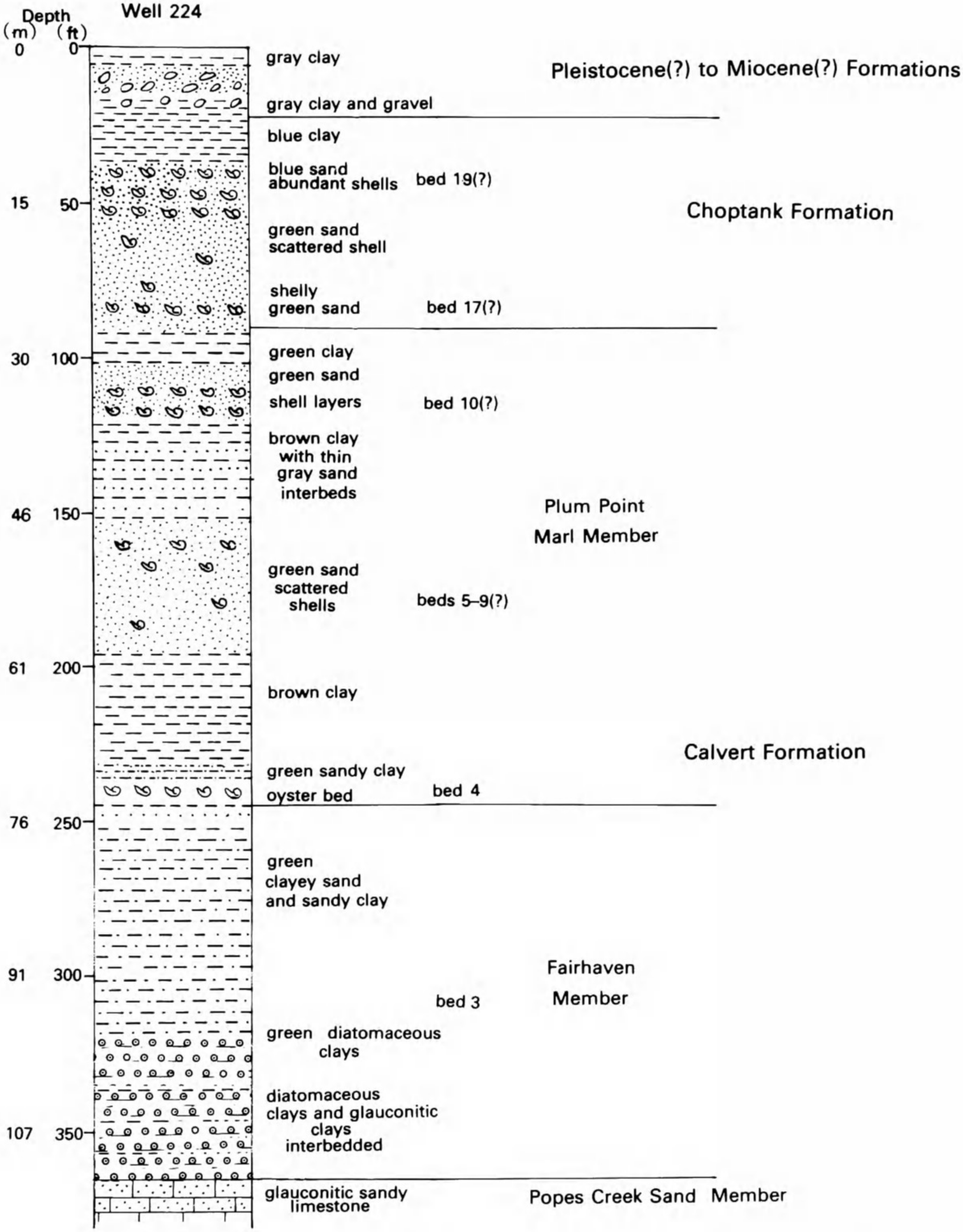

FIGURE 14.—Geologic column for Well 224, southeast of Easton, Talbot County, Maryland, showing deltaic influence in lower and middle part of Plum Point Marl Member and inner-shelf environments in Choptank Formation.

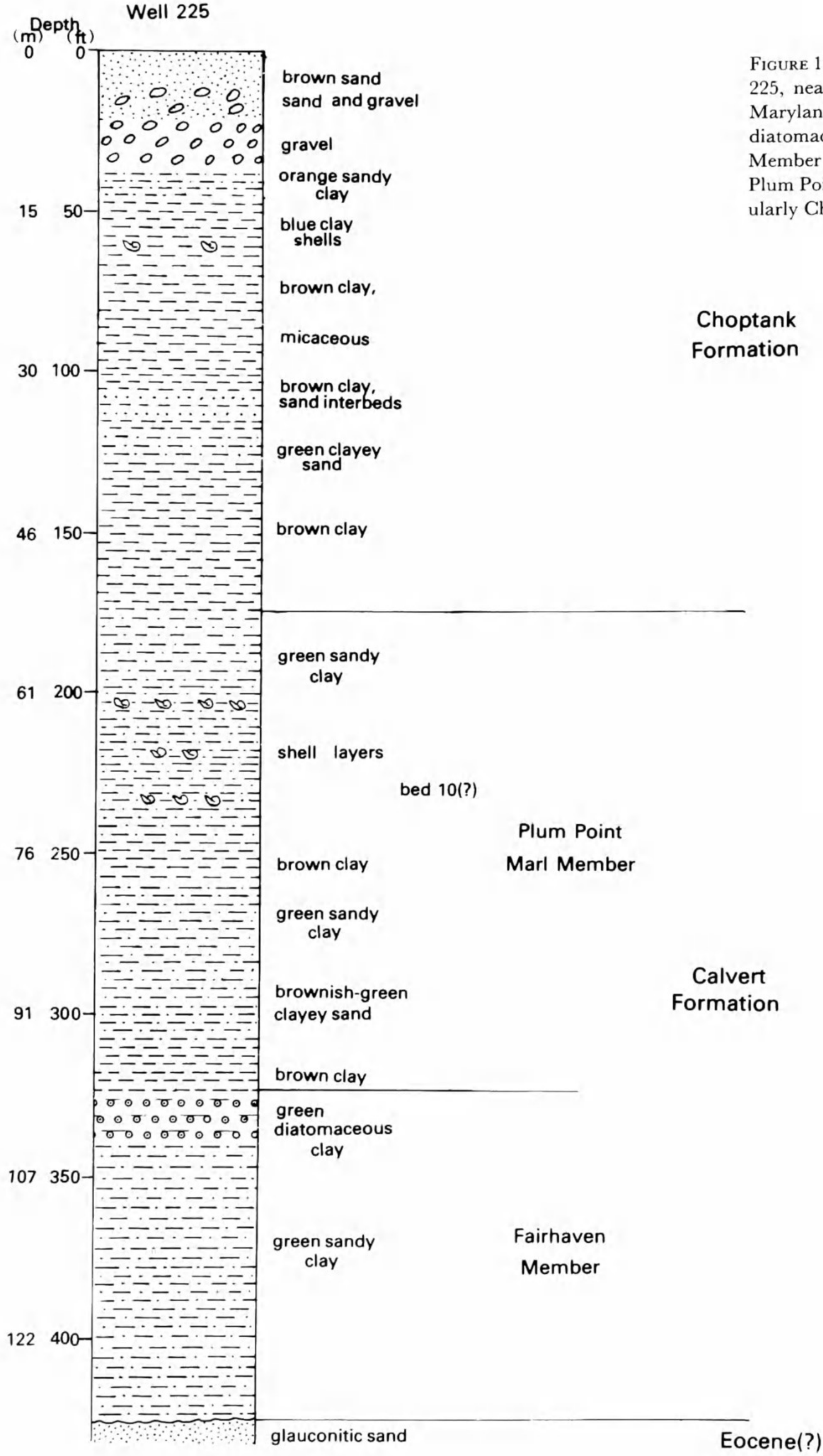

FIGURE 15.—Geologic column for Well 225, near Denton, Caroline County, Maryland, showing lesser amount of diatomaceous beds in Fairhaven Member and deltaic influence in Plum Point Marl Member and particularly Choptank Formation.

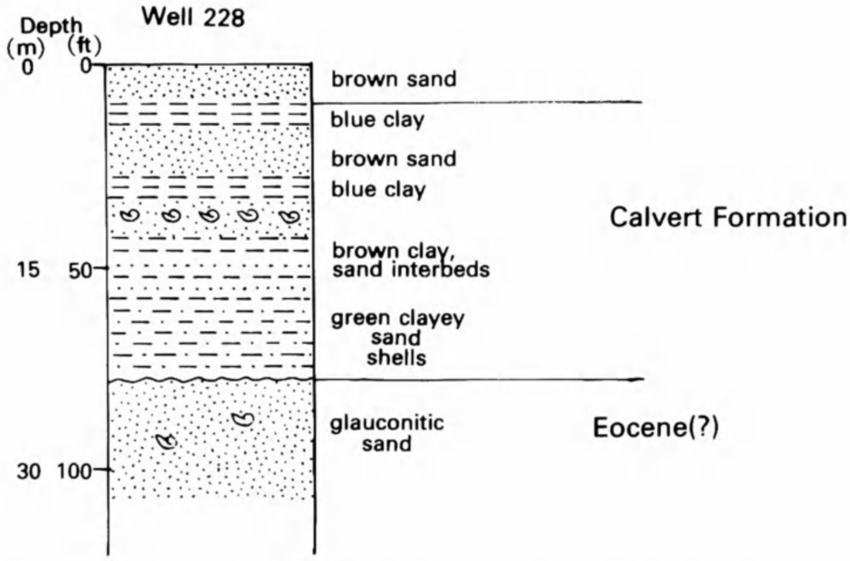

FIGURE 16.—Geologic column for Well 228, near Skipton, Talbot County, Maryland, showing deltaic influence in lower part of Calvert Formation.

(B.W. Blackwelder, pers. comm., 1977; R.K. Olsson, Rutgers University, pers. comm., 1977). The basal transgressive deposit of the Popes Creek Sand Member in the BG&E Well consists of slightly clayey fine to medium sand with pebbles as large as 11 mm, mollusks including *Pecten humphreysii*, and reworked clasts of Eocene sediment containing Foraminifera. The base is composed of 50 percent sand or more. The lowest sample has abundant planktonic Foraminifera (29 percent) and a relatively high species diversity (25). The most abundant benthic species is *Cibicides lobatulus*, which today lives in agitated inner- to middle-shelf environments. Other abundant species include *Valvulinaria floridana*, *Bolivina marginata*, *B. paula*, and *Uvigerina calvertensis*. The lower part of the member suggests deposition in a middle-shelf environment at depths as great as 80 meters and open ocean circulation. In the rest of the member, the percentage of sand decreases to between 25 and 35 percent, and the species diversity remains moderately high, in the low 20s. The planktonic percentage decreases to about 2 percent, and *Valvulinaria floridana* dominates the benthic assemblage. These changes suggest shallowing to near-shore sublittoral depths, probably less than 30 meters. This open marine environment of the Calvert transgression is found over the entire Salisbury embayment, as seen in northern Virginia, Maryland, Delaware, and southwestern New Jersey.

The Fairhaven Member also is lithologically uniform and widespread in the embayment from east-central Virginia to northeastern Maryland. In the BG&E Well, the lower part of this member is of shallow sublittoral deposition, characterized by species diversities of 16 to 21 and planktonic percentages of less than 3. The percentage of sand is less (under 25 percent). Some fluctuations from sublittoral depths as great as 30 meters to either shallower marine or possibly restricted marginal environments are seen upward in the Fairhaven in the intervals with low species diversities of 9 to 12 species marked also by the absence of planktonic specimens; these intervals occur between others that contain higher diversities of 14 to 20 species accompanied by planktonic specimens, although less than 2 percent. The shallow marine environment for this member continues eastward across the basin except for slightly more silty and sandy and less diatomaceous strata to the east and northeast of Easton, Maryland. In Well 231, brown clay is seen within the diatomaceous unit that, together with the slightly increasing clastic content in that area, suggests the possibility of the beginning of deltaic conditions.

The contact between the Fairhaven and the Plum Point Marl members on the western shore

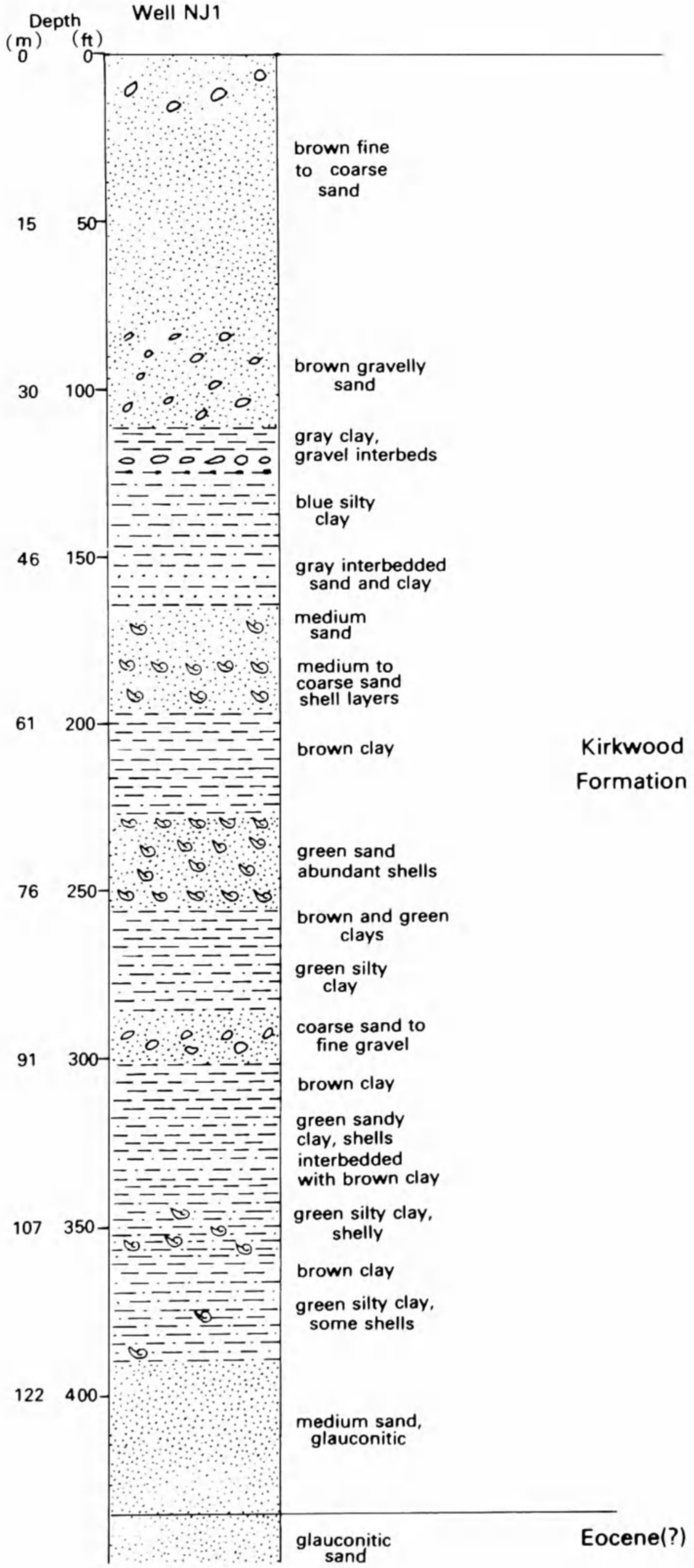

FIGURE 17.—Geologic column for Well NJ1, near Cedarville, Cumberland County, New Jersey, showing interbedding of deltaic and prodelta sediments in the Kirkwood Formation.

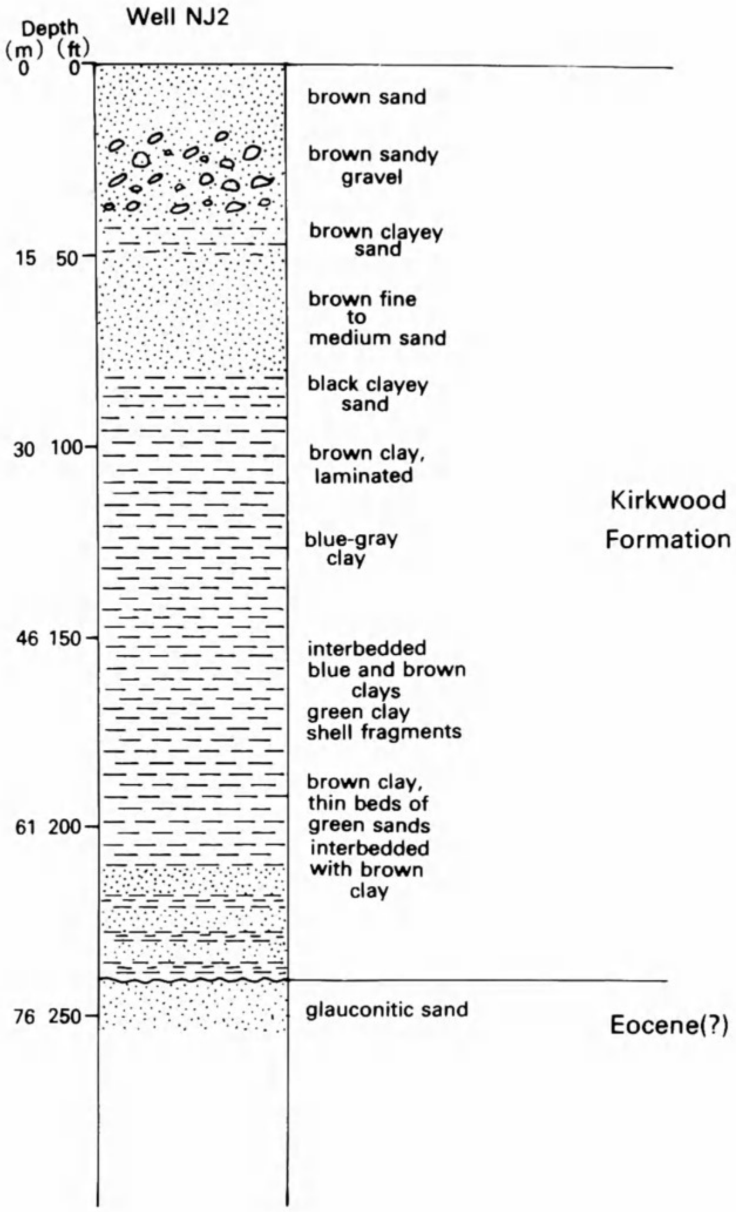

FIGURE 18.—Geologic column for Well NJ2, near Shirley, Salem County, New Jersey, showing largely deltaic section of Kirkwood Formation.

is marked by a disconformity, which may have been produced by either subaerial or submarine environmental conditions. At the base of the Plum Point Marl Member is an oyster (*Pycnodonte percrassa*) bed (bed 4) containing a fairly diverse foraminiferal assemblage of 22 to 29 species (dominated by *Cibicides lobatulus*, *Valvulinaria floridana*, and *Hanzawaia concentrica*) and several percent planktonic Foraminifera in the lower part. This sandy bed (65 to 77 percent sand) is an open marine deposit formed upon an undulating surface, probably in depths of less than 30 meters. In the BG&E Well, species diversity drops to 13 to 18 in the equivalents of beds 5 to 9 (sample numbers 30–35), planktonic specimens are absent, and the sand content decreases to as low as 2 percent. At the outcrop, molluscan assemblages in these beds are largely bands of *Corbula elevata*. *Valvulinaria floridana*, *Caucasina elongata*, and *Florilus pizarrense* are the dominant benthic species. The faunal characteristics and the high amount of clay suggest deposition in protected to marginal marine environments. The feature that may have sheltered this area is found on the Eastern Shore of Maryland. To the east and northeast of Easton, the interval of beds 5 to 9 contains thick brown clay and thin interbedded sand units, which strongly suggest deltaic influence in the center of

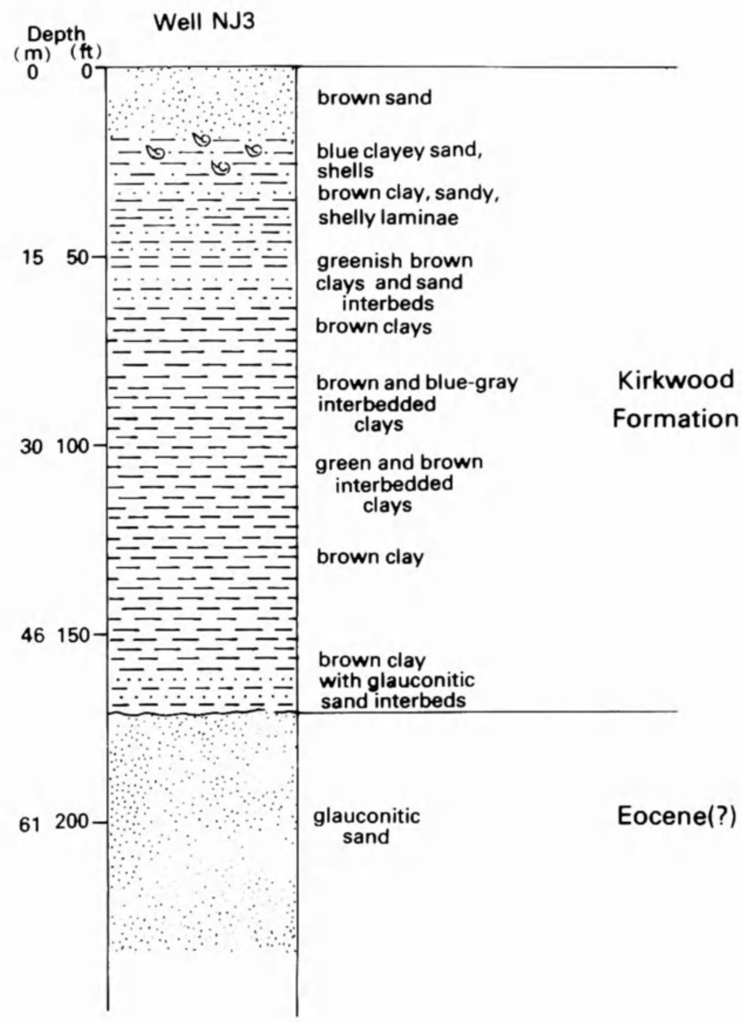

FIGURE 19.—Geologic column for Well NJ3, near Shiloh, Cumberland County, New Jersey, showing largely deltaic sedimentation with marine beds near top of section of Kirkwood Formation.

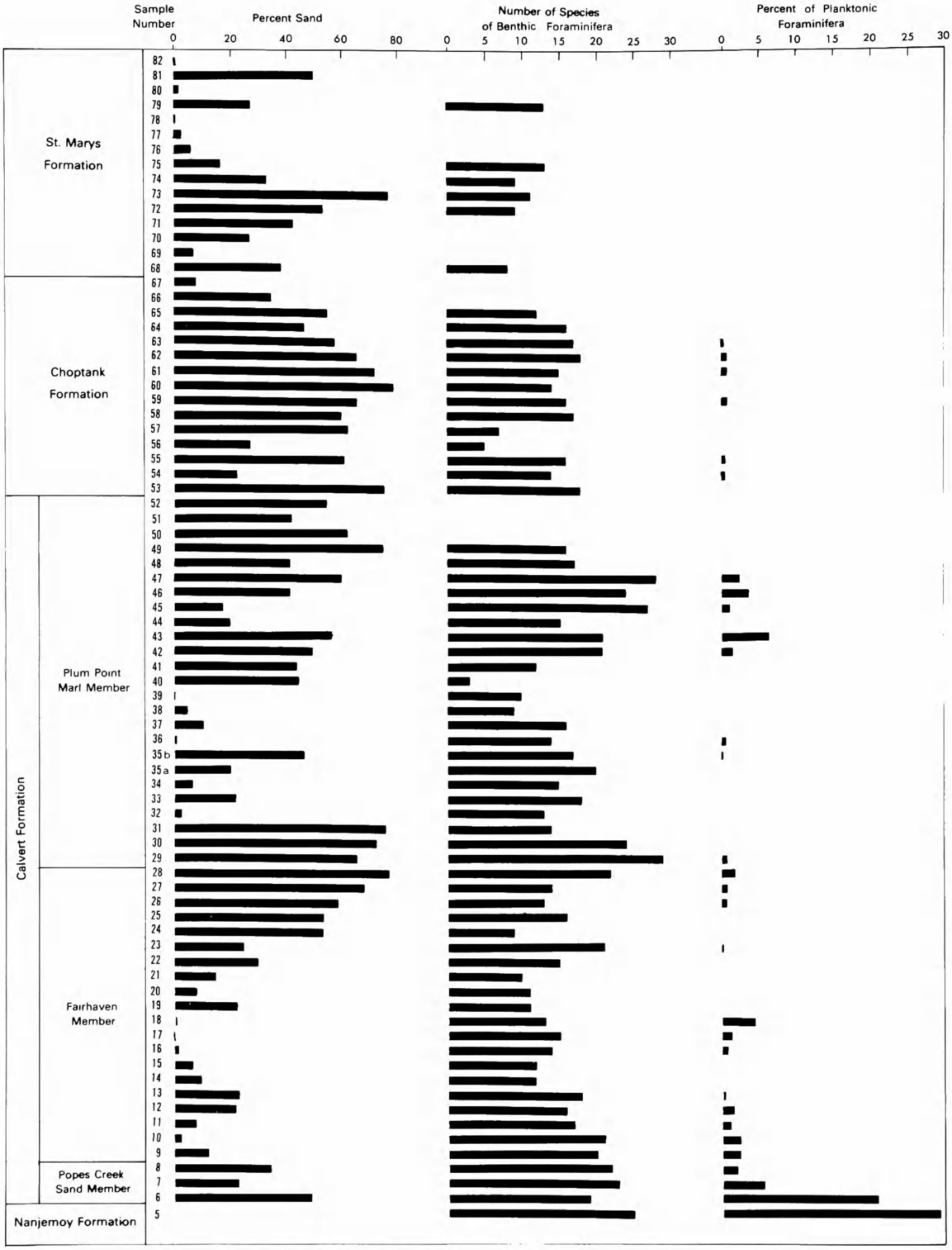

FIGURE 20.—Percentage of sand, number of species of benthic Foraminifera, and percentage of planktonic Foraminifera in total foraminiferal assemblage for samples 5–82 from the Baltimore Gas & Electric Company Well at Calvert Cliffs, Maryland. Location of samples in core is shown in Figure 5.

the Eastern Shore area. The southward outbuilding of the delta into the embayment from source areas in northeastern Maryland, western New Jersey, and Pennsylvania, with the accompanying freshwater influence, appears to have cut off open ocean circulation to the west in Maryland, resulting in an area of fine clastic input and normal to slightly brackish water. Vertebrate evidence to support this interpretation as a protected area is seen in the large number of long-beaked porpoises, typical of estuaries, found in these beds (Whitmore, 1971:32). The area under the influence of the delta is shown in Figure 21. Deltaic environments for the middle Miocene strata on the Eastern Shore were suggested by Gibson (1971). The units of brown clay and silty clay and thin interbeds of crossbedded gray sand as much as 5 cm thick are strongly suggestive of delta-front deposition (Reineck and Singh, 1975:321–338). The interbedded sand and clay do not contain mollusks on the Eastern Shore, but some shells are in brown clay interbeds in southwestern New Jersey. Intervals of fossiliferous green sand and clay occur between the brown clay intervals in wells on the Eastern Shore (Well 224, Figure 14, for example), suggesting that deltaic pulses alternated with more marine prodelta to inner-shelf environments. Isphording (1970) proposed that the Alloway Clay Member of the Kirkwood Formation in southwestern New Jersey accumulated in a sublittoral environment. In my opinion, the presence of thick sequences of carbonaceous brown and dark gray clay interbedded with thin sand suggests a deltaic, delta-front or prodelta, environment. The absence of shells in the brown clay was attributed by Isphording (1970) to solution by sulfuric acid resulting from weathering of the contained pyrite. However, in the cores from New Jersey wells (NJ1–NJ3), the brown clay does not contain shells or molds even though some of the more permeable interbedded sand does. This suggests a primary or early diagenetic absence of shells in the clay and a deltaic rather than marine origin.

Farther east in the Hammond Well (Figure 4: loc. 13), the entire Calvert section is composed of fossiliferous, glauconitic, gray silty clay, characteristic of prodelta and shelf deposition. The area of the Hammond Well appears to be seaward from the deltaic influence, as shown in the paleogeographic reconstruction (Figure 21).

Bed 10 is recognizable across much of the embayment in Maryland as a conspicuous shelly sand containing a high diversity of mollusks (65 species in the Calvert Cliffs, Glaser, 1971:21). West of Chesapeake Bay, it overlies beds 5 to 9 that have low molluscan diversities, and on the Eastern Shore it overlies the brown clay units (Figure 14). Even in southwestern New Jersey a fossiliferous sand is found on top of the brown clay (wells NJ1 and NJ3, and outcrops near Shiloh). Several shell beds containing diverse molluscan faunas are in beds 10 to 15 of the Calvert, and these beds also contain moderately high foraminiferal species diversities. Abundant benthic Foraminifera through this interval include *Valvulinaria floridana*, *Caucasina elongata*, *Cibicides lobatulus*, *Hanzawaia concentrica*, and *Epistominella* sp. Planktonic foraminiferal percentages reach 6 percent. These assemblages suggest reestablishment of open ocean circulation, and deposition on sandy bottoms in depths of less than 60 meters. However, periods of restricted marine conditions in the western part of the embayment are reflected in beds 11 and 15 in the BG&E Well (Figures 5, 20); macrofossils are rare, foraminiferal diversities are low, and planktonic foraminifers are absent. A general increase in sand occurs above bed 11 and continues through the Choptank Formation to beds that indicate restricted environments in the uppermost part of the Choptank and St. Marys formations.

Pungo River Formation

In the Albemarle embayment south of Virginia (Figure 1) a different sedimentary regime of a low clastic environment resulted in the deposition of phosphatic sand, diatomaceous clay, and carbonate deposits of the Pungo River Formation (Figure 3). As mentioned above, the area of transition between the Calvert and Pungo River formations

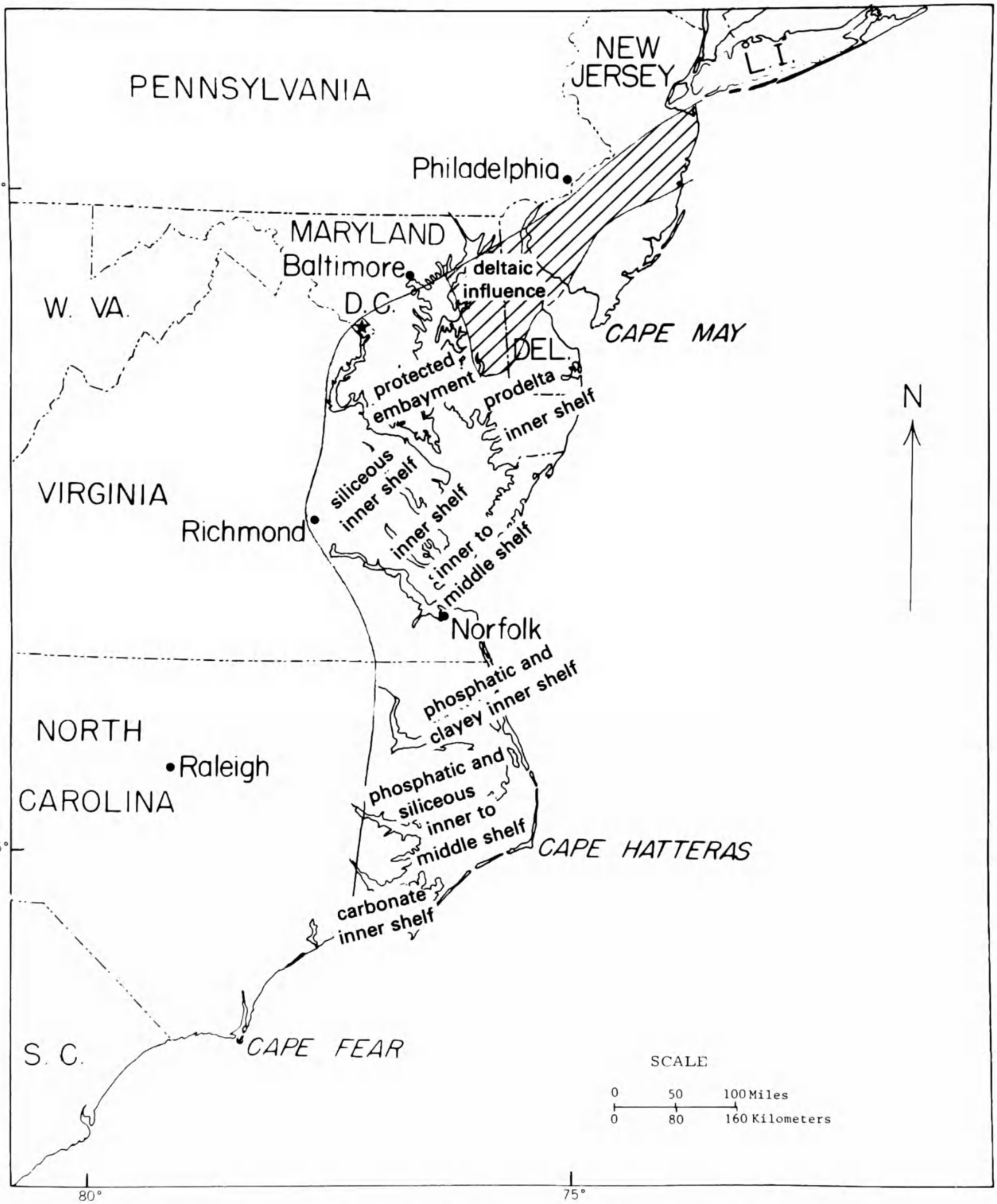

FIGURE 21.—Paleoenvironments postulated for lower half of Plum Point Marl Member of Calvert Formation and equivalent units, showing deltaic influence on Eastern Shore of Maryland and small amount of clastic sediment in the Albemarle embayment in North Carolina. Line indicates western limit of outcrops.

occurs in southeastern Virginia as seen in the Norfolk Moores Bridge Well (Figure 4: loc. 25).

The Pungo River Formation was named by Kimrey (1964) for the sequence of phosphatic sand and clay of middle Miocene age described by Brown (1958). The formation underlies much of the eastern part of the Coastal Plain in North Carolina (Figure 3). No natural outcrops of the formation are known, but it is well exposed in the Lee Creek Mine (Figure 4: loc. 33). The Pungo River is more than 400 feet (122 m) thick in wells drilled on the outer banks in the eastern part of the Albemarle embayment. The middle to inner middle-shelf environments of deposition represented by the formation at its western limits indicate that it originally was more widespread.

The thickest part of the Pungo River Formation in North Carolina is composed of phosphatic and diatomaceous clay, phosphatic sand, phosphatic limestone, and coquina. Kimrey (1965) described the lithofacies in the southern part of the embayment. The beds of clay are light to dark green, and many contain diatoms. The phosphate content varies from less than 1 to nearly 10 percent. The sand is composed of fine to medium quartz and phosphate grains. Phosphate content usually is 10 to 21 percent in bulk samples (Kimrey, 1965:9–14). The phosphatic grains are composed of collophane and are ovate, smooth, glossy, and brown. Sand-sized bone and tooth fragments also are common. Indurated beds of calcareous clay, phosphatic limestone containing dolomite, and indurated shell beds are scattered through the section.

Toward the New Bern arch (southern border of the Albemarle embayment), the upper part of the Pungo River Formation changes to calcareous clay, indurated limestone, phosphatic limestone, and bioclastic debris. North of this area, the equivalent strata are mostly beds of phosphatic and diatomaceous clay with minor phosphatic sand intervals.

I herein propose that this upper carbonate unit, including phosphatic limestone, calcareous clay, and coquina in the southern part of the embayment, be recognized as the Bonnerton Member of the Pungo River Formation. The type section is the AU-1-GRL core hole in the Aurora quadrangle, described by Kimrey (1965:17) (Figures 4: loc. 33; and 22). In this core hole, 32 feet (10 m) of white to light gray-green calcareous sand and phosphatic limestone occur from 120 to 152 feet (37 to 46 m). The name is derived from Bonnerton, Beaufort County, North Carolina, where the unit is typically developed. The Bonnerton is unconformably overlain by the Yorktown Formation; the contact is marked by burrows and small channels containing coarse, black, secondary phosphatic gravels. The lower boundary of the Bonnerton is marked by a change to greenish brown phosphatic sand, which contains phosphatic clay and limestone layers.

Twelve feet (3.7 m) of Bonnerton was exposed in the initial test pit of Texasgulf Inc., in the northeastern part of the Lee Creek Mine site north of Aurora (Figures 23, 24). This includes units 4 to 7 of Gibson (1967). Unit 7 is a yellow-green sandy coquina; unit 6 is interbedded bioclastic debris and phosphatic sand; unit 5 is highly fossiliferous phosphatic limestone; and unit 4 is interbedded phosphatic limestone and phosphatic sand. The lower contact is conformable, and is at the base of the lowest, light-colored limestone bed in Figures 24 and 25. The upper, unconformable contact with the Yorktown Formation is seen in Figures 23, 24, 26, and 27.

As shown by Kimrey (1965, fig. 6), the Bonnerton Member is extensive in the southern part of the embayment and reaches northwestward as far as Bonnerton. To the west of Bonnerton, apparently, this member was completely eroded away. The southernmost locality is in the Croatan Forest area near Great Lake (Figure 4: loc. 36). Here the Bonnerton consists of about 6 feet (1.8 m) of light yellow-green sandy shell hash in Great Lake Well 181. The Bonnerton thus extends at least 40 miles (64 km) north to south. North of Bonnerton, across the Pamlico River, the carbonate facies changes to beds of phosphatic and diatomaceous clay.

The Pungo River strata below the Bonnerton Member are dominantly phosphatic sand and moderately phosphatic to nonphosphatic clay, but include thin interbeds of diatomaceous clay

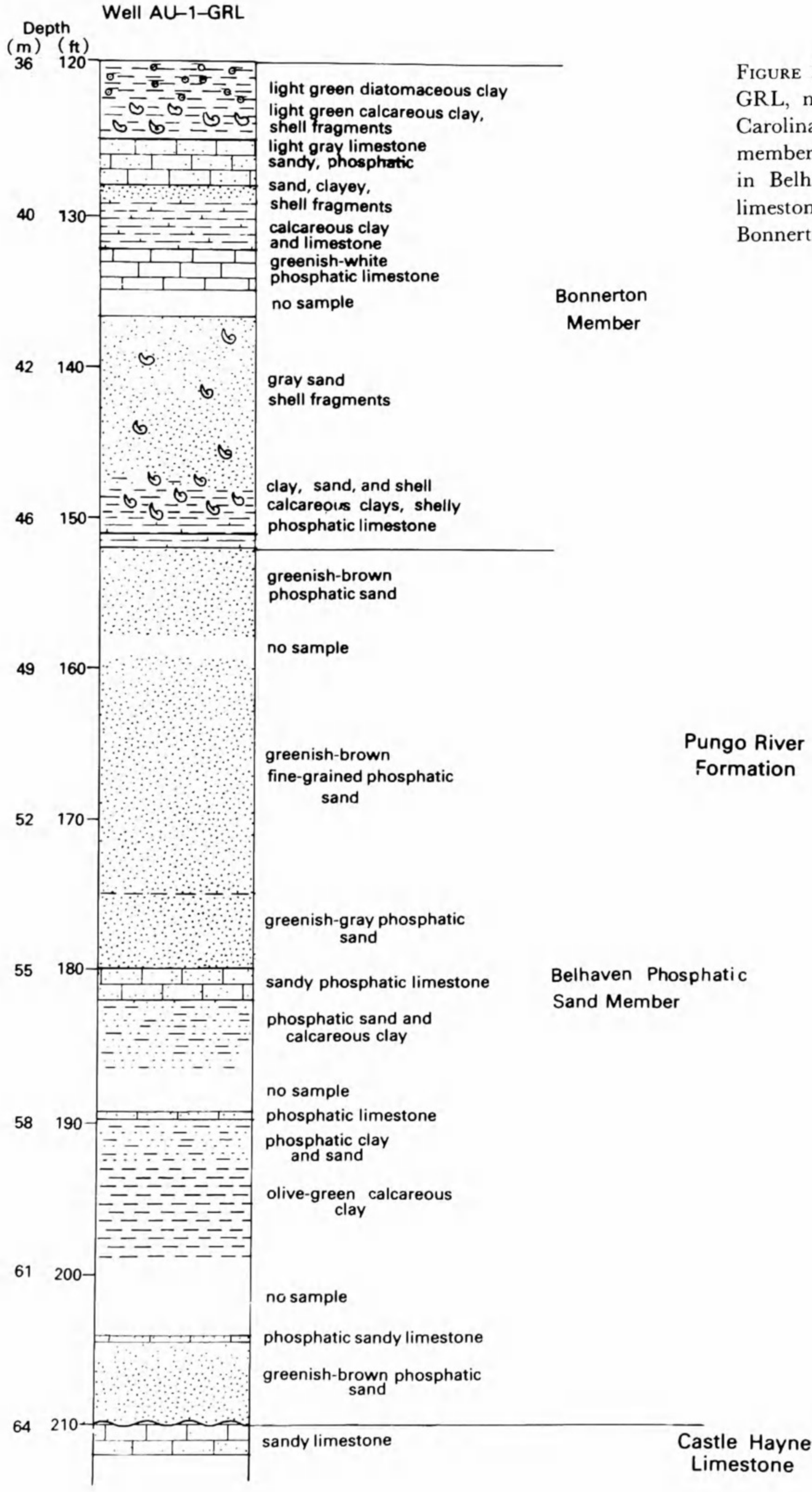

FIGURE 22.—Geologic column for Well AU-1-GRL, near Aurora, Beaufort County, North Carolina; type well for Belhaven and Bonnerton members. Note largely phosphatic sand section in Belhaven Phosphatic Sand Member and limestone, calcareous clay, and shelly sand in Bonnerton Member.

FIGURE 23.—Test pit at Texasgulf Inc. Lee Creek Mine. Water level is at middle of Pungo River Formation with 96 feet (29 meters) of section exposed. Arrow near right margin indicates contact between Pungo River and Yorktown formations in face; close-up of face is shown on Figure 24. Two clean faces in center above lowest bench are in lower and middle parts of the Yorktown Formation. Arrow in upper center indicates boulder beds or unit 7 of Gibson (1967), now considered in lower part of Croatan Formation.

and phosphatic limestone. I herein assign these highly phosphatic beds to the Belhaven Phosphatic Sand Member of the Pungo River Formation. It is so named because it is well developed near Belhaven, Beaufort County, North Carolina (Figure 4: loc. 32). The type section is the same core hole, AU-1-GRL (Kimrey, 1965:18–19; Figure 22), that constitutes the type section of the Bonnerton Member. The Belhaven is 58 feet (18 m) thick (152 to 210 feet (46 to 64 m) in the core hole), and is dominantly medium greenish brown phosphatic sand with some gray-green clay and limestone and dolomite beds. The upper part of this member was exposed in the Lee Creek Mine test pit (Figures 24, 25). The uppermost bed in this member is immediately below the limestone in Figure 25. A slightly indurated, dolomitic, diatomaceous clay bed can be seen at water level in the same figure. The phosphatic sand bed at the top of the Belhaven Member probably is the highest in P_2O_5 content over the area. The upper contact of the Belhaven is conformable, but the lowermost part is underlain by the Castle Hayne Formation (Eocene).

Thus, in the southern part of the basin the Bonnerton Member composes most of the section of the Pungo River. To the north near the Lee Creek Mine and northward toward Belhaven, both members are well developed, and northeast of this area most of the formation is composed of the Belhaven Member. Exact biostratigraphic control is not yet available, but the relationship

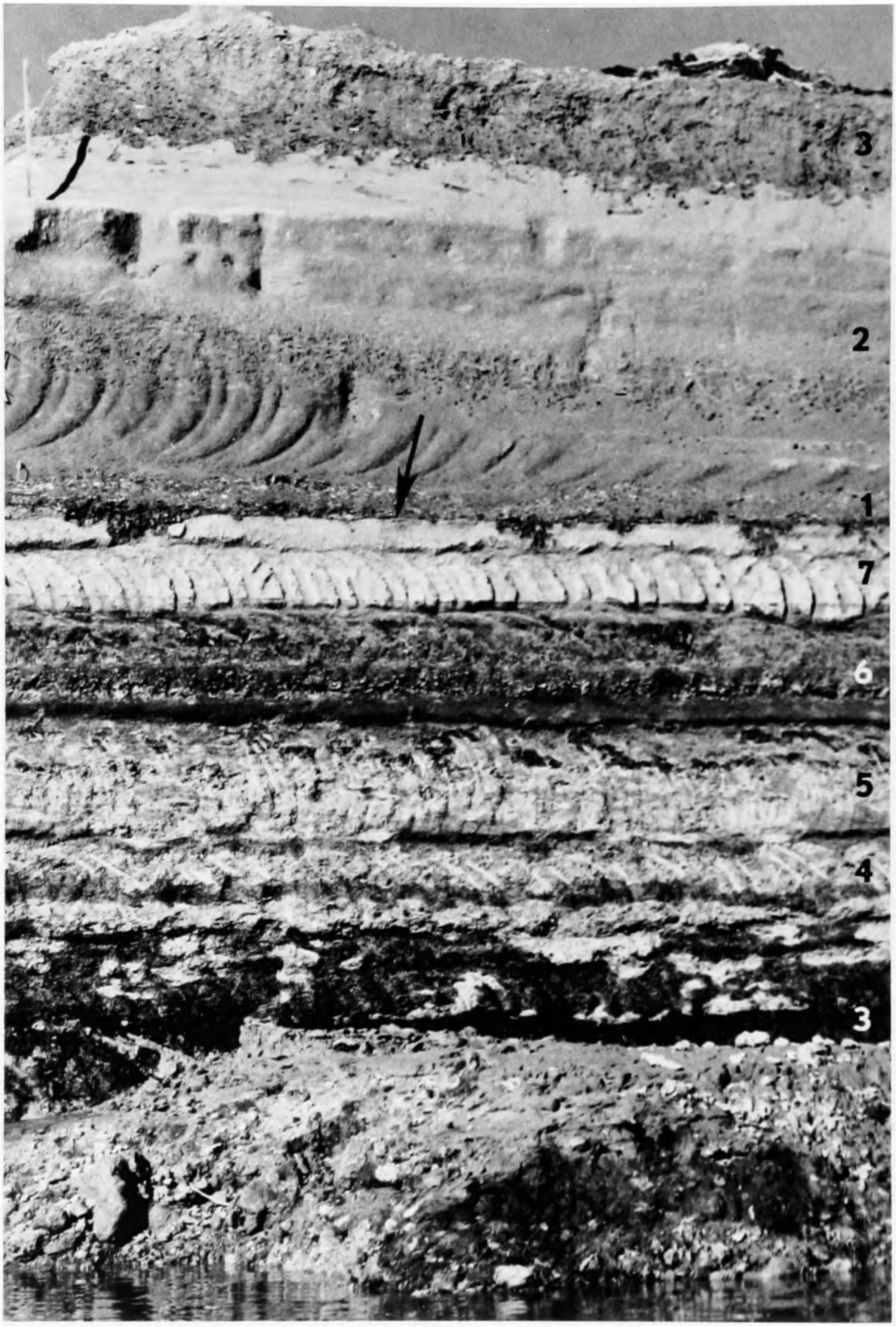

FIGURE 24.—Largely carbonate beds of the upper part of the Bonnerton Member of the Pungo River Formation overlain by *Placopecten clintonius* beds of the lower Yorktown Formation exposed in north wall of Lee Creek Mine test pit. Arrow indicates unconformity between the two formations. Three channels filled with phosphatic pebbles are visible. Numbers on right border correspond to units used in Gibson (1967).

FIGURE 25.—Contact between dark phosphatic sands of the Belhaven Phosphatic Sand Member and largely carbonate strata of the Bonnerton Member of Pungo River Formation in Lee Creek Mine test pits is at base of lowest light-colored carbonate unit about six feet (1.8 meters) above water level. Two feet (0.6 meters) of diatomaceous clay (unit 2 of Gibson, 1967) of the Pungo River Formation are exposed at water level. Contact between Pungo River and Yorktown formations is at lowest bench, a distance of approximately 20 feet (6 meters) above water level.

indicates that there is a partial to entire facies equivalency between the two members in different parts of the basin.

The lithology of the Pungo River changes northward in the Albemarle embayment. The limestone beds diminish and finally disappear, and the phosphatic sand is thinner, more clayey, and less phosphatic. In the core hole at Gatesville, North Carolina (Figure 4: loc. 27), the Pungo River Formation is only 20 feet (6 m) thick, and consists mainly of yellowish green to greenish brown calcareous, phosphatic, clayey sand. The Pungo River Formation continues northward into the southeastern part of the Salisbury embayment. Here in the Norfolk Moores Bridge Well, the upper 50 feet (15 m) is olive-green silty clay; the lower 10 feet (3 m), dark-olive phosphatic clayey sand.

Gibson (pp. 359–360) demonstrates that the Pungo River strata in the Lee Creek Mine belong to planktonic foraminiferal zone N8 to lower N9 of Blow (1969:229–234) that are of latest early and earliest middle Miocene age. To the northeast, Abbott and Ernissee (pp. 290–293) found Pungo River strata of this age and also of the younger, zone N11 age. Strata of the intervening zone N10 have not been documented in the area. Whether this is because the important index species of this relatively short time zone are absent, or whether this is a time of regression in the embayment represented by a disconformity is unknown.

ENVIRONMENT OF DEPOSITION.—The depositional environments of the Pungo River Formation were discussed by Gibson (1967) and were determined on the basis of the foraminiferal assemblages (Gibson, 1968). Gibson concluded that the beds of phosphatic sand of the Belhaven Member formed on the middle to outer shelf (approximately 100- to 200-m water depth). The carbonate and phosphatic clay beds in the Bonnerton Member formed on the middle to inner

FIGURE 26.—Unconformable contact (arrow) between Pungo River (light-colored) and Yorktown (dark-colored) formations in the test pit of the Texasgulf Inc. Lee Creek Mine. Channels in bryozoan hash bed at top of the Bonnerton Member of the Pungo River Formation are filled with phosphate pebbles. Lowermost Yorktown strata contain abundant *Placopecten clintonius* and medium sand to cobble-sized phosphate grains. Close-up of channel at left is shown in Figure 27.

shelf (150 m to less than 70 m in the uppermost bed, Gibson and Buzas, 1973:232).

In addition to the faunal evidence, the nature of the phosphatic sand, the organization of its beds extending tens of kilometers, and the interbedded limestone and diatomaceous clay led Gibson (1967:638, 642) to consider this phosphate deposit a primary deposit from seawater. The framework of deposition, particularly the depth of water, fit the Kazakov (1937) hypothesis of inorganic precipitation that has been used to explain numerous large phosphatic deposits. A weakness in this hypothesis is that the phosphate mineral found in these deposits does not commonly form in the laboratory (McConnell, 1958). The presence of large amounts of phosphatic fish bones and teeth may indicate that the postulated upwelling or mixing of currents and resultant high productivity biologically concentrated unusual amounts of phosphatic material in the sediments. Another possible method is phosphate replacement of existing carbonate material. Although replacement may explain the thin layers of phosphate in the top of underlying carbonate units, such as those in the Castle Hayne Formation, this origin for the major deposit has serious complications, because the molluscan fossils in the phosphatic sand are phosphatic internal molds. This manner of preservation indicates that the shell was still present when the phosphate material was introduced and that the shell was filled, not replaced. The ovoid shape of many of the phosphate pellets is similar to that of fecal pellets; these pellets may have formed by the addition of phosphate. We do not know the exact genesis of these deposits, but evidence to date strongly indicates that they are primary deposits from a middle- to outer-shelf environment.

Another characteristic of the Pungo River strata is the small influx of coarse clastic sediments. The offshore deposits are primarily phosphatic sand and diatomaceous clay that become more calcareous landward, indicating little clastic influx into the Albemarle embayment from that direction. Thus, the uplift of the Appalachians that affected the northern part of the Coastal Plain at this time, as seen in New Jersey, is not evident here.

The presence of clinoptilolite, volcanic glass, shards, and cristobolite in the Pungo River Formation led Rooney and Kerr (1964) and Gibson (1967) to suggest a volcanic influence in the depositional area. The importance of this influence still is largely unknown. However, this time interval is characterized by unusual deposits all along the Atlantic Coast. The deposits include diatomaceous clay containing shards and clinoptilolite in the Fairhaven Member of the Calvert Formation in Maryland (Taliaferro, 1933:28; Glaser, 1971:23) and Virginia (Reinhardt, Newell, and Mixon, 1980); phosphatic and diatomaceous clay and sand in North Carolina; and montmorillonite, cristobolite, and attapulgite in South Carolina and Georgia (Ernissee, Abbott, and Huddlestun, 1977). The only region apparently unaffected at this time is New Jersey, which was under a strong deltaic influence. The possibility was raised by Gibson and Towe (1971) that widespread siliceous deposits of a short timespan could be a result of marine volcanism, which influenced productivity through the addition of nitrogen and phosphorus into the water column. The increase in the levels of these nutrients, in addition to the added silica, could result in abundant siliceous organisms in the area, and thus increased deposition and enhanced preservation. Questions have been raised about the role of volcanism in these areas (Weaver and Wise, 1974;

FIGURE 27.—Unconformable contact between *Placopecten clintonius* beds of Yorktown Formation and bryozoan hash beds of the Bonnerton Member of the Pungo River Formation. Coarse phosphate pebbles fill channels in top of Pungo River; generally finer pebbles occur in shell bed of the Yorktown. Pen giving scale is 5 inches (12.7 cm) long.

Gibson and Towe, 1975). Weaver and Wise stressed the finding of siliceous organisms as proof that volcanic influence was not present or important. However, this missed the main point of the model proposed by Gibson and Towe (1971) that the volcanism largely would cause increased productivity of siliceous organisms in many environmental settings. The finding of these unusual deposits over a relatively short timespan of a few million years requires some explanation. One new piece of evidence, which indicates volcanic influence in the area, is the presence in the Pungo River Formation of large pieces of pumice, as much as 6 inches (15 cm) in diameter. These pieces have been uncovered during washing of the ore at the Lee Creek Mine. The pumice currently is being analyzed to determine the possible origin and significance.

Choptank Formation

The Choptank Formation was named by Shattuck (1902) from exposures along the Choptank River on the Eastern Shore of Maryland. Most subsequent work has been more concerned with the extensive exposures along the Calvert Cliffs on the western shore of Chesapeake Bay. The outcrop thickness varies from 45 to 55 feet (14 to 17 m) (Shattuck, 1904, pls. xxx, 5). The continuous BG&E core contains approximately 60 feet (18 m) of Choptank. Thicker sections occur in the subsurface to the east. The Hammond Well on the Eastern Shore of Maryland (Figures 4: loc. 13, and 6) contains 125 feet (38 m) (Anderson, 1948:19), and 150 feet (46 m) was found in Well 220 to the southwest of the Hammond Well (Figures 4: loc. 12 and 7); this appears to have been in the axis of the embayment during Choptank time.

The Choptank Formation in outcrop characteristically is quartz sand and silt, shelly in many places, with lesser clayey intervals and indurated limestone layers. The BG&E Well contains mostly muddy and silty fine sand (Figure 5; generally 50 to 70 percent sand, Figure 20). Minor silt and clay intervals are present, along with two indurated layers. Two intervals contain numerous molluscan shells (beds 17 and 19 in outcrop), and shells occur sparsely in the rest of the formation. Outcrops in the type area of the Choptank are similar to those found west of the Bay. However, two wells on the Eastern Shore contain a different facies of the Choptank Formation. Well 225 (Figure 15), northeast of the type area, contains mostly brown micaceous clay interbedded with scattered shell hash; the rest is green to blue, shelly, clayey sand containing quartz and phosphate pebbles, thickly interbedded with brown clay and gray sand laminae. In Well 227 (Figure 12), green sandy clay containing shells and sandy shell hash composes most of the formation, but the middle part contains interbedded shell hash and brown clay. To the southeast, in the Hammond Well (Figure 6), the Choptank is composed of limy, sparsely glauconitic, shelly, medium sands.

Shattuck (1904) divided the Choptank Formation into a series of zones (here termed "beds") numbered 16 through 20. As in Shattuck's division of the Calvert Formation, these zones are locally distinguishable by lithologic, not biostratigraphic, characteristics. One zone, was defined, however, by the abundance of fossils, particularly mollusks. Gernant (1970) mapped these "zones" in the Choptank Formation and redefined them as lithologic members. The nature of the upper contact of the Choptank is in dispute because Blackwelder and Ward (1976:12, 15) placed Gernant's uppermost member, the "Conoy," into an overlying unit, which they informally referred to as the "Little Cove Point" unit.

The distribution and thickness of the Choptank Formation is considerably restricted compared to the underlying Calvert Formation. The known distribution extends into northeastern Virginia as shown in Figure 28. In the Oak Grove core hole (Figure 4: loc. 19), located at approximately the known southern limit of the Choptank, slightly diatomaceous clay and silt were found that correlated with beds 18 and 19 of the Choptank Formation (Gibson et al., 1980). The Choptank strata of bed 18 and 19 age in the Oak Grove core sit upon the upper part of the Calvert Formation, signifying the southward disappearance of the

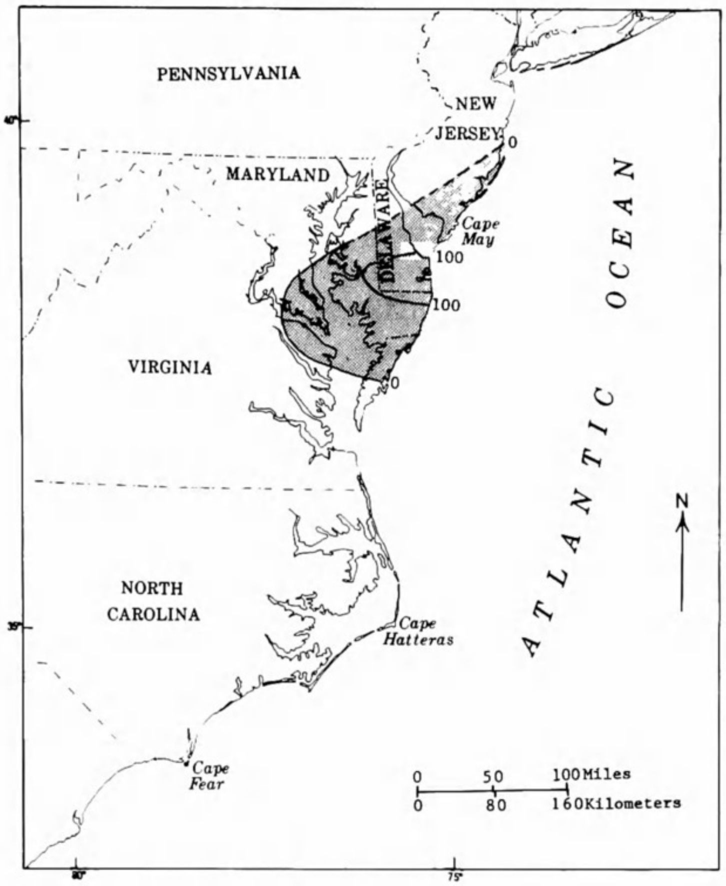

FIGURE 28.—Isopachous map of the Choptank Formation and equivalent units (middle Miocene). Contours are in feet; contours are indicated by dashed lines where locations are approximated (modified from Gibson, 1970).

lower beds 16 and 17 of the Choptank that still are present at the Nomini Cliffs on the Potomac River. No indication of Choptank-age strata has been found in southern Virginia and North Carolina. The northern extent of the formation in New Jersey is uncertain because Richards and Harbison (1942) treated the Calvert and Choptank formations as a single unit.

Because the Choptank Formation was deposited in very shallow marine water, its present distribution probably closely reflects the original extent of the Choptank sea (Figure 28). The distribution was restricted by uplift in various areas, including the Albemarle embayment in North Carolina, causing a markedly reduced areal extent of the Choptank seas.

ENVIRONMENT OF DEPOSITION.—The Choptank Formation was deposited mostly in shallow marine water (Gibson, 1962:63). Gernant (1970:45–52) also proposed that environments were less than 60 meters deep for the formation as a whole, but they were less than 25 meters deep, and possibly marginal marine, for some beds. Foraminiferal assemblages in the BG&E Well support these interpretations. Foraminiferal species diversity is less than 20 in all samples (most samples contained about 15), and the planktonic foraminiferal content varies from zero to less than 1 percent (Figure 20). These measures of foraminiferal abundance are similar in about 100 samples examined from other localities. On the Eastern Shore in the type area, similar shallow water deposits persist and shell hash is common. Gernant (1971:28) suggested that here much of the formation was deposited in shallower water than that west of Chesapeake Bay. The sediments usually are more than 50 percent sand, which, along with the foraminiferal data, suggests deposition in open shallow marine water of 15 to 30 meters depth or less.

On the Eastern Shore, evidence of deltaic influx into the eastern and northeastern part of the Choptank Formation is present in the subsurface. Well 225 (Figures 4: loc. 8, and 15) contains thick intervals of brown micaceous clay and interbeds of pebbly shell and gray sand that suggest delta-front deposition. To the southwest, Well 227 (Figures 4: loc. 9, and 12), farther away from the delta front, contains mainly shell hash and interbeds of brown clay in the middle part. In the Hammond Well (Figures 4: loc. 13, and 6). Choptank strata are limy and shelly medium-grained sand containing small amounts of glauconite, indicating shallow sublittoral deposition. The green shelly sand and shell hashes in wells 224 and 226, and the Hammond Well suggest that these strata accumulated in prodelta or inner-shelf environments; they mark the southern limit of deltaic influence (Figures 4, 29). The deltaic outbuilding at this time on the Eastern Shore did not significantly influence deposition in the western part of the embayment, because diverse molluscan, ostracode, and foraminiferal assemblages dominated by *Cibicides lobatulus*, *Bolivina paula*, *Valvulinaria floridana*, and *Buliminella elegantissima* indicate shallow open marine water of normal

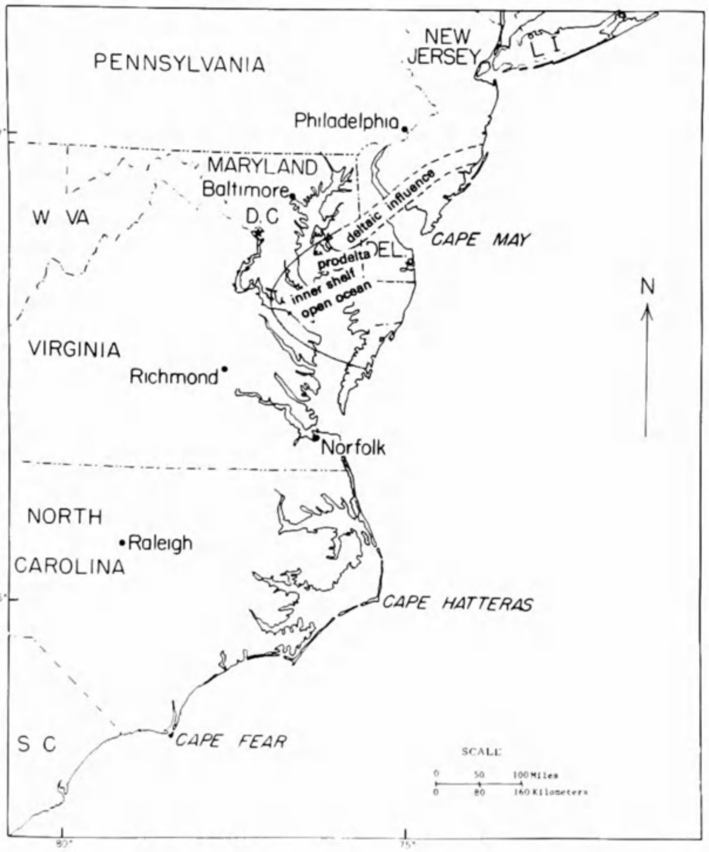

FIGURE 29.—Paleoenvironments postulated for the Choptank Formation and equivalent units, showing deltaic influence on Eastern Shore of Maryland and open marine shallow shelf in remainder of embayment. Line indicates limits of formation; line is dashed where limits are inferred.

salinity. More open access to the Atlantic Ocean must have prevailed at that time than in middle Calvert time.

St. Marys Formation

The St. Marys Formation was named from exposures in St. Marys County, Maryland, particularly those along the St. Marys River near the city of St. Marys (Shattuck, 1902). Other outcrops in St. Marys County are known along the southern bank of the Patuxent River and along the western shore of Chesapeake Bay. Outcrops also extend farther north along Chesapeake Bay into Calvert County. A few outcrops of equivalent age strata are in northern Virginia (Ward, pers. comm., 1971); otherwise, the St. Marys in northern Virginia and on the Eastern Shore is known only in the subsurface. The St. Marys Formation is geographically restricted as is the underlying Choptank Formation in Maryland and northern Virginia (Figure 30).

Shattuck (1904:lxxxv) divided the St. Marys into lithologic "zones" 21 to 24; the lower three zones are exposed in southern Calvert County and the upper one crops out in St. Marys County. A total thickness of 74 feet (23 m) for the four units combined was estimated (Shattuck, 1904: lxxxv), but no continuous outcrop section or sections exist. As much as 185 feet (56 m) is now known in the Hammond Well (Anderson, 1948:19) on the Eastern Shore (Figure 6). The outcropping St. Marys west of Chesapeake Bay comprises beds of blue clay, sandy clay, and clayey sand, commonly containing shell layers. Clay is more abundant than in the underlying Choptank Formation. The lower percentage of sand is typified in the BG&E Well, where sand is

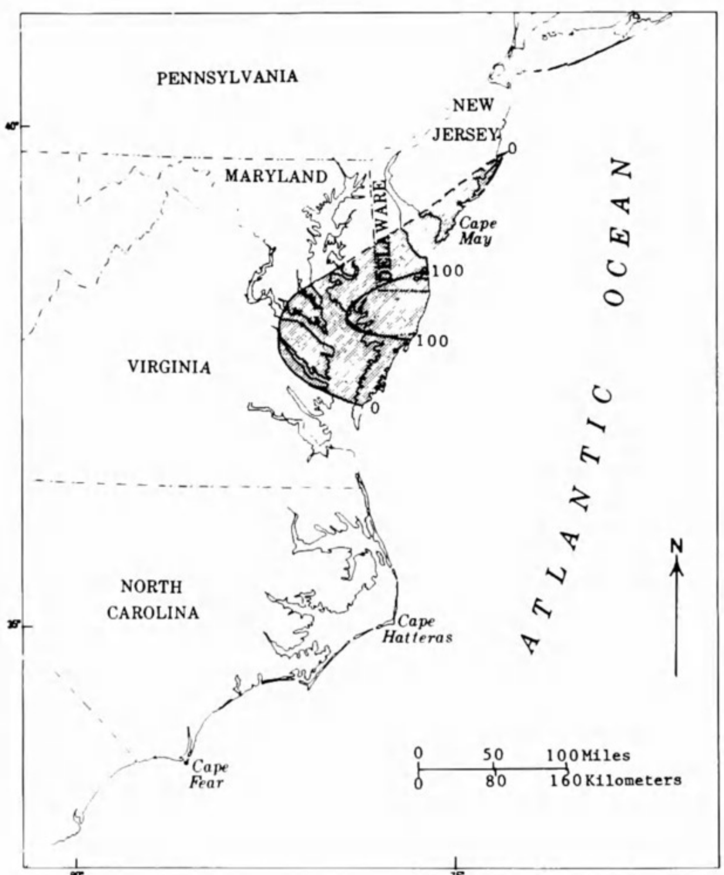

FIGURE 30.—Isopachous map of the St. Marys Formation and equivalent units (upper Miocene). Contours are in feet; contours are indicated by dashed lines where locations are approximated (modified from Gibson, 1970).

less than 50 percent in the lower part of the formation and less than 10 percent in the middle and upper parts (Figure 20). In the Hammond Well (Figure 6) on the Eastern Shore, the strata placed in the St. Marys are coarse sand and fine gravel containing shell fragments and some glauconite.

ENVIRONMENT OF DEPOSITION.—The St. Marys Formation was deposited in a shallow-marine to marginal-marine basin (Gibson, 1962:65; Gernant, 1971:28–30). Gernant (1971) suggested a shallow-subtidal to marginal-marine origin for all beds. In the BG&E core, the low species diversity of 13 or less, dominance of the assemblages by *Buliminella elegantissima*, *Buccella mansfieldi*, and *Cibicides lobatulus*, and the absence of planktonic foraminifers in most samples suggest depths of less than 30 meters for the marine beds. Organic rich brownish gray and dark gray clay beds containing only 2 percent sand or less suggest brackish to restricted marine deposition for at least part of beds 21 and 23. Bed 24, which constitutes the upper part of the St. Marys along the St. Marys River, contains richly fossiliferous sand and some interbedded nonfossiliferous clay. The shelly units are dominated by a relatively few molluscan species, primarily gastropods. Foraminiferal species diversities range from 15 to 20; the benthic assemblages are dominated by *Buccella mansfieldi*, *Florilus pizarrense*, *Buliminella elegantissima*, and *Quinqueloculina seminula*. Planktonic foraminifers usually form less than 1 percent of the assemblages, although one sample contains 9 percent. These foraminiferal assemblages suggest deposition in shallow marine conditions at depths of less than 30 meters. The nonfossiliferous clay probably represents restricted marginal-marine conditions.

The St. Marys strata in the Hammond Well on the Eastern Shore consist of coarse sand and fine gravel containing shell fragments. In New Jersey, the St. Marys fossils occur in beds followed by thick sequences of coarse clastic deposits (Richards and Harbison, 1942:171), which Isphording and Lodding (1969) and Isphording (1976) considered to overlie the Kirkwood Formation conformably. These medium- to coarse-sand and gravel beds, usually referred to the Cohansey Sand, suggest, as do those of the Hammond Well, that clastic debris was carried in by the same delta system that had been building in the area since middle Calvert time. The large influx of coarse clastic deposits at this time indicates uplift of the Appalachian source area as Gibson (1971) suggested. In the embayment to the west of this rapidly prograding delta sequence, open ocean circulation was cut off for significant periods of time, and deposits of restricted marine to brackish environments were formed as seen in beds 21 and 23 and part of 22. Open marine circulation must have been temporarily re-established during deposition of parts of bed 24 slightly to the south.

"VIRGINIA ST. MARYS" BEDS

The "Virginia St. Marys" beds represented a transition in Miocene depositional patterns in the Salisbury embayment as the axis of depositon moved south of that found in the Choptank and St. Marys formations. Mansfield (1943) divided the St. Marys outcrops in Virginia into three units. Mansfield questionably correlated the lowermost, stratum A, with beds 21 and 22 of the St. Marys in Maryland. Stratum A is an unfossiliferous silty clay found only in northernmost Virginia, and is presumably a marginal-marine or nonmarine unit occurring at the southern extremity of the St. Marys Formation. The overlying unit, termed "zone 1" by Mansfield (1943:6) was correlated with beds 23 and 24 of the St. Marys in Maryland. Zone 1 extends farther south than stratum A, reaching approximately the Rappahannock River. Mansfield believed that his highest unit, zone 2, was younger than the fossiliferous St. Marys in Maryland. The distribution of zone 2 reflects the continued southward shift in basin location; the zone as reported by Mansfield (1943;6) reached no farther northward than the Rappahannock River, and it extended southward to the James River in southern Virginia. My subsequent field investigations show that zone 2 extends to northern Virginia at the Nomini Cliffs on the Potomac River and even farther south into northeastern North Carolina along the Meherrin River in the vicinity of Murfreesboro (Figures 4: loc. 28; and 31). The foraminiferal assemblage of zone 2 strata at the Nomini Cliffs indicates a shallow marine environment. Even shallower marine or marginal-marine deposits probably continued into southern Maryland. Most of these strata probably have been stripped by erosion, but possibly some marine and probably some marginal-marine deposits of this age may be found as outliers in Maryland (Stephenson and MacNeil, 1954).

As Mansfield's zone 2 of the St. Marys is younger than the type St. Marys, and occurs largely in Virginia, I have used the informal term "Virginia St. Marys" beds to differentiate zone 2 beds from the type St. Marys Formation in Maryland (Gibson, 1971). Because the geographic distribution and lithology of the "Virginia St. Marys" beds (Figure 31) are similar to those of the immediately overlying Yorktown (Figure 32), and because they occupy the same depositional basin, I placed the "Virginia St. Marys" beds strata into the basal part of the Yorktown Formation (Gibson, 1971). Although the "Virginia St. Marys" beds are without question slightly older than the type Yorktown, the units have a similar genesis. This placement of these strata is similar to that by Olsson (1917:3) who recognized an intermediate fauna between the St. Marys and Yorktown faunas and termed this the "Murfreesboro" stage. Mansfield (1943) and Olsson (1917) placed these beds in the lower part of the Yorktown Formation. The stage name "Murfreesboro" is invalid, however, because of prior usage.

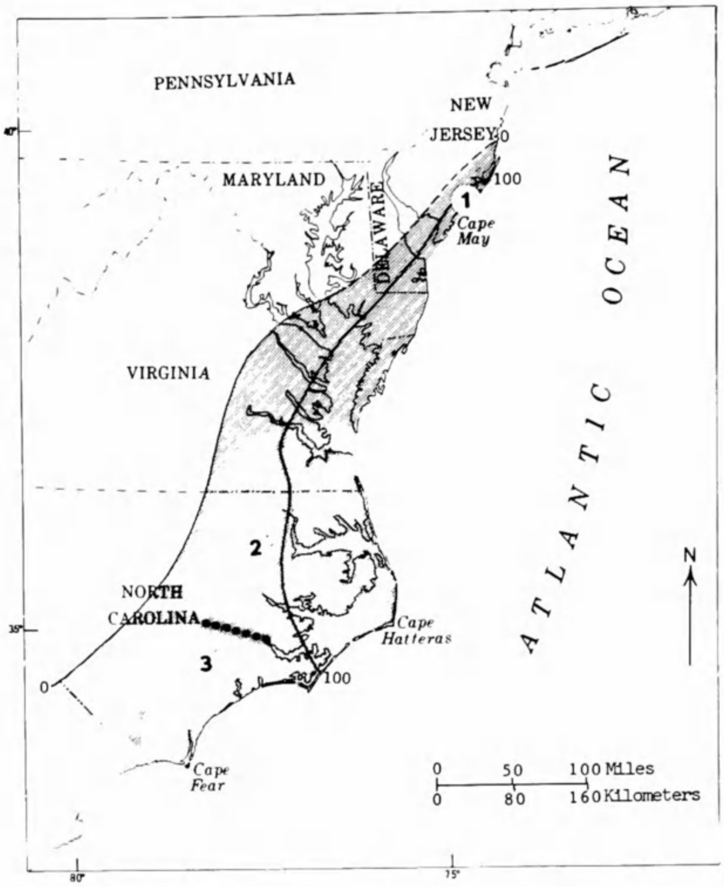

FIGURE 32.—Isopachous map of the Yorktown Formation and equivalent strata (contours are in feet): 1 = Cohansey Sand, 2 = Yorktown Formation and "Virginia St. Marys" beds, 3 = Duplin Formation. Formational limits are dashed where approximately located. The dotted line is the approximate location of the change between the latter two formations (modified from Gibson, 1970).

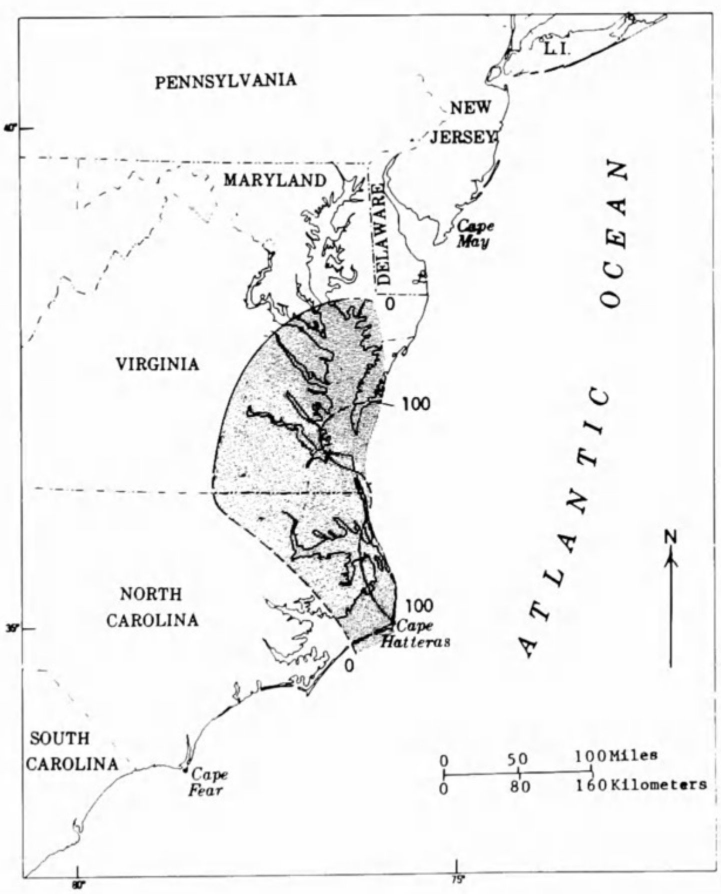

FIGURE 31.—Isopachous map of the "Virginia St. Marys" beds (upper Miocene). Contours are in feet and are indicated by dashed lines where locations are approximate.

The "Virginia St. Marys" beds are grayish blue to greenish blue clayey sand and sandy clay, commonly very shelly. The beds are 25 to 75 feet (7.6–23 m) thick in the outcrop belt in Virginia and thicken down-dip to more than 200 feet (61 m) in the Norfolk Moores Bridge Well. They generally sit upon the Calvert Formation in the Salisbury embayment in Virginia. In North Carolina, the "Virginia St. Marys" beds crop out near Murfreesboro (Figure 4: loc. 28). Strata to the east and southeast of Murfreesboro in the subsurface are placed in this unit. They contain a distinctly different foraminiferal assemblage, reflecting a deeper water environment, which is difficult to correlate with the microfaunas of outcrop sections.

The exact time of the "Virginia St. Marys" beds is uncertain because of the absence of diagnostic planktonic foraminifers in outcrop samples. In addition to the late Miocene age for the underlying St. Marys Formation, a late Miocene age is suggested by K/Ar dates of 8.7±0.4 my and 6.46±0.15 my on "Virginia St. Marys" beds by Blackwelder and Ward (1976:5). The upper age limit of latest Miocene to earliest Pliocene is drawn from the planktonic foraminiferal placement of the lowermost part of the Yorktown Formation into zone N19 (see p.363) and by the K/Ar date of 4.4±0.2 my on lower beds of the Yorktown (Blackwelder and Ward, 1976:8). That considerable late Miocene time is represented by the "Virginia St. Marys" beds is documented by the presence of three consecutive pecten range zones in these strata (Gibson, in prep.) Hiatuses are not unexpected in strata of shallow-marine origin, and at least three are present in the "Virginia St. Marys" beds. This interpretation arises from the sudden appearance of three different chronologic subspecies of pectens above undulating surfaces accompanied by slight changes in the sediments. These zones and hiatuses are best exposed in the James River Valley from Cobham Bay westward to Petersburg.

Environment of Deposition.—Initial deposition in the new center of deposition of the Salisbury embayment constitutes the "Virginia St. Marys" beds. Deposition of the lower strata took place in shallow marine water of less than 30 meters as interpreted from the low species diversities of benthic Foraminifera (less than 15), the dominance of *Elphidium excavatum*, and the sparsity of planktonic foraminifers. The distribution of these strata in Virginia is limited to the eastern part of the embayment. Equivalent strata are not known in the Albemarle embayment, which suggests that no significant subsidence took place there.

Beds of the *Chesapecten middlesexensis middlesexensis* total range subzone overlie the initial deposits of the "Virginia St. Marys" beds and form much of the middle and upper parts of Mansfield's (1943) zone 2 of the St. Marys in Virginia. These strata still represent shallow-marine environments of less than 30 meters and contain foraminiferal assemblages similar to those of the underlying beds. It is thought that they accumulated during a transgression in the Salisbury embayment, because they are found beyond the known geographic extent of the initial strata of the "Virginia St. Marys" beds.

In the highest part of the "Virginia St. Marys" beds, the transgressive sea extended considerably westward, reaching Petersburg (Lieutenant Run, Figure 4: loc. 23) and northward to the Nomini Cliffs (Figure 4: loc. 18). Deposition took place in shallow open marine water of less than 30 meters; the benthic foraminiferal assemblages have species diversities of 10 to 20 with *Elphidium excavatum* dominant, and few planktonic foraminifers occur. These strata contain a transitional form of *Chesapecten middlesexensis–C. jeffersonius*. Significant downwarping of the northern part of the Albemarle embayment began at this time because deposits of this age extend to the west of Halifax, North Carolina (Figure 4: loc. 29). Around Halifax, deposition occurred in shallow open marine water of 15 to 30 meters, marked again by the low species diversities of 12 to 20, few planktonic Foraminifera and dominance of *Elphidium excavatum*. To the east, near Murfreesboro, deeper water deposits are found; the species diversity of benthic Foraminifera increases to 45 and planktonic specimens increase to 5 to 8 percent. These beds accumulated in open marine water about 30 to 60 meters deep. According to Bailey (1973:53) these beds, which contained his assemblage I, formed in depths of 22 to 120 meters.

Yorktown Formation

The Yorktown Formation and its laterally equivalent formations represent one of the two most widespread transgressions of the Neogene seas in the central Atlantic Coastal Plain, the other having occurred during deposition of the Calvert Formation and equivalents. The Yorktown Formation is probably the most widespread of the Neogene transgressive units in the central and south-central parts of the Atlantic Coastal Plain.

The distribution of the Yorktown Formation and equivalent strata is shown in Figure 32; the distribution of the subdivisions of the Yorktown is shown in Figures 33 through 35. The Yorktown reaches thicknesses of greater than 300 feet (91 m) near Norfolk, Virginia, and probably also beneath the outer banks of North Carolina.

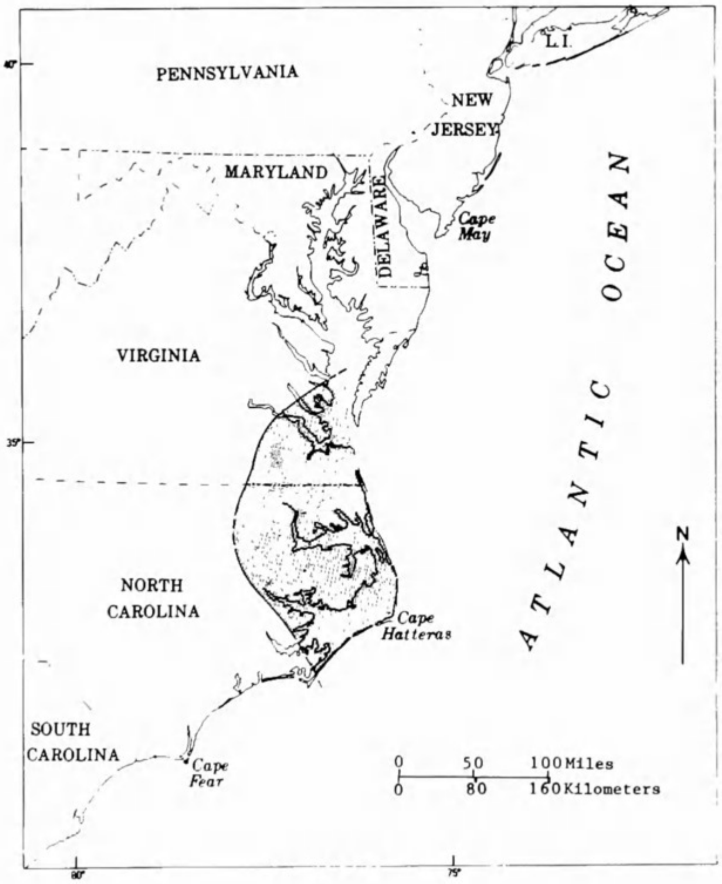

FIGURE 33.—Map of the distribution of the lower Pliocene zone 1 or *Placopecten clintonius* zone of the Yorktown Formation of Mansfield (1943). Limit of zone is indicated by a dashed line where approximately located.

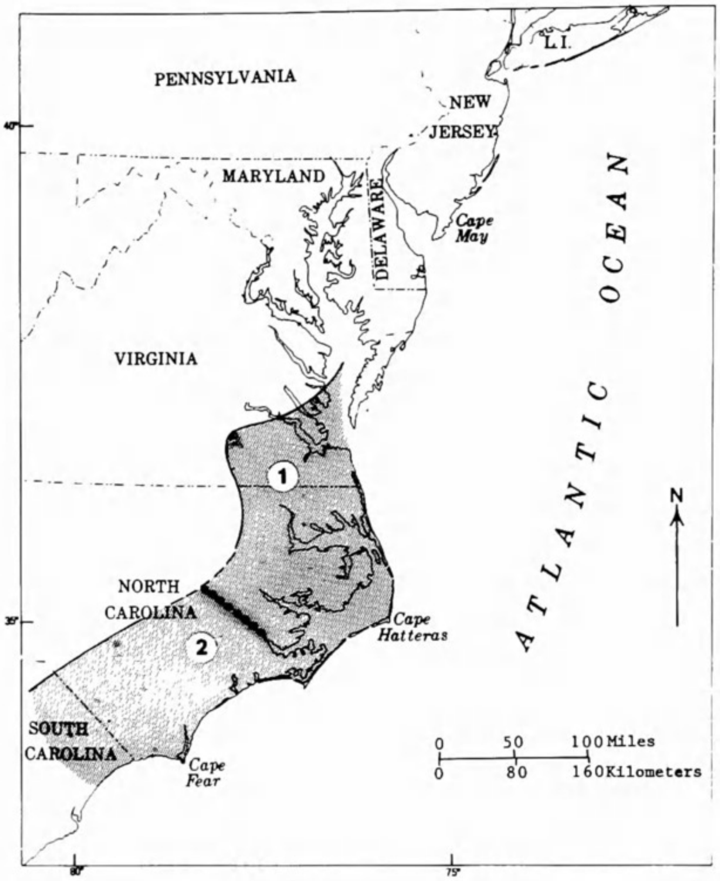

FIGURE 34.—Map of the maximum distribution of the lower and middle parts of zone 2 of the Yorktown Formation of Mansfield (1943) and equivalent strata (lower and upper? Pliocene). 1 = Manfield's Yorktown Formation, 2 = Duplin Formation; dotted line is the approximate location of change between formations.

The lithology of the Yorktown Formation is variable because the wide geographic distribution reflects a number of environments. Clastic units dominate northern Virginia and southern North Carolina, and indicate that the Piedmont uplift had proceeded southward by this time. Bluish clayey sand is dominant; bluish sandy clay is secondary; molluscan shells are common in most strata. The weathered deposits, particularly the sandier, more permeable, units are buff to yellow. Beds of shell hash, in which broken shells compose well over 50 percent of the sediment, are common and many are crossbedded, representing offshore bars and associated environments. Because these strata are very permeable, most are highly oxidized and some are indurated.

The distribution of the Yorktown Formation continued the significant change in depositional pattern seen in the underlying "Virginia St. Marys" beds. The locus of deposition shifted southward from southern Maryland to southern Virginia as the western shore of Maryland was uplifted. This trend toward a more southerly center of deposition began in the "Virginia St. Marys" beds and continued upward through the formation until southern Virginia (including the Norfolk arch) and northern and central North Carolina were covered by the Yorktown sea. The latest "Yorktown Formation" transgression and its equivalents (Waccamaw and Croatan formations) accumulated in a more restricted area covering only the southeastern part of Virginia and eastern North Carolina. The northern part of the central Coastal Plain from Maryland to southern Virginia was then a positive area.

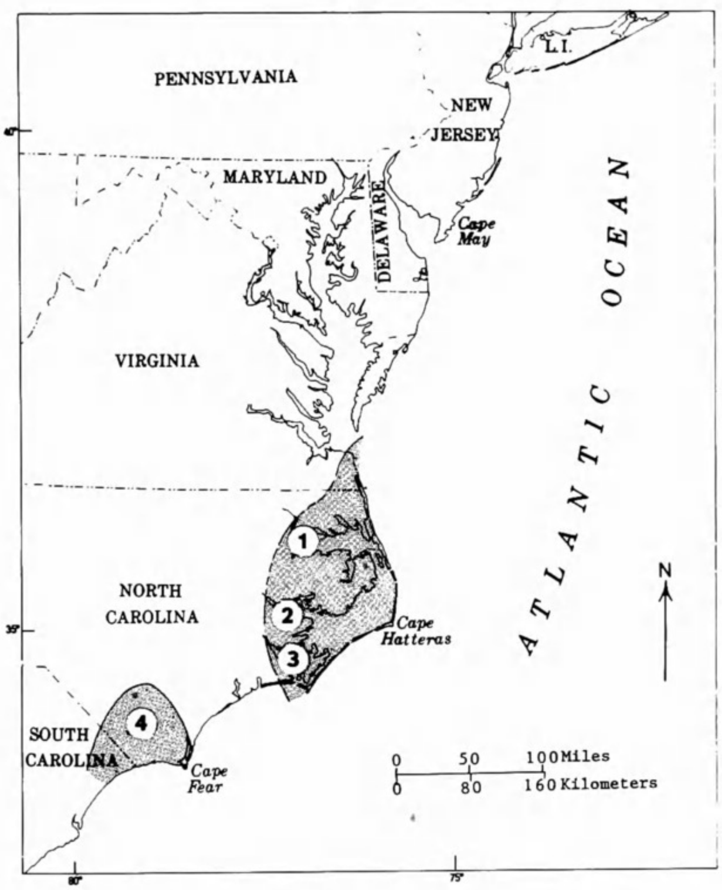

FIGURE 35.—Map of the distribution of the upper Pliocene and lower Pleistocene strata. Limit of strata is indicated by a dashed line where approximately located. 1 = "Yorktown" Formation, 2 = Croatan Formation, 3 = James City Formation of DuBar and Solliday (1963) (=Croatan), 4= Waccamaw Formation.

<table>
<tr><th colspan="3">VIRGINIA</th><th colspan="2">NORTH CAROLINA</th></tr>
<tr><td rowspan="4">YORKTOWN FORMATION</td><td rowspan="3">Zone 2</td><td>Beds at Suffolk, with bed at Biggs Farm at top</td><td>Uppermost Yorktown with bed at Mt. Gould at top</td><td>Duplin marl</td></tr>
<tr><td>Beds at Yorktown</td><td colspan="2">Equivalent to the beds at Yorktown, Va</td></tr>
<tr><td>Chama-bearing bed</td><td colspan="2">Chama-bearing bed</td></tr>
<tr><td colspan="2">Zone 1</td><td colspan="2">Zone 1</td></tr>
<tr><td colspan="2" rowspan="2">ST. MARYS FORMATION</td><td>Zone 2</td><td colspan="2">ST. MARYS FORMATION (?)</td></tr>
<tr><td>Zone 1</td><td colspan="2">(?)</td></tr>
</table>

FIGURE 36.—Correlation chart of the Yorktown and St. Marys formations according to Mansfield (1943).

The changes in distribution reflect upwarp in the central and northern Salisbury embayment in Maryland and northern Virginia and significant downwarping in southern Virginia and the Albemarle embayment in North Carolina.

The present definition of the Yorktown Formation does not imply continuity of deposition in all outcrop sections. The Yorktown Formation as used herein accumulated during early Pliocene through late Pliocene(?) time (Hazel, 1977; see also p.363). Faunal changes and lithologic discontinuities are present in the Yorktown Formation as documented by Gibson (1967) and Hazel (1977), and herein illustrated in Figures 24 and 26.

Mansfield (1943) divided the Yorktown Formation in Virginia into two faunal zones, the lower, zone 1, called the *Pecten clintonius* zone, and the upper, zone 2, called the *Turritella alticostata* zone. Zone 2 was divided into three units, in ascending order, the *Chama*-bearing bed, the beds at Yorktown, and the beds at Suffolk (Figure 36).

At the top of the Suffolk unit, he placed the bed at Biggs Farm (exposure not located by later workers), which he considered to be the youngest part of the Yorktown in Virginia.

Blackwelder and Ward (1976) proposed four member names for the Yorktown Formation in Virginia that encompass Mansfield's zone 1 and much of his zone 2. These four members are recognizable in the areas of the James and York rivers. Johnson (1969:10) proposed that some of the lithologically distinct beds or members of the Yorktown along the James and York rivers are lateral facies, but biostratigraphic correlation based on the pectens (Gibson, in prep.) supports Mansfield's (1943) view of a vertical succession of these beds.

Mansfield (1943) studied the Yorktown strata in North Carolina and compared them with the Virginia succession. The youngest part of the Yorktown in North Carolina recognized by Mansfield was at Mt. Gould Landing along the Chowan River. Mansfield (1943:12) concluded that the strata were younger than any Yorktown in Virginia. This conclusion is supported by Hazel (1977) on the basis of ostracodes and by Gibson (in prep.) on the basis of pectens. Gibson (1962) correlated the beds along the Chowan River with the Waccamaw Formation in southern North Carolina on the basis of benthic Foraminifera; this correlation is supported by Hazel (1977) and Gibson (p.364). These beds are further correlated with the Croatan Formation as used in the Lee Creek Mine and other places in east-central North Carolina on the basis of the ostracodes (Hazel, 1977), foraminifers (see p.364), and pectens (Gibson, in prep.).

Hazel (1977) found strata at Yadkin, Virginia, which he considered younger than any other strata in the Yorktown Formation in Virginia, and probably equal in age to the upper beds along the Chowan River. Strata containing benthic Foraminifera characteristic of latest Yorktown age also occur in the upper part of the Moores Bridge Well at Norfolk (Figure 4: loc. 25) at depths from about 90 to 115 feet (27 to 35 m). These strata are likely equivalents of the Yadkin deposits, and both may be the same age as those originally reported by Mansfield (1943) at Biggs Farm.

Beds equivalent to zone 1 of Mansfield's Yorktown, characterized by the presence of *Placopecten clintonius*, crop out only near Murfreesboro in North Carolina (Figure 4: loc. 28), but they are present in the subsurface southward to the Lee Creek Mine (Figures 23, 24, 27); they also extend to the east (Figure 33). Strata equivalent to zone 2 of Mansfield's zonation extend southward in North Carolina to New Bern (Figures 4: loc. 34; and 34).

South of central North Carolina, strata of Yorktown age are placed in the Duplin Formation (Mansfield, 1943).The historic basis for separating Duplin from Yorktown is the warmer water fauna of the Duplin rather than any striking lithologic change (Mansfield, 1943). According to Mansfield (1943:13), the Duplin Formation represents only the younger part of his zone 2 of the Yorktown. The diagnostic species of Duplin pectens and benthic foraminifers confirm its middle and late Yorktown age (see p.363). However, the youngest parts of the Yorktown Formation as exposed along the Chowan River in North Carolina are younger than the Duplin Formation.

In the Salisbury embayment, more than 200 feet (61 m) of Yorktown strata are present in wells in the southern part of the Delmarva Peninsula (Accomack Well, Virginia; Figure 4: loc. 20). Farther north on the Delmarva Peninsula, Anderson (1948:19) provisionally placed 200 feet (61 m) of sand and gravel described from the Hammond Well into a nonmarine facies of the Yorktown Formation. No biostratigraphic data are available to confirm this, however.

Richards and Harbison (1942) correlated part of the Cohansey Sand in New Jersey with the Yorktown Formation. The Cohansey is composed of coarse quartz sand and beds of clay and gravel. It contains few fossils, but has been tentatively correlated with the Yorktown. Isphording and Lodding (1969) considered the Cohansey to have accumulated in a regressive phase of late Miocene deposition, essentially a continuation of Calvert and Choptank deposition. This would place the lower part of the Cohansey in the middle Miocene, leaving its youngest beds undated. The presence of shallow-water strata of Miocene age offshore in the Cost B-2 Well (Smith et al. 1976:50) indicates that the Cohansey could be a regressive facies of any or all of the middle Miocene through Pliocene onshore units.

ENVIRONMENT OF DEPOSITION.—The Albemarle and Salisbury embayments contained open marine, inner- to middle-shelf environments followed by regressive marginal-marine environments during deposition of the lower and middle parts of the Yorktown Formation and equivalents. The greatest water depths postulated for these strata are 80 to 100 meters (Gibson, 1967:645) and are based on foraminifers. Bailey (1973:53–58) assigned similar depths (maximum of 120 m) to two intervals on the basis of mollusks. In general, the Yorktown Formation in the Albemarle embayment includes older strata deposited in deeper water than those deposited in the southern part of the Salisbury embayment.

The *Placopecten clintonius* zone (zone 1 of Mansfield's Yorktown Formation) is one of the most widespread units in the Yorktown Formation. This zone extends from east-central Virginia southward across the Norfolk arch into the Albemarle embayment and reaches southward almost to New Bern (Figures 4: loc. 34; and 33). The depositional depths of 80 to 100 meters in the Lee Creek Mine (Gibson, 1967), suggest that the zone originally was even more widespread, but has been partly removed by erosion. The *P. clintonius* zone is the oldest post-Pungo River deposit in the southern part of the Albemarle embayment and is the initial deposit of the Yorktown Formation in the Lee Creek Mine. This indicates that downwarping occurred here later than in the northern part. The lower several feet of this zone are rich in dark brown to black phosphatic nodules as large as 1 foot (30 cm) in diameter. These nodules are reworked by physical and chemical processes from the phosphatic sand of the Pungo River Formation. They formed in continental, marginal-marine, and marine environments in post-Pungo River time and were incorporated into the basal strata of the Yorktown Formation. Numerous vertebrate fossils, including bones of whales, porpoises, and seals, and shark teeth are included in this basal transgressive unit. Molluscan shells, particularly *Placopecten clintonius*, are abundant (Figures 26, 27). These figures also show the burrowed surface at the top of the Pungo River Formation and the reworked phosphatic nodules. The *Placopecten clintonius* zone, along with the underlying highest part of the "Virginia St. Marys" beds, represent the deepest water deposition of any outcropping Yorktown strata in North Carolina. The depositional depths for this zone in Virginia were not as great as in the Lee Creek Mine; most were 30 meters or less, as indicated by lower foraminiferal species diversity and fewer planktonic foraminifers (Gibson and Buzas, 1973:231).

The Yorktown strata above the *Placopecten clintonius* zone in central and northern North Carolina are part of a regressional sequence as shown in the Lee Creek Mine by Gibson (1967) and in northeastern North Carolina by Hazel (1971), Bailey (1973), and Gibson (unpub. data). In the Lee Creek Mine, middle beds of the Yorktown accumulated in water of 30 meters or less. In northern North Carolina, strata containing diverse foraminiferal and molluscan assemblages and common planktonic Foraminifera (*Placopecten clintonius* zone) grade upward into beds containing molluscan assemblages almost exclusively composed of *Mulinia congesta* and low-diversity foraminiferal assemblages dominated by *Elphidium excavatum* (Mansfield's zone 2) with no planktonic specimens. *Elphidium excavatum* also is characteristic of shallow-marine, lagoon, and sound environments. These assemblages are associated with laminated clay beds near Murfreesboro and Palmyra, North Carolina (Figure 4: locs. 28, 30), which suggest deposition in a lagoon or sound.

The regression or subsequent erosion probably caused the missing section in the upper part of Mansfield's zone 2 of the Yorktown in the Lee Creek Mine (Gibson, 1967, Hazel, 1977). Other Yorktown erosional surfaces, such as the one separating units 2 and 3 in the Lee Creek Mine (Figure 24), are present throughout Virginia and North Carolina. Whether these are submarine or subaerial scour surfaces is not known at present.

Generally, the environments as interpreted from foraminiferal assemblages show little change. In many sections, the molluscan assemblages, particularly the pectens, do change across the scour surfaces and suggest that some time is missing. These scour surfaces help in defining members of the Yorktown Formation in Virginia.

The initial deposition of the lower strata of the Yorktown occurred in shallower water than in the southern part of the Salisbury embayment in Virginia. The beds of the *Placopecten clintonius* zone were deposited in open marine water of less than 30 meters, and these depths were maintained during accumulation of much of the overlying Yorktown strata. The upper beds at Yorktown (zone 2 of Mansfield) contain high-angle, large-set crossbeds of medium to coarse sand and abundant shell hash. These are characteristic of barrier bars (Johnson, 1969:12, 24) and reflect a regression of the Yorktown sea in the Salisbury embayment. Beds belonging to zone 2 of Mansfield extend westward to Petersburg where they lie upon the uppermost part of the "Virginia St. Marys" beds (Figure 34). The upper beds at Petersburg are blue clay units, some containing bands of *Mulinia congesta* and foraminiferal assemblages dominated by 70 percent *Elphidium excavatum*. These upper beds probably were deposited in the lagoon or sound behind the barrier-bar sequence forming to the east.

This regression marked the end of Yorktown deposition in much of the Salisbury embayment in Virginia. In the southeastern part, however, a later transgression deposited upper Pliocene to lower Pleistocene strata seen at Yadkin (Hazel, 1977) and at Norfolk (Moores Bridge Well, see p. 74). This latest "Yorktown Formation" transgression covered much of the eastern part of the Albemarle embayment as seen in deposits along the Chowan River, at Terra Ceia, in the upper beds in the Lee Creek Mine, and near James City along the Neuse River (Figures 4: loc. 35; and 35). The beds along the Chowan River were placed in the Yorktown Formation by Mansfield (1943) and are provisionally referred there by Hazel (1977) and Gibson (see p.364). In the southern part of the Albemarle embayment these strata are placed in the Croatan Formation (Hazel, 1977). These beds also indicate a regressional sequence toward the top. In the Lee Creek Mine, the lower strata of the Croatan were deposited in an open marine environment about 30 meters deep; later beds were deposited in open marine water of less than 15 meters depth; uppermost beds accumulated in marginal-marine environments (Gibson, 1967). Bailey (1973) concluded that equivalent beds along the Chowan River accumulated initially in a shallow sublittoral environment, becoming even shallower estuarine, sound, lagoon, and inlet environments when the upper parts were deposited. Thus, at the end of the latest "Yorktown Formation" depositional cycle, a series of marginal-marine, sound, lagoon, and other estuarine environments was found from the Chowan River southward through the Lee Creek area to the Neuse River. Howard (1974) believed that the Croatan Formation near James City on the Neuse River (= James City Formation of DuBar and Solliday (1963); Hazel, 1977) formed in a shallow bay or sound; this would extend the marginal-marine belt to James City (Figures 4: loc. 35; and 35).

The crest of the Norfolk arch was covered mostly by marginal-marine deposition during Yorktown time. Occasionally, shallow-marine deposition occurred on part of much of the arch, particularly during deposition of zone 1 of the Yorktown (Clark and Miller, 1912:159). Wells on top of the arch (Figure 37) penetrate thick sequences of fine-grained sediments, primarily clay, largely devoid of megafossils, but with foraminiferal assemblages dominated by *Elphidium excavatum*. The precise age of these strata is uncertain at this time because of the limited faunas.

Erosion and/or nonmarine deposition took place in the northern and western parts of the Salisbury embayment during Yorktown time. In the northeast part of the embayment, coarse clastic deposits still were originating in the uplifted Appalachians as seen in the coarse clastic sequence of the Hammond Well and at Accomack on the Eastern Shore (Figure 4: locs. 13, 20). The

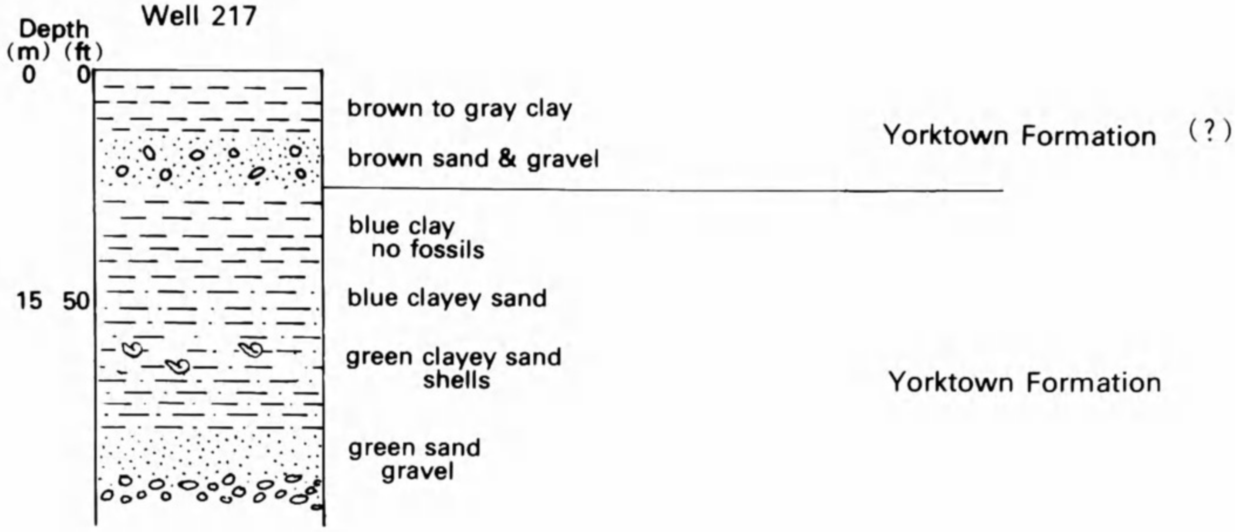

FIGURE 37.—Geologic column for Well 217, near New Bohemia, Prince George County, Virginia, showing small amount of open marine sediments in section in Yorktown Formation.

uplift of the northern source areas had moved southward by Yorktown time to include the adjacent Piedmont in Virginia and North Carolina, which supplied clastic sediments to the southern Salisbury and Albemarle embayments.

Farther south in North Carolina, the shallow environments persisted as seen in the Duplin Formation and younger part of the Waccamaw Formation. Strata of early Yorktown age are missing in this area. Copeland (1964:229) concluded that the Duplin Formation was deposited in depths of 30 to 60 feet (9 to 18 m). Howard (1974:129, 130) considered deposition to have been in water less than 37 meters deep and mostly less than 18. Gibson (unpub. data) found similar depths for many of the exposures. Additional evidence for near-shore deposition in southern North Carolina are the delta lobes, which DuBar et al. (1974:153, 171) attributed to the Duplin Formation.

The Waccamaw Formation was deposited on the Cape Fear arch in southern North Carolina during the later "Yorktown Formation" transgression. Deposition occurred in shallow open marine environments (Gibson, 1962:68). Howard (1974) recognized two environments in the Waccamaw in this area, one of shallow open marine (less than 15 m depth and high energy) and the second of lower salinity shallow bay. The shallowness of the Waccamaw environments to the south and the Croatan environments to the north suggests that the intervening area received no marine or marginal-marine deposition (Figure 35).

Addendum

Since the original submission of this manuscript in 1978, new stratigraphic knowledge has led to several changes in the stratigraphic nomenclature used herein. Ward and Blackwelder (1980) gave the name Eastover Formation to the beds previously and herein termed the "Virginia St. Marys." Gibson (1982) demonstrated that an older cycle of sand and diatomaceous clay beds of the Calvert Formation, termed the Dunkirk beds, underlies the Popes Creek Sand Member along the Patuxent River.

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