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Edited by R.B. Mixon

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By R.B. MIXON, DAVID S. POWARS, LAUCK W. WARD, *and* GEORGE W. ANDREWS

GEOLOGY AND PALEONTOLOGY OF THE HAYNESVILLE CORES—NORTHEASTERN VIRGINIA COASTAL PLAIN

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By R.B. Mixon, David S. Powars, Lauck W. Ward, and George W. Andrews

ABSTRACT

The Haynesville cores, obtained from three adjacent stratigraphic test holes in Richmond County in east-central Virginia, provide one of the more complete reference sections currently available for the Tertiary strata of the Virginia and Maryland Coastal Plain. The cored Tertiary section is 537 feet (ft) (164 meters (m)) thick and includes strata of late Paleocene, early and middle Eocene, late Oligocene, middle and late Miocene, and Pliocene ages. The Tertiary beds are separated from the Lower Cretaceous Potomac Formation by an unconformity representing a hiatus of approximately 40 million years (m.y.). Upper Cretaceous and lower Paleocene formations are absent, probably in part because substantial thicknesses of these strata were never deposited in this area, and in part because of relative uplift of the Norfolk arch and beveling of strata associated with episodic marine transgressions across the area.

The basal 19.5 ft (5.9 m) of the core consists of fine to coarse, quartzofeldspathic sand and mottled, rooted, sandy and clayey silts assigned to the uppermost part of the Potomac Formation. This interval is believed to have been deposited in fluvial channel and flood plain environments. The formation's rich, nonmarine palynomorph assemblage, which is dominated by spores of ferns, indicates assignment to Cretaceous pollen zone II of Doyle and Robbins (1977) and is Albian in age. Gymnosperm pollen and cysts of freshwater algae are also present. The Potomac beds are considerably more consolidated than the overlying Tertiary formations.

The glauconitic sand, silt, and clay of the Pamunkey Group (Paleocene and Eocene) are 264 ft (80 m) thick and include the Aquia, Nanjemoy, and Piney Point Formations and the Marlboro Clay. The Aquia Formation, which is of Thanetian age, consists of 118.4 ft (36 m) of variably shelly, glauconitic quartz sand and thin, sandy limestones deposited in outer and inner sublittoral environments. The Aquia is subdivided into the more poorly sorted, clayier, more calcareous Piscataway Member (below) and the better sorted, coarser, less calcareous Paspotansa Member (above). The Aquia sand grades upward into a thin, kaolinitic clay that probably is a truncated remnant of the Marlboro Clay. The lower Eocene Nanjemoy Formation, which unconformably overlies the Marlboro Clay, is a poorly sorted, very clayey and silty, fine to coarse glauconitic quartz sand about 91 ft (28 m) thick. The lower part of the Nanjemoy includes at least four repetitive lithic units consisting of intensely burrowed, very clayey and silty, very glauconitic sand and silt. Each unit is dominantly sand in the lower part and dominantly sandy silt and clay in the upper part. These beds, about 51 ft (16 m) thick, are assigned to the Potapaco Member of the Nanjemoy and are thought to be of early Ypresian age. The upper 40 ft (12 m) of the Nanjemoy is composed of less clayey, very micaceous, pebbly, glauconitic sand of the Woodstock Member, which is middle and late Ypresian in age. Foraminiferal assemblages indicate that the lower and middle Potapaco beds were deposited in gradually deepening shelf waters, whereas the upper Potapaco and the Woodstock were deposited in shoaling-upward, middle and inner sublittoral environments. The Woodstock Member is unconformably overlain by the middle Eocene Piney Point Formation, which consists of 55 ft (17 m) of richly fossiliferous, olive-gray, poorly sorted, medium to coarse glauconitic sand interbedded with carbonate-cemented sand and moldic limestone. The large oyster, *Cubitostrea sellaeformis*, is a guide fossil for this unit. Foraminiferal assemblages from the upper Piney Point suggest deposition in an outer sublittoral environment.

The upper Oligocene Old Church Formation is a 4-ft-thick (1.2-m-thick), shelly, muddy, fine to coarse quartz sand containing sparse glauconite and scattered fine pebbles of quartz and phosphate. The unit is characterized by the pelecypod *Mercenaria capax* and by abundant barnacle plates. The foraminiferal assemblage suggests an outer sublittoral depositional environment and a correlation with the late Oligocene zone N. 4a of Kennett and Srinivasan (1983). Regionally, as well as in the core, the top and bottom of the formation are erosional unconformities.

The diatomaceous and shelly sands of the Chesapeake Group (Miocene and Pliocene) are about 290 ft (88 m) thick and include the Calvert, St. Marys, Eastover, and Yorktown Formations. The Miocene Calvert Formation, which overlies the Old Church Formation, is 132.3 ft (40 m) thick and is divided into three parts. The lower 11.3 ft (3.4 m), herein informally named the "shelly sand beds," is composed of muddy, intensely bioturbated, fine to medium quartz sand containing abundant mollusks. A well-preserved planktonic foraminiferal assemblage is indicative of foraminiferal zone N. 8 and is of Langhian age. Above the shelly sand beds are 56.5 ft (17 m) of diatomaceous, clayey and silty, fine to very fine, olive-gray sand and sandy clay-silt, herein informally called the Plum Point beds, that are approximately equivalent to the Plum Point Marl Member of the Calvert Formation in Maryland. The upper 64.5 ft (20 m) of the Calvert, herein called the Calvert Beach

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beds, is similar to the underlying Plum Point beds but contains much more sand. Diatom assemblages in this unit indicate equivalence to the Calvert Beach Member of the Calvert Formation in Maryland. Diatomaceous strata of the Choptank Formation, which overlie the Calvert in much of the Virginia and Maryland Coastal Plain, are absent in the Haynesville cores.

The St. Marys Formation, consisting of 37 ft (11 m) of variably shelly, bluish- to pinkish-gray, very fine, muddy sand and clayey silt, unconformably overlies the olive-gray upper Calvert sands. These beds constitute two lithic sequences, herein designated units A and B, that appear to be separated by an unconformity. Comparison of the Haynesville core section with the more richly fossiliferous core hole and outcrop sections at nearby Essex Mill, southeast of Tappahannock, Va., indicate correlation of unit B with the Windmill Point beds of Ward (1984b). Unit A may be equivalent to the Little Cove Point beds of Blackwelder and Ward (1976), which are typically exposed in southernmost Calvert County, Md.

A 55.5-ft-thick (17-m-thick) section of the upper Miocene Eastover Formation unconformably overlies the muddy, fine sand of the St. Marys. The basal bed is a 4-ft-thick (1.2-m-thick) sand containing pebbles of quartz and phosphate. Approximately the lower half of the Eastover is rhythmically interbedded, laminated to thin-bedded, bluish-gray silty clay and clayey silt and very fine, micaceous quartz sand. The thick accumulation of fine sediment and the rhythmic mud/sand bedding suggests deposition in tidally influenced, shallow shelf waters behind a barrier or offshore bar complex. The upper, sandier part of the Eastover consists mainly of clayey and silty, very fine to fine sand that becomes cleaner and coarser (fine to medium sand) upward in the section. Fossil assemblages in nearby outcrops indicate that the upper Eastover was deposited in shallow, open-marine waters.

The Yorktown Formation includes about 65.5 ft (20 m) of loose, fine to coarse, pebbly sand, crossbedded in part, composing the uppermost part of the core section and the borrow-pit exposure at the drill site. Large, clay-lined decapod burrows (*Ophiomorpha*) and biogenic structures resembling heart urchin burrows suggest deposition in littoral and shallow neritic environments. These strata are considered to be an updip, marginal-marine facies roughly equivalent to the abundantly fossiliferous marine Yorktown of areas to the east and south.

INTRODUCTION

In 1984, as part of its studies of the geologic framework of the Atlantic Coastal Plain, the U.S. Geological Survey drilled a stratigraphic test hole in the outer Coastal Plain in northeastern Virginia. The test hole, one of a series of test holes along a Coastal Plain transect, is located in central Richmond County, Va., 0.65 mile (mi) (1.0 kilometer (km)) northwest of Haynesville, and 3 mi (5 km) east of Warsaw at lat 37°57′13″ N., long 76°40′26″ W. (see fig. 1). The test hole was drilled to a depth of 375 ft (114.3 m) from a land surface elevation of 72 ft (22 m) above sea level in a valley, considerably below the 140–150-ft (43–46 m) elevations of nearby stream divides[1]. The main objective was to obtain a fairly complete core of the Neogene section, which in this area includes more than 100 ft (30 m) of Pliocene sand and gravel (a marginal-marine facies of the Yorktown Formation) and about 215 ft (66 m) of Miocene sand, silt, and clay assigned to the Calvert, St. Marys, and Eastover Formations. In 1985, a second test hole (land surface elevation 87 ft (27 m)) was drilled upslope and about 150 ft (46 m) from the other test hole. The purpose was to complete the sampling of the Tertiary strata by coring the Oligocene, Eocene, and Paleocene sections, including the Old Church, Piney Point, Nanjemoy, and Aquia Formations. This test hole was cored to a depth of 556 ft (169 m), bottoming in sand, silt, and clay of the Lower Cretaceous Potomac Formation. Later, using the split spoon coring method, an additional shallow test hole was drilled at the Haynesville 2 core site to sample the uppermost sand and gravel section not recovered previously. Together, the cores from the three test holes (herein designated the Haynesville 1, Haynesville 2, and Haynesville 3 cores) provide the most complete Cenozoic stratigraphic section currently available in the Virginia Coastal Plain (fig. 2). (In this paper, material from the two cores generally is treated as a composite section and is referred to as the "Haynesville core.") Geophysical logs of the Haynesville 2 core hole, including single-point and multipoint electrical resistivity logs and natural gamma ray logs, are also available (see chap. A–pl. 1). The Haynesville core, the Oak Grove core from Westmoreland County, and the Exmore core from Accomack County, Va., (53.6 mi (86 km), southeast of Haynesville) are key tie points for a Cenozoic cross section extending from the Fall Line near Stafford, Va., southeastward across the Coastal Plain to the Atlantic Coast (Reinhardt, Newell, and Mixon, 1980; Mixon and Powars, 1984; Powars and others, 1987).

This paper focuses on the lithostratigraphy of the core but also briefly discusses the fauna and flora, the depositional environments, and the age and correlation of the individual formations and members. David S. Powars logged and photographed the cores and helped with the lithostratigraphic descriptions and interpretations. Lauck W. Ward identified the molluscan assemblages and helped with lithostratigraphic interpretations and correlations. George W. Andrews provided the diatom identifications and the diatom zonation for the Calvert Formation. Accompanying papers by McCartan, Poag, and Edwards discuss the mineralogy of the core, the foraminiferal stratigraphy and paleoenvironments, and the dinoflagellate cyst assemblages from the lower Tertiary formations.

FIGURE 1.—Map showing location of the Haynesville, Oak Grove, and Essex Millpond core holes in Richmond, Westmoreland, and Essex Counties, Va. ▶

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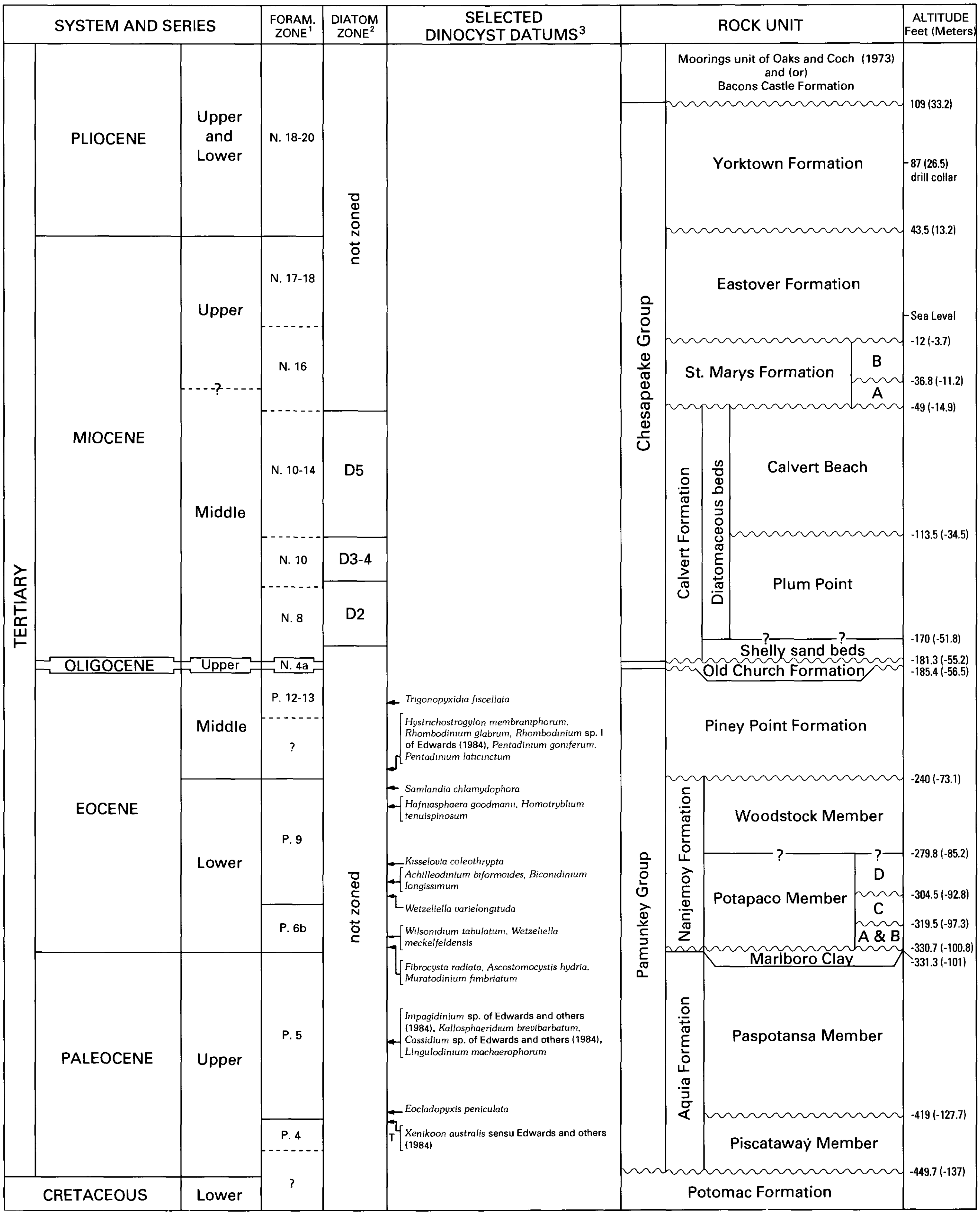
[1] *Sea level*: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.


77°
39°
38°
ANNE ARUNDEL
WASHINGTON
ARLINGTON
PRINCE GEORGES
Fairfax
FAIRFAX
ALEXANDRIA
Upper Marlboro
Herring Bay
EASTERN BAY
Tinkers Cr
Piscataway Cr
Mattawoman Cr
CHESAPEAKE
CHOPTANK
Tripps Bay
Little Choptank R
Harris Cr
VIRGINIA
MARYLAND
CHARLES
CALVERT
Zekiah Swamp Run
Nanjemoy Cr
PATUXENT RIVER
Chopawamsic Cr
Lunga Res
Aquia Creek
STAFFORD
Potomac Creek
KING GEORGE
Fredericksburg
POTOMAC RIVER
Wicomico River
ST MARYS
Lexington Park
Mattox Cr
Oak Grove core hole
Mill Cr
WESTMORELAND
Piney Point
St Marys R
South R
CAROLINE
ESSEX
RICHMOND
NORTHUMBERLAND
Polecat Cr
Reedy Cr
Warsaw
Haynesville core hole
Haynesville
Tappahannock
Totuskey Cr
Piscataway
Essex Millpond core hole
MARYLAND
VIRGINIA
Great Wicomico R
Ingram Bay
Mattaponi
KING AND QUEEN
KING WILLIAM
Pamunkey
RAPPAHANNOCK
LANCASTER
MIDDLESEX
Exol Swp
0 5 10 15 20 MILES
0 5 10 15 20 25 30 KILOMETERS



[1] Zones P. 4- N. 14 from Poag (chap. D, this vol.), Zones N. 16- N. 20 extrapolated from other sources.

[2] Andrews, 1988.

[3] Edwards (chap. C, this vol.); arrow indicates lowest occurrence, arrow with T highest occurrence.

FIGURE 2.—Tertiary and uppermost Cretaceous geologic column for the Haynesville, Va., area. Column extends from top of higher drainage divides (alt. ~140 ft), believed to represent relict depositional surfaces at top of upper Pliocene formations, downward to depth of −469 ft at bottom of Haynesville 2 core hole.

ACKNOWLEDGMENTS

We wish to thank Wayne L. Newell for making the Neogene core of the Haynesville 1 core hole available for study. Our discussion of depositional environments and the age and correlation of stratigraphic units is based, in part, on studies of the foraminiferal and dinocyst assemblages by C. Wylie Poag and Lucy E. Edwards, respectively. Dinocyst datums for the Paleocene and Eocene formations (fig. 2) were kindly provided by Lucy E. Edwards. We also thank Douglas J. Nichols for his study of the pollen assemblage from the Potomac Formation beds.

STRATIGRAPHY

POTOMAC FORMATION

DEFINITION

The Lower Cretaceous Potomac Formation in outcrop and in the subsurface of northeastern Virginia is a gently eastward dipping fluvial-deltaic sequence of sand, gravel, silt, and clay as much as 1,000 ft (305 m) or more thick (Glaser, 1969; Brown and others, 1972; Reinhardt, Christopher, and Owens, 1980). The formation thickens northeastward and eastward toward the deeper parts of the Salisbury embayment in southern Maryland, Delaware, and New Jersey (Spangler and Petersen, 1950). In Virginia, the Potomac Formation variously overlies metamorphic and igneous rocks of the crystalline basement complex and red beds of early Mesozoic rift basins. Locally, in northeastern Virginia, the Potomac is overlain unconformably by the Brightseat Formation of early Paleocene age. Where the Brightseat is absent, as in the Haynesville core hole, the Potomac is directly overlain by the Aquia Formation (upper Paleocene). In some inner Coastal Plain areas, however, the Calvert and Choptank Formations of early and middle Miocene age lap over the Aquia onto the thin, updip edge of the Potomac Formation beds.

The Haynesville 2 core hole penetrated only the uppermost 19.3 ft (5.9 m) of the Potomac Formation, which here consists of fine to coarse, quartzofeldspathic sand and sandy clay-silt (fig. 3; chap. A–pl. 1).

LITHOLOGY

The Potomac beds in the core (alt. −449.7 to −469 ft (−137 to −143 m)) include three thin, fining-upward lithic units; only the upper 6 ft (1.8 m) of the lowest unit was cored. This lowest unit is composed of light-olive-gray, silty, fine sand that grades upward to medium-olive-gray sandy and clayey silt. The sand and silt are characterized by conspicuous light-brown and yellowish-brown mottles, sand-filled burrows as much as 0.5 inch (in) (1.3 centimeters (cm)) in diameter, which may be invertebrate burrows, and branching, clay-lined, sand-filled tubules of varying diameters that are thought to be traces of rootlets. The uppermost foot (0.3 m) of the unit has irregular, branching, desiccation(?) cracks filled with dark-gray clay-silt (figs. 3*A*, 3*B*). The structures and brown mottles are suggestive of pedogenic processes.

The overlying 3.5-ft-thick (1.1-m-thick) unit (fig. 3*C*) consists of pebbly medium sand that grades upward into medium-olive-gray, fine, silty sand and hard, clayey silt containing finely crystalline iron sulfide. The pebbles are mainly subangular to subrounded, olive-gray, light-brown, and yellowish-brown clay-silt; fragments of lignite are also present.

The uppermost unit (fig. 3*D*) is a 10-ft-thick (3-m-thick) micaceous, crossbedded sand that is coarser grained, better sorted, less consolidated, and lighter colored than the underlying Potomac beds. The lower third of the unit is light-olive-gray to light-olive-brown, fine to coarse, loose sand containing rounded pebbles of vein quartz and irregular to rounded clasts of clay-silt. The loose sand is interbedded with thin, lenticular, partly indurated beds of fine to medium silty sand. Although no core was recovered from the basal foot (0.3 m) of this sequence, we infer that the lithology is coarse, gravelly sand. The middle and upper parts of the micaceous, feldspathic sand are light olive gray, fine to medium grained, and moderately well sorted. A sample from the unoxidized clay-silt clasts in this unit yielded well-preserved, nonmarine palynomorphs of Early Cretaceous age.

In the core, the Potomac beds are overlain with pronounced unconformity by shelly, glauconitic, quartz sands of the upper Paleocene Aquia Formation. Strata of Late Cretaceous and early Paleocene ages are absent.

FLORA

A rich palynomorph assemblage obtained from a sample (alt. −452 ft (−138 m)) from the uppermost Potomac beds is dominated by spores of ferns (D.J. Nichols, written commun., 1985). Gymnosperm pollen is also common. Only one species of angiosperm pollen, *Tricolpites albiensis*, is present. Cysts of freshwater algae are also present in the sample.

ENVIRONMENT OF DEPOSITION

The pervasive brown mottling, the branching, clay-filled desiccation(?) cracks, and the rooted, poorly sorted, clayey silt and fine sand of the lowest unit of the Potomac Formation suggest deposition in a vegetated part of a fluvial channel-flood plain complex that was subject to drying and oxidation during at least part of the year. The

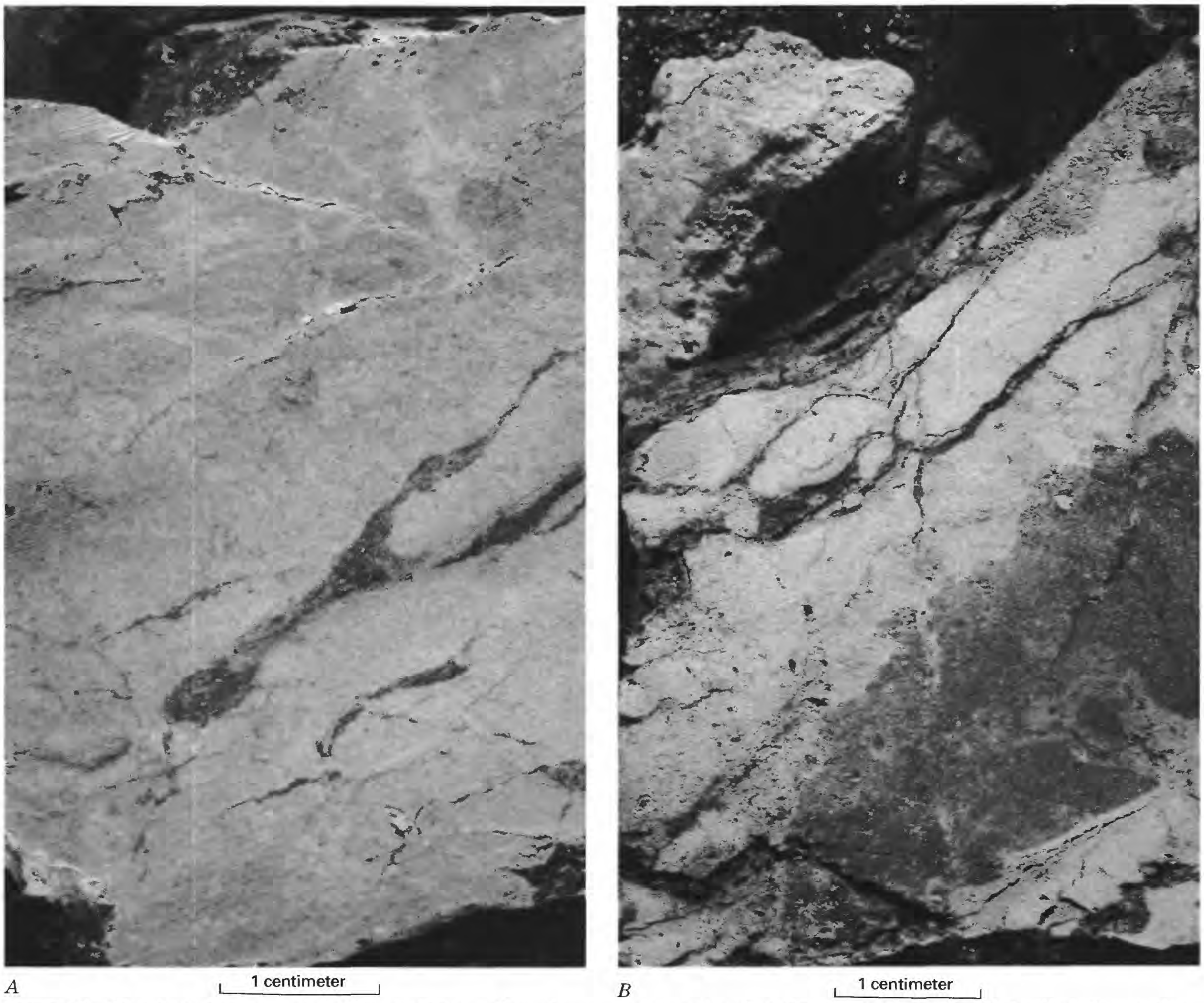


FIGURE 3.—Structure, texture, and bedding in Potomac Formation strata. *A*, *B*, Medium-olive-gray sandy and clayey silt in uppermost foot (alt. −463.1 and −462.8 ft) of lowest lithic unit in the Potomac core section. Irregular, branching cracks filled with dark-gray clay-silt were probably formed by pedogenic processes. Brown mottling (*B*, lower right) is common.

bedded, pebbly medium sand of the thin middle unit probably represents the fill of a small channel not part of, but associated with, the main channel system. The coarser, better sorted, cleaner, crossbedded sands of the uppermost fining-upward unit are suggestive of the fill of a larger fluvial channel. The large clasts of clay-silt in this unit probably resulted from undercutting of fine-grained bank materials. These interpretations are supported by the assemblage of nonmarine palynomorphs from the uppermost Potomac beds, described in the section on "Flora." Cysts of freshwater algae, which are part of the palynomorph assemblage, indicate a fresh, aquatic environment of deposition for the clay-silt constituting the clasts.

AGE AND CORRELATION

The diverse assemblage of palynomorphs obtained from the upper fining-upward sequence is indicative of an Albian age (Nichols, written commun., 1985). The assemblage is most comparable to the *Coronatispora valdensis-Trilobosporites humilis* assemblage zone of Bebout (1981). The assemblage is equivalent to pollen zone II of Doyle and Robbins (1977), but because their zonation is based on angiosperm pollen, which is exceedingly rare in the sample, direct comparison with their subzones of pollen zone II (II–A, II–B, II–C) is not possible.

The Potomac beds in the Haynesville core are equivalent, at least in part, to the "upper" Potomac Group beds

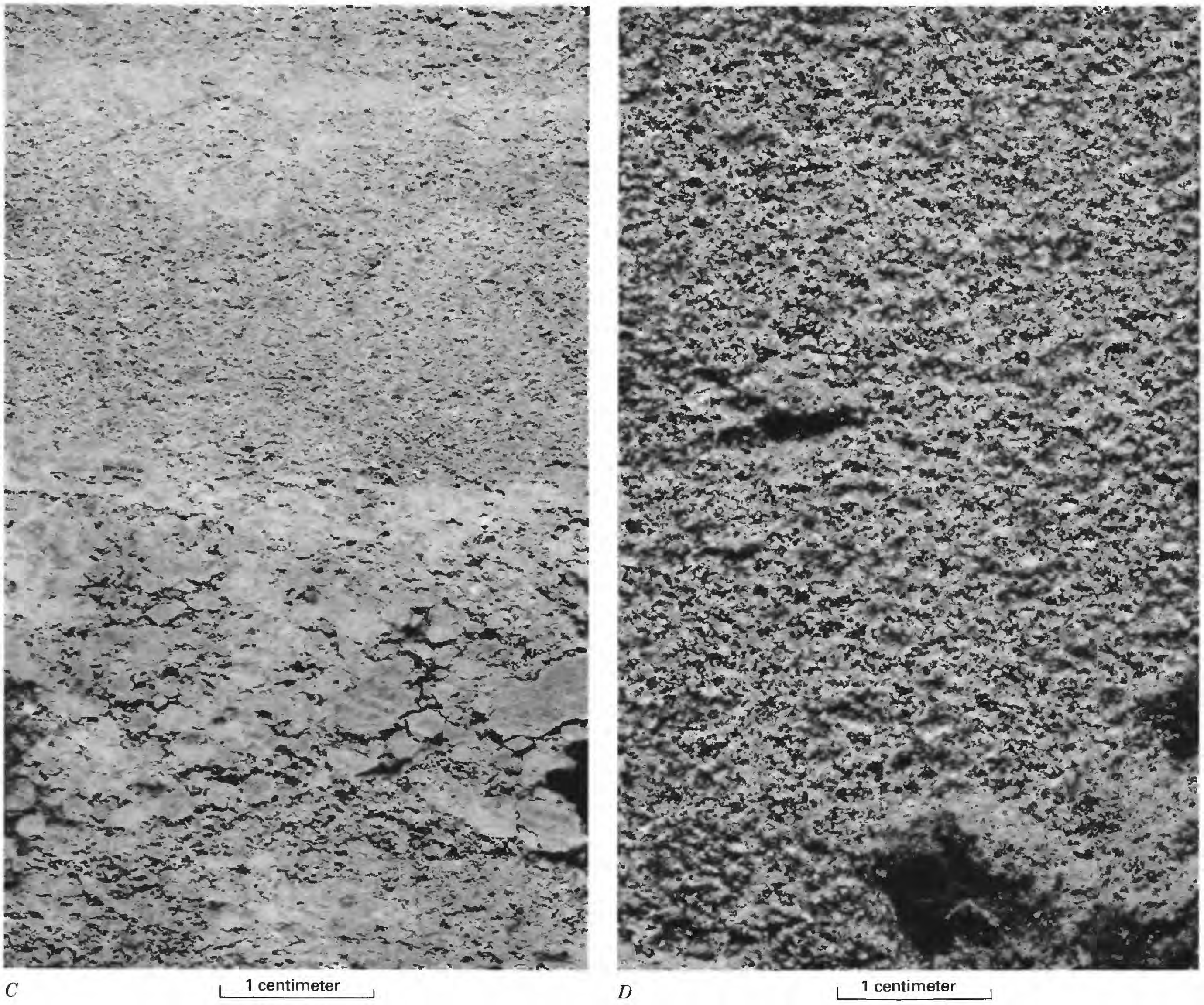


FIGURE 3.—*C*, Thin bed in middle part of core section (alt. −462.2 ft) consists, at base, of subangular to subrounded clasts of olive-gray, light-brown, and yellowish-brown clay-silt; unit grades upward to silty fine sand. *D*, Loose, fine to medium, micaceous, feldspathic quartz sand typical of upper part of Potomac section (alt. −454.3 ft). Scattered dark-gray clay clasts contain abundant nonmarine palynomorphs of Early Cretaceous age.

in the Oak Grove core (Reinhardt, Christopher, and Owens, 1980) in Westmoreland County, Va., and to the Patapsco Formation of Maryland. The term "Potomac Group" is no longer used in Virginia because there the Lower Cretaceous beds are not readily divisible into formational units (Seiders and Mixon, 1981; Meng and Harsh, 1984; Drake and Froelich, 1986).

AQUIA FORMATION

In the Haynesville core, the lower 118.4 ft (36 m) of the Pamunkey Group is the upper Paleocene Aquia Formation, a very poorly sorted to well-sorted, variably shelly, glauconitic quartz sand containing some limestone and carbonate-cemented arenites in its lower part (see figs. 4, 5). Here, as at many localities in the Virginia Coastal Plain, the Aquia can be subdivided into two lithic units (Ward, 1985), the more poorly sorted, clayier, siltier, and more calcareous Piscataway Member (below) and the better sorted, much less calcareous Paspotansa Member (above).

PISCATAWAY MEMBER

DEFINITION AND EXTENT

The Piscataway Member of the Aquia Formation was named for exposures of greensand along Piscataway

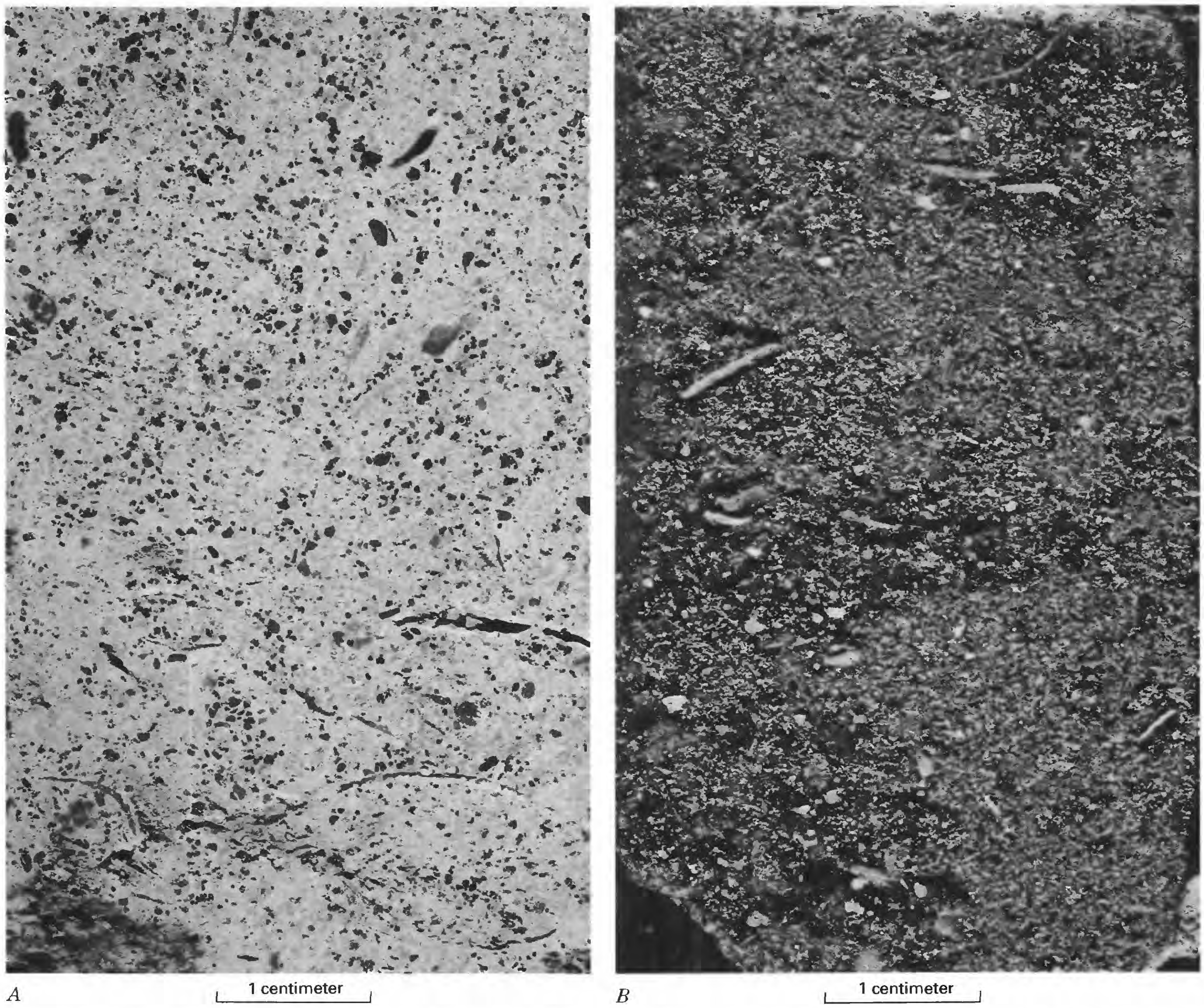


FIGURE 4.—Glauconitic quartz sands in middle and lower parts of the Piscataway Member of the Aquia Formation. *A*, Carbonate-cemented, glauconitic quartz sand containing abundant shell fragments and large foraminifers (alt. −424.7 ft). Matrix is micrite and sparry calcite. Glauconite is about 50 percent fresh glauconite and about 50 percent glauconite partly or completely altered to iron oxide. Large, rounded, brown grains are goethite. *B*, Very poorly sorted, muddy, fine sand (alt. −430.8 ft) containing abundant medium to very coarse grains of quartz and glauconite and worn shell fragments (*Gryphaeostrea*? sp.). Some coarse to very coarse quartz grains are iron stained.

Creek, Prince Georges County, Md. (Clark and Martin, 1901, p. 60–62). More recently, fossiliferous Aquia greensand exposed in bluffs on the west side of the Potomac River estuary about 1.5 mi (2.4 km) south of the mouth of Aquia Creek in Stafford County, Va., has been designated the principal reference section for the Aquia Formation and the Piscataway and Paspotansa Members (Ward, 1985, loc. 3). Ward (1985, p. 9) has revised the boundary between the two members downward to coincide with a significant lithic change from a poorly sorted, clayey sand below ("zones" 2–5 of Clark and Martin, 1901) to a well-sorted, micaceous, fine, silty sand above ("zones" 6–9 of Clark and Martin). Clark and Martin's "zone" 1 of the Aquia has been redefined as the Brightseat Formation (Bennett and Collins, 1952).

Numerous outcrops of the Piscataway occur in the inner Coastal Plain from Anne Arundel County, Md., south-southwestward to Chesterfield County near Petersburg, Va. (Ward, 1985). The Piscataway extends southeastward in the subsurface to the Chesapeake Bay area and the northern and central Delmarva Peninsula, where it is generally included in the Aquia Formation, undifferentiated, or in the Aquia's stratigraphic equivalent, the Vincentown Formation (Cushing and others,

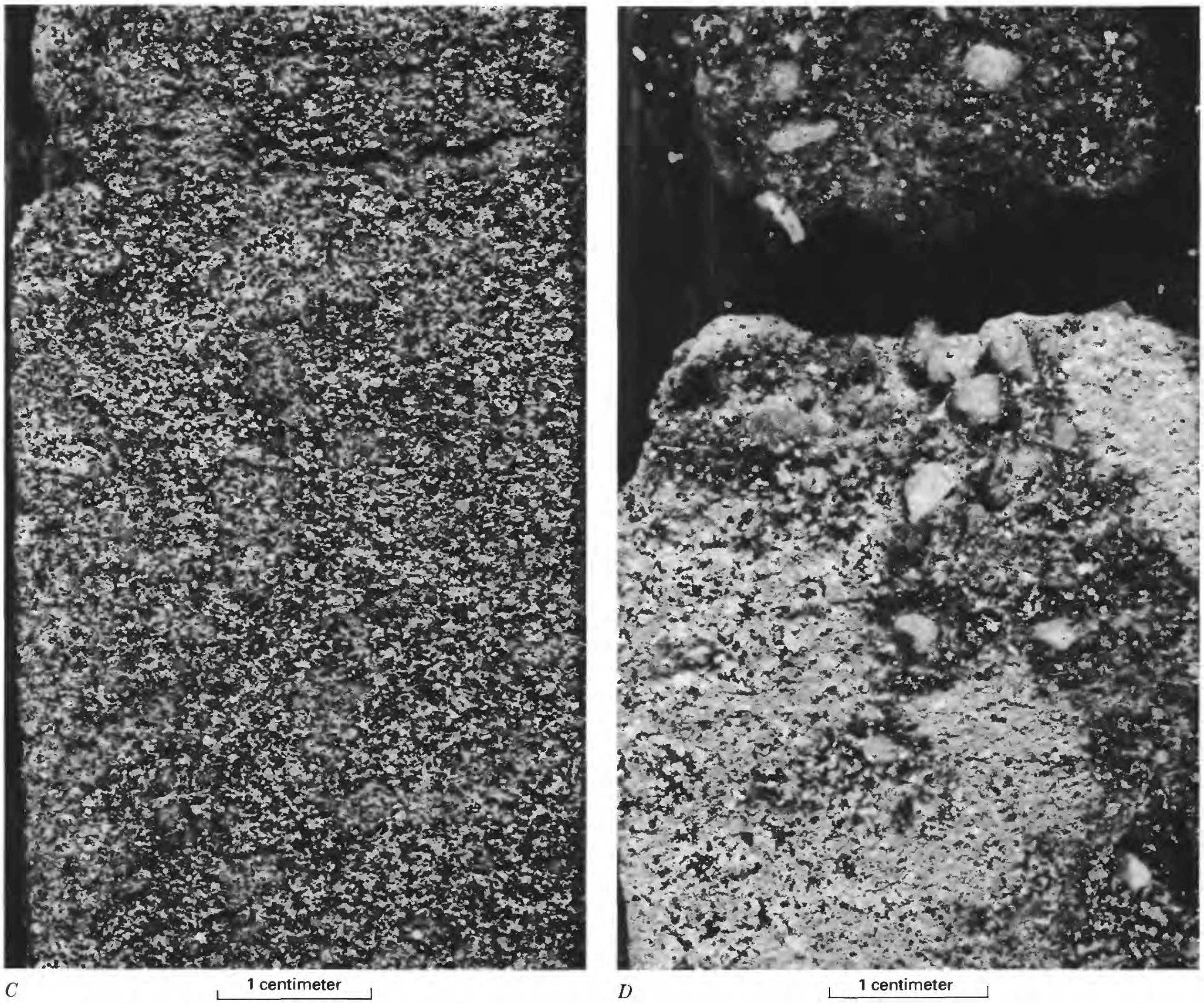


FIGURE 4.—*C*, Poorly sorted, weakly consolidated, fine to medium "salt and pepper" sand (alt. −436.3 ft) consists of dark-green to black, polylobate glauconite and subangular to subrounded quartz grains in light-olive-gray, calcareous mud matrix. *D*, Unconformable contact between fine to medium, shelly, glauconitic quartz sand of upper Paleocene Aquia Formation (above) and very light olive gray, micaceous quartz sand of the Lower Cretaceous Potomac Formation (below). Lower few inches of Aquia contain quartz and phosphate pebbles to a maximum of 0.5 in and scattered chalky shell fragments (alt. −449.7 ft).

1973; Minard, 1974; Trapp and others, 1984). The Haynesville site is about 55 mi (88 km) south-southeast of the Piscataway Creek locality and 45 mi (72 km) southeast of the reference section on the Potomac River near Aquia Creek, allowing us to study lithic and faunal changes in the Piscataway between the outcrop sections and the subsurface of the middle Coastal Plain.

LITHOLOGY AND CONTACT RELATIONS

In the core, the Piscataway Member (alt. −419 to −449.7 ft (−128 to −137 m)) is 30.7 ft (9 m) thick. As in outcrop sections, the abrupt contact between the dark, muddy, glauconitic shelf sand of the basal Piscataway and the directly underlying, much lighter colored and commonly partly oxidized fluvial-deltaic sand and clay of the Lower Cretaceous Potomac Formation is easily recognized and represents a major erosional unconformity (fig. 4*D*). The thin Brightseat Formation of early Paleocene age, which occurs below the Aquia Formation at many localities in Virginia and Maryland, is not present in the Haynesville core. In the core, the basal bed of the Piscataway (fig. 4*D*) contains shell fragments and pebbles of phosphate and quartz to 0.5 in (1.3 cm) in maximum dimension. Twelve feet (3.7 m) of core above

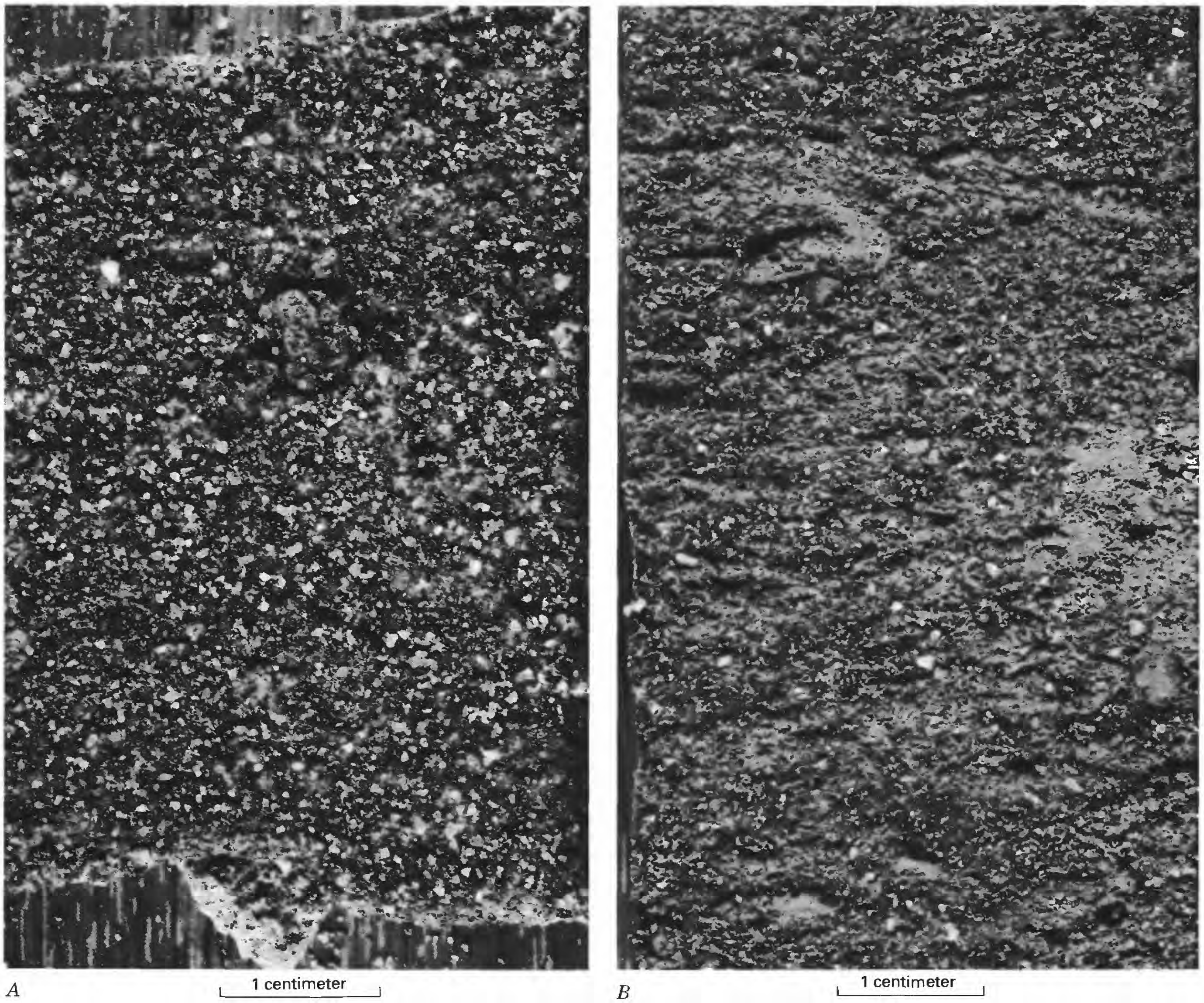


FIGURE 5.—Glauconitic quartz sand of uppermost Piscataway Member and Paspotansa Member of the Aquia Formation. *A*, Loose, poorly sorted to moderately well sorted, medium to coarse, very glauconitic quartz sand typical of most of the Paspotansa Member. Fresh, polylobate glauconite grains are black to grayish olive green. Smooth, well-rounded, elliptical, brown pellets of goethite are also present (alt. −403.4 ft). *B*, Very poorly sorted, olive-gray, glauconitic quartz sand containing scattered very fine pebbles (3–4 mm) of phosphate and quartz. Core sample is typical of lower 8 ft of Paspotansa Member (alt. −416.4 ft).

the basal bed of the Piscataway was not recovered, but, based on the gamma log curve (chap. A–pl. 1), it is presumed to be clayey, glauconitic sand. The middle and upper parts of the Piscataway, for which core recovery was excellent, consist mainly of poorly sorted, light- to dark-olive-gray, clayey and silty, glauconitic quartz sand that, in part, is weakly indurated by calcium carbonate (fig. 4*C*). Carbonate-cemented sand and thin, sandy limestone beds (figs. 4*A*, 5*D*) in the upper 10 ft (3 m) of the unit are white to pale greenish yellow (10 Y 8/2). These well-indurated, limy beds show as prominent spikes on the single-point resistivity log (chap. A–pl. 1). Current-generated bedding structures (fig. 6) are absent in the Piscataway except in the −425- to −430-ft (−130- to −131-m) interval where some small-scale crossbedding defined by imbricated shell fragments is evident.

The sand fraction is mostly fine to medium but contains a significant component of coarse to very coarse grains. The sand consists predominantly of subangular to subrounded quartz, polylobate glauconite, and minor amounts of feldspar and heavy minerals (see McCartan, chap. B, this vol.). The coarser, better sorted sandy beds in the uppermost part of the member contain some iron-stained quartz and medium to coarse goethite grains similar to those found in abundance in the overlying Paspotansa Member. Calcium carbonate, largely in the

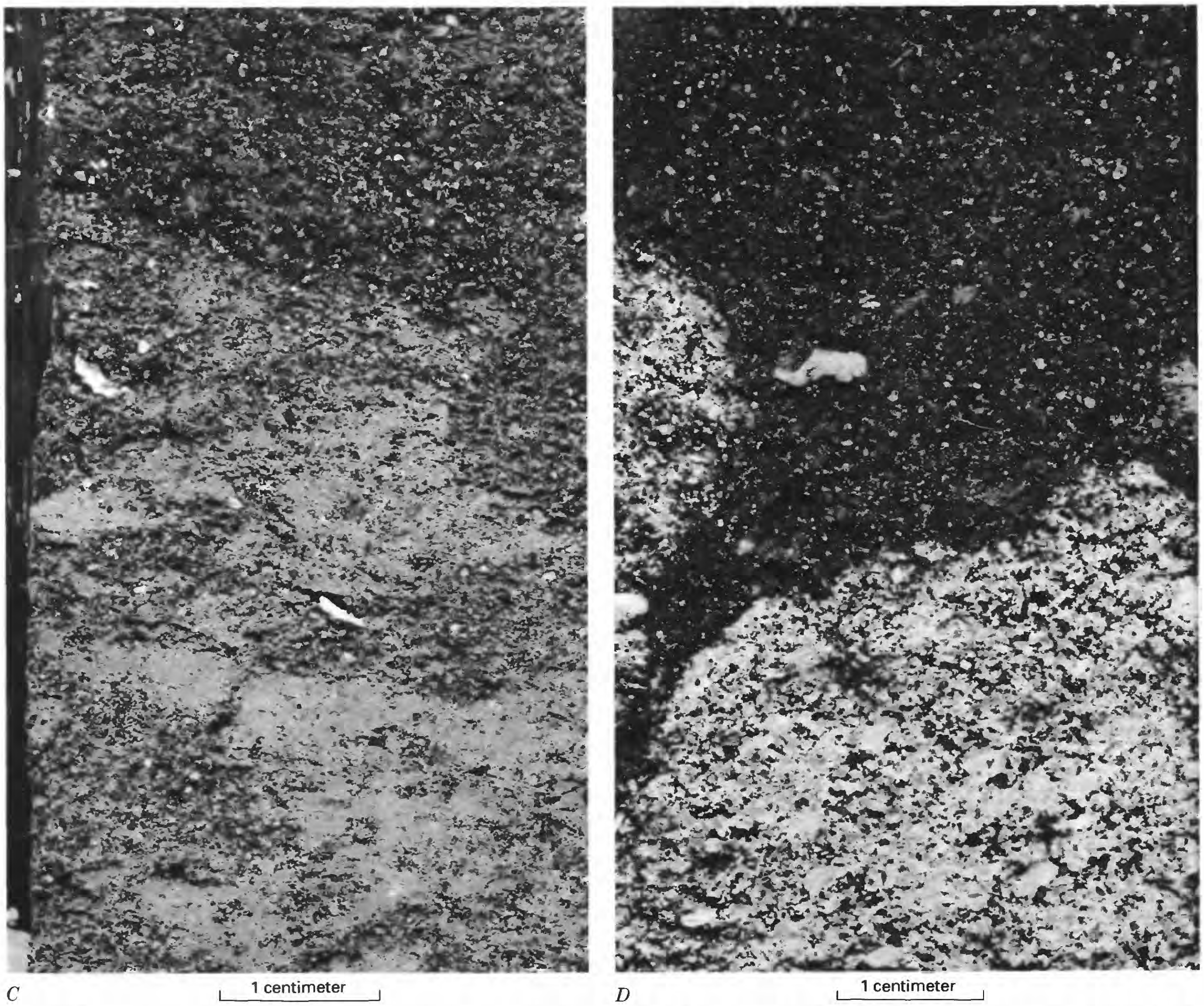


FIGURE 5.—*C*, Burrowed contact between very glauconitic basal sand of Paspotansa Member (above) and muddier, more calcareous sand of uppermost Piscataway Member (below) (alt. −419.2 ft). *D*, Dark-olive-gray, glauconitic quartz sand of Piscataway Member filling irregular surface of white to light-olive-gray, sandy, foraminiferal, micritic limestone. Iron-stained quartz grains and brown pelletoid iron oxides are common (alt. −421.5 ft).

form of shell fragments, foraminiferal tests, and micritic matrix, is common.

FAUNA AND FLORA

The Piscataway in the Haynesville core contains scattered, well-preserved bivalves, including *Ostrea alepidota*, *Gryphaeostrea* sp., and *Pecten* sp. However, the molluscan assemblage is much less diverse than at outcrop localities farther updip in King George, Stafford, Caroline, and Hanover Counties, Va. The Piscataway beds contain the richest planktonic foraminiferal assemblage encountered in the core (Poag, chap. D, this vol.). Dinocysts and fragments of bryozoans and echinoids are present in lesser amounts.

ENVIRONMENT OF DEPOSITION

Poor sorting, high clay-silt content, and the general absence of cross-stratification in the Piscataway suggest deposition in a low-energy environment. The relative abundance of limestone and calcareous sand in the Piscataway, compared with the overlying Paspotansa Member and Nanjemoy Formation, suggests a low rate of sedimentation. The Piscataway foraminiferal assemblage indicates that deposition of the middle part of the unit

FIGURE 6.—Current-generated bedding structures in upper part of the Piscataway Member of the Aquia Formation. Lower third of photo shows abrupt contact between finer (above) and coarser (below), shelly, glauconitic sand beds. Platy shell fragments in upper bed are aligned along poorly defined foresets dipping to left (alt. −425.5 to −426 ft).

took place in relatively deep water (100–150 m). Firm, sandy substrates provided favorable conditions for pectens and oysters and attachment surfaces for benthic foraminifers such as *Cibicides* and *Cibicidina* (Poag, chap. D, this vol.). During deposition of the upper part of the Piscataway, the water column was shallower (50–100 m), and the composition of the benthic foraminiferal assemblage suggests relatively high organic carbon and relatively low dissolved oxygen below the sediment-water interface.

AGE AND CORRELATION

The planktonic foraminiferal and dinoflagellate assemblages in the core indicate that the Piscataway Member is upper Paleocene (Thanetian) and belongs to foraminiferal zone P. 4 (see Poag, chap. D, and Edwards, chap. C, this vol.). The Piscataway appears to be equivalent to the upper part of the Beaufort Formation of North Carolina (Ward, 1985).

PASPOTANSA MEMBER

DEFINITION

The Paspotansa Member was named for outcrops in the vicinity of Paspotansa (now Passapatanzy) Creek, a tributary of the Potomac River in Stafford County, Va. (see Clark and Martin, 1901). In outcrops in the type area and elsewhere in the inner Coastal Plain of Virginia and Maryland, the Paspotansa consists of massive to very thick bedded, well-sorted, very fine to fine, glauconitic quartz sand (Clark and Miller, 1912; Gibson and others, 1980; Ward, 1984a, 1984b, 1985). Abundant, closely packed specimens of the large, high-spired gastropod *Turritella mortoni*, occurring in thin beds or lenses, are characteristic of the member throughout much of the inner Coastal Plain. In the Haynesville core, however, the Paspotansa Member is a much coarser grained, cleaner sand and contains no *Turritella mortoni.* This coarser facies of the Paspotansa appears to represent an extension from Maryland southward into Virginia of the "sandbank" facies of the upper Aquia Formation (see Hansen, 1974).

LITHOLOGY

In the core, the Paspotansa Member (alt. −331.3 to −419 ft (−101 to −128 m)) is 87.7 ft (27 m) thick. The member consists largely of moderately well sorted to well-sorted, thick-bedded to massive, medium to coarse, glauconitic quartz sand. Little or no clay and silt is present, so much of the sand is loose and very friable and extremely difficult to core. The mixture of light- and dark-colored grains, including both clear and iron-stained quartz, dark-green to black glauconite, and brown goethite pellets, gives the sediment a characteristic speckled appearance (fig. 5*A*). As in the Piscataway Member, the glauconite occurs mainly as polylobate grains. Goethite, in the form of smooth, lustrous, irregular to ellipsoidal brown pellets, is a much more common and more conspicuous component than it is in the upper Piscataway. Hansen (1974) indicates that differences in color, shape, size, and internal structure serve to differentiate the goethite pellets from the glauconite grains and suggests that the goethite may be authigenic rather than second-cycle glauconite altered to iron oxides. Very sparse, fragmentary shell material occurs in the middle part (altitude −381 to −385 ft (−116 to −117 m)) of the Paspotansa but is highly leached and is not identifiable.

Stratigraphy and Contact Relations

The lowermost part of the Paspotansa is medium-olive-gray to dark-olive-gray, very glauconitic quartz sand containing shark teeth and abundant, very fine pebbles of quartz (fig. 5*B*). The sharp, burrowed contact (fig. 5*C*) of this basal bed of the Paspotansa Member with the much clayier and more calcareous sands of the underlying Piscataway appears to be a minor unconformity representing a relatively brief period of nondeposition or erosion. Core recovery of the overlying, well-sorted, loosely packed sand of the main part of the Paspotansa was very poor (chap. A–pl. 1). However, the available core material and the electrical resistivity log for the borehole indicate that the Paspotansa includes two sequences of clean, well-sorted, medium to coarse sand. Each sequence is 30–40 ft (9–12 m) thick, and the base of each is marked by a sharp deflection to the right of the gamma-log curve. In the Maryland Coastal Plain, Aquia sand of similar sorting, coarseness, and mineralogy is believed to have been deposited in a shoaling, offshore sandbank complex as much as 20 mi (32 km) wide and 80 mi (129 km) long (Hansen, 1974, fig. 27). The Haynesville core hole is situated along the trend of this feature and serves to extend the "sandbank" facies into east-central Virginia. The uppermost coarse sand of the Paspotansa grades abruptly upward into about 8 in (20 cm) of light- to medium-gray clay that is rich in kaolinite (fig. 7). The gray kaolinitic clay unit is believed to be a truncated remnant of the Marlboro Clay, a thin but extensive upper Paleocene unit that conformably overlies the Aquia Formation in much of the inner Coastal Plain of Virginia and Maryland (Glaser, 1971). Burrows filled with dark-greenish-gray sand from the superjacent Nanjemoy Formation penetrate the thin Marlboro Clay to the top of (and probably into) the Paspotansa.

Fauna and Flora

The Paspotansa Member at the Haynesville site contains rare molluscan bivalves, but severe leaching has rendered them unidentifiable. *Turritella mortoni*, the dominant mollusk in the member in outcrop sections in inner Coastal Plain areas, is notably absent. The Paspotansa contains fairly abundant benthic and planktic foraminifers, but the assemblage is not as diverse as in the underlying Piscataway beds (Poag, chap. D, this vol.). The well-preserved but low-diversity dinocyst floras in the Paspotansa are typical of the upper Aquia elsewhere in Virginia (Edwards, chap. C, this vol.; Edwards and others, 1984).

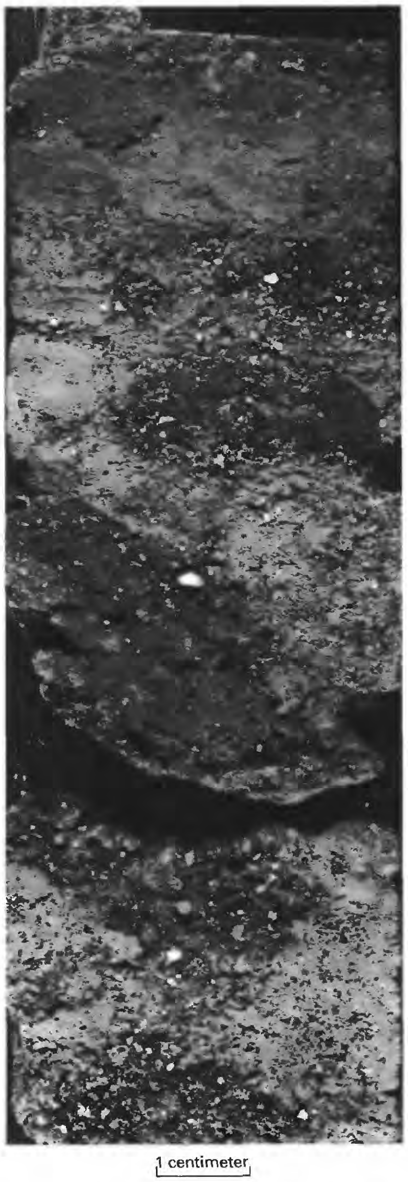


FIGURE 7.—Conformable contact between uppermost coarse sand of the Paspotansa Member of the Aquia Formation (lower 2 cm of photo) and thin, light-gray Marlboro Clay. The Marlboro Clay is penetrated by burrows filled with dark-greenish-gray sand from superjacent Nanjemoy Formation (alt. −331 to −331.3 ft).

Environment of Deposition

The good sorting of the medium to coarse sands of the Paspotansa and the very small amount of clay and silt suggest deposition in a high-energy environment, such as the offshore sandbank complex proposed by Hansen (1974). Extensive reworking and winnowing of sediment and removal of clay and silt created an environment unfavorable for many molluscan species and may account for the absence of the gastropod *Turritella mortoni* (see preceding section).

The benthic foraminiferal assemblages in both the lower and upper parts of the Paspotansa suggest inner sublittoral water depths of approximately 40 m and indicate a continuation of the shallowing trend noted in late Piscataway time (Poag, chap. D, this vol.). Dinoflagellate cyst assemblages in the upper part of the Aquia Formation, which show a decrease in species richness, also suggest shoaling-upward water depths (Edwards, chap. C, this vol.).

Age and Correlation

The planktonic foraminiferal assemblage in the core indicates assignment of the Paspotansa to foraminiferal zone P. 5 of the upper Paleocene (Thanetian). Gibson and others (1980), who studied the Oak Grove core in Westmoreland County, Va., placed the member in calcareous nannoplankton zone NP 9, which encompasses foraminiferal zone P. 5 and parts of zone P. 4 and P. 6. The Paspotansa is equivalent, in part, to the upper Vincentown Formation of New Jersey and the upper Beaufort Formation of North Carolina.

MARLBORO CLAY

DEFINITION AND EXTENT

The term "Marlboro clay" was first used by Clark and Martin (1901, p. 65) to refer to a thin (±20 ft (±6 m), but conspicuous unit of red and gray clay occurring above the Aquia Formation greensands and below similar greensands of the Nanjemoy Formation. The clay is typically exposed near the town of Upper Marlboro, eastern Prince Georges County, Md. (fig. 1). Early workers considered the Marlboro to be the basal member of the Nanjemoy Formation (Clark and Miller, 1912; Darton, 1947, 1951). Subsequently, Glaser (1971) described and mapped the Marlboro Clay over a wide area in southern Maryland and elevated the unit to formational rank (see also Gibson and others, 1980; Reinhardt, Newell, and Mixon, 1980; Ward, 1985). The Marlboro is now known to occur throughout much of the Coastal Plain of Virginia and Maryland west of the Chesapeake Bay (Cederstrom, 1957; Sinnott, 1969; Brown and others, 1972). The Marlboro in the Haynesville core section is the southeasternmost known occurrence of the unit on the Northern Neck of Virginia.

LITHOLOGY AND CONTACT RELATIONS

In the core, the uppermost coarse sand of the Paspotansa Member of the Aquia Formation grades abruptly upward into an 8-in-thick (20-cm-thick), light-gray to pinkish-gray, kaolinitic clay that is probably a remnant of a thicker Marlboro Clay section originally present at this locality. In comparison, a relatively thick (18 ft (5.5 m)) Marlboro Clay section in the Oak Grove core in Westmoreland County, Va., about 25 mi (40 km) northwest of Haynesville, consists of massively bedded to laminated, red and gray clay interbedded with lesser amounts of laminated and ripple cross-laminated silt (Reinhardt, Newell, and Mixon, 1980, figs. 5, 6).

As seen in outcrops in the inner Coastal Plain, the Haynesville core, and numerous other cores in Virginia (Mixon, unpub. data; Powars, 1986; Reinhardt, Newell, and Mixon, 1980), the contact with the underlying Aquia Formation is conformable, ranging from abrupt gradation to interbedding of lithologies in a narrow zone. At all these localities, the burrowed, uneven contact between the Marlboro and the overlying Nanjemoy Formation is clearly an erosional unconformity.

FLORA AND FAUNA

At other localities, the Marlboro Clay is characterized by low-diversity assemblages of dinocysts, agglutinated foraminifera, and freshwater algae (Nogan, 1964; Gibson and others, 1980; Edwards and others, 1984) that indicate a brackish-water environment of deposition. Locally, as on the James River east of Hopewell, Va., the Marlboro contains a few molds of small, indeterminate gastropods (Ward, 1985).

ENVIRONMENT OF DEPOSITION

The fossil assemblages, the laminated to very thin bedded, ripple-marked character of part of the Marlboro, the oxidized pale-red to reddish-brown clays rich in kaolinite, and the size and configuration of the Marlboro basin suggest deposition in very restricted, shallow, shelf waters or, possibly, in a barred embayment similar to the present-day Pamlico Sound (see also Powars, 1986). The apparent absence of well-developed flaser and lenticular bedding and mud cracks does not support deposition of the Marlboro in intertidal and supratidal mud flats. However, the planar laminations and ripple cross-laminated silt and clay (Reinhardt, Newell, and Mixon, 1980, fig. 6) indicate some current activity, perhaps in the subtidal zone. The sheetlike geometry of the Marlboro and its great extent argue against deposition in an estuary.

In this paper, the Marlboro is considered to be part of the upper Aquia depositional sequence. We suggest that the Marlboro was deposited as regressive, peridelta muds in restricted shelf waters probably separated, in part, from the open ocean by a broad, largely submarine bar complex. The complex may have developed as an extension of the relatively clean, coarse sands making up the "sandbank facies" of the upper Aquia Formation in Maryland and Virginia (see Hansen, 1974, and section describing Paspotansa Member).

AGE AND CORRELATION

At other localities, sporomorph data from the lower part of the Marlboro indicate a late Paleocene age (Frederiksen, 1979; Gibson and others, 1980). The upper Marlboro "is either uppermost Paleocene, perhaps representing slightly younger rocks than those previously studied in the southeastern United States, or else lowermost Eocene" (Gibson and others, 1980). Because of the thinness of the Marlboro Clay and its close relationship to the Aquia Formation, we believe that all of the Marlboro Clay is probably Paleocene.

NANJEMOY FORMATION

The lower Eocene part of the Haynesville core (alt. −240 to −330.7 ft (−73 to −101 m)) is the Nanjemoy Formation, a poorly sorted, clayey and silty, fine to coarse greensand that takes its name from Nanjemoy Creek in Charles County, Md. In inner Coastal Plain areas of both Maryland and Virginia, the Nanjemoy unconformably overlies the Marlboro Clay or the Aquia Formation and, in turn, is overlain with great unconformity by the lower and middle Miocene Calvert Formation. However, in the more complete sections of the middle Coastal Plain of Virginia and of St. Marys and Calvert Counties, Md., glauconitic sands of the middle Eocene Piney Point Formation and the upper Oligocene Old Church Formation are present between the Nanjemoy and the Calvert. In the Haynesville core, the Nanjemoy Formation differs from both the Aquia and the Piney Point Formations in that it is less calcareous and contains considerably more clay and silt as matrix. The sharply contrasting clayey and silty sand lithology of the Nanjemoy and its well-defined contacts with the underlying Aquia-Marlboro Clay sequence and the overlying Piney Point Formation are clearly shown by the electrical resistivity and gamma logs of the core hole (see chap. A–pl. 1).

As in outcrops in the inner Virginia Coastal Plain, the Nanjemoy Formation of the Haynesville core can be subdivided into a lower, very clayey and very glauconitic quartz sand (the Potapaco Member) and an upper, less clayey, very micaceous, glauconitic quartz sand containing scattered very fine to fine pebbles of quartz (the Woodstock Member). The lithology, paleontology, and general distribution of the Nanjemoy Formation and the Potapaco and Woodstock Members in Virginia and Maryland have been discussed by various workers (Clark and Martin, 1901; Clark and Miller, 1912; Darton, 1947, 1951; Glaser, 1971; Gibson and others, 1980; Reinhardt, Newell and Mixon, 1980; Ward and Krafft, 1984; Ward, 1985).

POTAPACO MEMBER

Definition

As originally defined in the upper Potomac River estuary area, the Potapaco Member included up to 65 ft (20 m) of shelly and clayey glauconitic sand and sandy silt (Clark and Martin, 1901). At the base of the Potapaco, a thin, red to gray, compact clay unit, termed the "Marlboro clay," separated the main part of the Potapaco from the Aquia Formation and served as an important and easily identified regional mapping horizon. Darton (1951) considered the Marlboro Clay to be the lower member of the Nanjemoy Formation; later, the unit was raised to formational rank by Glaser (1971). This usage modified the original definition of the Nanjemoy Formation and the Potapaco Member and required redefinition of those units by Ward (1985). Exposures along the Maryland side of the Potomac River, about 2.5 mi (4 km) upstream from Popes Creek in Charles County, Md., have been designated the principal reference section (lectostratotype) of both the Potapaco Member and the Nanjemoy Formation (Ward, 1985).

The Potapaco Member in the Haynesville core (alt. −279.8 to −330.7 ft (−85 to −101 m)) is the lower 50.9-ft-thick (16-m-thick) part of the Nanjemoy Formation (see chap A–pl. 1). The unconformable contact relations of the Potapaco with the Aquia-Marlboro Clay sequence have been described in the sections discussing the Paspotansa Member of the Aquia Formation and the Marlboro Clay. In the core, the top of the Potapaco is difficult to define and is arbitrarily placed at the top of a conspicuous, 4-ft-thick (1.2-m-thick) bed of medium-olive-gray clay (chap. A–pl. 1, alt. −279.8 ft). This clay bed is overlain by a medium to coarse, friable, glauconitic sand section typical of the Woodstock Member of the upper Nanjemoy; the contact between the clayey and sandy beds is marked by deep sand-filled burrows into the clay, suggesting a period of nondeposition. However, thin beds of medium to very coarse, dark-olive-gray, glauconitic quartz sand typical of the lower Woodstock also occur as much as 10 ft (3 m), or more, below the top of the 4-ft-thick (1.2-m-thick) clay bed. Thus, depending on placement of the contact at the top of the clay bed or at the base of the thin, coarse sand beds, the Potapaco-Woodstock boundary may be interpreted as a minor unconformity (diastem) or as a conformable contact with interfingering of Potapaco and Woodstock lithologies in a 10-ft (3-m) interval.

Lithology

In the core, the Potapaco is very poorly sorted, clayey and silty, glauconitic sand and sandy clay-silt that are sufficiently cohesive to enable complete core recovery from the unit. Here, the Potapaco section is thinner (50.9 ft versus 65 ft in the Oak Grove core, Westmoreland County, Va.) than in many updip areas and contains only very rare, fragmentary shell material. As is common elsewhere in the Virginia Coastal Plain, the Potapaco in the Haynesville core consists of four fining-upward sequences, herein designated units A–D. The relation of units A–D in the core to Beds A–D of Ward (1984b, 1985) as defined in the Potapaco outcrop belt in inner Coastal Plain areas needs more study. However, lithic similarity, stratigraphic position, and the dinocyst assemblage (see Edwards, chap. C, this vol.) of unit A in the core indicates equivalency to Ward's Bed A of the Potapaco. Similarly, our lithic units B and C appear to be equivalent to Ward's Bed B, and our unit D is roughly equivalent to Ward's Bed C.

Unit A.—The lower 4.8 ft (1.5 m) of the Potapaco Member, unit A (see figs. 8, 9; chap. A–pl. 1), is composed of thin-bedded to very thin bedded, dark- to light-greenish-gray, very clayey sand and clay-silt that contrast markedly with the directly underlying, very thin remnant of Marlboro Clay and the clean, well-sorted sand of the Paspotansa Member of the Aquia Formation. The abrupt, burrowed contact between unit A and the Marlboro Clay, evident in the Haynesville core and elsewhere in Virginia and Maryland, is a regional unconformity. The basal foot (0.3 m) of unit A contains scattered fine quartz pebbles, sand-sized grains and small nodules of phosphate, and clasts of light-gray to yellowish-gray clay probably derived from the Marlboro Clay (fig. 8*A*). A few fragmentary bivalves are also present. The fine to coarse, sandy lower part of unit A grades upward to fine sand and clay-silt. Interbedded, thin, lenticular beds and laminae of clay-silt and sand are common in much of the unit and are characteristic of the lowermost Nanjemoy at other localities in Virginia. The upper part of unit A is extensively bioturbated with sand-filled and clay-filled burrows (figs. 8*B*, 9).

Units B and C.—Units B and C of the Potapaco Member in the core (=Bed B of Ward, 1985) are also fining-upward, clayey and silty glauconitic sand and sandy clay-silt sequences and are, respectively, about 7 ft (2.1 m) and 15 ft (4.6 m) thick. The lower half of unit B is mostly fine to medium glauconitic sand that becomes very clayey and silty upwards (figs. 10*A*, 10*B*). The upper part of the unit is medium-olive-gray, sandy clay-silt (fig. 10*C*). Here, burrows are commonly filled with olive-black glauconitic sand. The basal bed of unit C consists of very glauconitic, fine to coarse sand containing scattered, very coarse quartz grains. The main part of the unit (fig. 11*A*) is very poorly sorted, intensely bioturbated, fine to coarse, dark-olive-gray to olive-black sand that becomes coarser and more clayey and silty in the upper 4 ft (1.2 m) (fig. 11*B*). In general, units B and C are thick- to massively bedded, but they also contain some very thin, lenticular beds and laminae of silty clay. Shell material is extremely sparse or absent.

Unit D.—Unit D (=Bed C of Ward, 1985) is about 25 ft (8 m) thick and consists mainly of fine to very coarse, dark-greenish-gray to dark-olive-gray glauconitic sand (figs. 12*A*, 12*B*). The unit also contains scattered fine quartz pebbles as much as 0.25 in (0.6 cm) long and pieces of lignite as much as 1 in (2.5 cm) long. Near the top of unit D, the sandy section grades upward into a 4-ft-thick (1.2-m-thick) bed of clay-silt (figs. 12*C*, 13*A*). Abundant laminae and thin, lenticular beds of clay-silt, disrupted by biogenic activity, are present in the lower 6 ft (1.8 m). Clay-filled burrows and clay-lined, sand-filled burrows are the most conspicuous structures in the middle and upper parts of the unit.

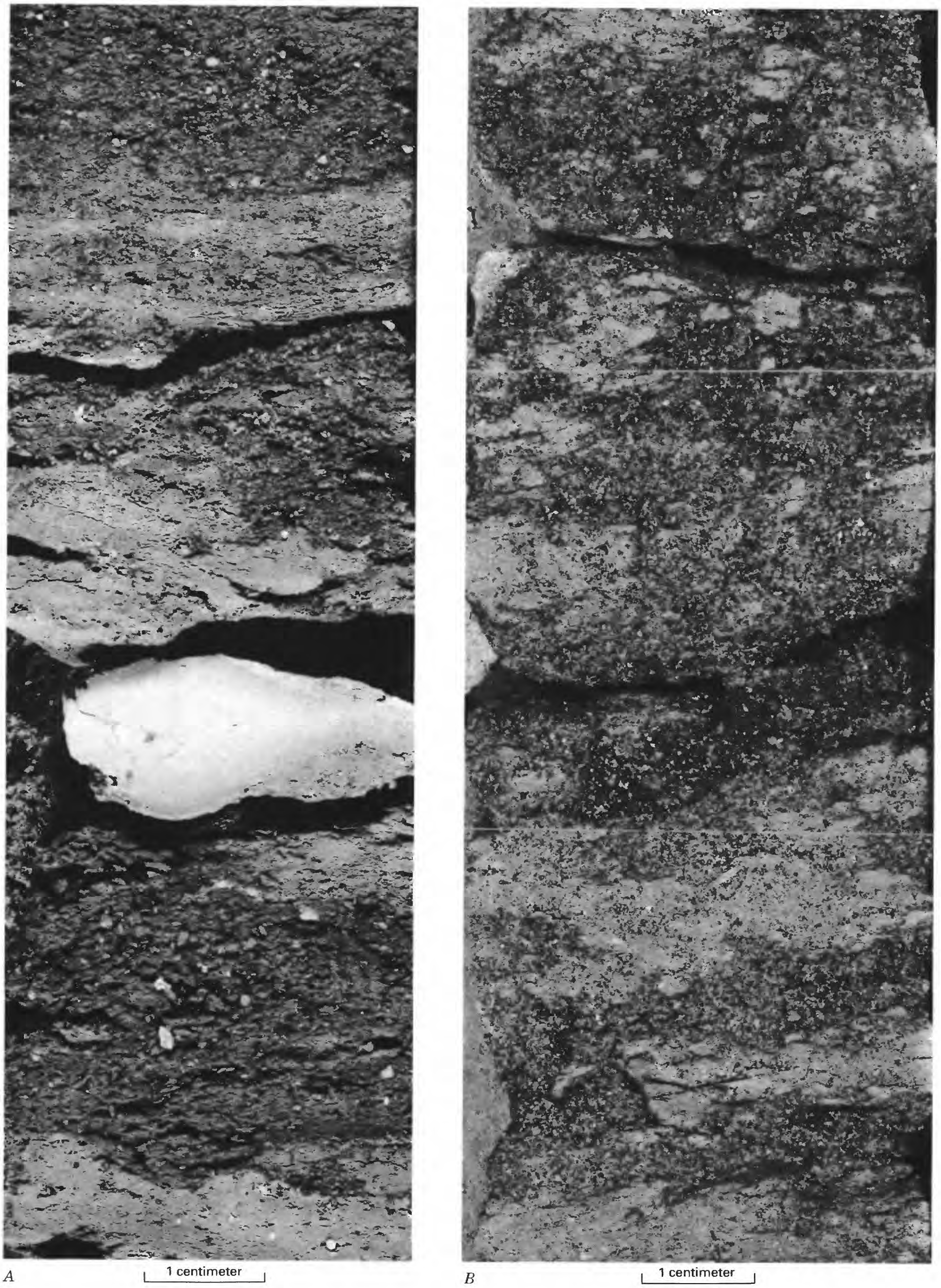
Fauna and Flora

The Potapaco beds of the Haynesville core contain extremely sparse molluscan shell material. The abundant molluscan molds and casts and the conspicuous beds packed with shells of the bivalve *Venericardia potapacoensis*, which are so characteristic of Bed B of the Potapaco Member in the classic outcrop sections along the Potomac, Rappahannock, and Pamunkey Rivers (Ward and Krafft, 1984; Ward, 1985), are notably absent in the core. The core contains fairly abundant dinocysts and benthic and planktic foraminifers (see Edwards, chap. C, and Poag, chap. D, this vol.).

Environment of Deposition

In the basal few feet of the Potapaco Member, thin to very thin beds of sand and clay-silt and scattered fine pebbles and shell fragments suggest moderate current

FIGURE 8.—Bedding, textures, and sand-filled burrows in unit A of the Potapaco Member of the Nanjemoy Formation. *A*, Thin-bedded, basal part of unit A showing fine to very coarse, glauconitic and phosphatic sand interbedded with finer sand and clay-silt. Light-gray, kaolinitic clay at very bottom of photo is top of Marlboro Clay. Oblong fragment of pale-gray clay 3 cm above contact is eroded clast of Marlboro Clay (alt. −330.3 to −330.7 ft). *B*, Sandy clay-silt of upper unit A containing abundant sand-filled burrows and, in upper right of photo, a small, vertical, clay-filled burrow (alt. −326.7 to −327.3 ft). ▶


A
1 centimeter
B
1 centimeter

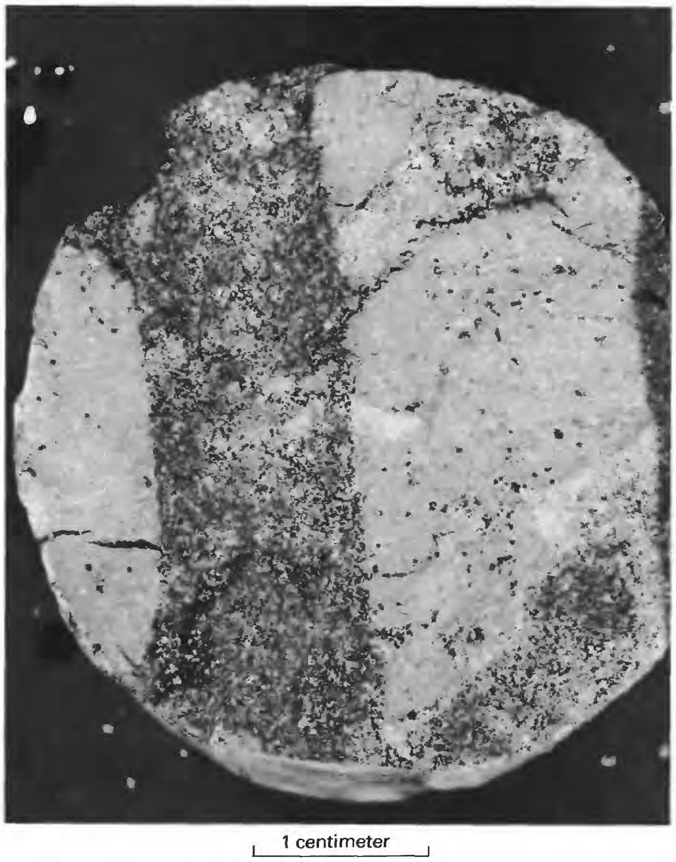


FIGURE 9.—Bedding-plane view of horizontal, branching, sand-filled (quartz and glauconite) burrow in clay-silt bed in upper 2 ft of unit A of the Potapaco Member of the Nanjemoy Formation (alt. −328 ft).

activity and relatively shallow water. The very poor sorting, thick to massive bedding, and intense burrowing typical of the overlying, main part of the Potapaco suggest deposition in a deeper water, low-energy environment. Gradually deepening shelf waters at the Haynesville site, from about 40–60 m during early Potapaco time to 100–150 m during middle Potapaco time, are also suggested by a change from dominantly benthic foraminiferal assemblages in units A and B to a dominantly planktonic assemblage in upper unit C (Poag, chap. D, this vol.). The deepening trend was reversed during deposition of unit D, in which benthic assemblages, characterized by *Cibicidoides* and *Bolivina*, regain dominance. Shallowing-upward water depths, as suggested by the foraminifer assemblages in unit D, range from 60–100 m near the base of the unit to 20–40 m near the top of unit D. The presence of coarser detrital materials in unit D compared with units B and C, the abundance of lignite, and the shallowing-upward water depths are thought to indicate proximity to a delta.

AGE AND CORRELATION

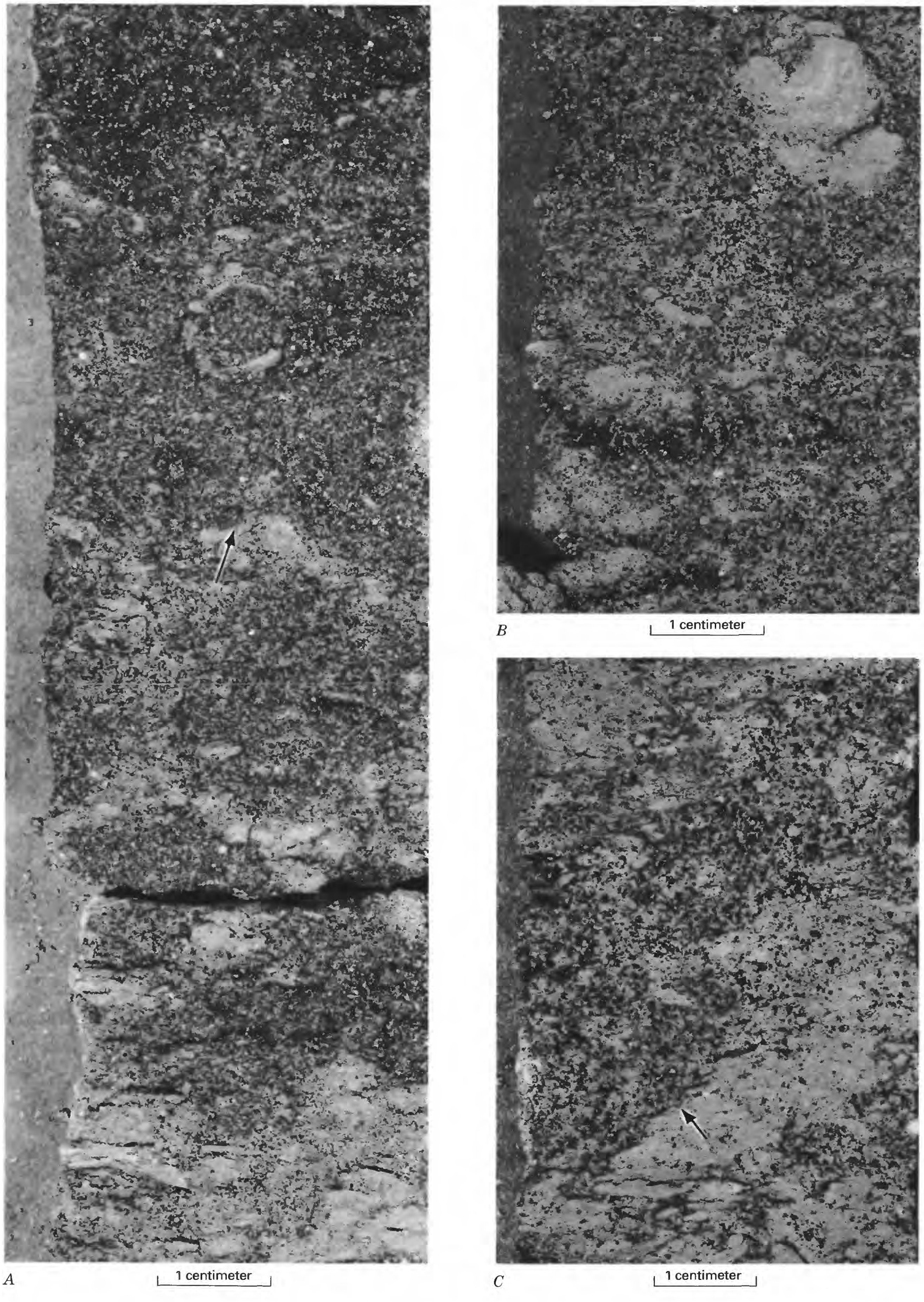
Planktonic foraminiferal assemblages in units A, B, and C of the Potapaco Member in the core suggest assignment to foraminiferal zone P. 6b of the early Eocene (Poag, chap. D, this vol.). The dinocyst assemblage suggests an equivalent Eocene age assignable to nannofossil zone NP 10 (Edwards, chap. C, this vol.). Unit D of the upper Potapaco Member is assigned to foraminiferal zone P. 9.

WOODSTOCK MEMBER

DEFINITION

The Woodstock Member of the upper Nanjemoy was named by Clark and Martin (1901) for exposures in the Potomac River bluffs near the old Woodstock plantation, about 1 mi (1.6 km) upstream from Mathias Point, King George County, Va. The outcrops at this locality have recently been designated the lectostratotype section for the Woodstock Member (Ward, 1985). Clark and Martin (1901, p. 66) describe the Woodstock in the Potomac River area as "fine, homogeneous greensands and greensand marls that are less argillaceous than the underlying Potapaco beds. The member has a thickness of 50 to 60 feet." In the Potomac River bluffs and at other localities in the inner Coastal Plain, the Woodstock is overlain with great unconformity by the lower and middle Miocene Calvert Formation. Middle and upper Eocene, Oligocene, and lowermost Miocene deposits are missing. Downdip in the subsurface and in outcrops on the Pamunkey and James Rivers (Ward, 1985), the Woodstock is overlain by the middle Eocene Piney Point Formation. The contact between the Woodstock and the Piney Point is an unconformity representing a hiatus estimated to be between 7.3 m.y. (Hazel and others, 1984) and about 6 m.y. (Poag, chap. D, this vol.). In updip outcrop areas, the contact between the Woodstock and the underlying Potapaco Member of the Nanjemoy is believed to be a minor unconformity, representing a relatively brief hiatus (Ward, 1985). In the Haynesville core, however, the nature and placement of the boundary are uncertain (see discussion in section describing the Potapaco Member).

FIGURE 10.—Textures and biogenic structures of unit B and uppermost unit A of the Potapaco Member of the Nanjemoy Formation. *A*, Burrowed contact (arrow) between fine to medium glauconitic sand of basal unit B (above) and intensely burrowed, sandy clay-silt of uppermost unit A (below) (alt. −326.3 to −326.7 ft). Cross section of clay-lined, sand-filled burrow visible just above base of unit B. *B*, Cross section of clay-filled burrow with backfills (upper right) in clayey and silty glauconitic sand, middle part of unit B (alt. −324.5 ft). *C*, Sand-filled burrow (arrow) in sandy clay-silt, upper part of unit B. Black grains are glauconite; white and light-reflectant grains are mainly quartz and muscovite (alt. −321 ft). ▶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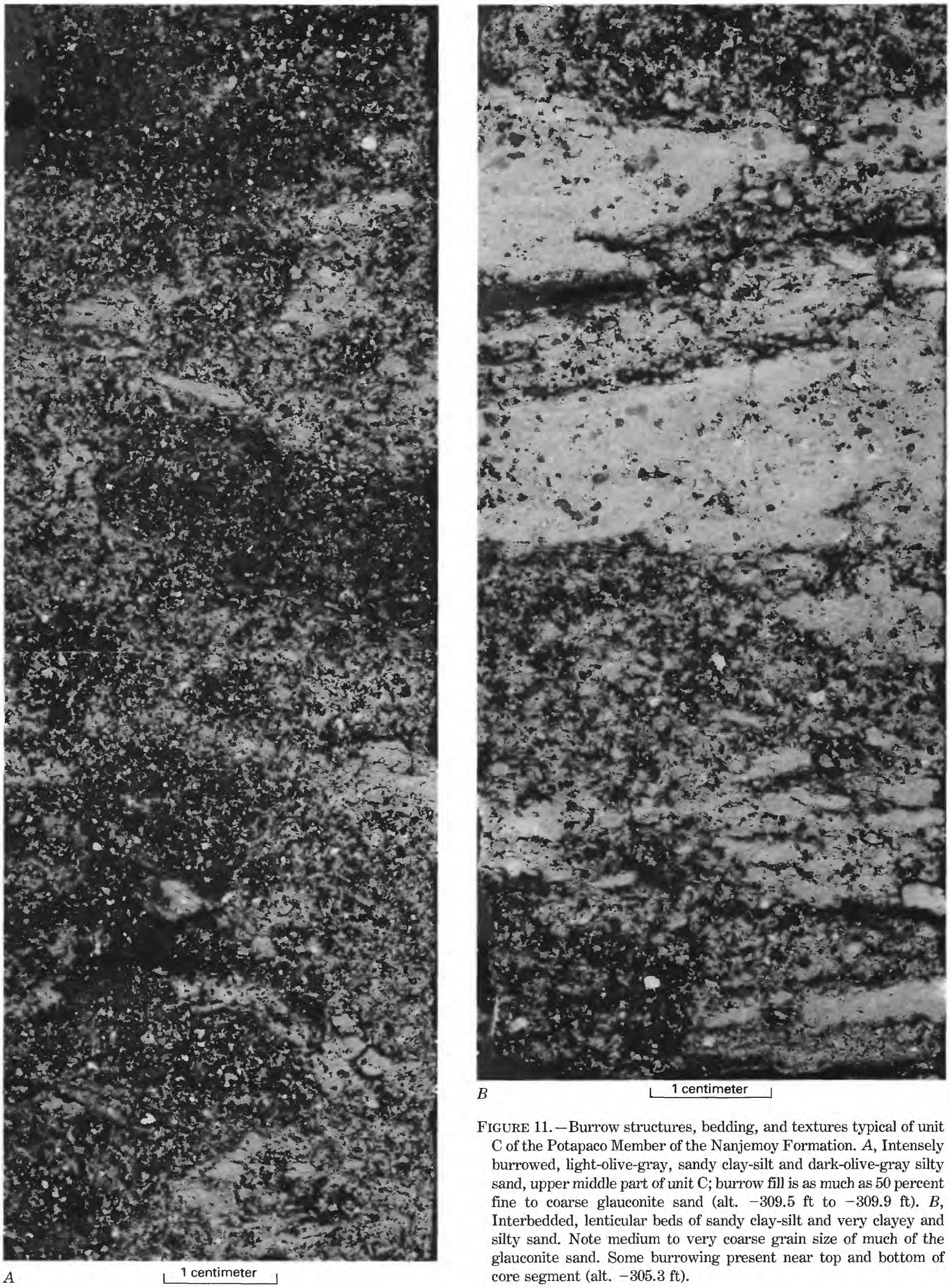


FIGURE 11.—Burrow structures, bedding, and textures typical of unit C of the Potapaco Member of the Nanjemoy Formation. *A*, Intensely burrowed, light-olive-gray, sandy clay-silt and dark-olive-gray silty sand, upper middle part of unit C; burrow fill is as much as 50 percent fine to coarse glauconite sand (alt. −309.5 ft to −309.9 ft). *B*, Interbedded, lenticular beds of sandy clay-silt and very clayey and silty sand. Note medium to very coarse grain size of much of the glauconite sand. Some burrowing present near top and bottom of core segment (alt. −305.3 ft).

Lithology

The upper 40 ft (12 m) of the Nanjemoy Formation in the Haynesville core (alt. −240 to −279.8 ft (−73 to −85 m)) is assigned to the Woodstock Member. In the core, the Woodstock (figs. 13*B*, 13*C*) is mainly dark-olive-gray, fine to coarse, sparsely shelly, glauconitic quartz sand that is coarser, less glauconitic, and more micaceous than the underlying Potapaco. In general, the Woodstock sands contain less clay and silt matrix than the sands of the Potapaco. Therefore, the Woodstock tends to be more friable than the Potapaco and easily washes out of the core barrel. Only about 50-percent core recovery was obtained.

At the base of the Woodstock (fig. 13*B*), dark-olive-gray to dark-greenish-gray, fine to coarse, very glauconitic sand is deeply burrowed into the 4-ft-thick (1.2-m-thick) silty clay bed that marks the top of the Potapaco Member (see discussion of the Potapaco-Woodstock contact in section on definition of Potapaco Member). The lower 10 ft (3 m) of the Woodstock fines upward to very fine to medium sand and is interbedded with clayey, burrowed sand similar to that of the Potapaco. Some thin beds of sand in this interval are 80–90 percent glauconite. At an altitude of −270 ft (-82 m), the lower Woodstock grades upward into a 20-ft-thick (6.1-m-thick) section of less clayey and silty, more friable, slightly shelly sand containing small clay-filled burrows and scattered, well-rounded quartz pebbles as much as 0.5 in (1.3 cm) in maximum dimension (fig. 13*C*).

The uppermost 10–11 ft (3–3.4 m) of the Nanjemoy, here included in the Woodstock Member, consists of dark-olive-gray, micaceous, glauconitic sand interbedded with thin to medium beds of yellowish-gray, carbonate-cemented sand. Although core recovery of this interval was very poor, the cemented beds are well delineated by the electrical resistivity log. Similar indurated beds are not known to occur in the Woodstock Member in updip Coastal Plain areas or in the Oak Grove core in Westmoreland County, Va. (Reinhardt, Newell, and Mixon, 1980; Ward, 1985).

Fauna and Flora

A fairly abundant, diverse, molluscan fauna has been reported in Woodstock outcrops along the Potomac and Pamunkey Rivers in the inner Coastal Plain (Clark and Martin, 1901; Ward, 1985). The bivalve *Venericardia ascia* Rogers and Rodgers, 1839, is characteristic and locally abundant and is easily distinguished from the much smaller *Venericardia potapacoensis* found in the underlying Potapaco Member (Ward, 1985). In the Haynesville core, however, only a few small, very poorly preserved mollusks were observed in the Woodstock—mainly in the middle part of the section. The Woodstock beds contain abundant benthic foraminifers and a sparse planktonic assemblage. Rich, well-preserved dinocyst floras are also present.

Environment of Deposition

In areas of outcrop in the inner Coastal Plain, the larger, diverse molluscan fauna in the Woodstock, compared with the nondiverse Potapaco assemblages, suggest a return to more open-marine, shallow-shelf conditions (Ward, 1985). At the Haynesville site, the sparse molluscan fauna provides few data for paleoenvironmental interpretation. The foraminiferal assemblages, however, indicate an inner sublittoral paleoenvironment with water depths of about 20–40 m during deposition of the lower and middle parts of the unit and 40–60 m during deposition of the upper part (Poag, chap. D, this vol.). The abundance of *Turrilina* and *Fursenkoina*, which are among the predominant benthic genera in the middle part of the unit, suggests waters containing lower than normal dissolved oxygen. The somewhat coarser, much more lignitic, pebbly sands of the Woodstock, the relatively shallow water depths, and the microfauna (Poag, chap D., this vol.) suggest a perideltaic environment.

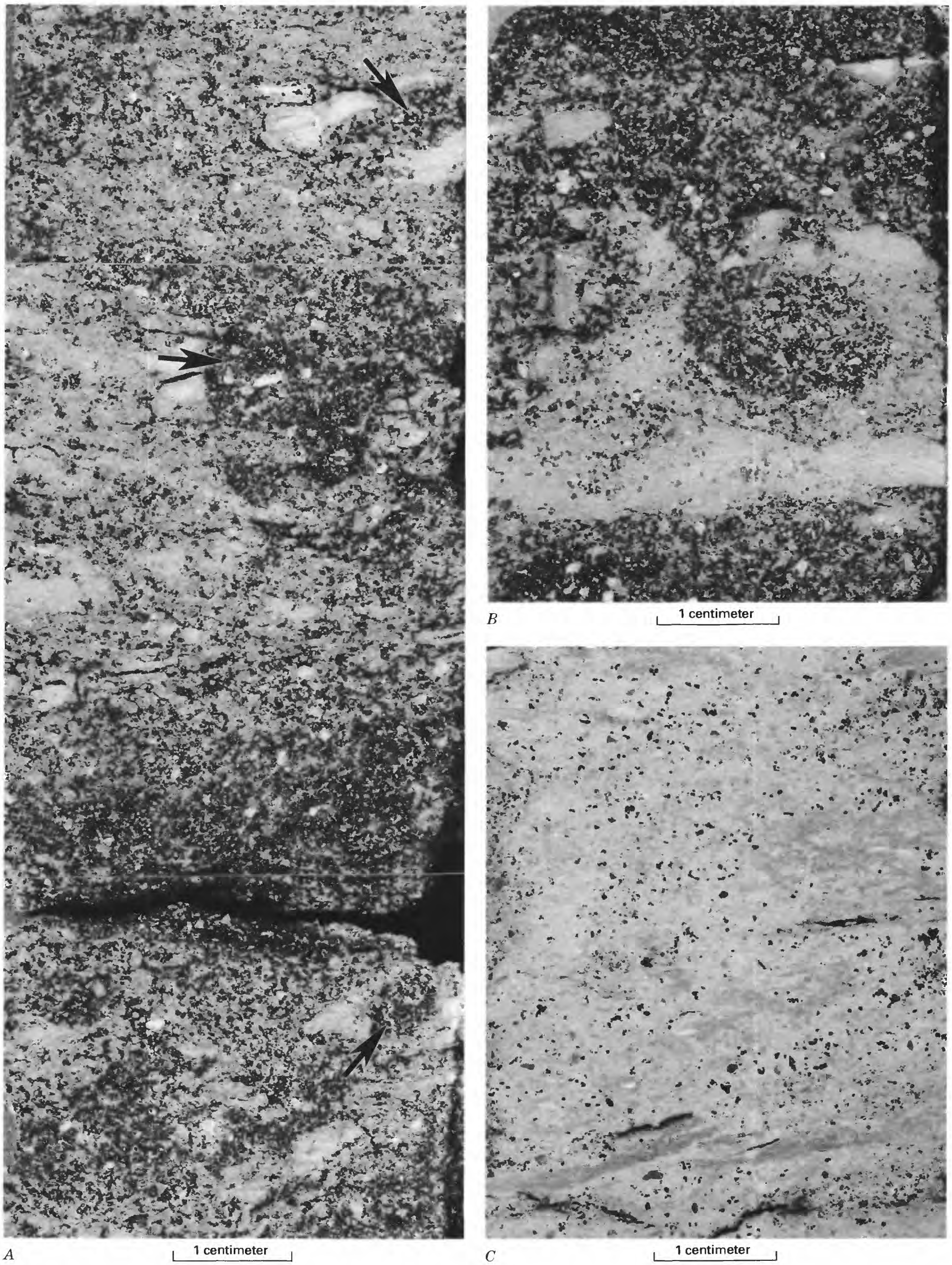
Age and Correlation

The sparse planktonic foraminiferal assemblage suggests that the lower part of the Woodstock in the core is no younger than zone P. 9 (late Ypresian). In beds here placed in the upper Woodstock (see section on lithology), Poag (chap. D, this vol.) notes the presence of *Subbotina frontosa*, which normally ranges no lower than zone P. 10, and suggests that the occurrence may be due to reworking downward by burrowing from the overlying Piney Point Formation.

PINEY POINT FORMATION

DEFINITION AND EXTENT

In the Haynesville core, the upper 54.6 ft (17 m) of the 264-ft-thick (80-m-thick) Pamunkey Group is the middle Eocene Piney Point Formation, a richly fossiliferous, olive-gray, poorly sorted, glauconitic sand that is commonly indurated, in part, by carbonate cement (figs. 14, 15). The formation was first described by Otton (1955) from drill cuttings from a water well at Piney Point, St. Marys County, Md., about 16 mi (26 km) northeast of the Haynesville site. The Piney Point beds occur farther northeast in a borehole at the Baltimore Gas and Electric Nuclear Power Station in Calvert County, Md., (Ward, 1985) and have been reported over a wide area of the Eastern Shore of Maryland and in Delaware (Hansen, 1967; Trapp and others, 1984). In Virginia, the Piney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Point is encountered in numerous water wells in the central and lower parts of the Northern Neck and the Middle Peninsula, where the formation is an important aquifer (Meng and Harsh, 1988). From the subsurface of the Middle Peninsula the Piney Point extends southwestward almost to the Fall Line, where it crops out at numerous localities along the Pamunkey River in Hanover and New Kent Counties, Va., and in deep ravines in northern Prince George County, Va., in the area east of Hopewell and south of the James River (Ward, 1985). At these inner Coastal Plain localities, the Piney Point is thinner because of truncation by the overlying Oligocene and Miocene formations.

LITHOLOGY

In the core, the Piney Point consists of light- to dark-olive-gray (5Y 5/2 and 5Y 3/2), medium to coarse, friable, glauconitic quartz sand interbedded with crumbly to very hard carbonate-cemented sand and moldic limestone (fig. 14). The more glauconitic beds are grayish olive green (5CY 3/2). Two types of glauconite are commonly present: fresh, dark-green to black grains and brown grains wholly or partly altered to ferric oxides. The glauconite grains are mainly simple, rounded to elliptical forms; a small percentage are polylobate. Very fine to fine, well-rounded quartz pebbles are scattered through much of the section. As in areas of Piney Point outcrop along the Pamunkey and James Rivers, the most conspicuous fossil is robust, calcitic shells of the large oyster *Cubitostrea sellaeformis* (Conrad, 1832) (see figs. 14*B*–14*D*). Aragonitic bivalves and gastropods are preserved only as molds and casts. In some strata, dissolution of aragonitic shells has produced a high moldic porosity (figs. 14*A*, 15*B*, 15*C*). Cavities are lined with sparry calcite or iron sulfides. The calcareous beds range from quartz-glauconite-feldspar arenites containing appreciable micritic and sparry calcite as cement and matrix material to micritic limestone containing abundant recrystallized foraminifers and less than 40 percent quartz and glauconite. These cemented sands and limestones tended to block up the core barrel near the beginning of each core run; thus, only about 25-percent core recovery was obtained from the Piney Point section.

◀ FIGURE 12.—Glauconitic quartz sand and sandy clay of unit D of the Potapaco Member of the Nanjemoy Formation. *A*, Dominantly fine to medium sand of lowermost unit D grading upward into a clayier and siltier interval. Arrows indicate irregular burrow filled with very glauconitic sand (upper middle of photo) and cross sections of tubelike, clay-lined, sand-filled burrows (upper and lower parts of photo) (alt. −301.7 to −302.2 ft). *B*, Thin, burrowed clay within fine to very coarse sand in lower middle part of unit (alt. −297 ft). *C*, Very poorly sorted, bioturbated, sandy clay-silt bed near top of unit D (alt. −284 ft). Inclined, lenticular clay laminae near bottom of photo suggest waning currents. Dark fractures are result of core desiccation.

STRATIGRAPHIC RELATIONS

We did not recover the 8-ft interval that included the contact between the relatively light colored, very calcareous, partly indurated, medium to coarse sands of the Piney Point Formation and the darker, more micaceous, finer sands of the underlying Nanjemoy Formation. Thus, the boundary between the two formations was determined by reference to the geophysical logs of the borehole and placed at the sharp deflection to the right of the single-point electrical resistivity curve (chap. A–pl. 1) at a depth of 327 ft (alt. −240 ft (−73 m)). The deflection occurs at the abrupt change in lithology as the probe passes up the hole from the much less resistive, clayey and silty sand of the Nanjemoy Formation to the very resistive strata of the Piney Point. The very distinctive faunal and floral assemblages in the Piney Point, compared with those in the underlying Nanjemoy, suggest that a lengthy hiatus separates the two formations. A break in deposition and an associated interval of erosion is also indicated by the irregular, deeply burrowed surface of unconformity separating the formations in outcrops along the Pamunkey River in Hanover County, Va., about 30 mi (48 km) southwest of the Haynesville site (Ward, 1985, figs. 34, 35).

In the core, as in exposures along the Pamunkey River, the Piney Point is overlain unconformably by the shelly, much less glauconitic sand of the Old Church Formation, which is of late Oligocene or early Miocene age (Ward, 1985, p. 51–58; Poag, chap. D, this vol.).

FAUNA AND FLORA

The Piney Point beds in the core contain fairly abundant molluscan shells, mainly fragments and whole valves of *Cubitostrea sellaeformis* (Conrad, 1832), and molds and casts of other bivalves and gastropods, including *Macrocallista* cf. *Macrocallista perovata* (Conrad, 1833) and *Turritella* cf. *Turritella nasuta* Gabb, 1860. The large oyster *Cubitostrea sellaeformis*, which serves as a marker for the middle Eocene of the Atlantic and Gulf Coastal Plains, is the most characteristic bivalve. The Piney Point beds also contain rich and diverse assemblages of foraminifers and dinoflagellates (see Poag, chap. D, and Edwards, chap. C, this vol.). Bryozoans are present but not abundant.

ENVIRONMENT OF DEPOSITION

In the core, the relatively clean, medium to coarse sand of the Piney Point, the abundance of very well rounded quartz pebbles, the beds of dominantly frag-

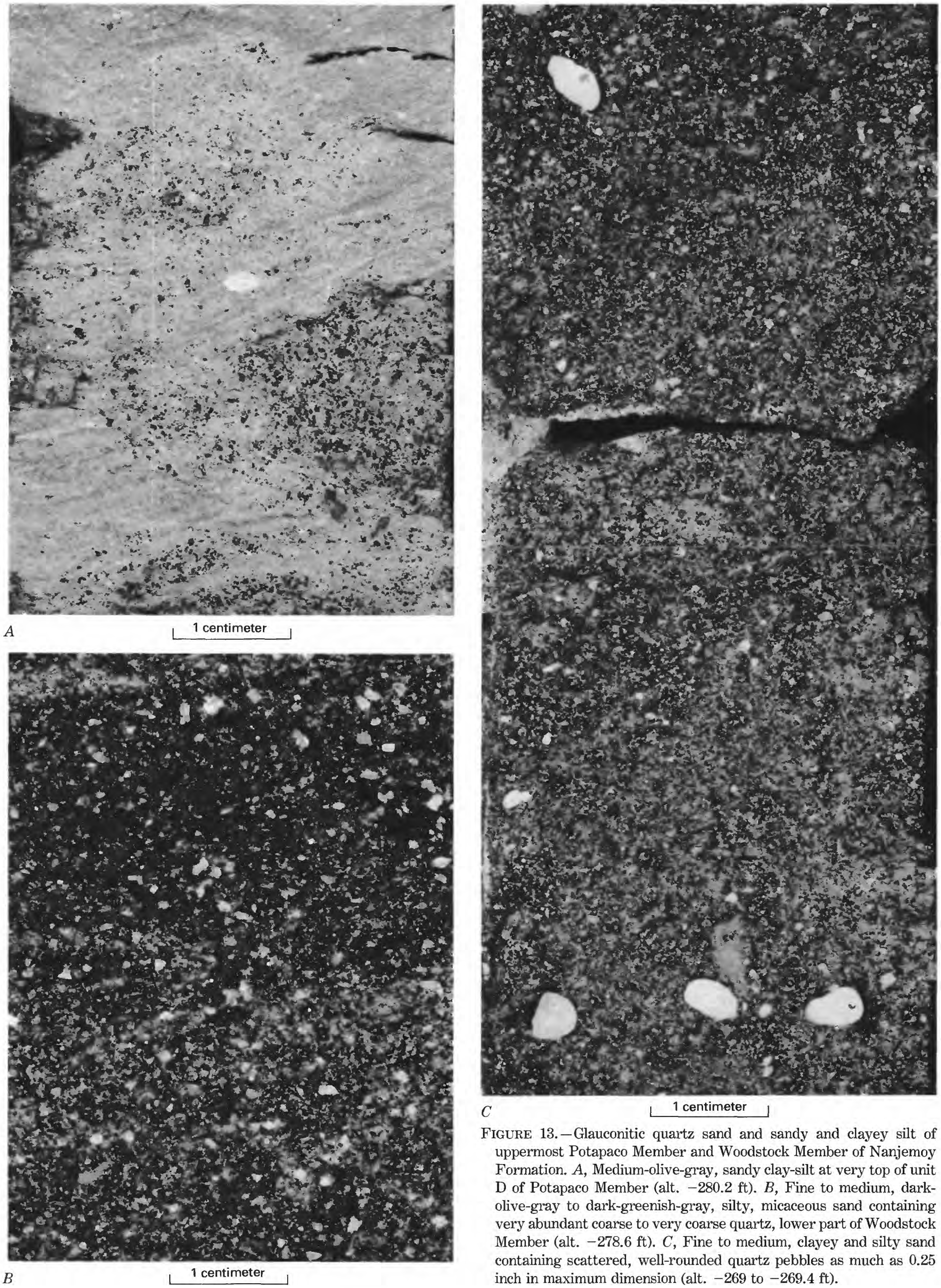


FIGURE 13.—Glauconitic quartz sand and sandy and clayey silt of uppermost Potapaco Member and Woodstock Member of Nanjemoy Formation. *A*, Medium-olive-gray, sandy clay-silt at very top of unit D of Potapaco Member (alt. −280.2 ft). *B*, Fine to medium, dark-olive-gray to dark-greenish-gray, silty, micaceous sand containing very abundant coarse to very coarse quartz, lower part of Woodstock Member (alt. −278.6 ft). *C*, Fine to medium, clayey and silty sand containing scattered, well-rounded quartz pebbles as much as 0.25 inch in maximum dimension (alt. −269 to −269.4 ft).

mental shell material, and the presence of some cross-bedding suggest reworking and winnowing of sediment in a high-energy depositional environment. The moderately diverse molluscan assemblages in Piney Point outcrops in the inner Coastal Plain of Virginia indicate a mild- to warm-temperate, shallow-shelf environment with normal marine salinity (Ward, 1985). Foraminiferal assemblages from the upper part of the Piney Point section in the core suggest outer sublittoral water depths (100–150 m) for the Haynesville site (Poag, chap. D, this vol.).

AGE AND CORRELATION

The planktonic foraminiferal suite from the uppermost Piney Point in the core (Poag, chap. D, this vol.) indicates undifferentiated zone P. 12–13 of the middle Eocene (Lutetian). Studies of calcareous nannoplankton and dinocysts from Piney Point outcrops in the Pamunkey River area (DiMarzio, 1984; Edwards, 1984) and of dinocysts from the Haynesville core (Edwards, chap. C, this vol.) indicate placement of the Piney Point in NP 16, which is equivalent to foraminiferal zone P. 12–13.

OLD CHURCH FORMATION

DEFINITION

The basal lithic unit in the Chesapeake Group in Virginia and Maryland is the upper Oligocene or lower Miocene Old Church Formation, a thin but widespread shelf deposit consisting of clayey and silty quartz sand, very minor amounts of glauconite, and abundant molluscan shell material (Ward, 1984b, 1985). The unit is very calcareous owing to the largely fragmental shell material and to large numbers of foraminifers and ostracodes. Formation thickness ranges from less than a foot (less than 0.3 m) in its area of outcrop in the inner Virginia Coastal Plain to slightly more than 4 ft (1.2 m) farther downdip in the Haynesville core hole. For many years, the extreme thinness of the Old Church and its areally restricted and somewhat isolated outcrop along the Pamunkey River caused it to be overlooked. More recently, recognition of the formation's distinctive lithology and fossil assemblages and the clear-cut unconformities bounding the top and bottom of the unit have made the Old Church a useful and important mapping horizon. Exposures on the right bank of the Pamunkey River at the downstream end of Horseshore Bend near the community of Old Church, Hanover County, Va., have been designated the type section of the formation (Ward, 1985).

LITHOLOGY

The Old Church Formation in the Haynesville core (alt. −181.3 to −185.4 ft (−55 to −57 m)) consists of slightly more than 4 ft (1.2 m) of very shelly, very fine to coarse, clayey, olive-gray quartz sand containing scattered granules and fine pebbles of quartz and phosphate (fig. 16). Very small amounts of green glauconite, possibly reworked in part, from the directly underlying, very glauconitic sand of the Piney Point Formation, are also present. The percentage of fragmental shell material is very high, especially in the upper 10 in (25 cm) of the unit, which is a sandy and pebbly shell hash dominated by *Mercenaria* sp. Although much of the rest of the Old Church is friable sand, it does contain irregular, indurated masses of shelly sand, 2 to 8 in (5 to 20 cm) thick, that are cemented by calcium carbonate (figs. 16*C*, 16*D*). The Old Church in the core is very similar in both lithology and thickness to the type Old Church cropping out along the Pamunkey River in Hanover and New Kent Counties, Va. (Ward, 1984b, 1985).

Though the Old Church is quite thin, it is lithically, faunally, and florally distinctive and, in the core, is easily differentiated from the unconformably underlying, much more glauconitic Piney Point Formation. At the erosional contact between the formations, pebbly quartz sand containing oysters and pectens typical of the Old Church (see fig. 17) directly overlies very glauconitic sand and carbonate-cemented hard beds of the Piney Point that contain abundant *Cubitostrea sellaeformis*, a large middle Eocene oyster. In the core, the shell hash of the upper Old Church is unconformably overlain by the less calcareous, phosphatic fine sand, silt, and clay of the Calvert Formation, whose basal bed contains the important guide fossil *Pecten humphreysii*.

FAUNA AND FLORA

The low-diversity molluscan assemblage in the core includes small pectens, oysters, and other bivalves and the scaphopod *Dentalium* sp. The large bivalve *Mercenaria capax* (Conrad, 1843), which is abundant in the core (fig. 16*B*), is also found in the Old Church Formation along the Pamunkey River and in the upper River Bend (upper Oligocene) and Belgrade (upper Oligocene/lower Miocene) Formations of North Carolina. This occurrence is the first known appearance of the genus *Mercenaria* on the Atlantic shelf. A list of molluscan taxa from the core includes

"Pecten" sp.
Anomia sp.
Pycnodonte sp.
Lucina? sp.
Astarte sp.

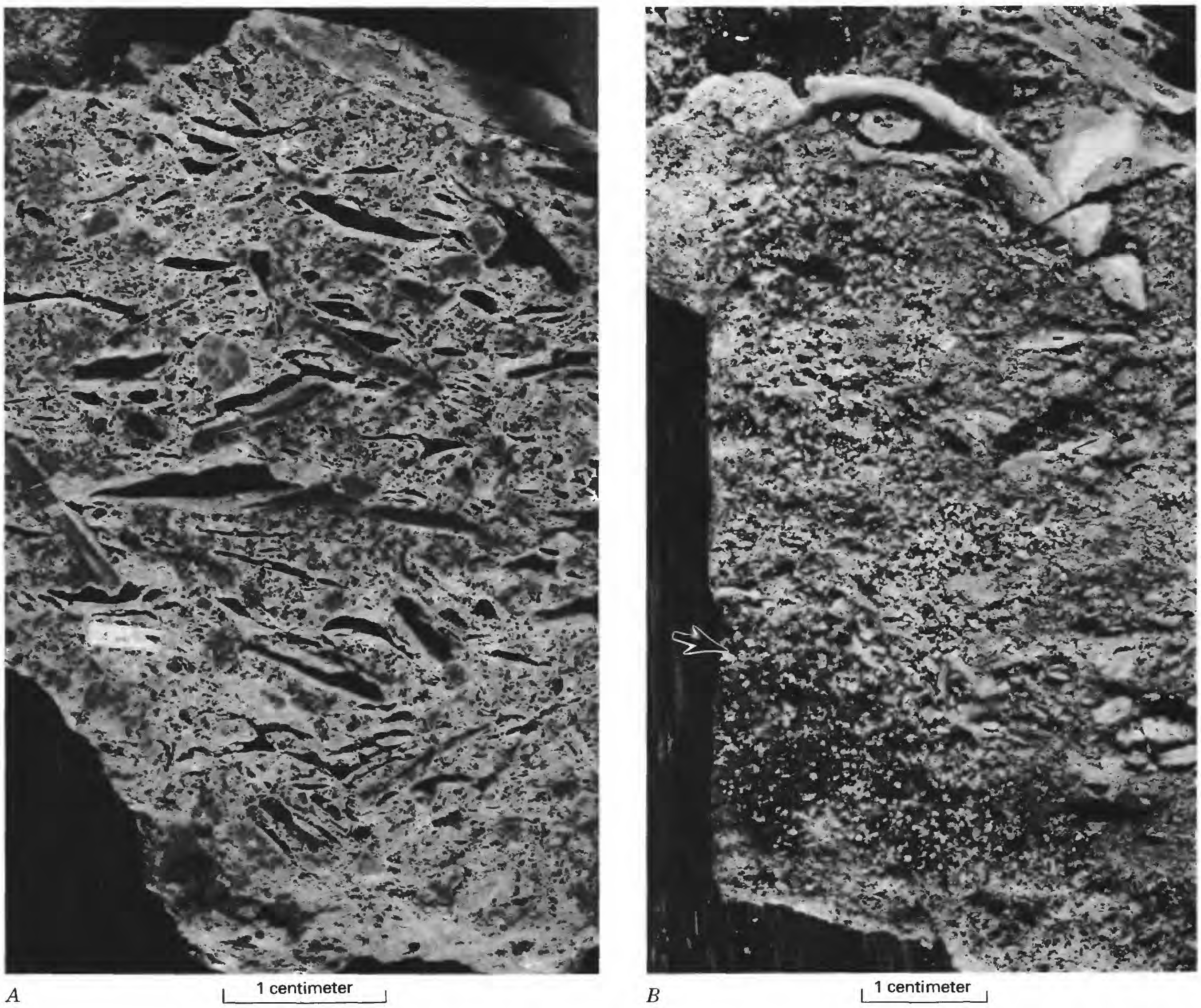


FIGURE 14.—Variation in shell content, cementation, and porosity in glauconitic quartz sands in middle part of the Piney Point Formation. *A*, Hard "shell rock" consisting of angular, recrystallized shell fragments in matrix of fine to coarse, pebbly sand (alt. −198.2 ft). Abundant glauconite includes fresh, dark-green to black grains and weathered, light-green grains. Cement includes microcrystalline and sparry calcite. Voids, formed by dissolution of aragonitic shell, are commonly lined by fine euhedral calcite. *B*, Friable sand with abundant fragmental shell material and soft, calcareous mud matrix; very finely crystalline iron sulfide is disseminated throughout. At top of photo are large fragments of the bivalve *Cubitostrea sellaeformis*. At bottom of photo, bedding contact (arrow) between shelly sand (above) and relatively well sorted, very glauconitic quartz sand (below), inclined downward to right, suggests high-energy depositional environment (alt. −200 ft).

Macrocallista sp.
Mercenaria capax (Conrad, 1843)
Dentalium sp.

The Old Church beds in the core also contain abundant barnacle plates (fig. 16*C*), echinoid debris, and rich foraminiferal and dinoflagellate cyst assemblages (see Poag, chap. D, and Edwards, chap. C, this vol.).

ENVIRONMENT OF DEPOSITION

The molluscan assemblage in the core and at other Old Church localities in Virginia (Ward, 1985, p. 54–55) indicate temperate waters. The foraminiferal assemblage suggests an outer sublittoral environment (100–150 m) having low values of dissolved oxygen at the sea floor.

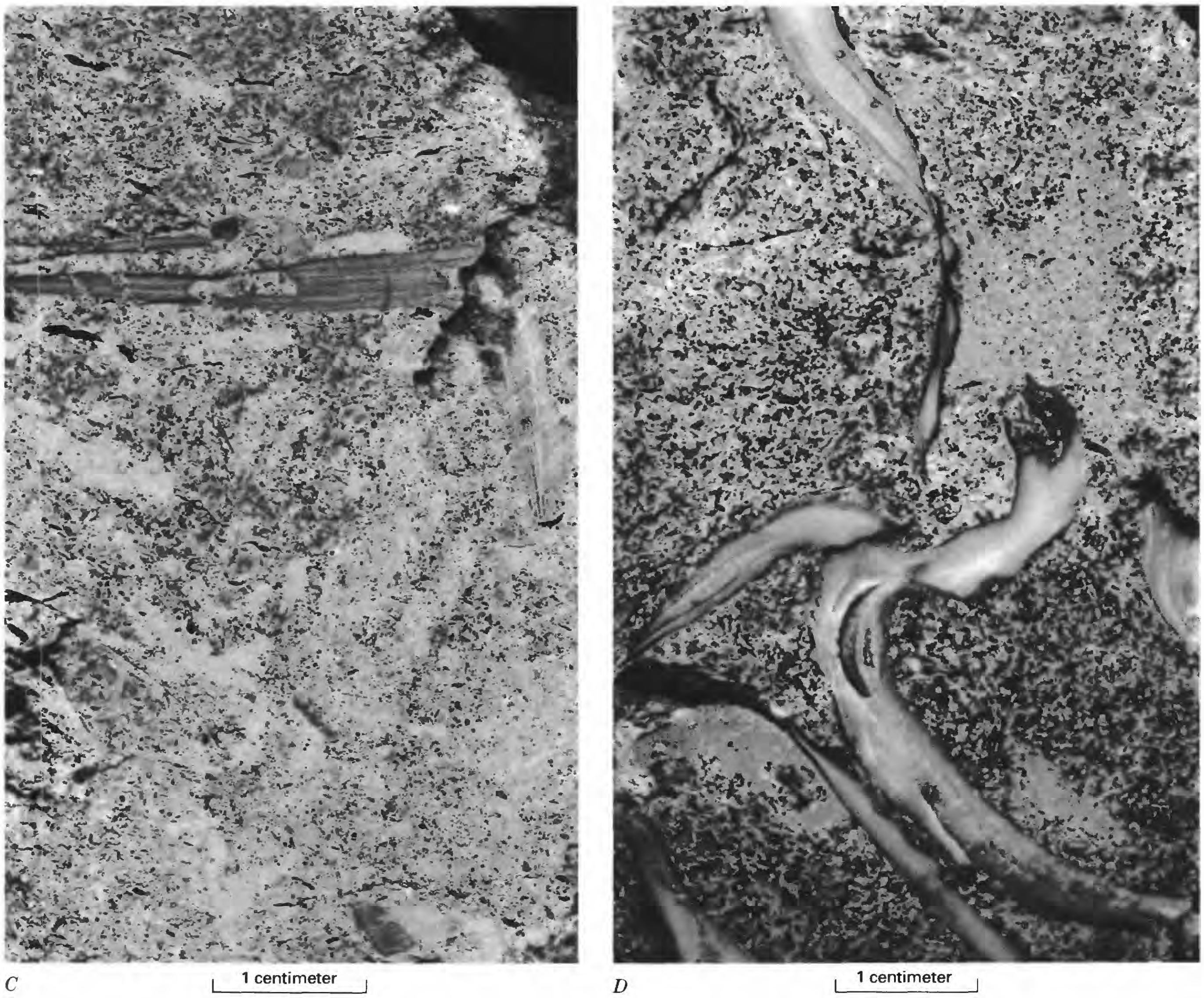


FIGURE 14.—*C*, Hard, partly cemented glauconite-quartz arenite showing typical fold in calcitic shell of adult *Cubitostrea sellaeformis*. Mottling is due to uneven occurrence of calcareous cement (alt. −206 ft). *D*, Partly cemented sand containing abundant whole valves of *Cubitostrea sellaeformis*; some specimens are articulated.

AGE AND CORRELATION

Previous studies of the fauna and flora of the Old Church have indicated that the formation is late Oligocene and (or) early Miocene in age (Ward, 1985). Both the ostracode data (J.E. Hazel, oral commun., 1984) and the pollen assemblage (N.O. Frederiksen, written commun., 1984) from the type section along the Pamunkey River are more suggestive of late Oligocene rather than early Miocene, but the evidence is somewhat inconclusive. An analysis of the rich foraminiferal assemblage (Poag, chap. D, this vol.) from the Haynesville core has yielded new data strongly suggesting that the Old Church section belongs to the late Oligocene zone N. 4a of Kennett and Srinivasan (1983).

The molluscan assemblage in the type Old Church that crops out along the Pamunkey River indicates correlation with the Belgrade Formation in North Carolina (Ward, 1985, p. 54–56).

CALVERT FORMATION

DEFINITION

Overlying the upper Oligocene Old Church Formation in the core, but separated from it by a major regional

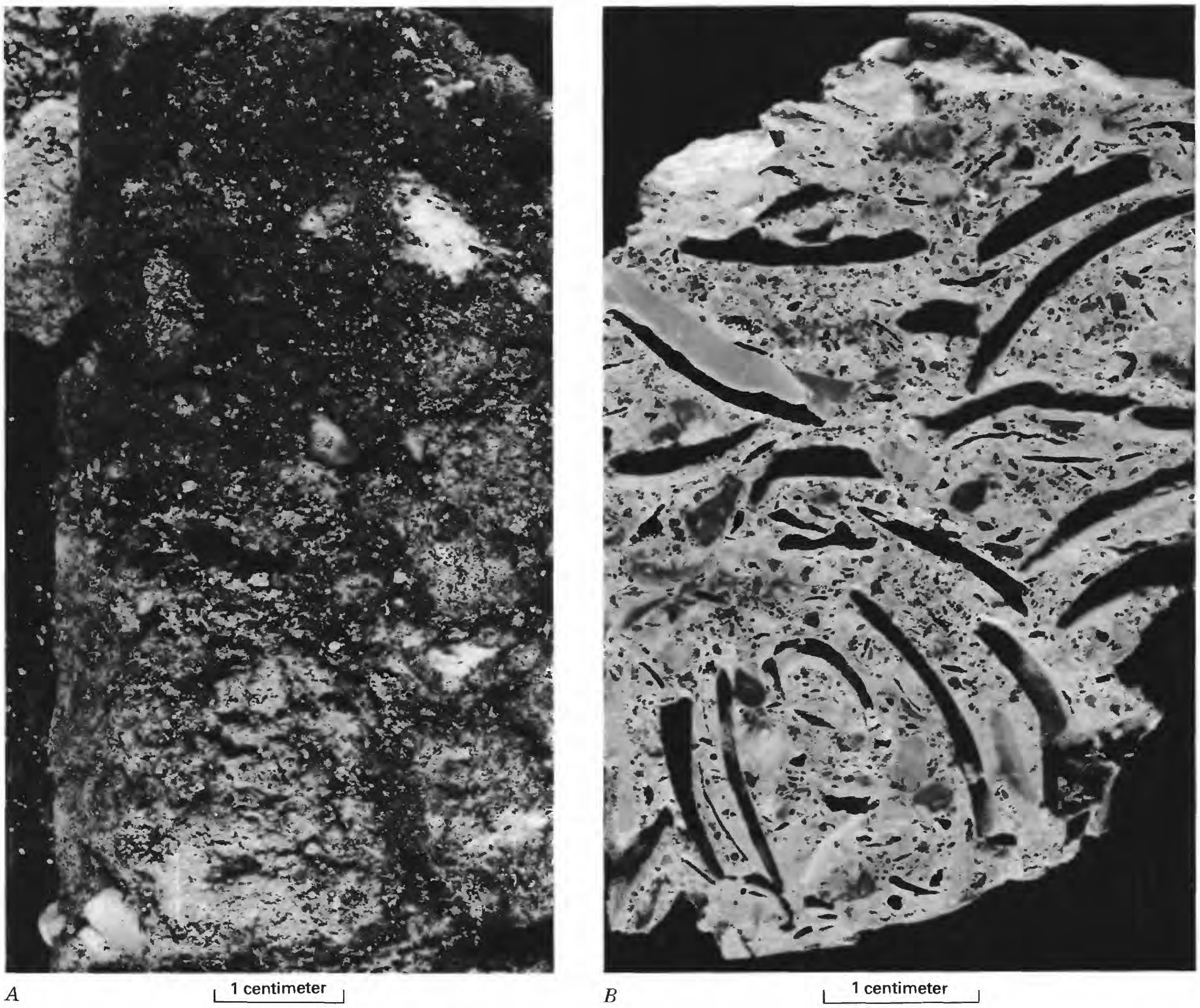


FIGURE 15.—Glauconitic quartz sand and sandy, micritic, fossiliferous limestone in upper part of the Piney Point Formation. *A*, Olive-gray to grayish-olive, loose, fine to very coarse, very glauconitic sand containing fine (0.25 in) quartz pebbles (upper part of photo) filling irregular surface (center) of very light gray, carbonate-cemented, pebbly and shelly sand (alt. −194 ft). *B*, Yellowish-gray, very sandy, micritic limestone containing abundant very well rounded pebbles of vein quartz and large, recrystallized shell fragments. Dissolution of aragonitic shell material has created high moldic porosity (alt. −194.9 ft).

unconformity, are middle Miocene beds of the Calvert Formation. Beds of early Miocene age, present in some areas of Virginia and Maryland, do not occur in the core. Regionally, the Calvert Formation consists of diatomaceous, variably shelly, fine quartz sand and sandy clay-silt that ranges in thickness from less than 20 ft (6.1 m), in updip areas to about 200 ft (60 m) downdip near the axis of the Salisbury basin. The Calvert Formation received its name from Calvert County in southern Maryland, where it is extensively exposed in high cliffs along the Chesapeake Bay (Shattuck, 1904). The Calvert Formation is widely distributed from Maryland and Delaware southward to southern Virginia. In North Carolina, equivalent strata are named the "Pungo River Formation"; in New Jersey, correlative beds are included in the Kirkwood Formation.

In the type area in Calvert County, the Calvert Formation is subdivided, from bottom to top, into the Fairhaven, Plum Point Marl, and Calvert Beach Members. The Fairhaven and Plum Point Marl Members were named and described by Shattuck (1904). The Calvert Beach Member was named by Gernant (1970), who considered it the lowest member of the overlying Choptank Formation.

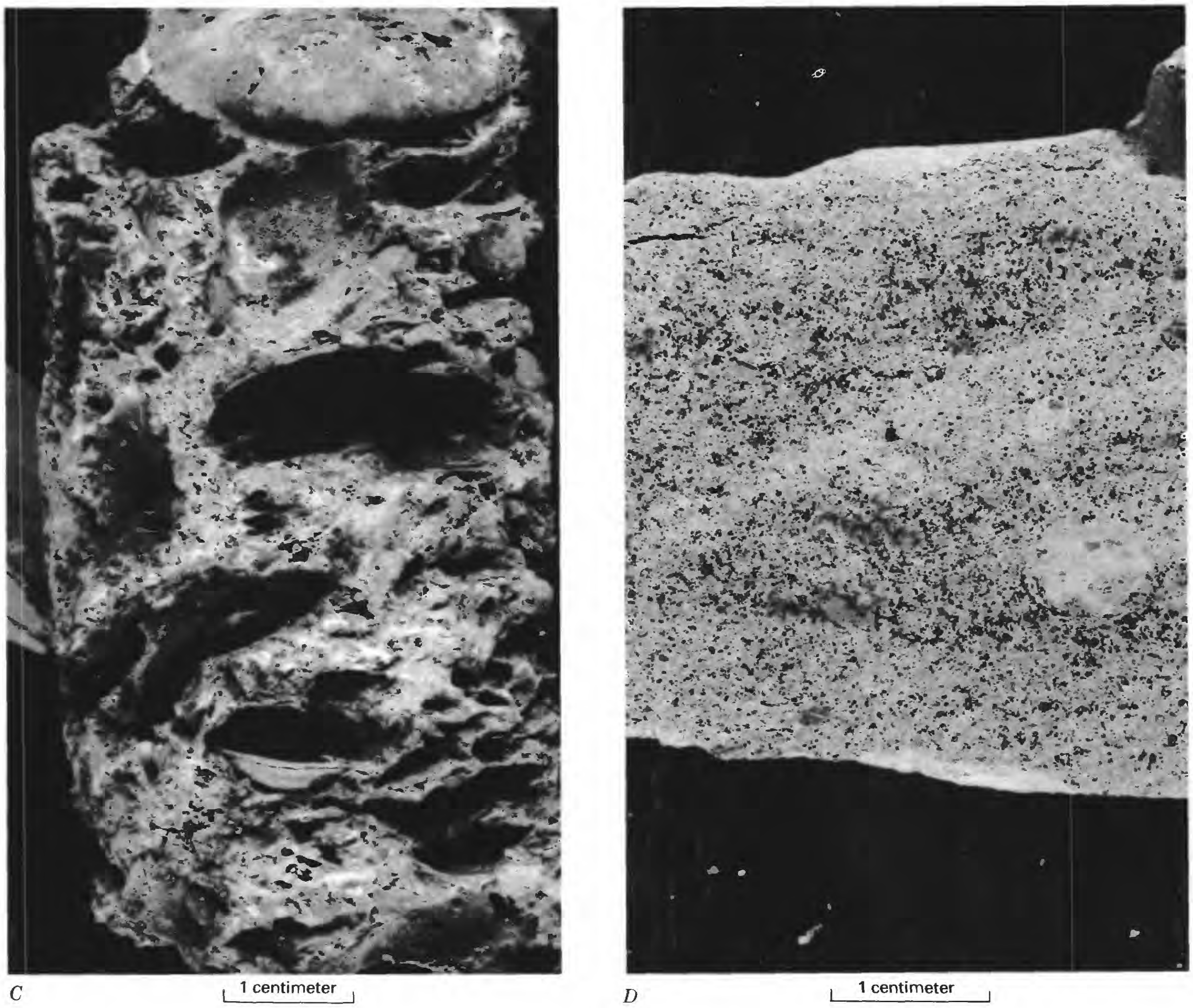


FIGURE 15.—*C*, Uncut core showing internal mold of aragonitic bivalve *Macrocallista* (top) and molds and casts of other mollusks (alt. −195.2 ft). Voids commonly lined with euhedral crystals of calcite and, more rarely, iron sulfide. *D*, Light-olive-gray, fine to medium, carbonate-cemented sand containing 9-mm quartz pebble (lower right) and rare wood fragments. Bed is about 1 ft below moldic limestone shown in *B*. Note bedding contact just below pebble (alt. −196.2 ft).

Recently, however, Ward (1984a, 1984b) demonstrated that the Calvert Beach is partly equivalent to Shattuck's (1904) "zones" 14–15 of the uppermost Calvert Formation and recommended that the Calvert Beach be placed in the underlying Calvert. Although the three members of the Calvert are similar lithically, they occupy different, though overlapping, depositional basins and are separated by unconformities of at least subregional extent. In Maryland, each member is characterized by an abundant fossil fauna and flora dominated by mollusks and diatoms.

LITHOLOGY

In the Haynesville core, the Calvert Formation occurs from altitudes of −49 to −181.3 ft (−15 to −55 m); it is 132.3 ft (40 m) thick. The core section includes (1) a lower shelly sand, about 11 ft (3.4 m) thick, that lacks diatoms but contains abundant mollusks and planktonic foraminifers, and (2) relatively thick middle and upper parts (Plum Point and Calvert Beach beds) that are very diatomaceous and contain very sparse mollusks and dominantly benthonic foraminiferal assemblages.

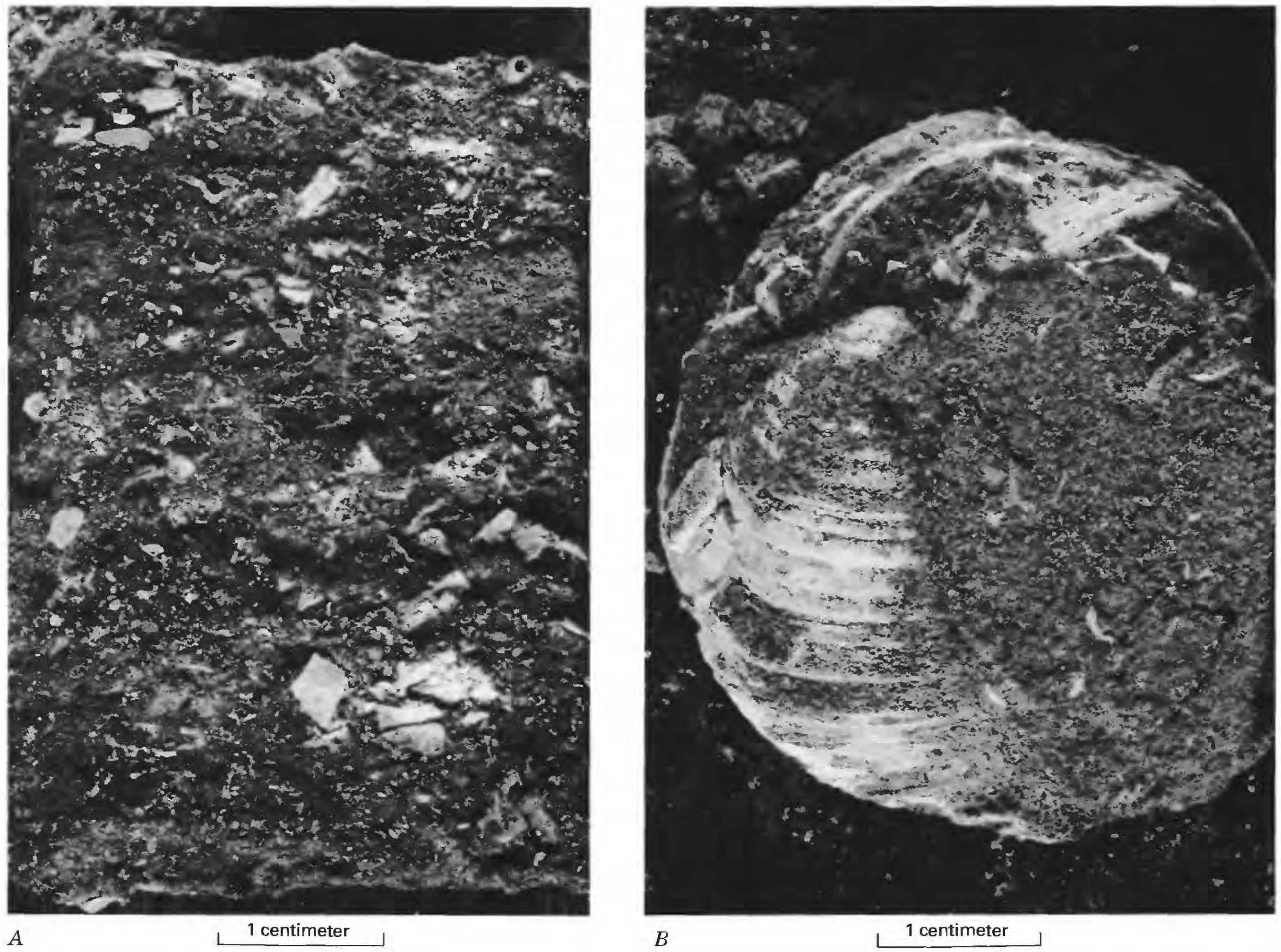


FIGURE 16.—Muddy, shelly quartz sand and hard, carbonate-cemented sand of the Old Church Formation. *A*, Muddy, very poorly sorted, fine to medium quartz sand and shell hash containing abundant coarse grains and granules of quartz (alt. −182 ft). Lithology is typical of upper part of formation. *B*, Bedding-plane view of sparsely glauconitic, muddy fine sand containing abundant whole valves of *Mercenaria capax*, the dominant Old Church mollusk present in the core (alt. −182.6 ft).

SHELLY SAND BEDS

The lowermost part of the Calvert Formation (alt. −170 to −181.3 ft (−52 to −55 m)) is very poorly sorted, clayey and silty, very fine to medium, olive-gray quartz sand containing scattered coarse grains and very fine to fine pebbles of phosphate and quartz. These beds are commonly light and dark mottled as the result of intense bioturbation. Planktonic foraminifera (Poag, chap. D, this vol.) and molluscan shell material (fig. 18), including fragments and whole valves of oysters, pectens, *Mercenaria* sp., and *Turritella* sp. are present in abundance. The calcitic shells, such as pectens and oysters, are fairly well preserved (fig. 18*A*). Aragonitic shell material is partially leached and chalky white (fig. 18*B–D*). Diatoms, which are abundant in the overlying Calvert strata, are absent in the shelly sand beds.

The shelly sand beds of the Calvert directly underlie very phosphatic Calvert sand that causes the most prominent right-hand deflection on the gamma log curve for the entire Miocene section (chap. A–pl. 1). Most workers making formational picks on the basis of the gamma log curve, and without samples, would likely place the lower contact of the Calvert too high—at the base of the prominent phosphatic sand deflection. On the electrical resistivity log for the core hole, the shelly sand beds are expressed as a strong deflection to the right that would be very difficult to differentiate from similar prominent deflections caused by the underlying sands and limestones of the Eocene Piney Point Formation. Therefore, based solely on interpretation of the electrical resistivity curve, placement of the unconformable contact between the shelly sand beds of the Calvert and the

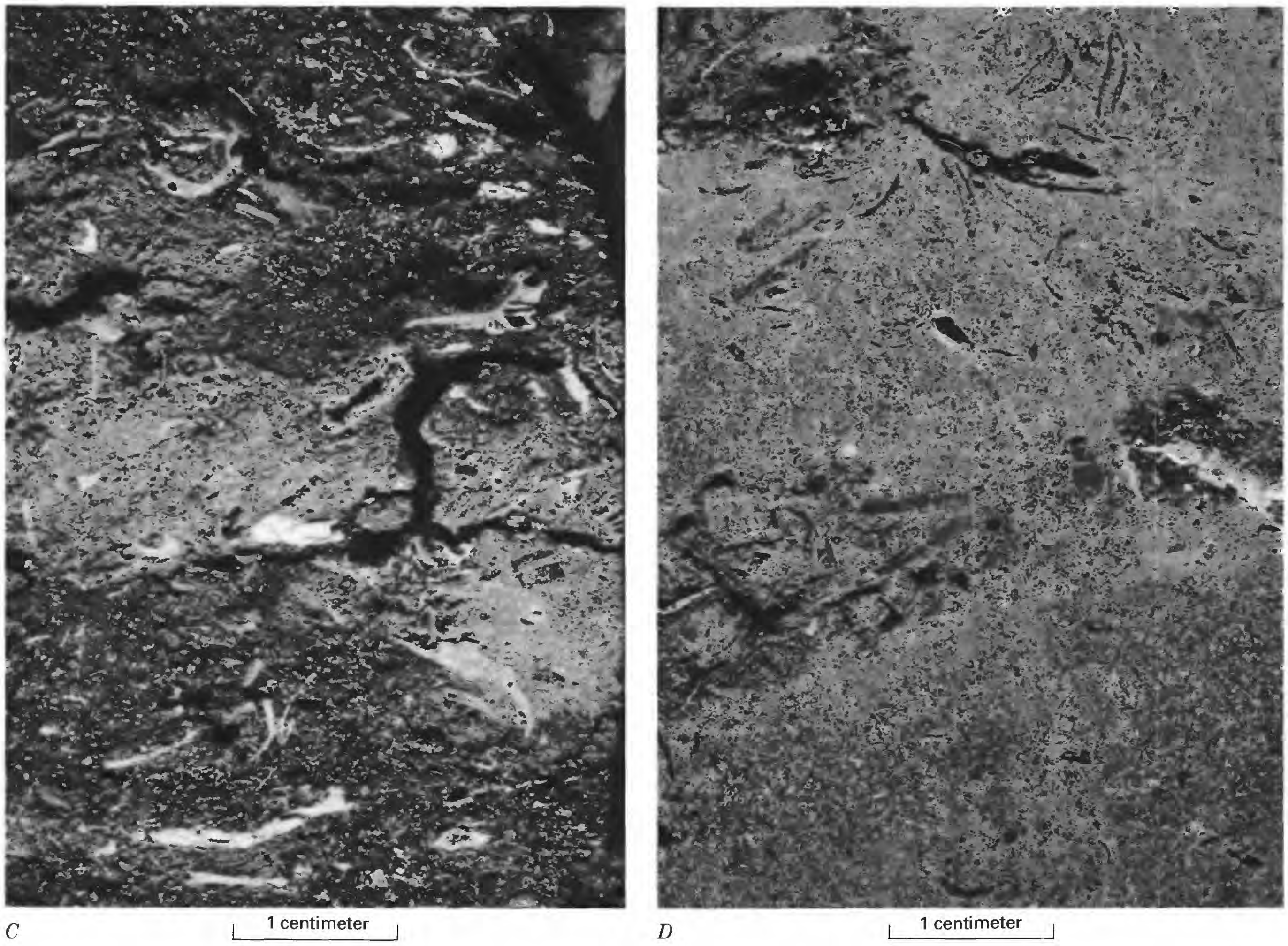


FIGURE 16.—*C*, Muddy sand and thin irregular bed (center) cemented with calcium carbonate (alt. −183.5 ft). Unit contains abundant fragments and whole valves of clams and scaphopods (*Dentalium* sp.) and scattered barnacle plates (center right). *D*, Carbonate-cemented, fine glauconitic quartz sand in lower part of Old Church Formation. Note 0.5-cm-long benthic foraminifers in upper part of photo (alt. −184 ft).

Piney Point Formation is also difficult. The intervening Old Church Formation is commonly too thin to have a clearly defined electric log signature.

DIATOMACEOUS BEDS

The diatomaceous part of the Calvert Formation in the core, extending from the top of the shelly sand beds to the base of the St. Marys Formation (alt. −170 to −49 ft (−52 to −15 m)) includes seven fining-upward sand-silt-clay sequences ranging in thickness from about 6 to 35 ft (1.8 to 11 m). The coarser, lower part of each sequence consists of 1 to 6 ft (0.3 to 1.8 m) of variably muddy, very fine to fine quartz sand that commonly contains scattered very fine pebbles of quartz and phosphate, marine vertebrate bones, fish teeth and scales, and fragments of wood (figs. 19*A*, 19*B*). These sandy beds contain extremely sparse shell material and, thus, contrast sharply with equivalent, abundantly shelly sands of the middle and upper Calvert in the type area in Calvert County, Md. The basal, fine, muddy sands of each fining-upward sequence grade upward into sandy clay-silt (figs. 19*C*, 19*D*) containing abundant diatoms, sponge spicules, and rare molds and casts of mollusks. Diatoms may be present in sufficient numbers to classify the clayey and silty sediment as an impure diatomite. The contact between the clay-silt of the upper part of each sequence and the basal sand of the directly overlying sequence is abrupt (fig. 19*B*). However, sand-filled burrows commonly extend downward from the basal sands as much as 2–3 ft (0.6–0.9 m) into clay-silts of the underlying unit (fig. 20*A*). In some cases, the uneven contacts between fining-upward sequences, the lag deposits at the base of sequences, and the faunal and floral differences across the contacts indicate a break in deposition possibly accompanied by erosion.

FIGURE 17.—Oysters and pectens in muddy fine sand at base of the Old Church Formation. Small pecten with bifurcating ribs (lower right) and smooth, undulant, thin-shelled pyncnodont oyster (left) are fossils typical of the Old Church. The calcitic oyster and pecten are well preserved, whereas the aragonitic mollusks are leached chalky white (alt. −185.4 ft).

The sediments within each fining-upward sequence are generally thick- to massively bedded; however, a few thin stringers of sand occur within the clay-silt sections (fig. 19*D*). Light and dark mottling, which is characteristic of much of the Calvert, appears to result from biogenic activity. Clay-filled and sand-filled burrows of various types are the most conspicuous sedimentary structures (figs. 19*B*, 19*C*, 20).

Plum Point beds.—The lower two sequences of the seven diatomaceous, fining-upward sequences described above (chap. A–pl. 1, alt. −113.5 to −170 ft (−35 to −52 m)) contain diatom assemblages that indicate equivalence, at least in part, to the Plum Point Marl Member of the Calvert (fig. 19). This member is typically exposed at Plum Point on the Chesapeake Bay in Calvert County, Md. (Shattuck, 1904). In the core, the herein informally named Plum Point beds are dominantly sandy, diatomaceous clay-silt. The lower 35-ft-thick (11-m-thick) sequence of the two fining-upward sequences included in the Plum Point contains the marker diatoms *Coscinodiscus lewisianus*, *Delphineis ovata*, *Rhaphoneis fusiformis*, and *Sceptroneis grandis*. These taxa suggest correlation with the upper part of East Coast diatom zone 2 of Andrews (1978, 1988) and the upper part of Shattuck's (1904) "zones" 4–9 of the Plum Point Marl Member. The infrequent occurrence of *Delphineis penelliptica* in these samples suggests nearness to the boundary between diatom zone 2 and the overlying zone 3 of Andrews (1978) or zone 3–4 of Andrews (1988). The Haynesville core hole is the first locality in Virginia where diatomaceous deposits having an age near the diatom zone 2-zone 3 boundary have been identified.

The overlying 22-ft-thick (7-m-thick) fining-upward sequence (alt. −113.5 to −135 ft (−35 to −41 m)) contains *Rhaphoneis adamantea* and *Rhaphoneis magnapunctata*, which are indicative of East Coast diatom zone 4 of Andrews (1978) and zone 3–4 of Andrews (1988). These diatoms suggest approximate equivalency to Shattuck's lithic "zones" 12 and 13 of the Plum Point Member in Maryland (Shattuck, 1904). Beds representing Shattuck's (1904) "zones" 10–11 appear to be missing from the Haynesville section, suggesting that the contact between the lower and upper sequences of the Plum Point at the Haynesville site (fig. 19*B*) represents a brief hiatus.

Calvert Beach beds.—The upper 64.5 ft (20 m) of the Calvert Formation in the core (alt. −49 to −113.5 ft (−15 to −35 m)), including the upper five sequences of the seven fining-upward sequences described above, are notable for having much better developed sands than occur in the underlying Plum Point Marl beds (see also the electrical resistivity log of the core, chap. A–pl. 1). This sandier section, herein informally named the Calvert Beach beds, contains a well-preserved diatom assemblage, including the marker diatoms *Delphineis angustata*, *Delphineis novaecaesaraea*, *Rhaphoneis gemmifera*, *Rhaphoneis lancettula*, and *Rhaphoneis parilis*. These species are indicative of Andrews' East Coast diatom zone 5 and suggest equivalency to the Calvert Beach Member of the Calvert Formation in Maryland (Gernant, 1970; Andrews, 1978, 1988; Ward, 1984a, 1984b). The Calvert Beach Member includes Shattuck's "zones" 14 and 15 as exposed in the Calvert Cliffs near Calvert Beach in southern Calvert County, Md.

Although the "zone" 14–15 diatom flora extends downward in the core to an altitude of −117 ft (−36 m), we place the Calvert Beach-Plum Point contact a few feet higher (−113.5 ft (−35 m)) at the base of a 5-ft-thick (1.5-m-thick) sand that causes a very pronounced deflection of the single-point electrical resistivity curve (chap.

A–pl. 1). Based on the available well log data, this sand appears to be mappable in the subsurface through much of the surrounding Virginia Coastal Plain. In the core, a few feet above the basal sand, there are fairly abundant reworked planktonic and benthic foraminifers of Eocene age, indicating erosion and wide dispersal of sediment from areas of Eocene outcrop in the inner Coastal Plain in early Calvert Beach time. In addition, McCartan (chap. B, this vol.) notes markedly higher proportions of hornblende, epidote, and other labile minerals in the nonopaque mineral assemblages of the upper Calvert and younger Tertiary formations.

The contact relationships between the Calvert Beach and Plum Point beds can be observed in Westmoreland County in outcrops in wave-cut cliffs along the Potomac River near Church Point, which is about 2 mi (3 km) southeast of Colonial Beach, Va., and 23 mi (37 km) northwest of the Haynesville site. At Church Point, the uneven Calvert Beach-Plum Point contact and the basal sandy lag deposits of the Calvert Beach, which contain abundant vertebrate bones and quartz pebbles as much as 3 to 4 in (7.6 to 10.2 cm) in maximum dimension, suggest an erosional unconformity involving considerable time.

In Maryland, the largest turnover of molluscan taxa in the lower Chesapeake Group (Calvert and Choptank Formations) occurs at the base of the Calvert Beach Member (Ward, 1985). A pronounced floral break, involving the extinction of important diatom species and the introduction of new species, also occurs at the base of the Calvert Beach (Andrews, 1978, fig. 4). Andrews estimates the hiatus to be about 0.7 m.y.

FAUNA AND FLORA

In the core, calcitic and aragonitic mollusks are present mainly in the sandier, lowermost 11 ft (3.4 m) of the Calvert Formation, where firm substrates provided conditions favorable for growth. The molluscan assemblage in these beds includes

Ostrea sp.
Pycnodonte percrassa (frag.)
Pecten humphreysii Conrad, 1842
Astarte thomasii Conrad, 1855
Marvacrassatella melinus (Conrad, 1832)
Cyclocardia sp. (=*Venericardia granulata* of Glenn, 1904, pl. 91, fig. 10, not of Say, 1824)
Mercenaria sp.
Melosia staminea (Conrad, 1839)
Turritella sp.

Both *Pecten humphreysii* (see fig. 18*A*) and *Marvacrassatella melinus* are guide fossils for the Fairhaven and Plum Point Marl Members of the Calvert Formation. *Pycnodonte percrassa* is known only from the lower and middle parts of the Plum Point Marl but may range downward into the Fairhaven Member. Fragments of the crustacean *Balanus* sp. and abundant planktonic foraminifers are also present in the lower, shelly and sandy part of the Calvert core. In the overlying, very clayey and silty middle and upper parts of the Calvert, diatoms and benthic foraminifers are the dominant fossil forms.

ENVIRONMENT OF DEPOSITION

The typically thick- to massively bedded, poorly sorted clay-silt and clayey and silty fine sand of the Calvert Formation suggest deposition in low-energy, fairly deep water environments well below wave base. Cross-stratification is generally absent, but a few cross-laminated beds indicate intermittent, weak bottom currents. Analysis of the foraminiferal assemblages (Poag, chap. D, this vol.) suggests gradually shallowing paleoenvironments at the Haynesville site ranging from outer sublittoral depths (100 to 150 m) during deposition of the lowermost Calvert to inner sublittoral depths (40 to 60 m) during deposition of the upper Calvert. According to Poag, the character of the foraminiferal assemblages in conjunction with the great abundance of diatoms and radiolarians indicate high-nutrient conditions, probably resulting from coastal upwelling.

AGE AND CORRELATION

Based mainly on Andrews' analysis of the diatom assemblages, we believe the diatomaceous Calvert beds in the Haynesville core to be equivalent, in large part, to the Plum Point Marl and Calvert Beach Members of the Calvert Formation as redefined by Ward (1984b). The basal shelly part of the Calvert in the core, which does not contain diatoms, is thought to be equivalent to the upper part of the Fairhaven Member or the lower part of the Plum Point Marl Member. The nearest sections in Virginia that are known to be equivalent to the Fairhaven Member, based on their diatom and silicoflagellate assemblages, crop out along the Rappahannock River just downstream from Wilmont Wharf at the King George County-Westmoreland County line (Ward, 1985) and in the nearby Oak Grove core section in Westmoreland County, Va. (Gibson and others, 1980).

The planktonic foraminiferal assemblage obtained from the lower shelly sand (see Poag, chap. D, this vol.) is indicative of zone N. 8 and is of Langhian age. The middle and upper parts of the Calvert section belong to undifferentiated planktonic foraminiferal zones N. 10–14 of the middle Miocene (lower and middle Serravallian). The diatom zonation enables refinement of this determination to planktonic foraminiferal zones N. 10–11.

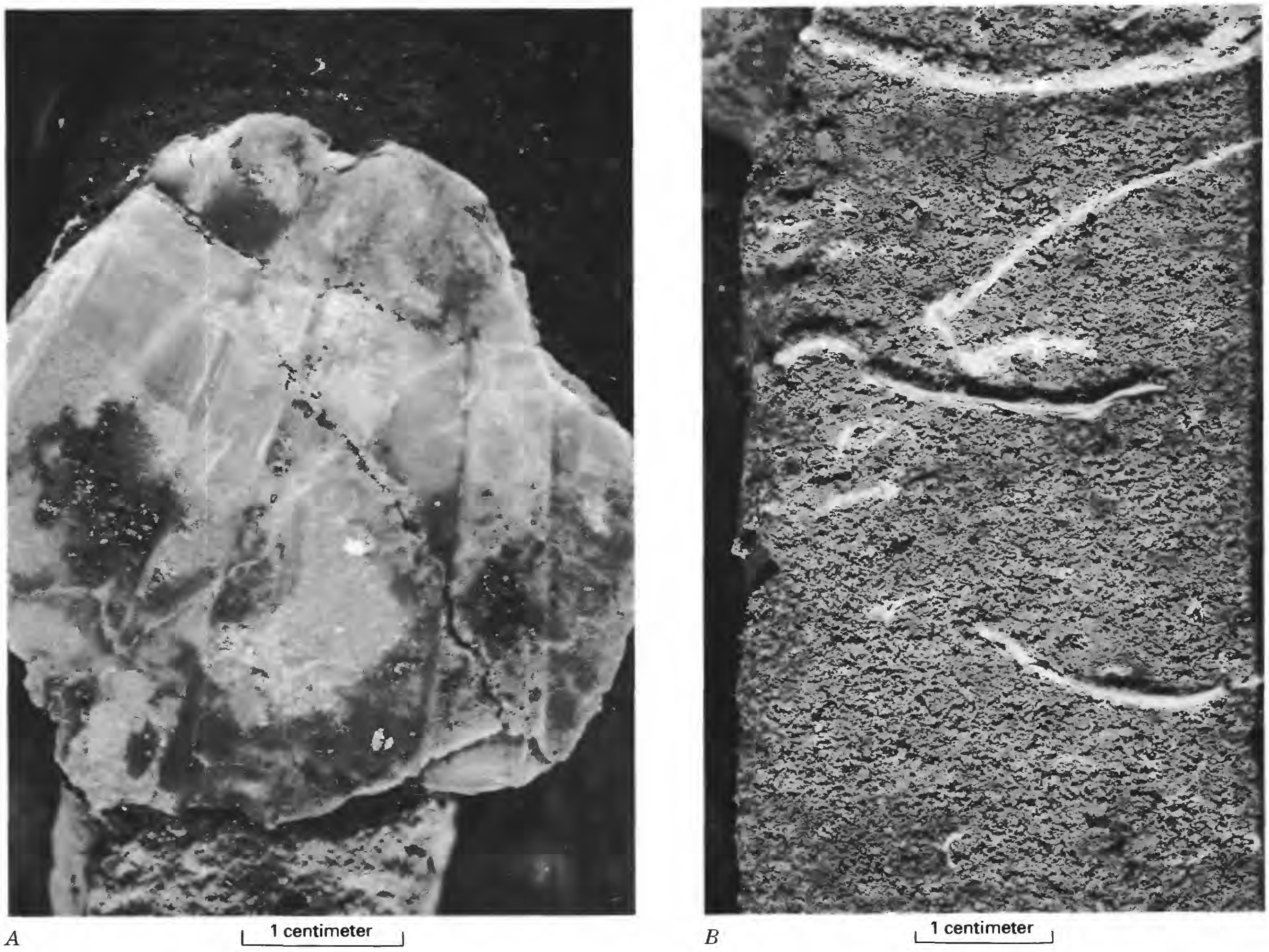


FIGURE 18.—Muddy and shelly, fine quartz sand of shelly sand beds of the Calvert Formation. *A*, Bedding-plane view of core showing interior part of valve of *Pecten humphreysii*, a lower Calvert guide fossil characteristic of Shattuck's "zones" 2–10 (alt. −181 ft). *B*, Disarticulated, aragonitic shells of pelecypods, variously oriented concave-up and concave-down, in light- and dark-mottled, intensely bioturbated, muddy sand typical of shelly sand member (alt. −172.2 to −172.9 ft).

ST. MARYS FORMATION

DEFINITION AND EXTENT

The upper middle and lower upper Miocene shelly sand of the St. Marys Formation is named for St. Marys County in southern Maryland, where the unit is exposed at numerous localities along the St. Marys River (Shattuck, 1902, 1904). The St. Marys is also well exposed in the Calvert Cliffs in southern Calvert County, Md., and is widely distributed but poorly exposed in a multicounty area in the lower parts of the Potomac and Rappahannock River drainage basins, Virginia. East of the Chesapeake Bay, the St. Marys Formation has been studied and mapped in the subsurface of the central and southern Delmarva Peninsula (Rasmussen and Slaughter, 1955; Sinnott and Tibbitts, 1968; Owens and Denny, 1979; Hansen, 1981). Based on the known distribution of the St. Marys, the Haynesville site is near the western margin of the preserved part of the St. Marys depositional basin. In the Haynesville core, the St. Marys directly overlies the Calvert Formation; the Choptank Formation, commonly present between the Calvert and the St. Marys, is absent.

LITHOLOGY

The St. Marys Formation in the Haynesville core, encountered at 12–49 ft (3.7–15 m) below sea level, consists of variably shelly, clayey and silty, very fine sand and lesser amounts of sandy clay-silt that is commonly bluish gray, greenish gray, and pinkish gray. These beds constitute two transgressive sedimentary sequences that, from the bottom up, are about 12 ft (3.7 m) and 25 ft (8 m) thick. For descriptive purposes, the two sequences are here informally designated, from

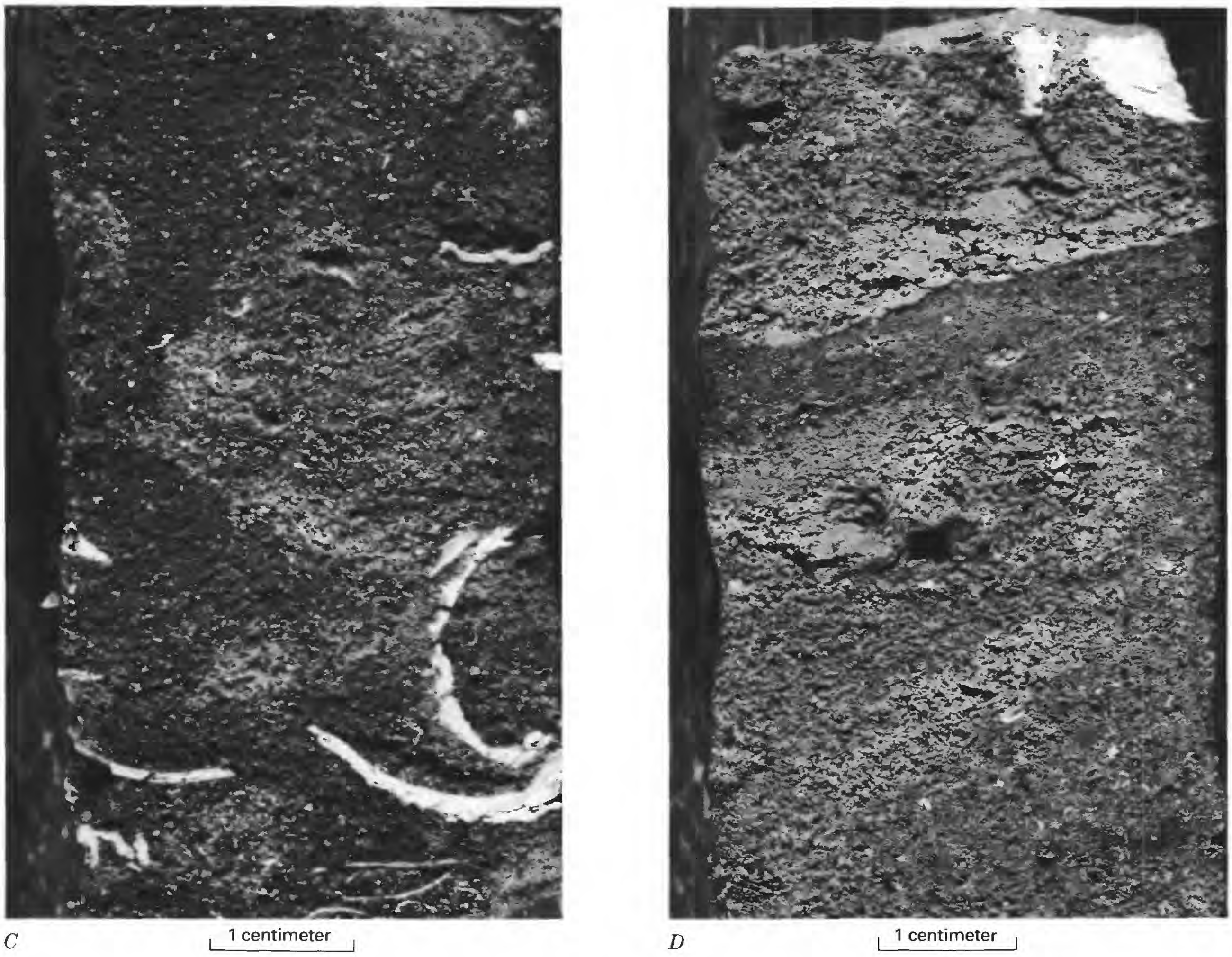


FIGURE 18.—*C*, Same as *B*. *D*, Thin-bedded and burrowed muddy sand with abundant phosphate (black grains), comminuted shell, and planktonic foraminifers (alt. −171.8 ft).

older to younger, units A and B of the St. Marys Formation. We did not recover the 5-ft section of core that includes the basal bed of unit A of the St. Marys and the uppermost part of the directly underlying Calvert Formation. Therefore, placement of the lower contact of unit A at 49 ft (15 m) below sea level is based on the abrupt shift to the right of the natural gamma curve resulting from passage of the probe from the upper quartzose sands of the Calvert Formation into the overlying, much more radioactive, clayey and silty phosphatic sand of the lowermost St. Marys (chap. A–pl. 1). Above the interval of no recovery is about 9 ft of very fine, greenish-gray, sparsely glauconitic quartz sand. Two shell beds in this interval (fig. 21) contain poorly preserved clams ("*Anadara*" sp., *Thracia* sp., *Chesapecten* sp.) and gastropods (*Turritella* sp.). At the top of unit A, the sand grades upward into 2 ft (0.6 m) of sandy and clayey silt penetrated by sand-filled burrows from the overlying unit B of the St. Marys (fig. 22).

In the core, the contact between units A and B of the St. Marys (alt. −36.8 ft (−11 m)) is abrupt and conspicuous and appears to be a minor erosional unconformity. The basal fine sand of unit B contains scattered medium to very coarse sand-sized grains and fine pebbles of quartz and phosphate. Fairly abundant shells and shell fragments, including *Isognomon* (*Hippochaeta*) sp., *Mercenaria* sp., "*Cardium*" sp., and *Turritella* sp., are also present. Greenish- to bluish-gray, clayey and silty sand in the lower and middle parts of Unit B grade upward to pinkish-gray sand and sandy clay-silt. The pinkish-gray color of the upper St. Marys also has been observed in outcrops of equivalent beds in the Tappahannock, Va., area, and in exposures in the extensive bluffs along the Rappahannock River between Tappahannock and the Fones Cliffs, which are in northwesternmost Richmond County. Unit B fines upward to an altitude of 20 ft (6.1 m) below sea level, where sandy clay-silt is abruptly overlain by coarser beds of very fine,

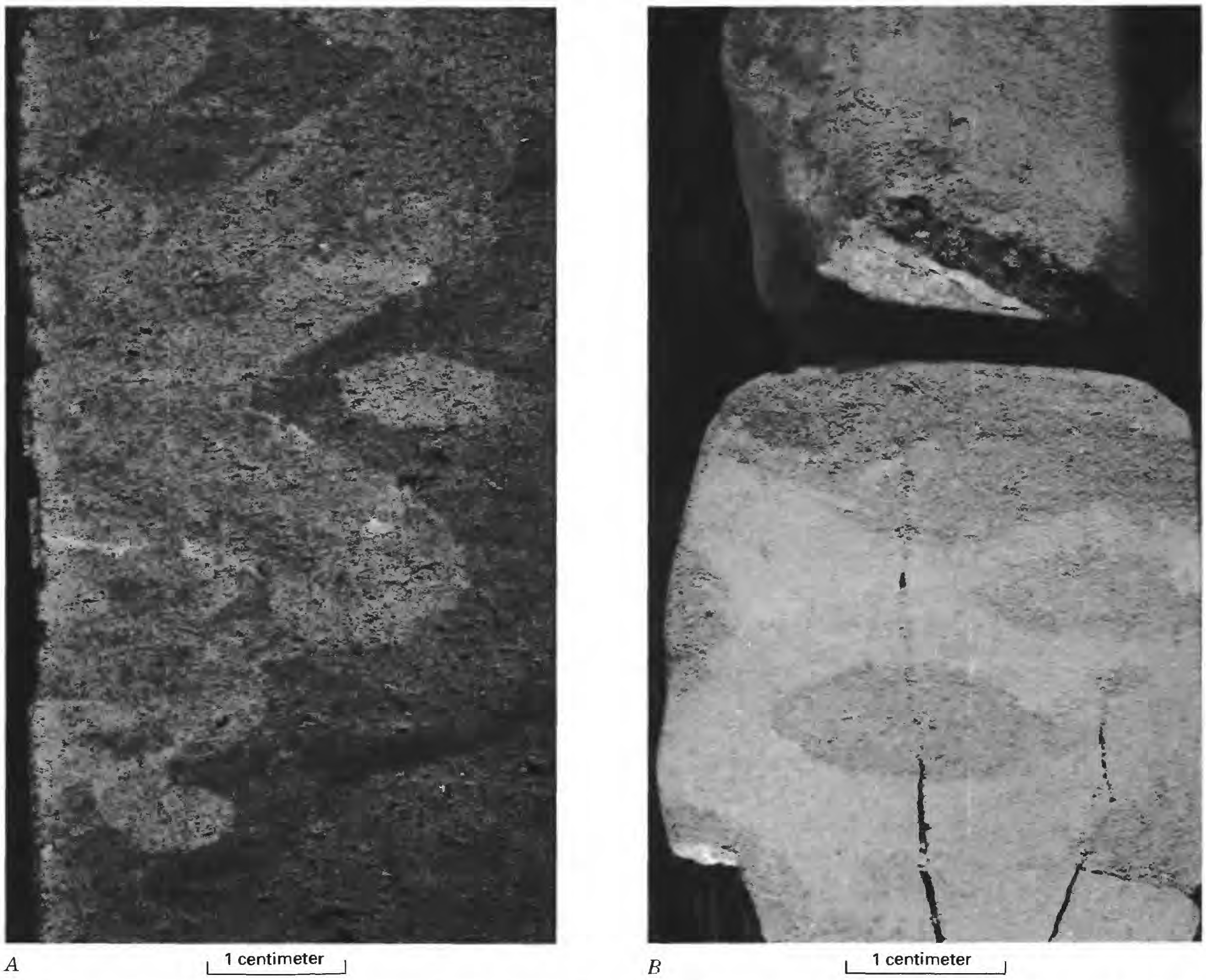


FIGURE 19.—Diatomaceous clay-silt and fine sand of Plum Point beds of the lower Calvert Formation. *A*, Burrowed, sandy and clayey, diatomaceous silt in lower part of lower fining-upward sequence of the Plum Point beds; black sand grains are phosphate (alt. −167.2 ft). *B*, Burrowed contact at 3.2-cm mark (alt. −135.1 ft) between basal fine sand and bone lag of upper fining-upward sequence of Plum Point beds and underlying lighter colored, diatomaceous clay-slit at the top of the lower sequence of Plum Point beds.

silty sand. Some finely crystalline iron sulfide (pyrite or marcasite) is present in the upper part of Unit B. Sand- and clay-filled burrows are the dominant sedimentary features. Thin to very thin wavy bedding and shear structures, believed to be caused by sediment loading, were also observed.

FAUNA AND FLORA

The poorly preserved molluscan assemblage in the two St. Marys sequences in the core includes the following taxa:

Chesapecten sp. (frag.)
"*Cardium*" sp. (large mold and cast)
Isognomon (*Hippochaeta*) sp.
"*Anadara*" sp.
Thracia sp.
Mercenaria sp.
Turritella sp.

The large mold and cast of "*Cardium*" sp. indicates that the above assemblage is post-Choptank in age. The presence of the pearlaceous bivalve *Isognomon* (*Hippochaeta*) sp. and the absence of *Glossus fraterna* (Say), which is widely distributed in the Eastover Formation, indicate equivalency with the St. Marys Formation of Maryland.

A few ghosts of large, disk-shaped diatoms were observed in the upper St. Marys sequence (unit B). The absence of diatoms or their lack of preservation in the St. Marys Formation, compared with the abundance of well-preserved diatomaceous material in the Calvert and

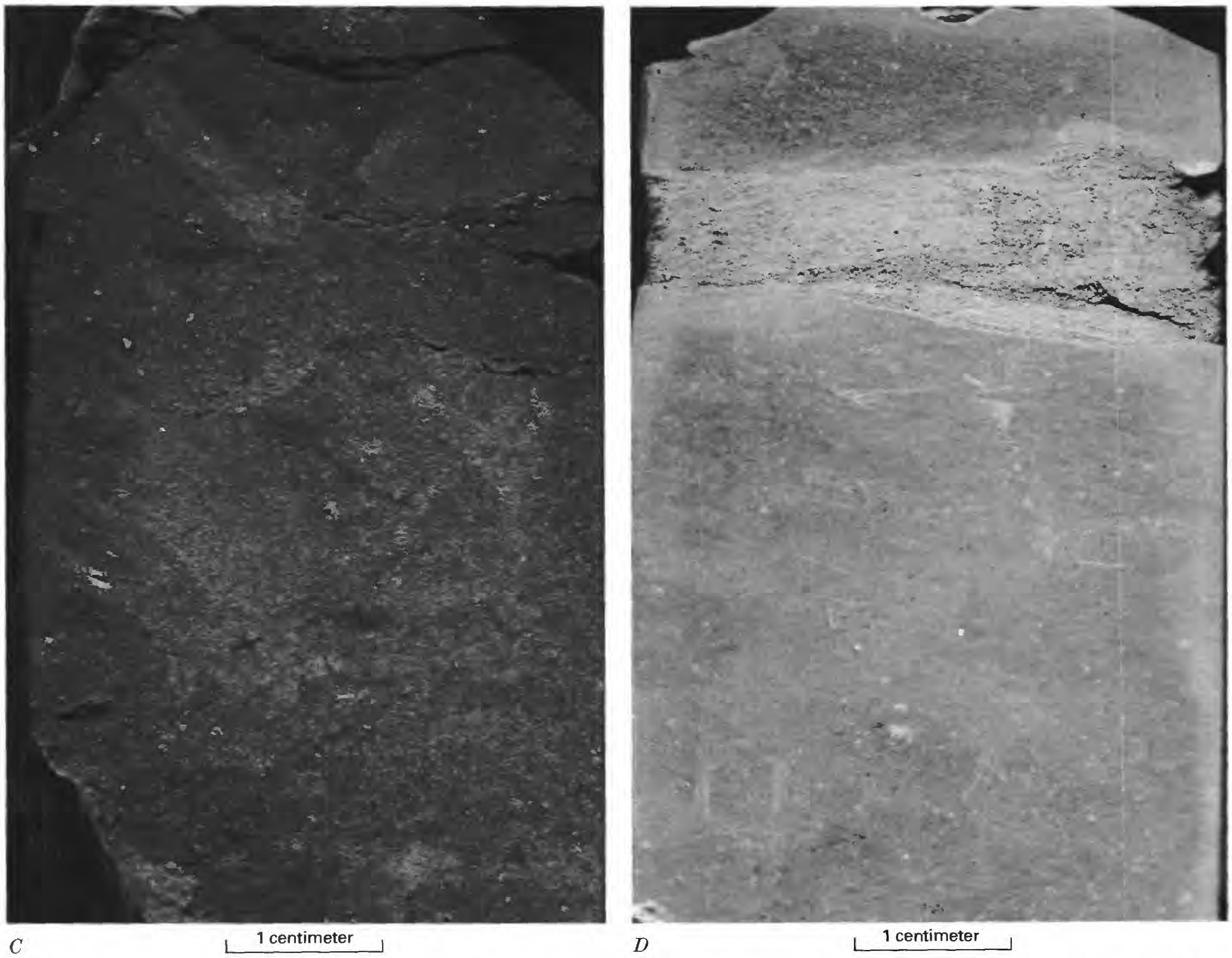


FIGURE 19.—*C*, Mottled, olive-gray, muddy quartz sand in lower part of upper fining-upward sequence of Plum Point beds (alt. −134 ft). *D*, Light-olive-gray, diatomaceous clay-silt and thin bed of crossbedded, very fine sand in uppermost part of Plum Point beds (alt. −114.1 ft).

Choptank Formations, is one of the more notable differences between the St. Marys Formation and the older Chesapeake Group formations.

ENVIRONMENT OF DEPOSITION

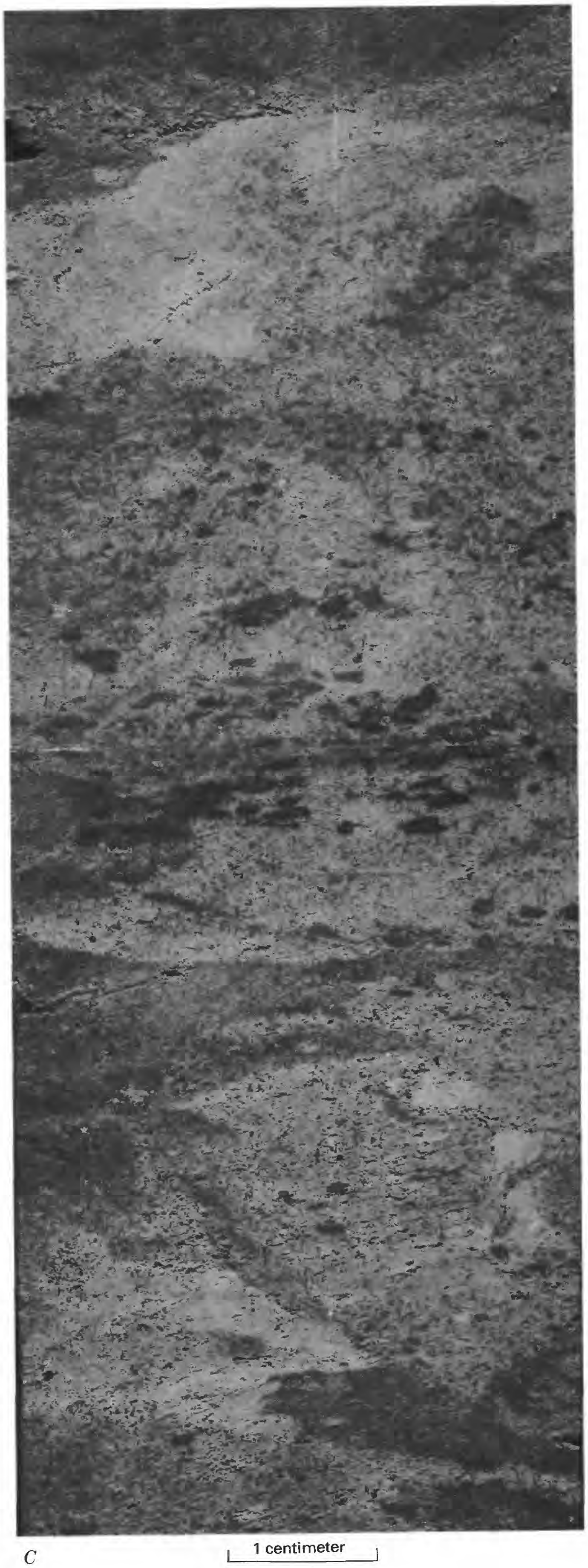
In the Haynesville core, the molluscan fauna in units A and B of the St. Marys is sparse and highly leached, indicating locally poor conditions for preservation. However, the nearby St. Marys outcrops (unit B) at Essex Millpond (fig. 1) and along Piscataway Creek, south of Tappahannock in Essex County, Va., contain highly diverse, well-preserved molluscan assemblages, indicating deposition in open-shelf waters of normal salinity. These assemblages also suggest subtropical to warm-temperate climatic conditions.

AGE AND CORRELATION

On the basis of lithology, thickness, stratigraphic position, and molluscan assemblages, we consider units A and B of the St. Marys in the Haynesville core to be equivalent to the much more abundantly fossiliferous, bipartite St. Marys section penetrated by a stratigraphic test hole at Essex Millpond in Essex County, Va., about 12 mi southwest of Haynesville (Wayne L. Newell, USGS, unpub. data). The very well preserved molluscan assemblage in the millrace exposures at Essex Millpond, (=unit B of the St. Marys of the Haynesville core) is characterized by the large bivalve *Chesapecten santamaria*. This guide fossil clearly indicates correlation with the upper St. Marys Formation (=Windmill Point beds of Ward, 1984b) in its type area along the St. Marys River in St. Marys County, Md.

A

B



C

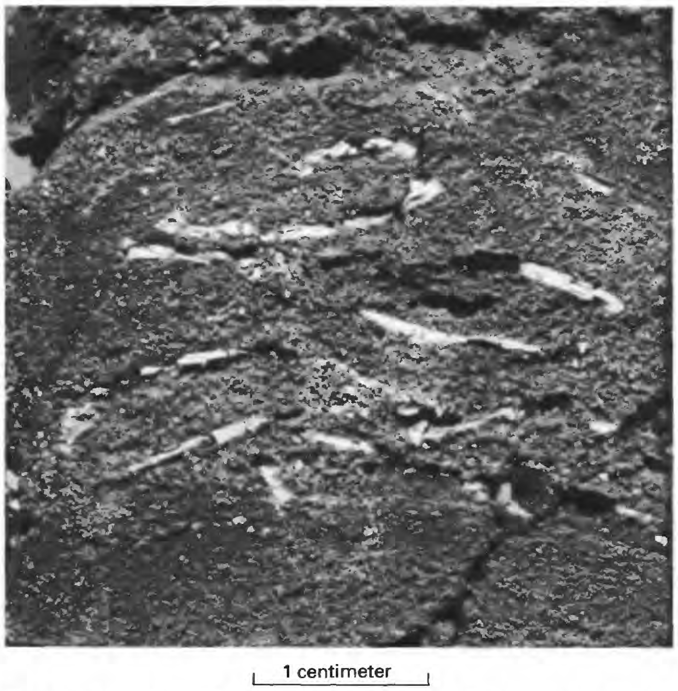


FIGURE 21.—Greenish-gray, very fine, sparsely glauconitic quartz sand containing abundant aragonitic bivalves and gastropods leached to a chalky white (alt. −47.8 ft), near base of unit A of the St. Marys Formation.

The St. Marys Formation has been considered to be of late middle Miocene (Serravallian) and (or) early late Miocene (Tortonian) ages (see Gibson, 1982, 1983a, 1983b). Samples from the St. Marys outcrops at Essex Millpond near Tappahannock, Va., have yielded a small planktonic foraminiferal assemblage indicative of foraminiferal zone N. 16 and supporting an early late Miocene age for the Windmill Point beds of the St. Marys Formation (Paul Huddlestun, Georgia Geological Survey, oral commun., 1986). The precise ages of the lower St. Marys unit at Essex Millpond and unit A of the St. Marys in the Haynesville core are speculative. It seems possible that these lower St. Marys beds in Virginia may be equivalent, in part, to the Little Cove Point beds of Blackwelder and Ward (1976) and Ward (1984b), which crop out in Calvert County, Md. Planktonic foraminifers have not been obtained from the St. Marys beds at the Maryland localities.

◀ FIGURE 20.—Biogenic structures in clayey silt and very fine sand of Calvert Beach beds of the upper Calvert Formation. *A*, Diatomaceous clayey silt in uppermost part of next to lowest fining-upward sequence of Calvert Beach beds (alt. −76.1 ft). Sand-filled burrows extend downward from basal sands of overlying sequence. *B*, Burrowed, silty, very fine, sparsely phosphatic quartz sand in lower part of sand-silt-clay sequence of upper Calvert Beach beds (alt. −68.1 ft). *C*, Lenticular bedded, very diatomaceous, sandy clay-silt containing abundant small, dark, clay-filled burrows in uppermost Calvert Beach beds (alt. −61.3 to −61.7 ft).

FIGURE 22.—Sandy and clayey silt of uppermost part of unit A of the St. Marys Formation penetrated by sandy burrow fills from overlying unit B (alt. −38.2 ft). The contact between units A and B is 16 in above top of core segment shown in photograph.

EASTOVER FORMATION

DEFINITION AND EXTENT

The upper part of the upper Miocene section in the Haynesville core, extending from an altitude of −12 to +43.5 ft (−3.7 to +13 m), is the Eastover Formation, a clayey and silty fine quartz sand and clay-silt commonly containing some molluscan shell material. The Eastover Formation is named for the Eastover Plantation in Surry County in the south-central Virginia Coastal Plain (Ward and Blackwelder, 1980). Abundantly fossiliferous Eastover beds are well exposed at the type section, which is about 3 mi (5 km) east of Eastover in wave-cut cliffs on the south bank of the James River. The Eastover is widely distributed in the Virginia and Maryland Coastal Plain, extending from the subsurface of the Eastern Shore westward to the Virginia Fall Line, where the unit laps over older Coastal Plain formations onto crystalline rocks of the Piedmont and continental red beds of the early Mesozoic Taylorsville basin. In Virginia, the Eastover is commonly divided into a lower member, the Claremont Manor, consisting of slightly to moderately shelly, poorly sorted, clayey and silty fine sand and sandy clay, and an upper member, the Cobham Bay, which is relatively well sorted, very shelly fine sand (Ward and Blackwelder, 1980; Ward, 1984b). In the Haynesville core, the Eastover likewise consists of a clayey and silty lower part and a better sorted, sandy upper part. Although these strata are probably equivalent to the Claremont Manor and Cobham Bay Members as developed in their type area along the James River, field mapping in intervening areas is needed to establish firm correlations.

LITHOLOGY AND STRATIGRAPHIC RELATIONS

In the Haynesville core hole, the Eastover Formation unconformably overlies muddy, fine sand of the St. Marys Formation that is very similar to part of the Eastover section. The contact between the two formations is abrupt and is marked by a lag of very fine to fine (¼ in (6 mm) maximum diameter) pebbles of quartz and phosphate. No core was recovered from the 8-ft (2.4-m) interval above the lowermost few inches of the Eastover. However, the single-point resistivity log of the core hole indicates a 4-ft-thick (1.2-m-thick) basal sand that grades abruptly upward into about 4 ft of very clayey and silty beds. Above the interval of no recovery is a 23-ft-thick (7-m-thick) section of dark-gray to bluish-gray, silty clay and clayey silt interbedded with lesser amounts of clayey and silty, very fine, micaceous sand. This fine-grained sequence above the basal sand, constituting approximately the lower half of the Eastover Formation in the core, is medium to thin bedded and laminated and contains abundant burrows (figs. 23*A–C*). Some intervals have lenticular and wavy bedding. The rhythmic mud/sand bedding typical of this unit is better developed in excellent exposures along the Rappahannock River in Essex and Middlesex Counties, near Butylo, Va., about 13 mi (21 km) due south of the Haynesville site. Small fragments of wood and iron sulfide concretions are common throughout this part of the section. Rare molds and casts of mollusks occur near the base of the Eastover. The lack of preserved shell material higher in the core, compared with nearby, shelly outcrop sections, is notable and somewhat puzzling. After drying and oxidation, sediment colors in the core section changed to shades of light gray, grayish orange, and yellowish brown, which are similar to colors of weathered outcrops.

The upper, sandier part of the Eastover Formation, extending from +19 to +33 ft (5.8 to 10 m), includes slightly clayey and silty, very fine to fine, gray, micaceous quartz sand containing abundant clay-silt laminae (fig. 23*D*). Black heavy minerals constitute as much as 5–10 percent of the sand. Above an altitude of 26 ft (8 m), the sand is oxidized, ranging from pale yellowish orange (10 YR 8/6) to dark yellowish orange (10 YR 6/6). An overlying 10.5-ft-thick (3.2-m-thick) unit of fairly clean, loose, fine to medium quartz sand (alt. 33–43.5 ft (10–13 m)), extending from the clayey and silty Eastover beds upward to the base of a fine to coarse, gravelly sand of the lower Yorktown Formation (chap. A–pl. 1), is here included in the Eastover. Samples of the clean, loose sand were not recovered by the wireline coring operation but were obtained in an adjacent shallow core hole by the split-spoon coring method.

FAUNA

The Eastover section in the Haynesville core is sparsely fossiliferous, containing only a very few molds and casts of mollusks. The sparsity of mollusks may be the result of locally unfavorable growth conditions or locally poor preservation of shell material. Therefore, to support our interpretations of Eastover depositional environments in this area, a list of fauna from shelly and sandy beds of the upper Eastover Formation exposed in new road cuts along Virginia Route 620, about 2 mi (3 km) west of the Haynesville site and just south of Garlands Millpond, is included as follows:

Bivalvia
- *Nucula proxima* Say
- *Nuculana acuta* (Conrad)
- "*Arca*" *carolinensis* (Dall)
- *Chesapecten middlesexensis* frag., juvenile
- *Anomia simplex* D'Orbigny
- *Parvilucina crenulata* (Conrad)

- *"Spisula" rappahannockensis* Gardner
- *Tellina* sp.
- *Mesodesma* sp. (new)
- *Lirophora* sp. (new)
- *Mercenaria berryi* (Gardner)
- *Caryocorbula inequalis* (Say)

Gastropoda
- *Vitrinella lipara* (H.C. Lea)
- *Crepidula fornicata* (Linn)
- *Busycotypus coronatum* (Conrad)
- *Crucibulum* sp.
- *Nassarius* cf. *Nassarius peralta* (Conrad)
- *Nassarius* sp.
- *Bulliopsis quadrata* (Conrad)
- *Fusinus rappahannockensis* Gardner
- *Terebra simplex* Conrad
- *Acteocina canaliculata* (Say)

Brachiopoda
- *Discinisca lugubris* (Conrad)

Crustacea
- *Balanus* sp.

The molluscan assemblage at Garlands Millpond is dominated by the small bivalve *"Spisula" rappahannockensis* Gardner, which is considered to be a guide fossil for the Eastover Formation (Blackwelder and Ward, 1976, p. 44–45). The assemblage is similar to those in upper Eastover outcrops along the Rappahannock River below Bowlers Wharf (Ward and Blackwelder, 1980, loc. 2) and at Union Mills near Downings, Va., which are 10.5 mi (17 km) southwest and 7.5 mi (12 km) southeast of the Haynesville site, respectively.

ENVIRONMENT OF DEPOSITION

The predominance of horizontally bedded, fine-grained sediment (clay, silt, very fine sand) in the lower Eastover Formation and the substantially lower species diversity of the molluscan assemblage, compared with assemblages in the upper Eastover and the directly underlying St. Mary's Formation, suggest deposition in a fairly low energy, restricted basin on the inner shelf. The dark sediment color and the abundance of iron sulfide indicate reducing conditions. The sequence of alternating medium to thin beds and laminae of mud and sand, showing an upward transition from simple interlayering to lenticular and wavy bedding, suggests shallow waters affected by tidal currents.

The coarser, cleaner sand of the upper Eastover in the core and the fairly diverse molluscan assemblages in nearby exposures of upper Eastover beds (Garlands Millpond, Union Mills, Bowlers Wharf) indicate deposition in fairly shallow, open-marine waters. Taxa such as *Scaphella* sp., *Peristernia* sp., *Oliva idonea* Conrad, and *Lirophora* sp. from the Bowlers Wharf locality suggest warm, subtropical climatic conditions.

AGE AND CORRELATION

The Eastover strata in the Haynesville core are correlated with the type Eastover Formation because of lithic similarity and stratigraphic position. The equivalency of at least the sandy, upper part of the Eastover section in the core to the Cobham Bay Member is indicated by nearby exposures of shelly Eastover sand that contain well-preserved molluscan assemblages typical of the Cobham Bay (see preceding section on "Fauna" and Ward and Blackwelder, 1980).

Gibson (1983b) tentatively placed the Eastover beds in Virginia in the uppermost part of foraminiferal zone N. 16, and in N. 17 and N. 18, which are of late Tortonian, Messinian, and early Zanclian ages. Samples from the upper Eastover beds at Laytons Landing on the Rappahannock River, about 11 mi (18 km) due south of Haynesville, Va., have yielded planktonic foraminifera indicative of zone N. 17 of middle late Miocene age (Paul Huddlestun, oral commun., 1986).

YORKTOWN FORMATION

DEFINITION AND EXTENT

The Yorktown Formation was named by Clark and Miller (1906) for exposures of shelly sand and clay in cliffs along the York River near Yorktown in York County, southeastern Virginia. There, the formation is as much as 60 ft (18 m) thick and contains fossils assemblages indicating a shallow-shelf depositional environment. The lithology and paleontology of the Yorktown have been described by many workers, including Clark and Miller (1912), Mansfield (1943), Johnson (1972, 1976), and Ward and Blackwelder (1980). Mainly on the basis of studies of well-exposed sections along the James, York, and Rappahannock Rivers in southeastern and central Virginia, Ward and Blackwelder (1980) redefined the Yorktown Formation and divided it into the Sunken Meadow, Rushmere, Mogarts Beach, and Moore House Members. These members have not been recognized in the more updip Haynesville, Va., area, where the Yorktown consists of poorly fossiliferous, fine to coarse sand and sandy gravel believed to have been deposited in various marginal-marine environments (Stephenson and MacNeil, 1954; Newell and Rader, 1982). The Yorktown Formation is widely distributed in the Middle Atlantic Coastal Plain, extending from the subsurface of the Virginia and Maryland Eastern Shore (Owens and Denny, 1984; Mixon, 1985) westward across the Coastal Plain to the edge of the Piedmont at Richmond and Petersburg, Va. The formation occurs southward to the Fort Barnwell and New Bern areas of Craven County,

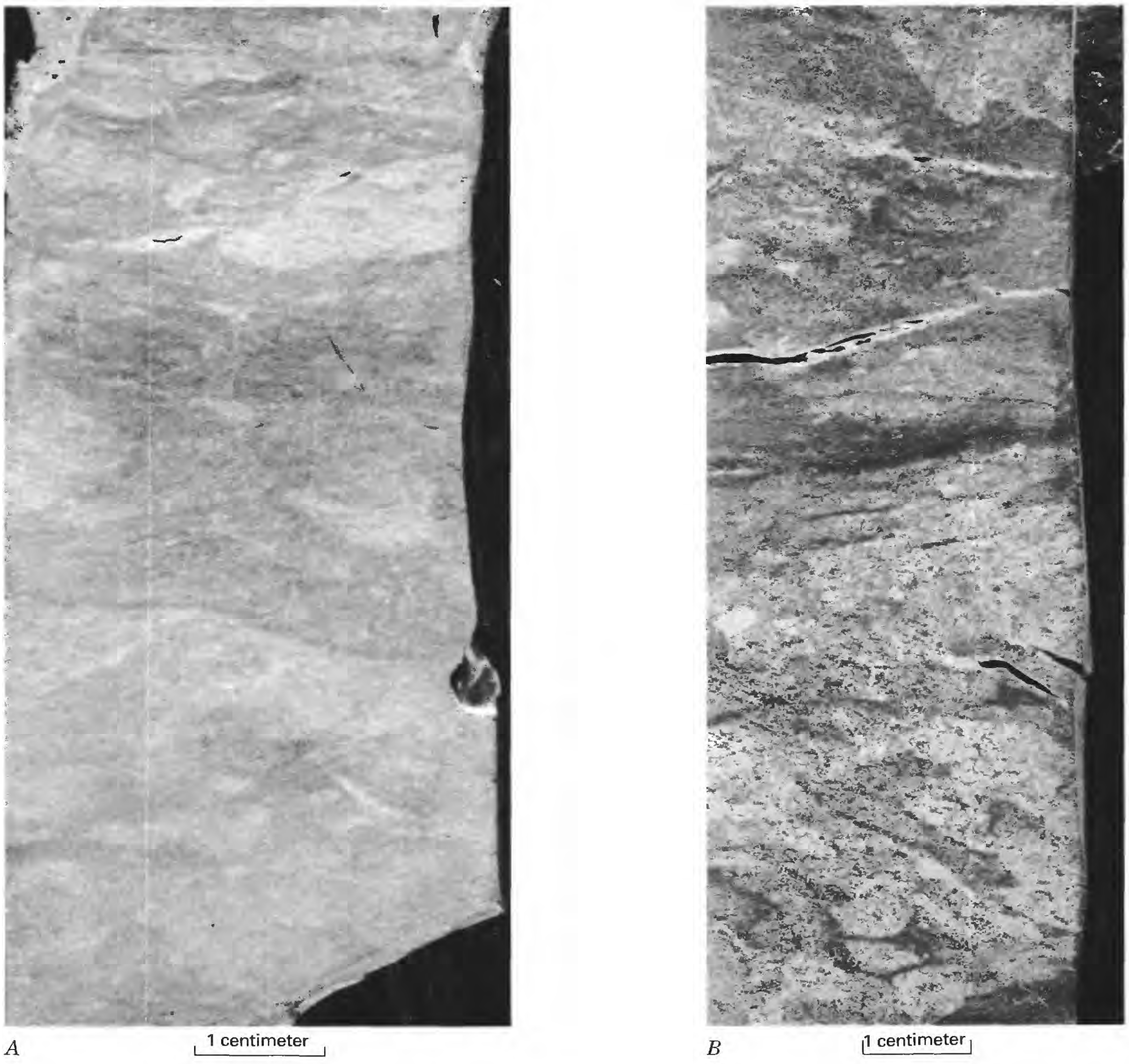


FIGURE 23.—Interbedded, laminated, and thin-bedded bluish-gray clay-silt and very fine sand of the Eastover Formation. *A*, Alternating, very thin, irregular beds of silty clay (middle) and sandy silt (top and bottom) in lower part of Eastover Formation (alt. −3.2 ft). *B*, Extensively bioturbated, very fine sand and silty clay (alt. 11.8 ft).

N.C. (Ward and Blackwelder, 1980), and northward at least as far as St. Marys County, Md. (McCartan, oral commun., 1986).

LITHOLOGY AND STRATIGRAPHIC RELATIONS

At the Haynesville site, the Yorktown Formation includes 43.5 ft (13 m) of fine to coarse quartz sand, occurring in the subsurface between the Eastover Formation and the floor of the borrow pit where test holes 2 and 3 were drilled, and about 22 ft (7 m) of similar deposits exposed in the pit walls. The top of the Yorktown Formation and the contact relationships between the Yorktown and the overlying sandy and gravelly strata that cap the higher interfluve areas were not observed in the vicinity of the Haynesville site. Presumably, the Yorktown in this area is overlain unconformably by thin deposits of the Bacons Castle Formation and (or) the "Moorings unit" of Oaks and Coch (1973).

The lower 2–3 ft (0.6–0.9 m) of the Yorktown and the formational contact with the Eastover were not within a sampled interval; thus, placement of the contact at an altitude of 43.5 ft (13 m) is based on the driller's observation of the base of a gravel bed at that horizon. The lowest Yorktown sample (alt. 46 ft (14 m)) is the uppermost part of a poorly sorted, pebbly lag deposit and is an abrupt change from the finer, better sorted sand and clay-silt of the upper Eastover Formation. Regional truncation and overlap of the Eastover and older Coastal

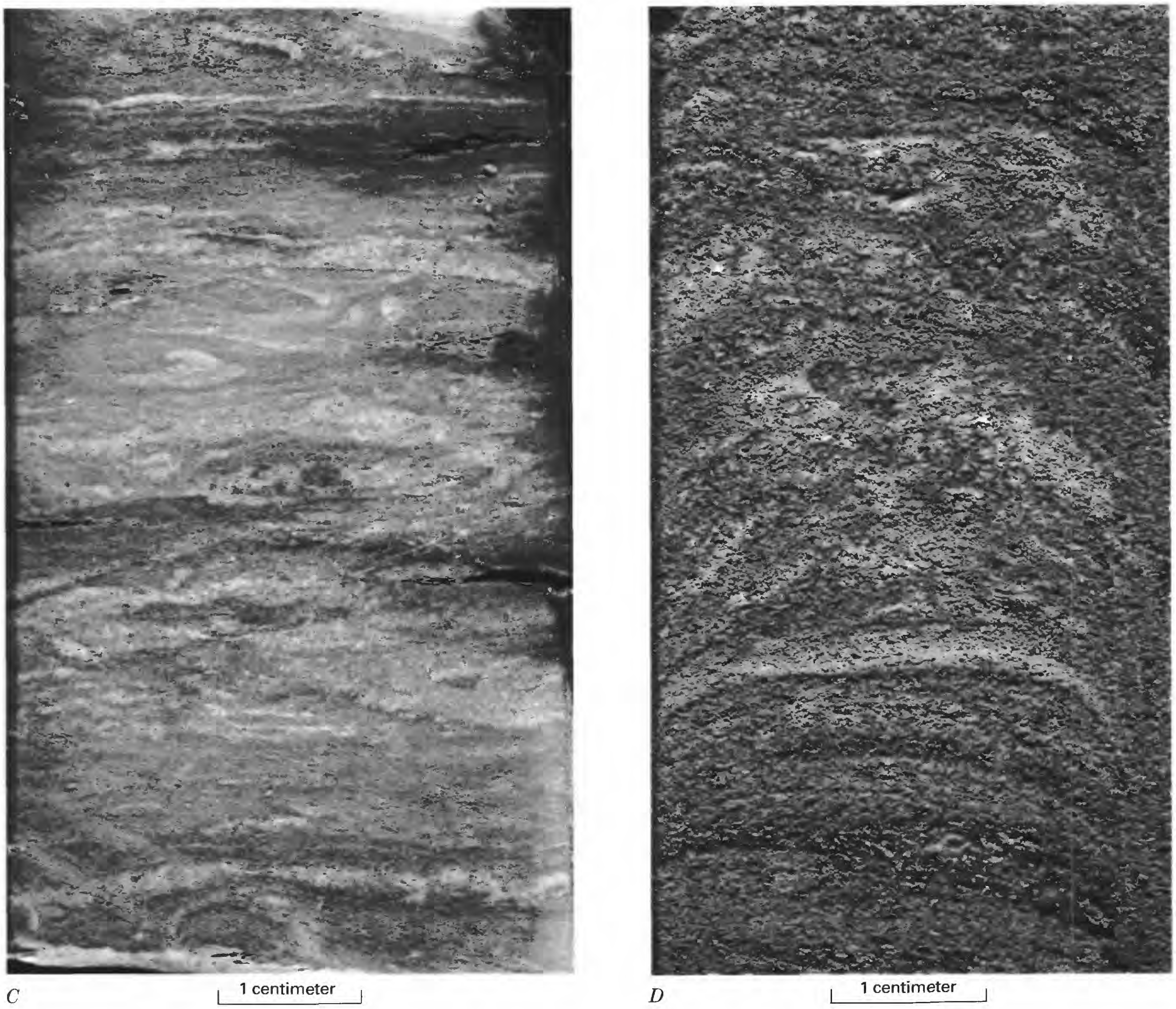


FIGURE 23.— *C*, Alternating laminae of bluish-gray, silty clay and clayey and silty, very fine sand with some burrows and abundant iron sulfide (alt. 16.5 ft). *D*, Burrowed and laminated, very fine to fine, clayey and silty, micaceous quartz sand and sandy clay-silt typical of upper part of Eastover Formation (alt. 27.4 ft).

Plain formations by the Yorktown and the presence of thin but extensive lag deposits at the base of the Yorktown throughout northeastern Virginia indicate that in this area the lower boundary of the formation is an erosional unconformity.

Overlying the basal pebbly sand of the Yorktown is 22.5 ft (7 m) of moderately well sorted to poorly sorted, very slightly clayey and silty, fine to medium quartz sand containing minor amounts of mica and black heavy minerals. A few clay laminae and clay-lined burrows are present throughout this interval. Unoxidized beds in the lower part of the interval are very light gray to white, but the dominant colors are light brown and pale to dark yellowish orange. The upper 40 ft (12 m) of the Yorktown, including the uppermost part of the core and the outcrop section at the Haynesville site, is crossbedded, fine to very coarse, pebbly, very light gray to yellowish-gray sand. Most of the pebbles are quartz, but one 4-ft-thick (1.2-m-thick) sand bed contains abundant, rounded, 1- to 4-in (2.5- to 10-cm) clasts of yellowish-gray clay.

PALEONTOLOGY AND PALEOENVIRONMENT

Calcareous fossil material, if ever preserved in the Haynesville area, has been removed by leaching. However, two types of trace fossils suggest an abundance of marine life. The most common trace fossil, present in the core and in nearby outcrops, is large, clay-lined burrows of the *Ophiomorpha nodosa* type. *Ophiomorpha nodosa* closely resembles burrows of the crustacean *Callianassa major*, which lives in littoral and shallow neritic environments along the present-day Atlantic Coast (Weimer and Hoyt, 1964; Howard, 1971b). A less common biogenic structure, resembling heart urchin burrows (Howard, 1971a, fig. 10), occurs in the upper Yorktown beds in the borrow-pit exposure at the Haynesville site.

The *Ophiomorpha nodosa* and the heart urchin(?) burrows suggest that the Yorktown at the Haynesville site was deposited in very shallow, nearshore-shelf waters. The large- and small-scale trough crossbedding and the coarse, cleanly washed sand and gravel of the upper Yorktown indicate deposition in a high-energy environment affected by strong currents and breaking waves.

AGE AND CORRELATION

The Yorktown Formation was long considered Miocene in age (MacNeil, 1938; Mansfield, 1943; Brown and others, 1972). Recently, however, studies based on planktonic foraminifers and ostracodes have placed the Yorktown in foraminiferal zones N. 18, N. 19, and N. 20 of the early and early late Pliocene (Akers, 1972; Ward and Blackwelder, 1980; Gibson, 1983a, 1983b; Hazel, 1983). The correlation of the sandy and gravelly Yorktown beds in the core with the highly fossiliferous, marine Yorktown to the south and east is based on reconnaissance studies by Blackwelder and Ward (1976), Ward and Blackwelder (1980), and Newell and Rader (1982) and an unpublished geologic map of the Tappahannock, Va., area by Newell.

SUMMARY AND DISCUSSION

1. At the Haynesville core site, the upper Paleocene Aquia Formation overlies the Lower Cretaceous Potomac Formation with great unconformity. Upper Cretaceous formations, the lower Paleocene Brightseat Formation, and the lowermost part of the Aquia Formation are absent. Similar unconformable relationships between Cretaceous and Tertiary sections have been reported in a core from the Oak Grove test well, Westmoreland County, Va. (Reinhardt, Newell, and Mixon, 1980). There, the Aquia overlies the Potomac Formation but includes, at its base, as much as 41 ft (12 m) of strata that may be equivalent to the Brightseat Formation (Gibson and others, 1980, p. 16). Elsewhere in the northern Virginia Coastal Plain, our shallower core holes and numerous outcrops and water well sections spanning the Cretaceous-Tertiary boundary clearly show a regional erosional unconformity representing most or all of Late Cretaceous time and, commonly, part of the Early Cretaceous and the early Paleocene. This regional unconformity is also recognized offshore on the Atlantic Continental Shelf (Poag, 1987). Recognition of a major unconformity between the Cretaceous and Tertiary sections at the Haynesville site agrees with the findings of Reinhardt, Newell, and Mixon (1980, p. 4), who question the stratigraphic usefulness of the "transitional beds," a subsurface unit of glauconitic sand and brightly colored, variegated clay and silt occurring near the top of the Cretaceous section in Virginia (see Teifke, 1973). These beds were thought to be a transition between the very glauconitic lower Tertiary strata and the feldspathic quartz sands of the Patuxent Formation, a Lower Cretaceous rock unit that, in Virginia, is now included in the Potomac Formation. We conclude that the "transitional beds" reflect the mixing of rotary drill cuttings from both Lower Cretaceous and lower Tertiary formations. Similarly, the Mattaponi Formation as defined by Cederstrom (1957) at the type well at Colonial Beach, Va., includes the middle and lower parts of the Aquia Formation, as much as 334 ft (102 m) or more of the Potomac Formation and, possibly, the Brightseat Formation. More recently, it has been recommended that the name Mattaponi Formation be abandoned (Ward, 1984b, p. 18), a conclusion with which we concur.

2. The Aquia Formation consists of 118.4 ft (36 m) of very poorly sorted to well-sorted, variably shelly, glauconitic quartz sand that is interbedded, in its lower part, with sandy limestone and carbonate-cemented arenite. In the core, as at other localities in the Virginia and Maryland Coastal Plain, the Aquia is subdivided into two members which appear to be separated by a minor unconformity. The Piscataway Member, below, is more poorly sorted, clayier, siltier, and more calcareous than the overlying Paspotansa Member. The Paspotansa beds are moderately well sorted to well-sorted, thick- to massively bedded, medium to coarse, glauconitic sand containing abundant brown goethite pellets. The Paspotansa is a much coarser grained, cleaner, more friable sand than in inner Coastal Plain areas and appears to represent an extension southward into Virginia of the "sandbank" facies of the upper Aquia Formation in Maryland (Hansen, 1974). The Piscataway beds are assigned to foraminiferal zone P. 4, whereas the Paspotansa belongs to zone P. 5.

3. In the core, the uppermost coarse sand of the Paspotansa Member of the Aquia Formation grades abruptly upward into an 8-in-thick (20-cm-thick), light-gray to pinkish-gray, kaolinitic clay that is believed to be the truncated, downdip remnant of the Marlboro Clay. The Marlboro at the Haynesville site is the southeasternmost known occurrence of the unit on the Northern Neck of Virginia. Elsewhere in the inner and middle Coastal Plain of Virginia and Maryland, the Marlboro is a thin (0–30 ft (0–9 m)) but extensive unit of gray to reddish-brown plastic clay which commonly contains

minor amounts of interbedded very thin beds and laminae of silt and, rarely, very fine sand. Outcrops and other cores in Virginia (Reinhardt, Newell, and Mixon, 1980; Mixon and Powars, unpub. data) also show conformable contact relationships, ranging from abrupt gradation to interbedding of lithologies, with the underlying Aquia Formation. We consider the Marlboro Clay to be part of the upper Aquia depositional sequence and suggest that the unit was deposited as regressive, peridelta muds in restricted shelf waters. The basin of deposition may have been separated, in part, from the open ocean by a broad, largely submarine bar complex that developed as an extension of the clean, coarse sands making up the "sandbank facies" of the upper Aquia Formation in Maryland and Virginia (see section describing Paspotansa Member in this paper and Hansen, 1974). In the Haynesville core and in our other core holes in Virginia the contact between the Marlboro Clay and the overlying Nanjemoy Formation is an erosional unconformity.

4. The lower Eocene Nanjemoy Formation consists of about 91 ft (28 m) of very poorly sorted, clayey and silty, glauconitic quartz sand and sandy clay-silt. The lower 50.9 ft (16 m) of the Nanjemoy, assigned to the Potapaco Member, includes four repetitive lithic units, each consisting of intensely burrowed, very clayey and silty, very glauconitic sediments that are dominantly silty sand in the lower part and dominantly sandy silt and clay in the upper part. The lithic units, which are herein designated, from bottom to top, units A, B, C, and D, may represent separate, minor fluctuations of sea level. Units A–D of the Nanjemoy in the core are partly equivalent to Beds A–D of Ward, which have been differentiated in the inner Coastal Plain in the outcrop area of the Potapaco (Ward, 1984a, 1984b, 1985) and in numerous core holes in King George, Stafford, and Caroline Counties, Va. (Mixon and Powars, unpub. data). The upper 39.8 ft (12 m) of the Nanjemoy consists of less clayey and less glauconitic, very micaceous, pebbly sand of the Woodstock Member. Lithologies characteristic of the Potapaco and Woodstock interfinger over a 10–15 ft (3–4.6 m) interval, and the member boundary is arbitrarily placed at a conspicuous burrowed contact between a 4-ft-thick (1.2-m-thick) clay (below) and an overlying, friable sand that is typical of the Woodstock Member. The lower and middle Potapaco beds (units A–C) were deposited in gradually deepening shelf waters, whereas the upper Potapaco (unit D) and the Woodstock represent deposition in shoaling-upward waters of middle and inner sublittoral paleodepths (Poag, chap. D, this vol.). The combination of coarser, more lignitic sediments and shoaling-upward waters suggests perideltaic conditions.

5. The middle Eocene Piney Point Formation is separated from the underlying Nanjemoy Formation by a regional unconformity. In the core, the Piney Point consists of 54.6 ft (17 m) of light- to dark-olive-gray, friable, medium to coarse, glauconitic quartz sand interbedded with calcium carbonate-cemented sand and moldic limestone. The Piney Point beds contain abundant mollusks, including the large oyster *Cubitostrea sellaeformis*, an important marker for the middle Eocene of the Atlantic and Gulf Coastal Plains. Aragonitic bivalves and gastropods are preserved only as molds and casts. The dissolution of shell material has produced a high moldic porosity in the Piney Point; consequently, the formation is an important aquifer in parts of the Virginia Coastal Plain. Foraminiferal assemblages from the Piney Point suggest an outer sublittoral paleoenvironment. The planktonic foraminiferal suite indicates assignment to undifferentiated zones P. 12–13 of the middle Eocene (Lutetian).

6. The upper Oligocene or lower Miocene Old Church Formation in the core is a 4-ft-thick (1.2-m-thick) muddy, fine to coarse, sparsely glauconitic quartz sand containing scattered pebbles of quartz and phosphate. The Old Church beds are very calcareous because of abundant molluscan shells, barnacle plates, foraminifers, and ostracodes. The pelecypod *Mercenaria capax* is the dominant mollusk. The foraminiferal assemblage in the core suggests an outer sublittoral depositional environment and assignment to the upper Oligocene zone N. 4a of Kennett and Srinivasan (1983). The top and bottom of the Old Church are bounded by erosional unconformities of regional extent.

7. The Haynesville core provides one of the thicker and more complete sections of the lower middle Miocene Calvert Formation currently available for study in the Virginia Coastal Plain west of Chesapeake Bay. In the core, the formation consists of 132.3 ft (40 m) of variably shelly and diatomaceous, clayey and silty, olive-gray quartz sand and sandy clay-silt; these strata are divisible into three main lithic units. The lower, 11.3-ft-thick (3.4-m-thick) unit is a muddy, intensely burrowed, fine to medium sand that contains abundant mollusks and planktonic foraminifers but lacks diatoms. The unit, herein informally named the shelly sand beds, is equivalent to the upper part of the Fairhaven Member or, possibly, the lower part of the Plum Point Marl Member of the Calvert Formation of Maryland. The shelly sand beds are overlain by a 56.5-ft-thick (17-m-thick) unit of diatomaceous, clayey and silty, fine to very fine sand, and sandy clay-silt that is equivalent to the middle(?) and upper Plum Point Marl Member.

The upper, 64.5-ft-thick (20-m-thick) Calvert unit in the core is equivalent to the Calvert Beach Member of the Calvert Formation in Maryland. The Calvert Beach beds are similar, lithically, to the underlying Plum Point beds but have much better developed sands. In Maryland, the largest turnover of molluscan taxa in the lower Chesapeake Group (Calvert and Choptank Formations) occurs at the base of the Calvert Beach. A floral break, involving the extinction of important diatom species and the introduction of new species, also occurs at the Plum Point-Calvert Beach boundary. These data suggest an erosional unconformity at the base of the Calvert Beach representing as much as 0.7 m.y. (Andrews, written commun., 1987).

8. The upper middle and (or) lower upper Miocene St. Marys Formation in the core consists of 37 ft (11 m) of variably shelly, clayey and silty, very fine sand and sandy clay-silt that is commonly bluish gray, greenish gray, and pinkish gray. These strata form two transgressive sedimentary sequences that, from bottom to top, are herein informally designated units A and B. The conspicuous, burrowed contact between the two units is probably a minor erosional unconformity. Unit A, which is 12 ft (3.7 m) thick and contains poorly preserved bivalves and gastropods (*"Anadara"* sp., *Thracia* sp., *Chesapecten* sp., *Turritella* sp.), may be equivalent to the Little Cove Point beds of Blackwelder and Ward (1976) and Ward (1984b), which crop out in the Calvert Cliffs along the Chesapeake Bay in southern Calvert County, Md. Unit B is 25 ft (8 m) thick and contains *Isognomon* sp., *Mercenaria* sp., *"Cardium"* sp., and *Turritella* sp. Unit B is considered to be equivalent to the upper St. Marys Formation (=Windmill Point beds of Ward, 1984b) in the type area in St. Marys County, Md. Samples from Unit B outcrops at nearby Essex Millpond in Essex County south of Tappahannock, Va., have yielded planktonic foraminifers indicative of zone N. 16 of the early late Miocene (P. Huddlestun, Georgia Geological Survey, oral commun., 1986).

9. The upper Miocene Eastover Formation in the core consists of 55.5 ft (17 m) of clayey and silty, fine quartz sand and clay-silt that unconformably overlie lithically similar deposits of the St. Marys Formation. From bottom to top, the core section includes (1) a 4-ft-thick (1.2-m-thick) basal sand containing very fine to fine pebbles of quartz and phosphate, (2) a 27-ft-thick (8-m-thick), medium- to very thin bedded sequence of dark-gray to bluish-gray, silty clay and clayey silt interbedded with lesser amounts of clayey and silty, very fine sand, and (3) about 25 ft (8 m) of dominantly very fine to fine, slightly muddy sand that is cleaner and coarser (fine to medium sand) toward the top of the unit. In the core, the very clayey and silty, lower Eastover is unfossiliferous; its rhythmic mud/sand bedding suggests deposition in very restricted shallow-shelf waters affected by tidal currents. The upper, sandy Eastover of the core is also unfossiliferous; however, fairly diverse molluscan assemblages in equivalent beds in nearby outcrops indicate deposition in shallow, open-marine waters. Upper Eastover beds cropping out at Laytons Landing on the Rappahannock River, about 11 mi (17.7 km) south of Haynesville, have yielded planktonic foraminifers indicative of zone N. 17 of the middle late Miocene.

10. Loose, fine to very coarse, pebbly sand containing *Ophiomorpha* burrows make up the uppermost 43.5 ft (13 m) of the core and the overlying 22-ft-thick (7-m-thick) section exposed in a borrow pit at the drill site. These sandy strata are herein considered to be an updip, marginal-marine facies of the Pliocene Yorktown Formation. In the core and in nearby outcrops, the Yorktown beds unconformably overlie the Eastover Formation and underlie thin sandy and gravelly deposits thought to represent the Bacons Castle Formation and (or) the "Moorings unit" of Oaks and Coch (1973). The finer grained, better sorted, slightly clayey and silty, burrowed sand of the lower Yorktown is believed to have been deposited in a relatively low energy, nearshore-shelf environment. In contrast, the crossbedded, relatively poorly sorted, dominantly medium to very coarse, pebbly sand of the upper Yorktown suggests deposition in a high-energy, very shallow water environment affected by waves and currents. Studies of planktonic foraminiferal and ostracode assemblages from other localities in Virginia and North Carolina indicate an early and early late Pliocene age for the Yorktown Formation.

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Mineralogy of the Haynesville, Virginia, Cores

By LUCY McCARTAN

GEOLOGY AND PALEONTOLOGY OF THE HAYNESVILLE CORES—NORTHEASTERN VIRGINIA COASTAL PLAIN

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[Plate is in pocket]

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MINERALOGY OF THE HAYNESVILLE, VIRGINIA, CORES

By Lucy McCartan

ABSTRACT

Dominant detrital minerals in the Lower Cretaceous through upper Miocene Coastal Plain deposits of the Haynesville, Va., cores are quartz, feldspar, kaolinite, illite, and illite/smectite mixed-layer clay. The heavy mineral fraction of the detrital sand suite, mainly ilmenite with significant amounts of epidote, hornblende, garnet, staurolite, tourmaline, and zircon, reflects a primary origin in the metamorphic and igneous rocks of the Piedmont province to the west. A large proportion of detrital minerals not very resistant to abrasion, such as feldspar, epidote, and hornblende, is present only in the St. Marys (middle to late Miocene) and Eastover (late Miocene) Formations and is probably indicative of a significant rate of uplift in nearby source areas. Minerals resistant to abrasion, such as quartz, zircon, and tourmaline, concentrated by reworking of older sediment, dominate the sand fraction at the base of the Calvert (middle Miocene) and St. Marys Formations.

The vertical and lateral distribution of various detrital clay minerals, authigenic minerals, and weathering products indicates conditions within the depositional environment. Abundant kaolinite, the clay mineral in the Haynesville cores that has the coarsest crystal plates, signals a shallow shelf or marginal marine environment, whereas abundant illite/smectite and illite reflect more seaward or deeper water environments. The upper part of the Aquia Formation (Paleocene), the Marlboro Clay (Paleocene), the lower part of the Calvert Formation (middle Miocene), the upper part of the St. Marys Formation, and probably most of the Eastover Formation in the Haynesville cores contain clay suites dominated by kaolinite and were probably deposited in shallow, relatively high energy environments. Glauconite tends to form and accumulate on the shallow shelf away from river mouths and is a large part of the Paspotansa Member of the Aquia Formation, the Nanjemoy Formation (early Eocene), the Piney Point Formation (middle Eocene), and the base of the St. Marys Formation; it is also a significant proportion of the heavy mineral fraction of the Old Church Formation (Oligocene to Miocene). The percentage of glauconite varies inversely with that of sulfide, which also forms in the shallow shelf environment but at places or during times of greater influx of river-borne plant fragments. Goethite, probably formed by oxidation of glauconite as well as other iron-rich clays and an important indicator of weathering, is found in the upper part of the Aquia Formation, the Nanjemoy Formation, and reworked into the base of the Piney Point Formation.

INTRODUCTION

This report gives a description and interpretation of the detrital and nondetrital minerals of the Haynesville, Va., core[1]. The mineralogy of the section at the Haynesville site is typical of sediments in the Salisbury embayment (compare Glaser, 1971; Reinhardt, Christopher, and Owens, 1980; and Reinhardt, Newell, and Mixon, 1980). The detrital mineral suite reflects the composition of the source terranes, the history of transportation from the source to final burial, and, to a lesser extent, the process of postdepositional oxidation due to groundwater movement. The nondetrital minerals and the distribution of detrital clays are more sensitive to the environmental conditions within the depositional basin. Consideration of the mineralogy of the Haynesville core can help form a picture of the regional paleogeography and tectonics of the southern edge of the Salisbury embayment from the Early Cretaceous through the late Miocene.

Detrital minerals in the core include quartz and feldspar; amphiboles, epidote, garnet, chlorite, chloritoid, and apatite; staurolite, sillimanite, kyanite, and andalusite; zircon, tourmaline, rutile, and spinel; ilmenite and magnetite; and illite/smectite mixed-layer clay, illite, and kaolinite. These minerals were derived originally from metamorphic and igneous rocks, mainly in the Piedmont province, and recycled in some cases through Appalachian and Coastal Plain sedimentary rocks.

Nondetrital (authigenic and diagenetic) minerals include glauconite, goethite, calcite, aragonite, cristobalite, apatite and other phosphates, and sulfides. The formation of most or all of these minerals required or was enhanced by one or more biogenic processes. All of the minerals may have been reworked from their original deposits into subsequent units within the basin.

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[1] The "Haynesville core" is actually a composite of three cores drilled 150 ft (46 m) apart (see Mixon and others, chap. A, this vol.).

DETRITAL MINERALS

The detrital mineral suite can be subdivided into light and heavy (including opaque and nonopaque) sand-size minerals and minerals in the clay-size fraction. Samples of washed sand finer than 0.25 millimeter (mm) were separated in bromoform (specific gravity 2.85); the light and heavy sand fractions were counted in index oil mounts on a petrographic microscope. Centrifuged samples of material finer than 2 micrometers (μm) dried on glass slides were analyzed on an X-ray diffractometer before and after glycolation and heating to determine the clay-size minerals.

SAND-SIZE FRACTION

LIGHT FRACTION

Quartz, feldspars, and rock fragments constitute over 90 percent of the detrital material in most sand samples from the Haynesville core (table 1). Feldspar and rock fragments are less resistant to abrasion and solution than quartz. Their abundance, as in the upper Miocene (chap. B–pl. 1), suggests an influx of first-cycle sediment, probably owing to relatively rapid uplift and erosion of a nearby source area such as the Piedmont province.

Clasts that may be partially devitrified volcanic glass (fig. 1) are a significant component of the St. Marys and Eastover Formations. Volcanogenic material could have been derived from the Caribbean or western North American volcanic regions, which were active during the Miocene (Christiansen and Lipman, 1972; Case and Holcombe, 1980). The inferred volcanic clasts, typically 0.1–0.05 mm long with a length-to-width ratio of between 1 and 2, are commonest in fine-grained beds. They have abundant inclusions, many with strong negative relief, and low birefringent patches. The index of refraction of the host material and the low birefringent areas is between 1.55 and 1.56. Some grains have a thin rim (0.005 mm) that is yellowish and has an index of about 1.55, possibly illite or smectite. Other grains have wider rims (as wide as 0.01 mm) that are similar to the core material but have fewer inclusions and generally slightly higher birefringence (fig. 1). The narrow clay(?) rims might be due to weathering just after deposition. The wider rims are possibly the result of more thorough devitrification of the outer margin of the clasts. Such clasts are absent from the Lower Cretaceous beds and are sparse in the Upper Cretaceous and Cenozoic section.

HEAVY FRACTION

The dominant heavy minerals and mineral groups are ilmenite, staurolite, epidote, and garnet. Ilmenite and its weathering products (brown ilmenite, composite ilmenite-leucoxene grains, and leucoxene) are the most abundant detrital materials in heavy mineral grain counts. Because ilmenite is a ubiquitous accessory in the source rocks, its usefulness as a source indicator is limited, but it is discussed briefly in the section on "Weathering."

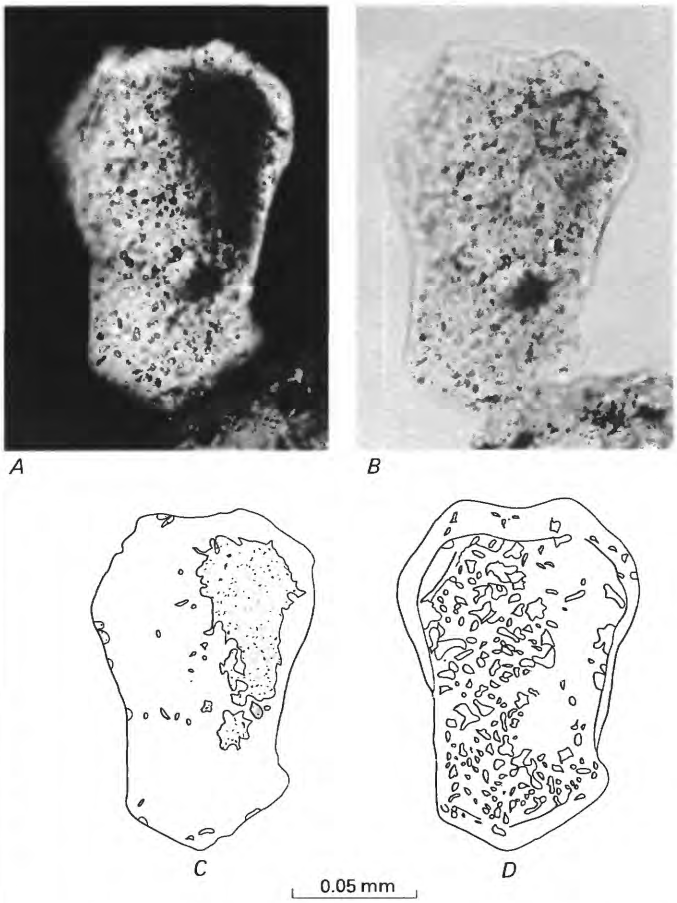

FIGURE 1.—Silt grain from the St. Marys Formation, possibly volcanic ash. Typical of many grains in the St. Marys and Eastover Formations; also sparsely present in the Choptank and Nanjemoy Formations. *A*, Crossed nicols; dark spots are extinct in all orientations. *B*, Plane light; refractive index of oil is 1.54, and index of matrix of grain is about 1.553; dark spot near center may be brown glass. *C*, Drawing of *A*; stippling shows major areas of low birefringence. *D*, Drawing of *B*; some outlined inclusions have indices of refraction higher than that of the matrix, but most indices are lower (the latter inclusions are interpreted as mainly voids filled with fluid). Scale is for drawings.

The nonopaque detrital heavy mineral suite evolved gradually from one dominated by zircon, staurolite, and epidote in the Cretaceous to one dominated by epidote, garnet, staurolite, and tourmaline in the early Miocene (chap. B–pl. 1). A change in the nonopaque mineral

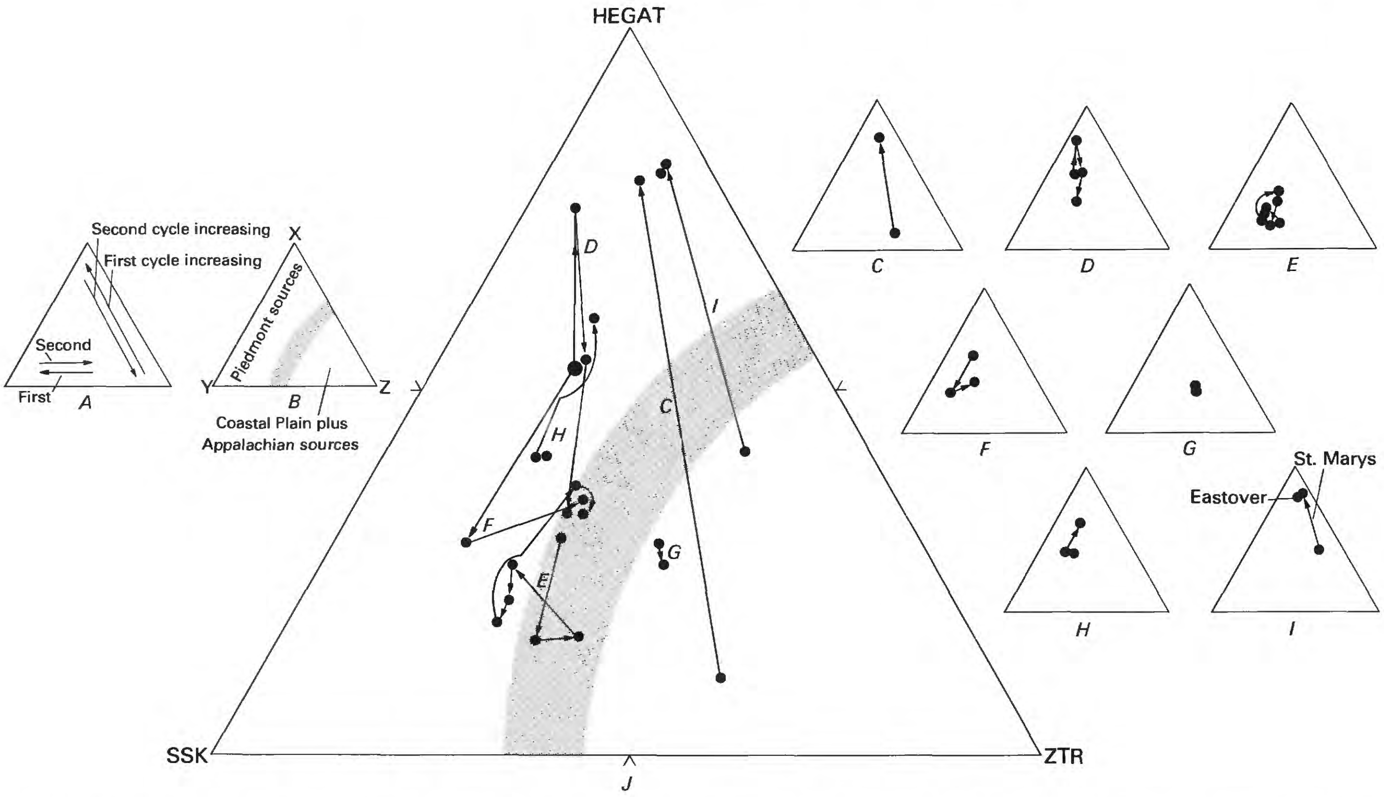

FIGURE 2.—Triangle diagrams showing proportions of selected heavy minerals in the Haynesville core. Data are from table 1, recalculated to 100 percent for this suite of minerals. All the triangles have the same assemblages: HEGAT (hornblende, epidote, garnet, actinolite, tremolite) are the most sensitive to physical and chemical degradation and were derived from iron- and calcium-rich igneous and metamorphic rocks; SSK (sillimanite, staurolite, kyanite) are slightly more resistant and indicate a more aluminous metamorphic source rock; and ZTR (zircon, tourmaline, rutile) are very resistant to instratal solution and abrasion and were derived originally from igneous rocks but in the present context were largely recycled through sediments or sedimentary rocks. *A*, Empirical trends due to physical and chemical durability of the three mineral assemblages. *B*, Likely source areas, with arbitrary boundary (stippled arc) between compositions implying Piedmont province metamorphic (X, Y) and Appalachian and Coastal Plain province sedimentary sources (Z) (X, HEGAT; Y, SSK; Z, ZTR). *C*, Potomac Formation. *D*, Aquia Formation. *E*, Nanjemoy Formation. *F*, Piney Point Formation. *G*, Calvert Formation. *H*, Choptank Formation. *I*, St. Marys and Eastover Formations. *J*, All units in Haynesville core, except Old Church Formation, combined. Arrows point from lower to higher elevations and from stratigraphically older to younger samples. Shaded bands in triangles *B* and *J* are arbitrary source rock boundaries.

assemblage occurred briefly during the middle Eocene, and more dramatically in the later part of the middle Miocene. At those times, the proportions of SSK (mainly sillimanite, staurolite, and kyanite) and ZTR (mainly zircon, tourmaline, and rutile) dropped as the basin was flooded with epidote, hornblende, and finally, in the late Miocene, with a variety of other labile minerals (collectively designated HEGAT).

Proportions of the nonopaque heavy minerals are plotted on triangle diagrams (figs. 2*A*–2*J*) in three groups: HEGAT are the least resistant to intrastratal chemical degradation and, except for garnet, to abrasion; SSK are slightly more resistant and represent a different local source than HEGAT; and ZTR are the most chemically and physically resistant minerals. A high proportion of HEGAT and SSK suggests erosion of a first-cycle source; high ZTR indicates stripping of deeply weathered Piedmont rocks or reworking of minerals from sedimentary rocks or unconsolidated sediment. Using these principles, interpretations can be made concerning the sources and history of the sediments prior to final burial.

Small triangles *A* and *B* in figure 2 give the empirical models for the interpretations, and the remainder of the small triangles give the data for each unit in the Haynesville core except the Old Church Formation. The St. Marys and Eastover Formations are shown together on triangle *I* (fig. 2*I*). All the data are combined on the large triangle (fig. 2*J*).

Judging from the nonopaque heavy minerals, units at the top (most of the St. Marys and Eastover Formations) and bottom (Potomac Formation) of the core record

TABLE 1.—*Mineralogy of*

[In percent. tr, trace; A, abundant; P,

Formation	Altitude of sample		Fine sand fraction																			
			Light fraction (specific gravity <2.85)						Heavy fraction (specific													
									Nonopaque detrital													
	Meters	Feet	Qz	Ks	Pl	Ms	Cb	Rf	Hb	Ep	Gr	Ac	Tm	Ct	Cd	Bi	Px	Mo	St	Sl	Ky	An
Eastover																						
	+3.5	+12′1″	67	4	tr	4	5	19	12	18	6	12	6	18	12	–	–	–	6	–	–	–
St. Marys																						
	−4.5	−15′	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	−8	−26′4″	38	3	1	3	–	54	27	52	–	–	–	2	–	tr	–	–	2	3	tr	–
	−11.5	−38′10″	68	1	1	–	–	30	6	15	15	–	–	–	6	–	–	–	–	12	3	–
Calvert																						
	−18	−60′2″	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	−26	−86′4″	45	5	9	–	1	40	9	33	12	–	–	tr	6	–	–	–	12	9	–	3
	−31	−101′4″	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	−37	−123′3″	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	−46	−150′6″	90	1	1	–	–	8	2	8	8	–	2	6	2	2	–	–	17	12	6	2
	−53	−174′4″	94	4	1	–	tr	tr	1	4	29	–	–	–	7	–	–	–	28	5	tr	5
Old Church																						
	−55	−183′2″	97	1	1	–	–	1	–	8	16	–	4	–	–	–	–	–	4	20	12	–
	−56	−184′9″	94	1	3	–	–	2	–	17	9	–	–	–	3	tr	–	–	21	7	–	4
Piney Point																						
	−57	−186′8″	98	2	–	–	–	–	–	8	26	–	–	–	3	–	–	–	32	3	–	3
	−62	−200′4″	94	2	4	–	–	–	4	8	12	–	–	–	2	–	–	2	37	12	–	6
	−68	−223′3″	93	2	–	–	–	5	12	18	18	–	–	–	6	–	–	–	23	tr	–	6
Nanjemoy																						
	−74	−243′3″	91	4	–	–	–	4	6	25	3	–	–	–	tr	–	–	–	11	8	3	17
	−75	−245′	88	2	–	9	–	1	12	13	12	–	–	–	–	–	–	–	13	25	–	–
	−86	−281′7″	55	30	–	10	5	–	3	12	–	3	–	tr	–	tr	–	–	30	12	tr	15
	−87	−283′8″	90	3	5	–	–	2	4	8	8	–	–	–	–	–	–	–	30	–	–	25
	−90	−294′6″	74	13	–	–	–	13	6	11	5	–	–	–	5	–	–	–	22	4	11	14
	−92	−301′6″	91	4	3	2	–	–	–	3	13	–	–	–	–	–	–	–	32	3	3	10
	−93	−306′5″	76	7	2	15	–	–	–	8	8	–	–	–	–	–	–	–	38	–	15	–
	−98	−321′7″	85	8	2	–	–	5	–	8	17	–	–	–	3	tr	2	–	38	2	8	–
Marlboro Clay																						
	−100	−330′8″	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Aquia																						
	−101	−333′	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	−114	−375′3″	84	3	–	–	–	12	3	13	13	–	–	–	5	–	–	–	20	8	–	13
	−126	−413′8″	81	9	6	3	–	–	9	16	23	tr	–	–	3	–	tr	–	26	tr	3	–
	−128	−420′10″	97	3	–	–	–	–	19	16	40	–	–	–	4	–	–	–	14	–	3	–
	−132	−433′10″	99	1	–	–	–	–	4	18	28	–	–	–	3	–	–	–	23	7	tr	–
	−137	−450′4″	57	1	4	–	30	7	–	42	7	–	–	2	–	tr	–	–	5	tr	2	5
	−139	−455′8″	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	−142	−464′6″	87	4	tr	tr	11	7	–	11	tr	–	–	tr	–	–	–	–	30	tr	3	–
			Quartz	Potassium feldspar	Plagioclase	Muscovite	Clay balls	Rock fragments	Hornblende	Epidote	Garnet	Actinolite	Tremolite	Chlorite	Chloritoid	Biotite	Pyroxene	Monazite	Staurolite	Sillimanite	Kyanite	Andalusite

the Haynesville core

present; dashes indicate none]

gravity >2.85											Fossils					Clay fraction												
				Opaque+nondetrital																								
Zr	Tr	Ru	Sp	Gl	Go	Su	Il	I/L	Lu	% of heavy fraction	Fo	Di	Pl	T/B	Or	I/S	Il	Ka	Ca	Ap	9A	8A	Ar	Cr	Gi	Go	Fs	Gy
6	6	tr	–	1	–	99	–	–	–	95	A	A	–	–	–	22	15	56	–	–	–	–	–	–	7	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	22	33	44	–	–	–	–	–	–	–	–	–	–
4	8	1	–	–	–	80	20	–	–	25	–	–	–	–	–	23	38	36	–	–	–	–	–	–	4	–	–	–
12	30	tr	–	99	–	1	–	–	–	98	–	P	P	–	–	48	30	6	9	7	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	58	28	8	–	5	–	–	–	–	–	–	–	–
tr	15	tr	–	1	–	80	17	tr	2	99	A	P	–	–	–	47	26	26	–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	45	29	14	–	12	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	30	19	38	5	8	–	–	–	–	–	–	–	–
10	17	4	–	1	–	32	38	tr	30	87	A	A	–	A	A	39	18	26	12	–	–	–	–	–	5	–	–	–
4	13	3	–	7	–	15	16	tr	10	58	–	–	–	A	A	18	22	4	–	13	29	6	–	9	–	–	–	–
8	28	tr	–	62	–	16	19	1	2	94	A	P	–	P	A	32	27	4	20	17	–	–	15	–	–	–	–	–
19	17	3	–	17	–	53	24	tr	5	96	A	–	–	A	A	42	23	4	–	–	–	–	–	–	–	–	–	–
6	17	3	–	14	–	68	14	tr	5	91	–	–	–	A	A	18	54	–	18	11	–	–	–	–	–	–	–	–
6	10	tr	–	13	–	80	5	tr	2	86	–	–	–	P	A	6	12	–	49	–	–	–	14	4	–	–	–	14
tr	18	–	–	45	45	9	1	–	–	89	A	–	–	–	P	34	38	23	–	6	–	–	–	–	–	–	–	–
tr	28	–	–	32	65	1	2	–	–	96	–	–	–	–	P	–	–	–	–	–	–	–	–	–	–	–	–	–
tr	25	–	–	–	97	3	–	–	–	99	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
tr	21	3	–	14	–	11	46	3	26	77	–	–	–	–	P	80	20	–	–	–	–	–	–	–	–	–	–	–
4	13	8	–	22	–	60	6	tr	12	83	–	–	–	–	–	100	–	–	–	–	–	–	–	–	–	–	–	–
5	14	4	–	34	16	42	6	tr	2	90	P	–	P	A	–	–	–	–	–	–	–	–	–	–	–	–	–	–
6	26	3	–	36	5	20	11	tr	12	57	A	–	P	P	–	–	–	–	–	–	–	–	–	–	–	–	–	–
8	23	tr	–	26	–	63	7	tr	4	91	A	–	P	A	P	70	28	–	2	–	–	–	–	–	–	–	–	–
2	20	tr	tr	24	–	63	6	tr	7	91	P	–	P	–	–	70	25	5	–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	23	17	52	–	8	–	–	–	–	–	–	–	–
–	–	–	–	70	30	–	–	tr	–	99	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
8	15	3	–	10	90	tr	–	–	–	81	P	–	P	–	–	38	30	28	–	5	–	–	–	–	–	–	–	–
7	12	1	–	15	–	53	25	tr	7	58	A	P	–	A	–	53	35	5	7	–	–	–	–	–	–	–	–	–
1	1	1	–	–	95	–	5	–	–	84	A	A	A	P	–	42	31	4	24	–	–	–	–	–	–	–	–	–
9	8	tr	–	1	–	1	78	6	14	66	A	–	–	–	–	29	15	2	52	2	–	–	–	–	–	–	–	–
25	2	10	–	–	–	–	82	9	9	26	–	–	–	–	–	43	11	31	–	14	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	26	16	15	–	44	–	–	–	–	–	–	–	–
33	8	14	–	–	–	–	54	10	36	86	–	–	–	–	–	37	–	48	–	–	–	–	–	–	–	8	6	–
Zircon	Tourmaline	Rutile	Spinel	Glauconite	Goethite	Sulfides	Ilmenite	Ilm/Leucoxene	Leucoxene	Opaques as percentage of heavy minerals	Forams	Diatoms	Dinocysts	Teeth/Bones	Other fossils (mainly shells)	Illite/Smectite	Illite	Kaolinite	Calcite	Apatite	9Å phosphates	8Å phosphates	Aragonite	Cristobalite	Gibbsite	Goethite	Feldspar	Gypsum

significant influxes of first-cycle, relatively labile, high-grade, low-alumina, metamorphic and igneous minerals. During the Paleocene through the early part of the middle Miocene, repeated switching from low- to high-alumina source rocks occurred. This pattern is inferred from staurolite abundance. The base of the St. Marys Formation (middle Miocene), the Old Church Formation (upper Oligocene and lower Miocene), and the middle of the Potapaco Member of the Nanjemoy Formation (lower Eocene) record significant periods of reworking of older sedimentary rocks and unconsolidated sediment, judging from the high ZTR (mainly tourmaline) content. The same explanation applies to samples from the Potomac Formation (464 feet (ft) below sea level; 141 meters (m) below sea level[2]) and the St. Marys Formation (−38 ft; −12 m) that reflect conditions prior to the additions of first-cycle material noted above.

A subtle trend can be discerned in the heavy mineral column of chapter B–plate 1 that parallels the trend in the Miocene of the light mineral column: both suites are increasingly labile upward. Hornblende, epidote, and, finally, actinolite, tremolite, chlorite, and chloritoid are present in higher proportions than tourmaline and staurolite in the upper part of the sequence. The lower Tertiary light mineral trend, however, is not clearly revealed in the heavy mineral data.

The top of the Lower Cretaceous sequence appears to have had a large influx of epidote and a little feldspar. Similar patterns are present in the middle of the Potapaco Member of the Nanjemoy Formation and in the St. Marys Formation, and all indicate stripping of fairly fresh Piedmont province rocks rather than recycling of Appalachian or Coastal Plain material.

Other trends are present. Staurolite dominates the entire nonopaque heavy mineral suite between about −150 ft (−46 m) and −400 ft (−122 m) and is still significant below 400 ft. Samples from the upper part of the St. Marys Formation and the Eastover Formation, however, have very little staurolite. Zircon, generally more abundant through the Cretaceous and Paleocene, is gradually replaced by tourmaline as the dominant ZTR mineral; rutile is present in very small proportions throughout the sequence.

The nonopaque heavy minerals in the Haynesville core show the influence of source rock type and, to a lesser extent, transportation and postdepositional weathering (fig. 2*J*). At the base (C, Potomac Formation) and top (I, St. Marys and Eastover Formations) of the core, the source is first sedimentary (ZTR-rich) and then metamorphic (iron- and calcium-rich Piedmont rocks). The intermediate units in the core are derived from more aluminous sources. The exceptional sample, from the lower part of the Aquia Formation (fig. 2*D*, the sample with the most HEGAT), contains more garnet than hornblende and epidote and is also probably derived from aluminum-rich Piedmont rocks.

CLAY-SIZE FRACTION

True clay minerals as well as other types of minerals are found in the clay-size fraction (less than 2 μm). The proportions of various minerals in the clay fraction were determined by a method designed to reflect only the trends. The method may not represent the true proportion of each mineral; nor are these results necessarily quantitatively comparable to those in other studies.

Illite/smectite (mixed-layer clay), illite, and kaolinite are the most important clay minerals in the Haynesville core (chap. B–pl. 1). The wide variations in proportions of the three types of clay minerals are probably related mainly to size sorting by currents (Gibbs, 1977). Kaolinite crystals are usually several times larger than crystals of the other clay minerals, and the large crystals tend to settle out of the water sooner than the smaller crystals. Abundant kaolinite suggests a depositional environment nearer shore and with more water motion than the seaward domain of deposits rich in illite and illite/smectite. Kaolinite is abundant in the Potomac Formation, the Paspotansa Member of the Aquia Formation, the Marlboro Clay, the middle of the Calvert Formation, and the Eastover Formation; thus, these deposits were probably deposited relatively near shore. Conversely, kaolinite is sparse in the Nanjemoy, Piney Point, and Old Church Formations and is also only a minor phase in the Calvert and St. Marys Formations. These kaolinite-poor parts of the sequence were probably deposited farther from shore.

NONDETRITAL MINERALS

Calcite, aragonite, apatite, and at least some of the cristobalite in the Haynesville core were probably deposited by organisms in skeletons, or are postdepositional recrystallization products of biogenic materials. A family of phosphates, some of which are present in the Haynesville core, appears to be derived through complex postdepositional biogenic and abiotic processes in deposits rich in apatitic fossils. Calcareous shells, bones, and teeth are common in many beds in the Haynesville core, such as at the base of the Calvert Formation. Sparry calcite crystals with pyramidal terminations are especially notable in the middle of the Piney Point Formation. Siliceous diatoms are found only in the Calvert Forma-

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[2] *Sea level:* In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

tion, but cristobalite, commonly associated with diatoms, is found in both the Calvert and the upper part of the Piney Point Formation. Cristobalite is also associated with volcanogenic material.

Sulfide minerals alternate with glauconite throughout much of the marine part of the core (Tertiary). The two are found in deposits rich in organic carbon, the main difference being that land-derived plant debris is more commonly associated with the sulfide facies. Sulfides and plant fragments in fine-grained sediment have been interpreted elsewhere as indicative of marine deltaic influence (Owens and Sohl, 1969; Minard and others, 1976), and they occur also in nonmarine deposits such as at the base of the Haynesville core (Potomac Formation).

Sulfide minerals in the Haynesville core probably crystallized from iron and sulfate ions in anoxic interstitial water and in organic tissue through the microchemical action of bacteria. The reduced oxidation state was maintained mainly by the buffering action of plant material. When sulfides are exposed to air, they immediately tend to oxidize to sulfates; the abundance of sulfide in this core indicates that none of the hiatuses were periods of subaerial exposure.

Glauconite appears to form in an oxygenated shallow marine shelf environment from illitic and smectitic clays through a variety of processes (Triplehorn, 1966). Whereas a sulfide-rich zone may reflect an influx of river mud, a glauconite bed probably records a time when there was little direct input from land areas.

WEATHERING

In the discussion above, most of the effects of "weathering" (oxidation) have been ignored because they have not played a significant role in the history of the Haynesville core. Dioctahedral vermiculite, a common weathering product in porous surficial deposits (Owens and others, 1983), is absent in this core. Gibbsite and goethite, other important oxidation minerals, are generally present only as minor components. Long-term oxidation due to groundwater moving through sand, however, has noticeably altered some of the minerals. Leucoxene and iron oxide have formed at the expense of ilmenite in many samples, and glauconite has bleached or gone to goethite, especially in parts of the Aquia Formation. Among the nonopaque minerals, rutile and zircon are the least weathered—even the quartz shows pitted surfaces and rusty rinds in many samples. In some places in the core, such as in Calvert and Aquia samples from 86 and 421 ft (26 and 128 m) below sea level, the clayey texture probably impeded water movement, reduced oxidation, and helped preserve a mineral suite that is more labile than the average for the unit. Elsewhere, such as in the Piney Point Formation at 225 ft (69 m) below sea level, the presence of sand- and clay-size carbonate may have chemically buffered the labile minerals despite free-flowing ground water.

Some Paleocene and Eocene beds contain abundant polished, sand-size goethite pellets (fig. 3, table 1), presumably reworked from oxidized glauconite sand contained in marine units that were exposed landward of the Haynesville site. Hansen (1974), however, concluded that the goethite pellets in the Aquia formed concurrently with the glauconite and were not reworked from older material.

COMPARISON OF THE HAYNESVILLE AND OAK GROVE CORES

The mineralogy of the Oak Grove, Va., core (Reinhardt, Christopher, and Owens, 1980; J.P. Owens and M.H. Hess, *in* Reinhardt, Newell, and Mixon, 1980) is generally similar to that of the Haynesville core. Most of the same minerals in roughly the same proportions are present in both cores. In addition, many of the trends are similar. For example, in both cores, staurolite is the dominant aluminosilicate throughout the Tertiary; kaolinite is the major clay mineral at the top and base of most units; and garnet-epidote dominates the HEGAT field in the Calvert, where chloritoid is also an important phase.

Vermiculite, however, was not found in the Haynesville core. Its presence in the Calvert Formation and at formational boundaries in the Pamunkey Group in the Oak Grove core is probably due to weathering of the illite and illite/smectite after deposition. The Calvert Formation at the Oak Grove site is yellow gray, suggesting oxidation of the iron minerals. The dark-olive-green color of the Calvert in the Haynesville core indicates a more reduced state of the iron minerals. More thorough weathering of the Oak Grove core is also suggested by its lower sulfide content, although that may be due in part to a lower influx of plant debris.

In the Oak Grove core, the proportion of unstable heavy minerals (HEGAT) decreases upward in the Pamunkey Group, whereas at the Haynesville site there is less HEGAT in the middle than at the top and bottom. This difference probably reflects local source differences as well as the more intense weathering at the Oak Grove site.

Proportions of clays were estimated by slightly different techniques in the two cores, so the contrast between the apparent dominance of illite/smectite in the Haynesville clay fraction and illite in the Oak Grove core may be an artifact.

The 60-ft-thick (18-m-thick) section of calcareous Piney Point lithology present in the middle of the Haynesville

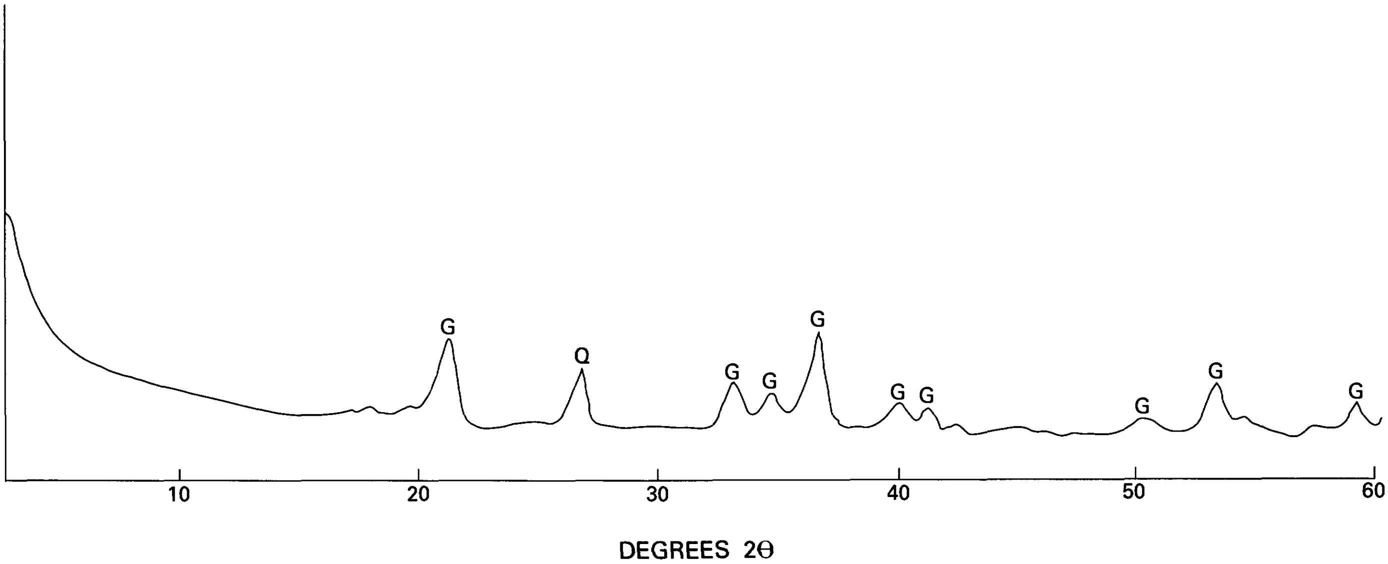

FIGURE 3.—X-ray diffractogram of goethite (G) pellets from the top of the Aquia Formation (333 ft (101 m) below sea level). Q is the main quartz peak; quartz is a normal accessory in goethite pellets.

core is missing from the Oak Grove core, and the 50-ft-thick (15-m-thick), kaolinite-dominated Marlboro Clay section in the Oak Grove core is represented in the Haynesville core by a single clast at the base of the Nanjemoy Formation.

Mineralogic differences between the two localities are probably related to their relative positions in the depositional basin and to the postdepositional enhancement of weathering due to higher elevation. The elevation of the Oak Grove site is about 180 ft (55 m), and the Haynesville site is 72 ft (22 m) above sea level. The Oak Grove core site has been exposed continuously since the lower Pliocene, while the Haynesville core site has been covered by the sea at least twice during that time period. Also, changes in the shape of the basin during the Tertiary resulted in the Haynesville site being updip from the Oak Grove site during the Cretaceous and early Paleocene, but downdip from the Oak Grove site from late Paleocene on (fig. 4).

TECTONICS AND SEDIMENTATION

MAJOR CYCLES

Mineralogic trends in the Haynesville core are useful in the interpretation of patterns of sedimentation and tectonics. Upward-increasing proportions of feldspar and rock fragments suggest an acceleration of uplift in some source areas during deposition of the Aquia Formation and the Potapaco Member of the Nanjemoy Formation (from about −435 ft (−133) to about −280 ft (−85 m)), followed by relative stability during deposition of the Woodstock Member of the Nanjemoy Formation and the Piney Point and Old Church Formations. Rate of uplift increased again throughout the Miocene (from about −80 ft (−24 m) to somewhere between −30 and +10 ft (−9 and +3 m)). The culmination of the cycle of uplift in Virginia coincided with middle and late Miocene global tectonic and igneous activity (Christiansen and Lipman, 1972; Case and Holcombe, 1980; Keller and Barron, 1983; McCartan and Gettings, 1985).

MINOR CYCLES

Repeated episodes of relatively rapid sedimentation, suggested by sulfide-rich beds, occurred several times during the Tertiary, alternating with periods of slow deposition, indicated by glauconitic beds. The two facies are separated in some places by beds lacking either glauconite or sulfide and by erosional or nondepositional hiatuses.

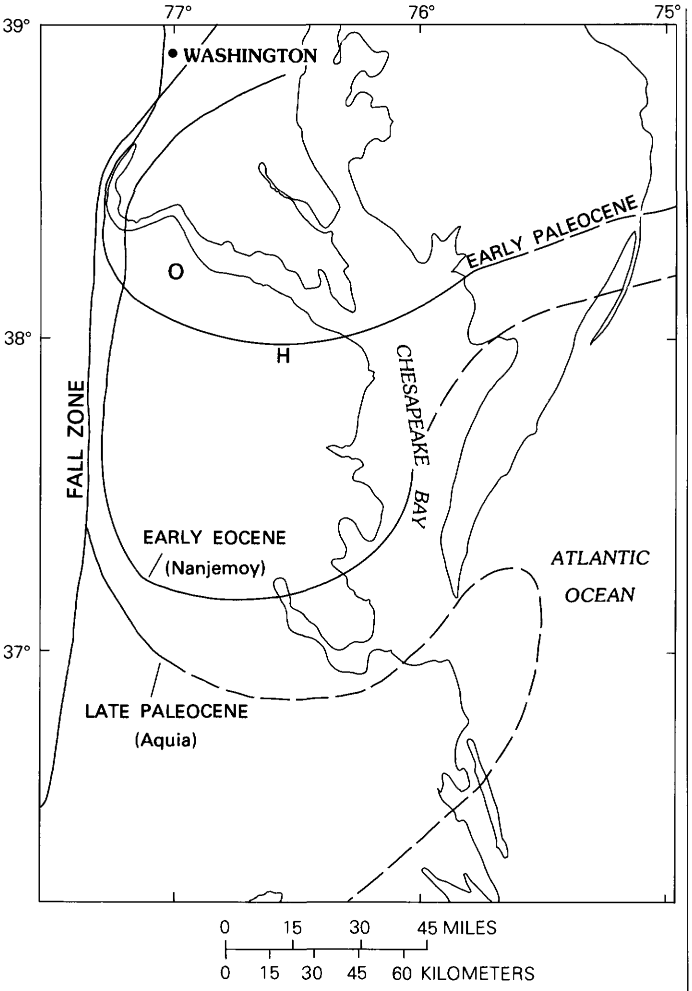

FIGURE 4.—Depositional basin configuration during the Tertiary (after Ward, 1985). O, Oak Grove; H, Haynesville. Solid lines show inferred basin margins based on abundant data; dashed lines are less well constrained.

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Dinoflagellate Cysts from the Lower Tertiary Formations, Haynesville Cores, Richmond County, Virginia

By LUCY E. EDWARDS

GEOLOGY AND PALEONTOLOGY OF THE HAYNESVILLE CORES—NORTHEASTERN VIRGINIA COASTAL PLAIN

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NORTHEASTERN VIRGINIA COASTAL PLAIN

DINOFLAGELLATE CYSTS FROM THE LOWER TERTIARY FORMATIONS, HAYNESVILLE CORES, RICHMOND COUNTY, VIRGINIA

By Lucy E. Edwards

ABSTRACT

The lower Tertiary record in the Haynesville cores includes the Aquia Formation (upper Paleocene), the Marlboro Clay (not sampled), the Nanjemoy Formation (lower Eocene), the Piney Point Formation (middle Eocene), and the Old Church Formation (upper Oligocene or lower Miocene). All contain well-preserved dinoflagellate cyst floras which include many stratigraphically important species.

The age of the lowest Aquia Formation in the Haynesville cores is late Paleocene but not earliest late Paleocene. Strata equivalent to the lowest Aquia in other cores are absent. Depositional environment ranges from high-energy open-sea to marginal-marine to inner neritic conditions.

Deposition appears to have been essentially continuous throughout late Paleocene and early Eocene time. However, relative to other cores to the northwest, deposition in the Haynesville area slowed during the early Eocene. The environment of deposition of the Nanjemoy Formation ranges from restricted marine to inner neritic. A regional unconformity separates the lower Eocene Nanjemoy from the middle Eocene Piney Point Formation. Dinocysts in the upper part of the Piney Point show evidence of transport and do not represent their original paleoenvironment.

Sediments of late Eocene and early Oligocene age are absent from the Haynesville cores. The thin Old Church Formation bears a rich dinocyst flora of late Oligocene or early Miocene age.

INTRODUCTION

The Haynesville 1 core was drilled by the U.S. Geological Survey in July 1984 at lat 37°57′13″ N., long 76°40′26″ W., approximately 33 miles (mi) (53 kilometers (km)) southeast of Fredericksburg in Richmond County, Va. (fig. 1). Altitude at the drill head is 72 feet (ft) (22 meters (m)) above sea level[1]. The core was drilled to a depth of 375 ft (114.3 m) and bottomed in lower Eocene sands. Sixteen months later, the Haynesville 2 core was drilled, approximately 150 ft (46 m) from the previous location. Altitude at the drill head is 87 ft (27 m), and the hole penetrated 556 ft (169 m) of sediments, bottoming in Cretaceous sands and clays. Together, the two cores constitute a very complete stratigraphic section of the lower Tertiary in the Virginia Coastal Plain. The lithostratigraphy of the cores is treated elsewhere in this volume (Mixon and others, chap. A, this vol.).

The lower Tertiary in the Haynesville cores is represented by the Aquia Formation (upper Paleocene), the Marlboro Clay (Paleocene or Eocene), and the Nanjemoy (lower Eocene), Piney Point (middle Eocene), and Old Church Formations (upper Oligocene or lower Miocene). These units consist predominantly of glauconitic sands and silts and contain abundant, well-preserved dinoflagellate cysts. The biostratigraphy of these dinocysts is the focus of this paper.

McLean (1971a), Goodman (1975), and Witmer (1975) have described dinocyst floras from the Paleocene and Eocene of Virginia and Maryland in unpublished theses. Taxonomic papers on the dinocyst floras include McLean (1971b, 1972, 1973a, 1973b, 1974, 1976), Edwards (1982), and Goodman and Witmer (1985).

Biostratigraphic information about the dinocysts has been presented in Goodman (1979, 1984), Edwards (1984a), Hazel and others (1984), and Edwards and

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[1] *Sea level*: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

others (1984). Of particular relevance is the detailed biostratigraphic study of the Oak Grove core (fig. 1), a deep core hole in Westmoreland County, Va., by Gibson and others (1980).

ACKNOWLEDGMENTS

The study of the Haynesville cores and other cores from the Virginia Coastal Plain is part of a joint effort and could not have been done without R.B. Mixon and D.S. Powars (USGS, Reston), whose help is gratefully acknowledged. I thank C.W. Poag (USGS, Woods Hole), L.M. Bybell (USGS, Reston) and T.G. Gibson (USGS, Reston) for sharing information and valuable insight. T.G. Gibson, R.B. Mixon, and D.K. Goodman (Arco, Dallas) provided most helpful comments on early versions of this work.

MATERIAL AND METHODS

This study is based on 20 samples from the lower Tertiary formations in the Haynesville cores. Of these, 7 are from the Haynesville 1 core and 13 are from the Haynesville 2 core. Throughout the text, sample positions are given relative to altitude. U.S. Geological Survey paleobotanical numbers, depths, and altitudes for samples are given in table 1.

Sediments were processed according to standard palynological techniques. Sediment was treated with hydrochloric and hydrofluoric acids and oxidized using nitric acid. Organic material was separated using a $ZnCl_2$ heavy liquid solution (specific gravity 1.8), stained with Bismark brown, sieved at 10 and 20 micrometers (μm), and mounted for light microscope observation using glycerin jelly. One sample from the Old Church Formation was also examined under the scanning electron microscope.

TABLE 1.—*Sample positions*

USGS paleobotanical number	Depth in Haynesville 1 core (feet)	Depth in Haynesville 2 core (feet)	Altitude	
			feet	meters
R3341D	255.5		−183.5	−55.9
R3341CC	258.3		−186.3	−56.8
R3341BB	271.6		−199.6	−60.8
R3341AA	306.4		−234.4	−71.4
R3341C	315.5		−243.5	−74.2
R3341B	326.4		−254.4	−77.5
R3412J		360.6	−273.6	−83.4
R3412I		371.2	−284.2	−86.6
R3412H		381.2	−294.2	−89.7
R3341A	373.6		−301.6	−91.9
R3412G		400.3	−313.3	−95.5
R3412F		409.9	−322.9	−98.4
R3412E		415.8	−328.8	−100.2
R3412D-2		427.7	−340.7	−103.8
R3412D-1		465.4	−378.4	−115.3
R3412D-0		497.0	−410.0	−125.0
R3412D		503.0	−416.0	−126.8
R3412C		506.8	−419.8	−128.0
R3412B		521.9	−434.9	−132.6
R3412A-1		536.2	−449.2	−136.9

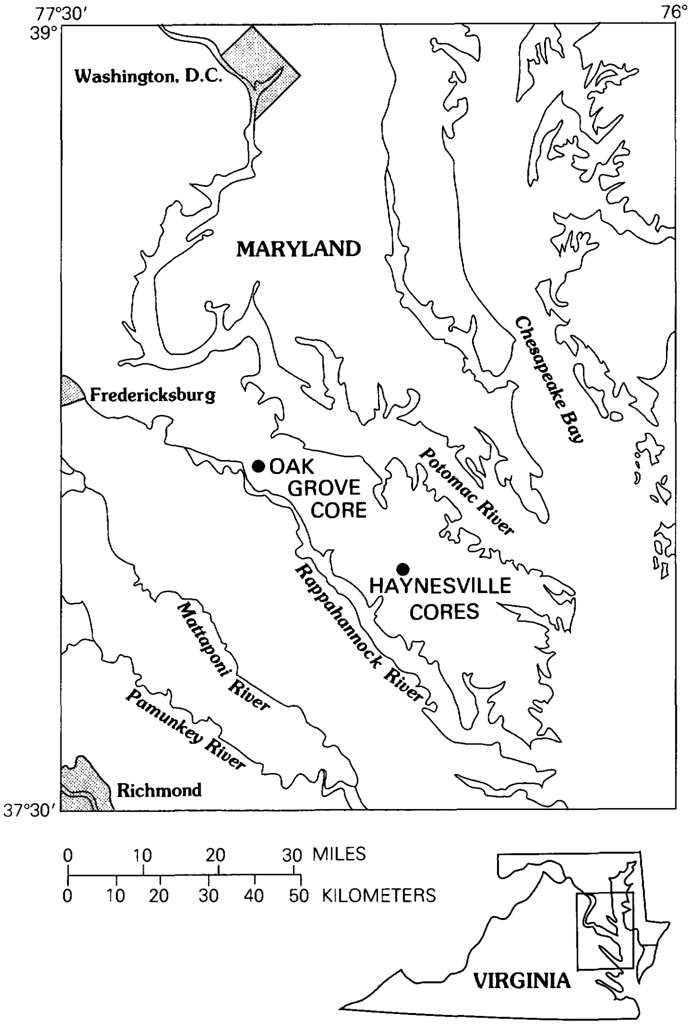

FIGURE 1.—Index map of parts of eastern Virginia and southern Maryland showing the location of the Haynesville and Oak Grove cores.

All samples were studied to determine the dinoflagellate-cyst flora present. For each sample, the total number of different forms present (species richness) was tabulated (fig. 2). As all samples are based on approximately the same amount of raw material treated in the same way, the species richness can be used in a general way to make paleoenvironmental inferences. Selected stratigraphically important forms are recorded in figure 3.

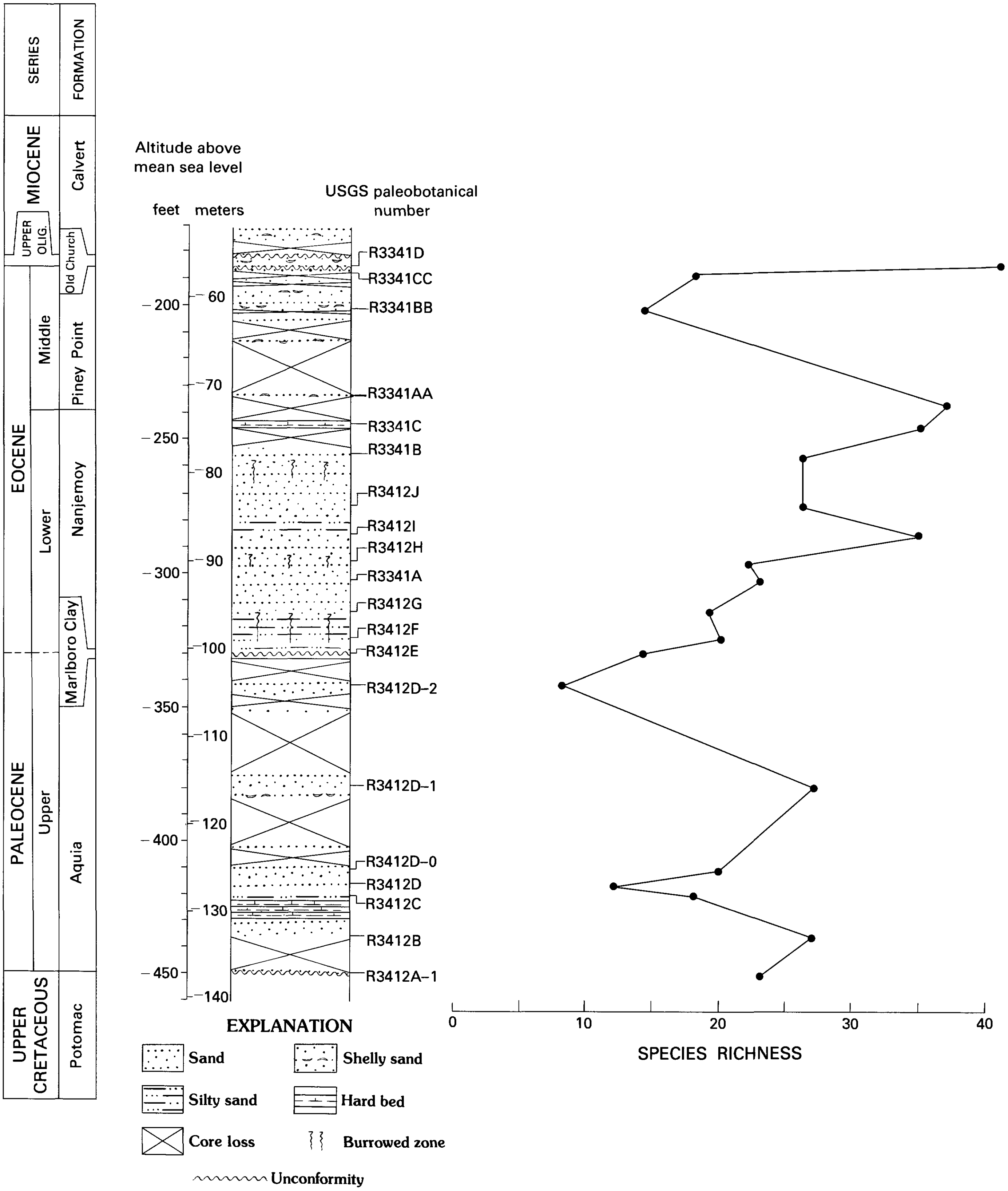

FIGURE 2.—Graph showing the number of species present per sample (species richness) in the Haynesville cores.

A detailed taxonomic study of the lower Tertiary dinocysts present in the Haynesville cores is beyond the scope of this study. Many of the forms noted herein remain in informal nomenclature. Selected stratigraphically important forms are illustrated in plates 1–5.

DINOCYSTS OF THE AQUIA FORMATION

The Aquia Formation in the Haynesville 2 core is 118.4 ft (36 m) thick and was encountered from −449.7 ft (−137 m) to −331.3 ft (−101 m) altitude. The formation consists mostly of clayey to silty, medium to coarse glauconitic quartz sand. At −419 ft (−128 m) altitude, a pebbly sand and a slight color change mark a lithologic break. Carbonate-cemented beds are found in the 10 ft (3 m) immediately below this break. Above the break, considerable core loss occurred, owing at least in part to a decrease in clay and silt in the upper Aquia sands.

Seven samples from the Aquia Formation were examined for dinoflagellate cysts. Species richness for these is shown in figure 2. The occurrences of selected stratigraphically significant dinocyst taxa are shown in figure 3.

Three samples from the lower Aquia (R3412A–1, R3412B, and R3412C) contain a moderately rich, well-preserved dinocyst flora. All contain *Xenikoon australis* sensu Edwards and others, 1984 (pl. 1, fig. 4) and *Deflandrea* cf. *D. dartmooria* of Edwards and others, 1984 (pl. 1, fig. 6). The lowest sample (R3412A–1) contains the highest occurrence of *Thalassiphora delicata* (pl. 1, fig. 1). *Palaeoperidinium pyrophorum* and *Fibradinium annetorpense* are conspicuously absent from these samples. Samples R3412A–1 and R3412C are dominated by species of *Areoligera*.

Two samples (R3412D and R3412D–0) directly above the lithologic change at −419 ft (−128 m) altitude contain well-preserved but somewhat low-diversity dinocyst floras dominated by Peridiniacean cyst sp. C of Edwards, 1980 (pl. 1, fig. 12). Sample R3412D contains the lowest occurrence of *Eocladopyxis peniculata* (pl. 2, fig. 1). R3412D–0 contains the lowest occurrence of the *Turbiosphaera magnifica*-complex (pl. 2, fig. 4).

Above an interval of core loss, in the upper part of the Aquia, sample R3412D–1 contains a rich, well-preserved dinocyst flora. Lowest occurrences include the *Apectodinium homomorphum*-complex (pl. 2, fig. 3), *Adnatosphaeridium robustum* (pl. 2, fig. 5), *Wetzeliella*? sp. (pl. 2, fig. 6), *Impagidinium* sp. of Edwards and others, 1984 (pl. 2, fig. 2), *Kallosphaeridium brevibarbatum* (pl. 2, fig. 9), *Cassidium* sp. of Edwards and others, 1984 (pl. 2, fig. 8), and *Lingulodinium machaerophorum* (pl. 2, fig. 11). The highest sample from the Aquia, R3412D–2, contains a rather sparse but similar dinocyst flora.

AGE AND CORRELATIONS

The Aquia Formation as proposed by Clark and Martin (1901) consists of nine “zones” in its type area along the Potomac River. These “zones” were based on a combination of lithologic and biostratigraphic evidence. Using dinocyst biostratigraphy, Gibson and others (1980) were able to recognize some of these “zones” in the Oak Grove core (fig. 1).

The Haynesville dinocysts can be tied to the Oak Grove core and to some of Clark and Martin’s “zones.” The lower “zones” recognized in the Oak Grove core were not found in the Haynesville core, that is, zone 1, containing *Palaeoperidinium pyrophorum*, and zone 2, containing *Fibradinium annetorpense*. The three lower samples from the Aquia in the Haynesville core thus appear to be younger than the sample from 398 ft (121 m) in the Oak Grove core (recognized as Clark and Martin’s zone 2 by Gibson and others, 1980). The highest occurrence of *Xenikoon australis*, at −419.8 ft (−128 m) altitude in the Haynesville core, correlates with the top of Clark and Martin’s zone 4 and a sample at 381 ft (116 m) in the Oak Grove core.

The lowest occurrence of *Eocladopyxis peniculata* (alt. −416.0 ft (−127 m) in the Haynesville core) approximates the base of Clark and Martin’s zone 5 and correlates with a sample at 368 ft (112 m) in the Oak Grove core. The upper part of the Aquia Formation lacks diagnostic dinocyst events, but there is no reason to suspect an absence of Clark and Martin’s zones 6–9 in the Haynesville core.

The Aquia Formation in the Oak Grove core has been dated by calcareous nannofossils and planktonic foraminifers (Gibson and others, 1980). Zone NP 5 was recognized from 413 to 402 ft (126 to 123 m) in the Oak Grove core, NP 6–?NP 7 from 398 to 387 ft (121 to 118 m), NP 8 from 384 to 372 ft (117 to 113 m), and NP 9 from 358 to 341 ft (109 to 104 m). Foraminiferal zone P. 4 was recognized from 384 to 378 ft (117 to 115 m). Dinocyst correlations with the Oak Grove core suggest that the lower three Haynesville samples (R3412A–1, R3412B, R3412C) correspond to zones NP 6–NP 8. The upper four Aquia samples in the Haynesville core correspond to zone NP 9 and perhaps part of NP 8.

Jan du Chêne (1977) recognized 11 dinoflagellate associations in the Schlieren Flysch in Switzerland. The lower three Aquia samples from the Haynesville core correlate with his *Ceratiopsis speciosa* Association. The upper two Aquia samples (R3412D–1 and R3412D–2) correlate with his *Apectodinium homomorphum* Association. The middle two Aquia samples (R3412D and R3412D–0) lack diagnostic forms. Both the *C. speciosa* and the *A. homomorphum* Associations are of late Paleocene age. A chart by Williams and Bujak (1985)

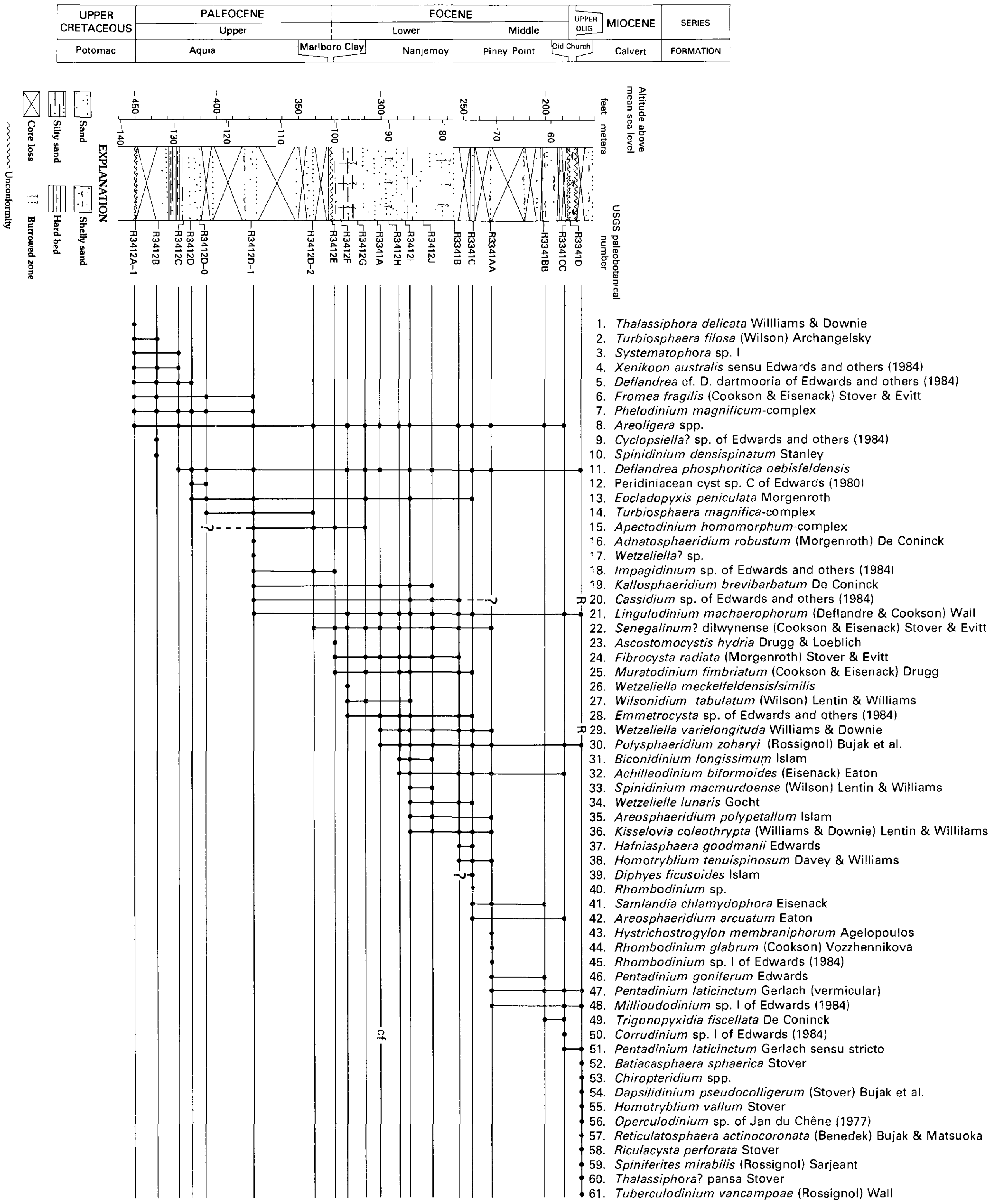

FIGURE 3.—Range and occurrence chart of dinoflagellate cysts and acritarchs recovered from the Haynesville cores. R indicates reworked specimens.

correlates the *C. speciosa* Association with NP 5–NP 8. The *A. homomorphum* Association is roughly equivalent with NP 9, although it is unlikely that either the lower or upper boundaries of the nannofossil and dinocyst zones coincide (see, for example, Morton and others, 1983; Berggren and others, 1985; Heilmann-Clausen, 1985; Williams and Bujak, 1985).

The Haynesville dinocyst flora from the Aquia can be compared with dinocyst floras from Gulf Coast material. The lower three Aquia samples appear to be younger than the Coal Bluff Member of the Naheola Formation, which contains *Fibradinium annetorpense* and *Xenikoon australis* sensu Edwards and others, 1984 (Edwards, unpub. data), but older than the Nanafalia Formation, which contains *Eocladopyxis peniculata* and *Apectodinium homomorphum* (Edwards, 1980). The upper four Aquia samples correlate with the Nanafalia or Tuscahoma Formations or both.

PALEOENVIRONMENT

Two of the lower three samples from the Aquia Formation in the Haynesville core, like the lower part of the Aquia in the Oak Grove core, are dominated by species of *Areoligera*. Downie and others (1971) postulated that their *Areoligera* association represents an open-sea environment. Islam (1984) noted that this association is thought to prefer high-energy environments and is thus more common in sandy sediments. The samples at −416 ft and −410 ft altitude in the Haynesville 2 core are dominated by Peridiniacean cyst sp. C of Edwards, 1980, and likely represent deposition under other than normal marine conditions (Edwards, 1980) (lagoonal, estuarine, or brackish-water environment). Within the upper part of the Aquia Formation, the diverse dinoflagellate cyst assemblage suggests an inner neritic environment. A decrease in species richness in the uppermost Aquia may indicate a shoaling upwards.

THE MARLBORO CLAY

The Marlboro Clay is found in the Haynesville 2 core from −331.3 ft (−101 m) to −330.7 ft (−100.8 m) altitude. This light-gray to pinkish-gray kaolinitic clay overlies the coarse sands of the Aquia Formation and is approximately 0.7 ft (0.2 m) thick. This unit is riddled with sand-filled burrows of the overlying Nanjemoy Formation and was not sampled for dinoflagellate cysts. In the Oak Grove core, Frederiksen (1979) suggested on the basis of pollen evidence that most of the Marlboro Clay is Paleocene in age and that the Paleocene-Eocene boundary is at or slightly below the contact between the Marlboro Clay and the Nanjemoy Formation. Gibson and others (1980) suggested a brackish-water environment of deposition for the Marlboro in the Oak Grove core.

DINOCYSTS OF THE NANJEMOY FORMATION

The Nanjemoy Formation in the Haynesville 1 and 2 cores is 90.7 ft (28 m) thick and occurs from −330.7 ft (−101 m) to −240 ft (73 m) altitude. The formation consists of clayey, silty, fine to coarse glauconitic quartz sand. The lower member of the Nanjemoy, the Potapaco Member, consists of a series of fining-upwards sequences that grade from dominantly sand to dominantly silt and clay. The upper member of the Nanjemoy, the Woodstock Member, is fine to coarse glauconitic sand that is less clayey and more micaceous than the underlying Potapaco Member. The Potapaco-Woodstock boundary is placed at −280 ft (85 m) altitude at the top of a 4-ft-thick (1.2-m-thick) sandy clay (Mixon and others, chap. A, this vol.).

Nine samples from the Nanjemoy Formation were examined for dinocysts and acritarchs. Species richnesses for these samples are shown in figure 2. The occurrences of selected stratigraphically important taxa are shown in figure 3.

The lowest Nanjemoy sample (R4312E), from a clayey interval, contains the lowest occurrences of *Ascostomocystis hydria*, (pl. 2, fig. 7), *Fibrocysta radiata*, (pl. 2, fig. 10), and *Muratodinium fimbriatum* (pl. 3, fig. 3). Species richness is low, and *Senegalinium*? *dilwynense* (pl. 2, fig. 12) and *A. homomorphum* are relatively abundant.

Samples R3412F and R3412G are also dominated by *S.*? *dilwynense*. R3412F contains the lowest occurrences of *Wilsonidium tabulatum* (pl. 3, fig. 8) and *Wetzeliella meckelfeldensis*/*similis* (pl. 3, fig. 6).

Samples R3341A and R3412H are dominated by *Wetzeliella varielongituda* (pl. 3, fig. 2). R3412H contains the lowest occurrences of *Achilleodinium biformoides* (pl. 3, fig. 12) and *Biconidinium longissimum* (pl. 3, fig. 10).

The thin sandy clay at the top of the Potapaco Member is separated above and below by burrowed surfaces. A sample of this clay (R3412I) contains a rich, well-preserved dinocyst flora. The lowest occurrences of *Kisselovia coleothrypta* (pl. 3, fig. 1), *Spinidinium macmurdoense* (pl. 3, fig. 5), *Wetzeliella lunaris* (pl. 3, fig. 7), and *Areosphaeridium polypetallum* (pl. 4, fig. 2) are found here.

Samples from the Woodstock Member of the Nanjemoy (R3412J, R3341B, R3341C) contain rich, well-preserved dinocyst floras dominated by *Spinidinium macmurdoense* or species of *Wetzeliella*. Sample R3341B contains the lowest occurrences of *Hafniasphaera good-*

manii (pl. 3, fig. 11) and *Homotryblium tenuispinosum* (pl. 4, fig. 1). The uppermost sample in the Nanjemoy (R3341C) contains the lowest occurrence of *Samlandia chlamydophora* (pl. 4, fig. 3).

AGE AND CORRELATIONS

The succession of dinocyst occurrences in the Nanjemoy in the Haynesville cores is quite similar to that in other nearby cores and outcrops. For the Potomac River area, Edwards and others (1984) recognized the following succession of acritarch and dinocyst first occurrences in the Potapaco Member of the Nanjemoy Formation (in ascending order): *Ascostomocystis hydria* (base of the member), *Wilsonidium tabulatum, Wetzeliella hampdenensis, Biconidinium longissimum, Emmetrocysta* sp. of Edwards and others, 1984 (pl. 3, fig. 9), *Homotryblium tasmaniense, Achilleodinium biformoides,* and *Wetzeliella varielongituda/samlandia.* In the Haynesville cores, *A. hydria* is found in the lowest Nanjemoy sample (R3412E), followed by *W. tabulatum* and *Emmetrocysta* sp. (R3412F), then *W. varielongituda* (R3341A), and then *B. longissimum* and *A. biformoides* (R3412H). Samples R3341A and R3412H are dominated by *W. varielongituda*, and lithologically and florally appear to represent Bed C, burrowed Potapaco (in the use of Ward, 1986). The lowest occurrence of *Kisselovia coleothrypta* is found in R3412I, the highest sample in the Potapaco.

Within the Woodstock Member, Edwards and others (1984) list range bases (in ascending order): *K. coleothrypta, Homotryblium caliculum, H. tenuispinosum/pallidum, Hafniasphaera goodmanii, Spinidinium* sp. of Goodman, 1979, and *Wetzeliella* sp. of Goodman, 1979. In the Haynesville cores, *H. goodmanii* and *H. tenuispinosum* first occur together above an interval of core loss in the middle of the Woodstock (R3341B).

The lowest Nanjemoy is early Eocene in age. The dinocyst flora correlates with the lower part of the Bashi Formation in the Alabama Gulf Coast. In both Virginia and the Gulf Coast, material of this age has been assigned to nannofossil zone NP 10 (Gibson and others, 1980, 1982). The lowest occurrence of *W. tabulatum* is an important dinocyst horizon that occurs within NP 10 at approximately the level of the first occurrence of the nannofossil *Tribrachiatus contortus* (Gibson and others, 1986). Gibson and Bybell (1984) report that in northern Virginia, the Nanjemoy contains strata belonging to NP 10, NP 11, and NP 12; in central Virginia, Nanjemoy strata that may belong to NP 13 occur.

Goodman (1984) discussed possible correlations of the Nanjemoy in Virginia and Maryland with European dinocyst zonations and included comments on differences in taxon ranges and difficulties in correlation. He concluded that the basal Nanjemoy correlates with the *Eatonicysta ursulae* (LC–2) Assemblage Zone of Bujak and others (1980) and thus is of early, but not earliest, Ypresian age (NP 11). Correlation with LC–2 was based on the lowest occurrences of *Adnatosphaeridium multispinosum* and *Spiniferites monilis.* Both of these species have recently been reported in older material (NP 9 or NP 10) in the eastern North Atlantic (Brown and Downie, 1984).

The lowest Nanjemoy sample (R3412E) in the Haynesville cores contains representatives of the *Apectodinium homomorphum*-complex and lacks definitive *Wetzeliella* species. As noted by Knox and others (1983, p. 73), "*W. astra* should be regarded as part of the *homomorpha* plexus and may not by wholly reliable as a separate zonal index species." This statement is particularly true in regard to North American forms, which certainly need further study. Thus, the lowest Nanjemoy correlates with the *A. homomorphum* Association of Jan du Chêne (1977) and probably with the *Apectodinium hypercanthum* Zone of Caro (1973) and Costa and Downie (1976), although possibly with the *Wetzeliella astra* Zone of Costa and others (1978).

The Nanjemoy sample 7.9 ft (2.4 m) above the base (R3412F) contains *Wilsonidium tabulatum* and forms transitional between *Wetzeliella meckelfeldensis* and *W. similis.* This sample and the next higher one (R3412G) correlate with the *W. tabulatum* Association of Jan du Chêne (1977) and with the *W. meckelfeldensis* or *W. similis* Zones of Costa and Downie (1976). Nanjemoy samples R3341A and R3412H correlate with the *W. varielongituda* Zone of Costa and Downie (1976).

As noted earlier, the highest sample from the Potapaco Member of the Nanjemoy (R3412I) contains the lowest occurrence of *Kisselovia coleothrypta.* This species marks the base of the *K. coleothrypta* Zone (Caro, 1973). Costa and Downie (1976) equated the base of this zone with the base of NP 12. However, Islam (1983) noted that the *W. varielongituda/K. coleothrypta* Zone boundary appears to be diachronous relative to the assemblage zones of Bujak and others (1980). In the Oak Grove core and in outcrops in Maryland, Goodman (1984) noted the nearly simultaneous lowest occurrences of several species, including *K. coleothrypta, Spinidinium macmurdoense,* and *W. lunaris,* and correlated this horizon with the base of Bujak and others' (1980) *Kisselovia reticulata* (LC–3) Assemblage Zone. This same horizon is represented in Haynesville sample R3412I. Islam (1983) considered Bujak and others' (1980) zone LC–3 to be equivalent to zone B–1. Williams and Bujak (1985) show no equivalence and even a hiatus between these two zones.

As noted by Goodman (1984), it is difficult to correlate the Woodstock Member of the Nanjemoy with Bujak and others' (1980) zones owing to the lack of index forms in the middle and upper part of their *Homotryblium abbreviatum* (B–1) Assemblage Zone. The lowest occurrence of *Samlandia chlamydophora* (R3341C) may prove to be a useful horizon for correlation within zone B–1. The lowest occurrence of *Areosphaeridium arcuatum* in the same sample may be the result of burrowing from the overlying Piney Point Formation as this species first occurs in Bujak and others' (1980) *Areosphaeridium arcuatum* (B–4) Assemblage Zone.

PALEOENVIRONMENT

Dinocyst assemblages throughout the Nanjemoy in the Haynesville cores are dominated by peridiniacean taxa and thus represent predominantly estuarine to inner neritic environments.

The three lowest Nanjemoy samples (R3412E, R3412F, R3412G) have low-diversity dinocyst assemblages dominated by *Senegalinium*? *dilwynense*. They probably represent a restricted marine environment, gradually becoming inner neritic.

The remaining Nanjemoy samples are dominated by species of *Wetzeliella* or by *Spinidinium macmurdoense*. Downie and others (1971) suggested that their *Wetzeliella* association represents an estuarine environment. Williams (1977) qualified this to "lagoonal, estuarine, or brackish water environments." In the Nanjemoy, the assemblages dominated by *Wetzeliella* species probably extend into inner neritic environments.

The highest sample from the Potapaco Member of the Nanjemoy (R3412I) consists of an assemblage that is considerably more diverse than samples above or below it. This diversity may represent a somewhat more offshore environment or may simply be the result of the smaller grain size of the sediment.

Goodman (1979) recognized six dinoflagellate cyst communities in the Woodstock Member of the Nanjemoy from Popes Creek, Md. He related these communities to possible fluctuations in local environmental conditions from relatively more offshore to more inshore within a predominantly shallow neritic to estuarine regime. Ford and Goodman (1987) found that trends in diversity marked two cycles (from offshore to nearshore), which correspond to Clark and Martin's (1901) "zones" 16 and 17.

DINOCYSTS OF THE PINEY POINT FORMATION

The Piney Point Formation in the Haynesville cores is 54.6 ft (16.6 m) thick and was encountered from altitudes of −240 ft (−73.2 m) to −185.4 ft (−56.5 m). The formation consists of poorly sorted, fossiliferous, glauconitic quartz sand that in many places is indurated by carbonate cement.

Three samples from the Piney Point Formation were examined for dinoflagellate cysts. Species richnesses for these are shown in figure 2. The occurrences of selected stratigraphically significant dinocyst taxa are shown in figure 3.

The lowest sample from the Piney Point (R3341AA) contains a well-preserved, diverse dinocyst flora. Many species have their lowest occurrences in this sample, including *Hystrichostrogylon membraniphorum* (pl. 4, fig. 6), *Rhombodinium glabrum* (pl. 4, fig. 7), *Rhombodinium* sp. I of Edwards, 1984 (pl. 4, fig. 8), *Pentadinium goniferum* (pl. 4, fig. 9), and vermicular forms of *Pentadinium laticinctum* (pl. 5, fig. 2).

The two upper samples from the Piney Point (R3341BB, R3341CC) contain moderately well preserved dinofloras in which no species is dominant. However, the dinocysts are noticeably size-sorted; only the smaller dinocyst forms are abundant. Sample R3341BB contains the lowest occurrence of *Trigonopyxidia fiscellata* (pl. 4, fig. 10). Sample R3341CC contains *Areosphaeridium arcuatum* (pl. 4, fig. 5), which was also observed (but probably as the result of burrowing) in the uppermost Nanjemoy sample.

AGE AND CORRELATIONS

The dinocysts of the Piney Point Formation from the Pamunkey River area, central Virginia, have been discussed in Edwards (1984a). The Haynesville dinocyst flora is quite similar to this. In both the Haynesville core and the Putneys Mill core in central Virginia, the lower part of the Piney Point is relatively diverse and contains distinctive species of *Rhombodinium*, and the upper part is less diverse and is dominated by small dinocyst forms. In each core, *Trigonopyxidia fiscellata* is restricted to the upper part of the formation.

The dinocyst assemblages in the Piney Point indicate a middle Eocene age and suggest correlation with the upper two-thirds of the Lisbon Formation in Alabama (the *Cubitostrea sellaeformis* zone) and the Castle Hayne Formation in North Carolina.

Using calcareous nannofossils, DiMarzio (1984) considered the entire Piney Point Formation in the Pamunkey River area to be middle Eocene in age and within CP14a of Bukry (1973). This zone and subzone correlates with the upper part of NP 16 (Berggren and others, 1985).

It is difficult to correlate the Piney Point dinoflora with the assemblage zones of Bujak and others (1980). The lowest occurrences of *A. arcuatum* and *H. membraniphorum* indicate that the Piney Point is no older than their *Areosphaeridium arcuatum* (B–4) Assemblage Zone. Edwards (1984a) noted that the uppermost Piney Point in the Pamunkey River area could be as young as

Bujak and others' (1980) *Heteraulacacysta porosa* (BAR–1) or *Areosphaeridium fenestratum* (BAR–2) Assemblage Zones.

An unconformity of regional extent separates the Piney Point from the underlying Nanjemoy Formation. In central Virginia, Hazel and others (1984) estimated that this unconformity represents a hiatus of about 7.3 million years (m.y.). The close similarity between the Haynesville and central Virginia sections suggests that this is a reasonable estimate for the duration of the hiatus in the Haynesville area. At a minimum, strata representing time equivalent to zones NP 14, NP 15, and part of NP 16 are absent.

PALEOENVIRONMENT

The lowest sample from the Piney Point (R3341AA) contains a diverse dinocyst flora representing normal marine conditions. Wetzeliellaceae are still prominent, so it is unlikely that deposition was far offshore. The upper two samples from the Piney Point (R3341BB, R3341CC) contain dinofloras that appear to be sized-sorted and thus probably do not represent their original paleoenvironment.

DINOCYSTS OF THE OLD CHURCH FORMATION

The Old Church Formation in the Haynesville cores was encountered from −185.4 ft (−57 m) to −181.3 ft (55 m) altitude. The unit is about 4 ft (1.2 m) thick and consists of shelly, glauconitic, silty quartz sand.

A single sample from the Old Church (R3341D) was examined for dinocysts. The dinoflora is well preserved and diverse. Forty-one indigenous dinocyst taxa were observed. Minor reworking of both Nanjemoy and Piney Point specimens was noted. Stratigraphically significant taxa from the Old Church are shown in figure 3 and include *Batiacasphaera sphaerica* (pl. 5, fig. 3), *Chiropteridium lobospinosum* (pl. 5, fig. 4), *Dapsilidinium pseudocolligerum* (pl. 5, fig. 5), *Homotryblium vallum* (pl. 5, fig. 6), *Operculodinium* sp. of Jan du Chêne, 1977 (pl. 5, fig. 7), *Reticulatosphaera actinocoronata* (pl. 5, fig. 8), *Riculacysta perforata* (pl. 5, fig. 9), *Spiniferites mirabilis* (pl. 5, fig. 10), *Thalassiphora*? *pansa* (pl. 5, fig. 11), and *Tuberculodinium vancampoae* (pl. 5, fig. 12). The dinocyst flora of the Old Church in the Haynesville core is better preserved but otherwise similar to the flora found in the Old Church along the Pamunkey River (Edwards, 1984a).

AGE AND CORRELATIONS

The dinocyst flora of the Old Church indicates a late Oligocene or perhaps early Miocene age (Edwards, 1984a). Many of the taxa observed here were also observed by Stover (1977) in material from the Oligocene and lower Miocene of offshore South Carolina.

An unconformity of regional extent separates the Old Church from the underlying Piney Point Formation. At a minimum, strata representing late Eocene and early Oligocene are absent.

PALEOENVIRONMENT

The Old Church sample contains a diverse dinocyst assemblage. Abundant *Polysphaeridium zoharyi* (pl. 5, fig. 1) suggest a tropical to subtropical, nearshore environment.

UPPER PALEOCENE AND LOWER EOCENE COMPARISONS

The Oak Grove core (approximately 25 mi (40 km) northwest of the Haynesville cores; see fig. 1) and nearby cores in King George and Stafford Counties were used by Edwards and others (1984) to construct a composite range chart for late Paleocene and early Eocene dinocysts in the Virginia Coastal Plain. Because Edwards and others (1984) used the footage in the Oak Grove core as the basis for their composite unit scale (their text-fig. 2), comparisons between the Oak Grove-based composite and the Haynesville cores are relatively straightforward.

Figure 4 shows a graphic correlation plot (see, for example, Shaw, 1964; Edwards, 1984b) of the Haynesville cores (horizontal axis) and the Oak Grove-based composite (vertical axis). Dinocyst events (lowest and highest observed occurrences) are plotted as points corresponding to their depths in the cores represented by their respective axes. For all plotted points, uncertainty boxes are drawn to account for unsampled intervals. Uncertainty levels were not shown explicitly on the range chart of Edwards and others (1984); these are estimated by taking the next lower (for lowest occurrences) and the next higher (for highest occurrences) levels at which any other event is shown.

The geometry of graphic correlation plots is such that time-equivalent levels on the two axes form a line of correlation. Figure 4 shows the approximate limits of reasonable correlations between the Haynesville cores and the Oak Grove-based composite. These limits allow one to make several observations concerning the Aquia and Nanjemoy Formations in the Haynesville cores.

1. The lowest Aquia Formation in the Haynesville cores is younger than the lowest Aquia in the cores at and to the northwest of the Oak Grove site.

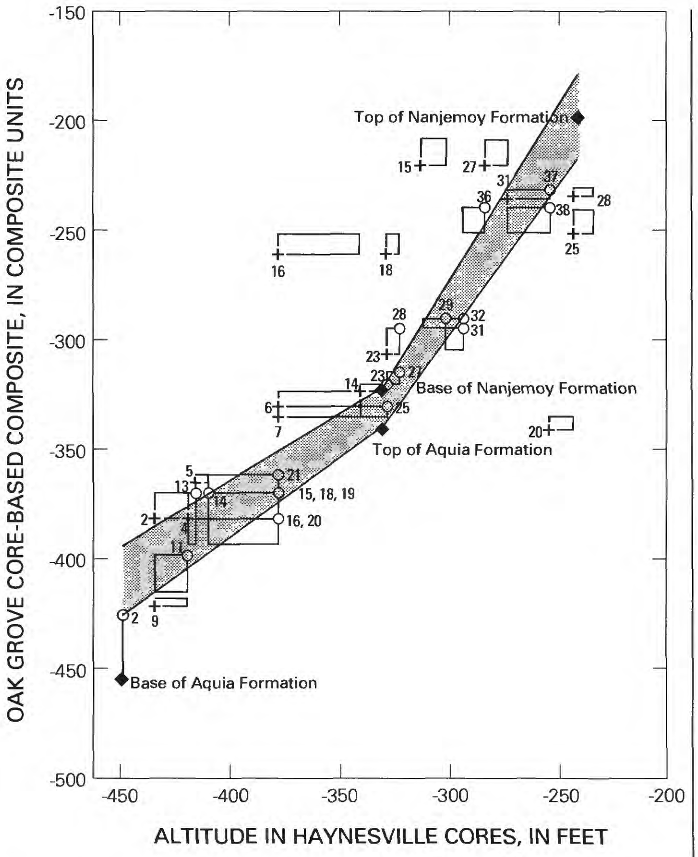

FIGURE 4.—Graphic correlation plot of dinocyst occurrence events in the Haynesville cores and in the Oak Grove core-based composite. Oak Grove-based composite is from Edwards and others (1984). First occurrence events are plotted with "o" and last occurrence events are plotted with "+." Uncertainty boxes extending from points represent unsampled intervals; see text for discussion. Numbers adjacent to symbols marking first and last occurrence events correspond to numbered taxon names in figure 3. The range of probable correlation is given by the shaded band between solid lines. For any depth in the Haynesville cores, the level of time-equivalency in the Oak Grove core can be read off the vertical axis by projection *up* to the solid lines and *over* to the vertical axis. The two values from the projections to the two solid lines give approximate upper and lower limits of equivalency.

2. The ages of the lowest Nanjemoy Formation in the two areas are approximately equivalent.
3. The upper part of the Aquia Formation in the Haynesville cores is likely time-equivalent to the upper part of the Aquia Formation, and possibly to part of the Marlboro Clay, in the area of the Oak Grove core. The relative sparseness of the dinofloras and the lack of sampling of the Marlboro Clay in the Haynesville cores preclude more precise determination.
4. The relative sedimentation rates are such that during late Paleocene time, sediment accumulation was more rapid in the area of the Haynesville cores than near the Oak Grove site. During early Eocene time, the depositional regime changed and sediment accumulation was more rapid near the Oak Grove site.
5. Despite the differences in accumulation rates during late Paleocene and early Eocene time, similar depositional histories are reflected in the Haynesville cores and in the area of the Oak Grove core. Discontinuities may be present, but (1) they are of such a small magnitude as to be undetectable with the core recovery and sample intervals of the present study, or (2) they represent identical hiatuses in the Haynesville cores and in the area of the Oak Grove core.

CONCLUSIONS

The lower Tertiary sediment record in the Haynesville cores includes the Aquia Formation (upper Paleocene), a very thin remnant of the Marlboro Clay (not sampled), the Nanjemoy Formation (lower Eocene), the Piney Point Formation (middle Eocene), and the Old Church Formation (upper Oligocene or lower Miocene). The lowest Aquia in the Haynesville cores is late Paleocene but not earliest late Paleocene in age and is younger than the lowest Aquia in other cores in Virginia. The environment of deposition ranges from high-energy open marine to marginal marine to inner neritic.

Deposition was essentially continuous throughout late Paleocene and early Eocene time. However, relative to the Oak Grove core and other cores to the northwest, deposition at the Haynesville site slowed during the early Eocene. A regional unconformity separates the lower Eocene Nanjemoy Formation from the middle Eocene Piney Point Formation.

An unconformity also separates the Piney Point Formation from the Old Church Formation. Sediments of late Eocene and early Oligocene age are absent from the Haynesville cores. The thin Old Church Formation bears a rich dinocyst flora of late Oligocene or early Miocene age.

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PLATES 1–5

[Contact photographs of the plates in this report are available, at cost, from the U.S. Geological Survey Photographic Library, Federal Center, Denver, CO 80225]

PLATE 1

FIGURE 1. *Thalassiphora delicata* Williams & Downie. Dorsal view of dorsal surface (× 560), sample R3412A–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 19.9×96.1.

2. *Turbiosphaera filosa* (Wilson) Archangelsky. Ventral view of ventral surface (× 560), sample R3412A–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 17.6×94.6.

3. *Systematophora*? sp. I. Right lateral view, upper focus (× 510), sample R3412A–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 35.9×79.9.

4. *Xenikoon australis* sensu Edwards and others (1984). Focus on upper surface (× 560), sample R3412A–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 36.1×103.3.

5. *Areoligera* sp. Dorsal view of ventral surface (× 510), sample R3412A–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 35.0×90.3. This is one of several morphotypes probably representing several species; the species have not been differentiated in the present study.

6. *Deflandrea* cf. *D. dartmooria* of Edwards and others (1984). Ventral view of dorsal surface (× 420), sample R3412D (2), Aquia Formation, upper Paleocene. Slide coordinates, 18.6×74.7. The concave sides of the epicyst of this form distinguish it from *D. dartmooria* sensu stricto.

7. *Deflandrea oebisfeldensis* Alberti. Dorsal view of dorsal surface (× 560), sample R3412D–2 (2), Aquia Formation, upper Paleocene. Slide coordinates, 35.1×103.5. This species and *Deflandrea phosphoritica* Eisenack are grouped as *Deflandrea phosphoritica/oebisfeldensis* on the occurrence chart (text fig. 3).

8. *Cyclopsiella*? sp. of Edwards and others (1984). Focus on upper surface (× 560), sample R3412B (2), Aquia Formation, upper Paleocene. Slide coordinates, 35.1×97.8.

9. *Phelodinium* sp. Ventral view of mid-focus (× 560), sample R3412B (2), Aquia Formation, upper Paleocene. Slide coordinates, 29.5×76.6. This and closely similar forms are grouped as *Phelodinium magnificum*-complex on the occurrence chart (text fig. 3).

10. *Spinidinium densispinatum* Stanley. Ventral view at mid-focus (× 560), sample R3412B (2), Aquia Formation, upper Paleocene. Slide coordinates, 36.4×97.6.

11. *Fromea fragilis* (Cookson & Eisenack) Stover & Evitt. Focus on upper surface (× 560), sample R3412D–0 (2), Aquia Formation, upper Paleocene. Slide coordinates, 28.2×107.6.

12. Peridiniacean cyst sp. C of Edwards (1980). Ventral view of dorsal surface (× 560), sample R3412D (2), Aquia Formation, upper Paleocene. Slide coordinates, 34.8×100.0.


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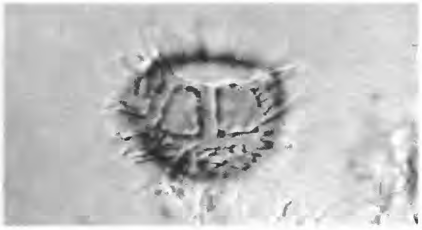
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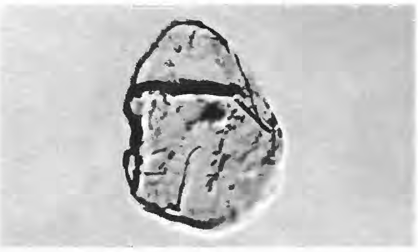
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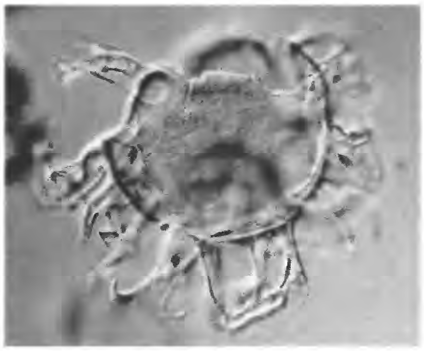
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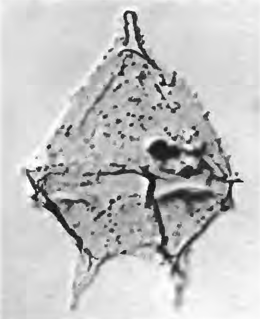
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THALASSIPHORA, *TURBIOSPHAERA*, *SYSTEMATOPHORA*?, *XENIKOON*, *AREOLIGERA*, *DEFLANDREA*, *CYCLOPSIELLA*?, *PHELODINIUM*, *SPINIDINIUM*, *FROMEA*, AND PERIDINIACEAN CYST

PLATE 2

FIGURE 1. *Eocladopyxis peniculata* Morgenroth. Interior view of hypocyst (× 560), sample R3412D–0 (1), Aquia Formation, upper Paleocene. Slide coordinates, 20.8×102.2.

2. *Impagidinium* sp. of Edwards and others (1984). Ventral view of ventral surface, slightly oblique (× 560), sample R3412D–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 24.6×106.7.

3. *Apectodinium quinquelatum* (Williams & Downie) Costa & Downie. Dorsal view at mid-focus (× 560), sample R3412D–2 (1), Aquia Formation, upper Paleocene. Slide coordinates, 33.4×99.5. Because of the considerable intergradation between end-member species, *Apectodinium* spp. in the Haynesville cores are grouped as *Apectodinium homomorphum*-complex on the occurrence chart (text fig. 3).

4. *Turbiosphaera* sp. aff. *T. magnifica* Eaton. Left lateral view at mid-focus (× 560), sample R3412D–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 18.8×102.0. Forms show variable development, from vague separations to discrete, fibrous processes; endocyst often elongate with apical and antapical protrusions. This and closely similar forms are grouped as *Turbiosphaera magnifica*-complex on the occurrence chart (text fig. 3).

5. *Adnatosphaeridium robustum* (Morgenroth) De Coninck. Apical view of apex (× 560), sample R3412D–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 17.6×106.6.

6. *Wetzeliella*? sp. Ventral view of dorsal surface (× 560), sample R3412D–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 22.8×89.2. This form is small and thin walled and bears short, relatively sparse processes.

7. *Ascostomocystis hydria* Drugg & Loeblich. Orientation unknown (× 560), sample R3412E (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 27.8×73.7.

8. *Cassidium* sp. of Edwards and others (1984). Interior view of antapex (× 560), sample R3412D–1 (2), Aquia Formation, upper Paleocene. Slide coordinates, 25.9×101.4.

9. *Kallosphaeridium brevibarbatum* De Coninck. ?Right lateral view, upper focus (× 560), sample R3341A (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 32.7×104.7.

10. *Fibrocysta radiata* (Morgenroth) Stover & Evitt. Dorsal view at mid-focus (× 560), sample R3412I (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 20.9×110.8.

11. *Lingulodinium machaerophorum* (Deflandre & Cookson) Wall. Apico-dorsal view, upper focus (× 560), sample R3412I (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 37.2×104.1.

12. *Senegalinium*? *dilwynense* (Cookson & Eisenack) Stover & Evitt. Dorsal view at mid-focus (× 560), sample R3412F (1), Nanjemoy Formation, lower Eocene. Slide coordinates, 37.8×93.1.


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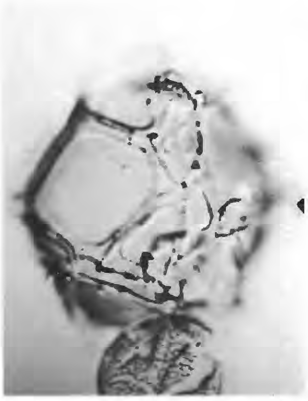
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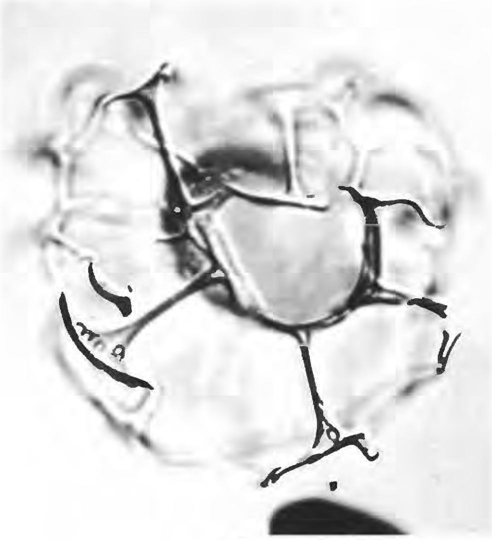
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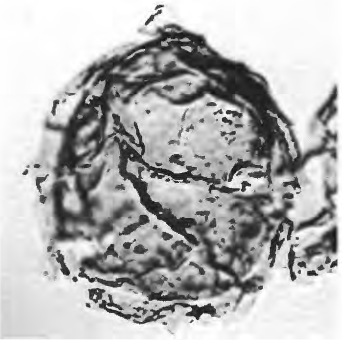
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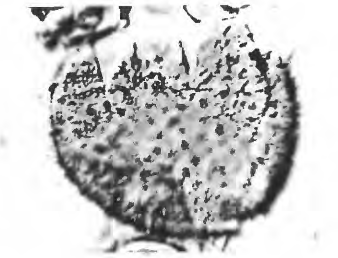
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EOCLADOPYXIS, IMPAGIDINIUM, APECTODINIUM, TURBIOSPHAERA, ADNATOSPHAERIDIUM, WETZELIELLA?, *ASCOSTOMOCYSTIS, CASSIDIUM, KALLOSPHAERIDIUM, FIBROCYSTA, LINGULODINIUM*, AND *SENEGALINIUM*?

PLATE 3

FIGURE 1. *Kisselovia coleothrypta* (Williams & Downie) Lentin & Williams. Ventral view of dorsal surface (× 560), sample R3412I (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 35.3×75.4.

2. *Wetzeliella varielongituda* Williams & Downie. Dorsal view of dorsal surface (× 560), sample R3341A (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 37.1×76.5.

3. *Muratodinium fimbriatum* (Cookson & Eisenack) Drugg. Dorsal view of dorsal surface (× 560), sample R3412G (1), Nanjemoy Formation, lower Eocene. Slide coordinates, 22.6×109.3.

4. *Diphyes ficusoides* Islam. Orientation unknown, optical section (× 560), sample R3341C (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 32.0×84.3.

5. *Spinidinium macmurdoense* (Wilson) Lentin & Williams. Ventral view of dorsal surface (× 560), sample R3412J (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 36.0×91.0.

6. *Wetzeliella meckelfeldensis* Gocht. Ventral view of dorsal surface (× 560), sample R3412F (1), Nanjemoy Formation, lower Eocene. Slide coordinates, 21.2×97.8. This species and *Wetzeliella similis* Eisenack are grouped as *Wetzeliella meckelfeldensis/similis* on the occurrence chart (text fig. 3).

7. *Wetzeliella lunaris* Gocht. Dorsal view of dorsal surface (× 560), sample R3412J (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 26.4×106.5.

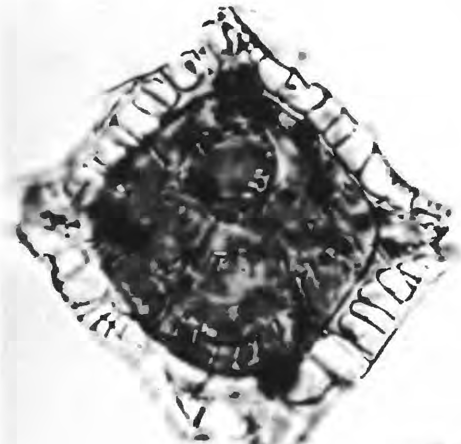
8. *Wilsonidium tabulatum* (Wilson) Lentin & Williams. Dorsal view of dorsal surface (× 560), sample R3412F (1), Nanjemoy Formation, lower Eocene. Slide coordinates, 37.1×76.8.

9. *Emmetrocysta* sp. of Edwards and others (1984). Ventral-apical view, upper focus (× 560), sample R3412H (1), Nanjemoy Formation, lower Eocene. Slide coordinates, 25.7×111.1.

10. *Biconidinium longissimum* Islam. Orientation unknown, focus on upper surface (× 560), sample R3412J (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 31.7×94.9.

11. *Hafniasphaera goodmanii* Edwards. Right-lateral view, somewhat oblique, upper focus (× 560), sample R3341C (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 33.2×91.0.

12. *Achilleodinium biformoides* (Eisenack) Eaton. Ventral view of optical section (× 560), sample R3341B (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 37.3×81.4.



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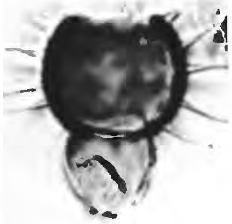

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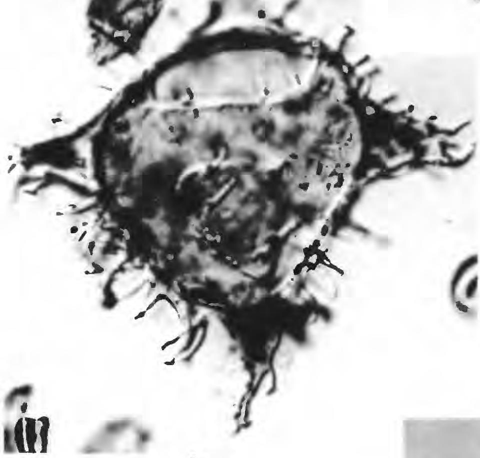

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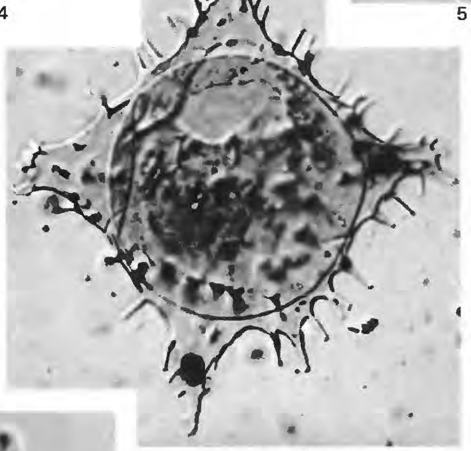

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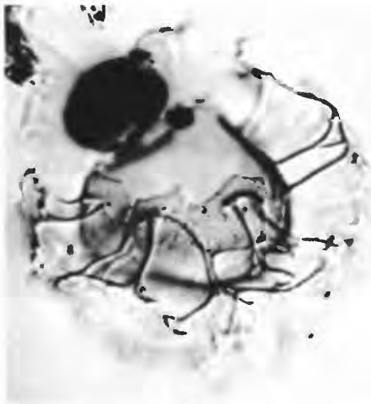

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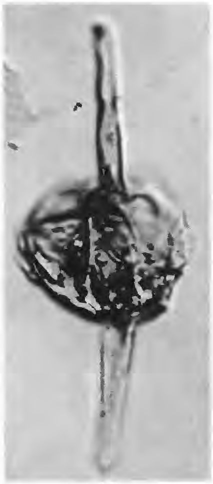

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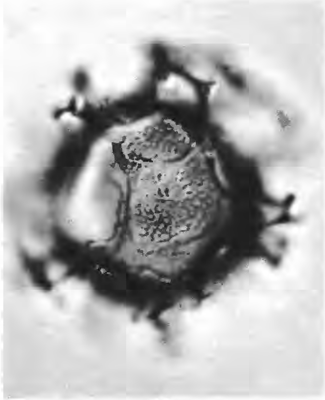

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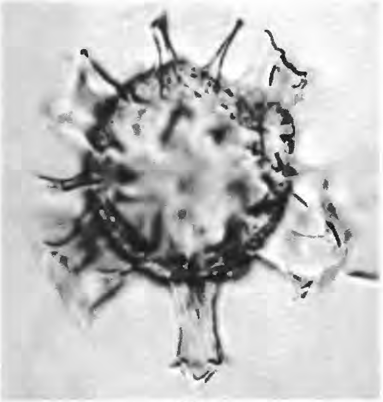

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KISSELOVIA, WETZELIELLA, MURATODINIUM, DIPHYES, SPINIDINIUM, WILSONIDIUM, EMMETROCYSTA, BICONIDINIUM, HAFNIASPHAERA, AND *ACHILLEODINIUM*

PLATE 4

FIGURE 1. *Homotryblium tenuispinosum* Davey & Williams. Interior view of hypocyst (× 560), sample R3341B (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 27.1×83.5.

2. *Areosphaeridium polypetallum* Islam. Orientation unknown, upper focus (× 560), sample R3412I (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 30.6×107.8.

3. *Samlandia chlamydophora* Eisenack. Left-lateral view, optical section (× 560), sample R3341C (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 33.2×106.0.

4. *Rhombodinium* sp. Dorsal view of dorsal surface (× 560), sample R3341C (2), Nanjemoy Formation, lower Eocene. Slide coordinates, 23.2×111.9.

5. *Areosphaeridium arcuatum* Eaton. Orientation unknown, mid-focus (× 560), sample R3341CC (1), Piney Point Formation, middle Eocene. Slide coordinates, 18.8×80.4.

6. *Hystrichostrogylon membraniphorum* Agelopoulos. Left-lateral view, optical section (× 560), sample R3341AA (1), Piney Point Formation, middle Eocene. Slide coordinates, 24.9×80.5.

7. *Rhombodinium glabrum* (Cookson) Vozzhennikova. Ventral view of dorsal surface (× 560), sample R3341AA (1), Piney Point Formation, middle Eocene. Slide coordinates, 33.3×102.0.

8. *Rhombodinium* sp. I of Edwards (1984). Ventral view of dorsal surface (× 560), sample R3341AA (1), Piney Point Formation, middle Eocene. Slide coordinates, 33.1×104.4.

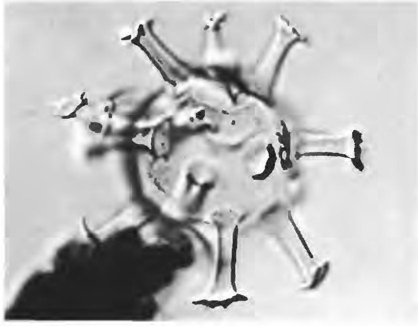
9. *Pentadinium goniferum* Edwards. Left-lateral view, somewhat oblique, optical section (× 560), sample R3341AA (1), Piney Point Formation, middle Eocene. Slide coordinates, 17.8×78.1.

10. *Trigonopyxidia fiscellata* De Coninck. Ventral view of dorsal surface (× 560), sample R3341BB (1), Piney Point Formation, middle Eocene. Slide coordinates, 25.9×90.0.

11. *Corrudinium* sp. I of Edwards (1984). Left-lateral view, somewhat oblique (× 560), sample R3341CC (1), Piney Point Formation, middle Eocene. Slide coordinates, 25.2×75.5.

12. *Millioudodinium* sp. I of Edwards (1984). Left-lateral view, focus on upper surface (× 560), sample R3341AA (1), Piney Point Formation, middle Eocene. Slide coordinates, 34.0×80.1.

13. *Pentadinium laticinctum* Gerlach sensu stricto. Apico-ventral view, upper focus (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 36.6×99.8.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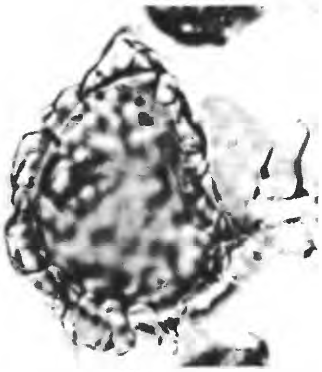
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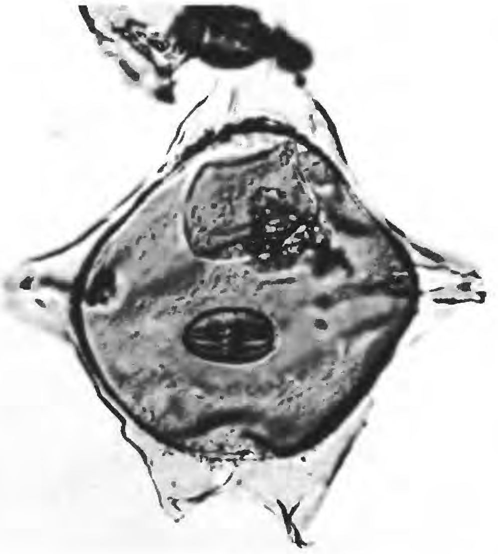
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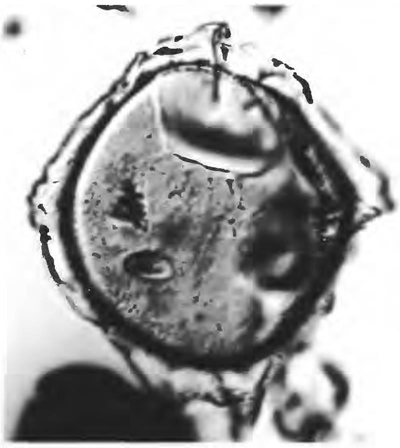
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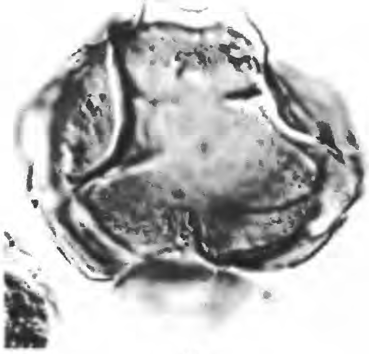
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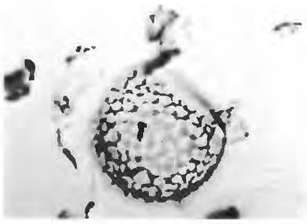
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HOMOTRYBLIUM, *AREOSPHAERIDIUM*, *SAMLANDIA*, *RHOMBODINIUM*, *HYSTRICHOSTROGYLON*, *PENTADINIUM*, *TRIGONOPYXIDIA*, *CORRUDINIUM*, AND *MILLIOUDODINIUM*

PLATE 5

FIGURE 1. *Polysphaeridium zoharyi* (Rossignol) Bujak et al. Exterior view of hypocyst (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 37.7×103.5.

2. *Pentadinium laticinctum* Gerlach (vermicular). Oblique view of posterior-dorsal surface (× 720), sample R3341D, Old Church Formation, upper Oligocene. Scanning electron micrograph. The vermicular surface distinguishes this form from *P. laticinctum* sensu stricto.

3. *Batiacasphaera sphaerica* Stover. View of archeopyle (× 1600), sample R3341D, Old Church Formation, upper Oligocene. Scanning electron micrograph.

4. *Chiropteridium lobospinosum* (Gocht *in* Weiler) Gocht. Ventral view of ventral surface (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 36.4×83.2. This and other species are grouped as *Chiropteridium* spp. on the occurrence chart (text fig. 3).

5. *Dapsilidinium pseudocolligerum* (Stover) Bujak et al. Antapical view of antapex (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 36.6×84.8.

6. *Homotryblium vallum* Stover. Exterior view of hypocyst at mid-focus (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 34.2×79.1.

7. *Operculodinium* sp. of Jan du Chêne (1977). Ventral view of ventral surface (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 36.8×102.9.

8. *Reticulatosphaera actinocoronata* (Benedek) Bujak & Matsuoka. Orientation unknown, upper focus (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 26.7×93.7.

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10. *Spiniferites mirabilis* (Rossignol) Sarjeant. Ventral view, optical section (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 27.3×91.6.

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12. *Tuberculodinium vancampoae* (Rossignol) Wall. Antapical view of antapex (× 560), sample R3341D (2), Old Church Formation, upper Oligocene. Slide coordinates, 27.1×98.2.


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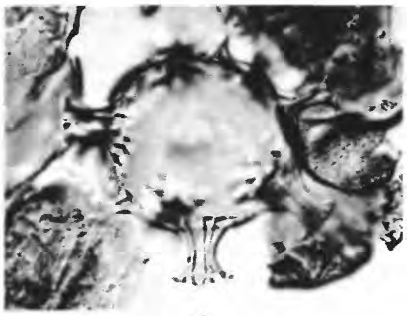
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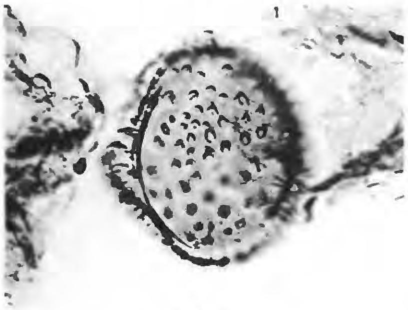
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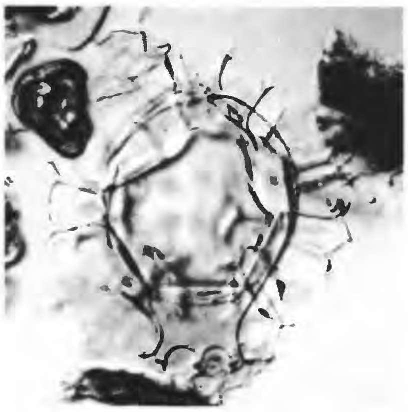
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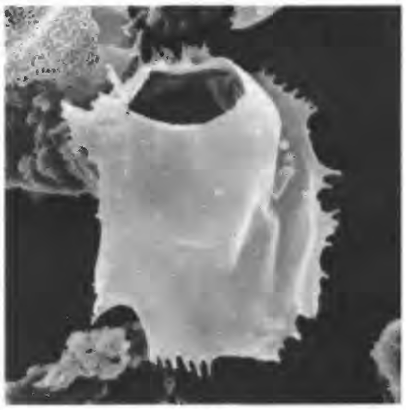
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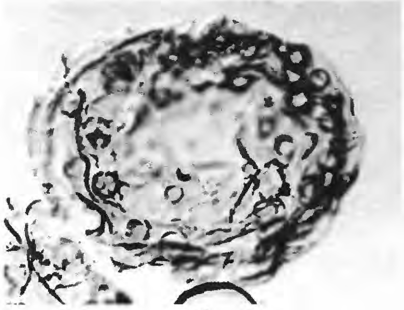
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POLYSPHAERIDIUM, PENTADINIUM, BATIACASPHAERA, CHIROPTERIDIUM, DAPSILIDINIUM, HOMOTRYBLIUM, OPERCULODINIUM, RETICULATOSPHAERA, RICULACYSTA, SPINIFERITES, THALASSIPHORA? AND *TUBERCULODINIUM*

Foraminiferal Stratigraphy and Paleoenvironments of Cenozoic Strata Cored Near Haynesville, Virginia

By C. WYLIE POAG

GEOLOGY AND PALEONTOLOGY OF THE HAYNESVILLE CORES—NORTHEASTERN VIRGINIA COASTAL PLAIN

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FORAMINIFERAL STRATIGRAPHY AND PALEOENVIRONMENTS OF CENOZOIC STRATA CORED NEAR HAYNESVILLE, VIRGINIA

By C. Wylie Poag

ABSTRACT

Twenty-five foraminiferal samples from two adjacent core holes near Haynesville, Va., contain marine Cenozoic assemblages ranging stratigraphically from the upper Paleocene (planktonic foraminiferal zone P. 4) to the middle Miocene (planktonic foraminiferal zones N. 10–14). Four regional unconformities separate five major depositional sequences (formations) and correlate well with the regional stratigraphic framework of the Salisbury embayment and seaward parts of the Baltimore Canyon trough. Benthic and planktonic microfaunal attributes (species richness, generic richness, generic predominance, benthic percentage, and biofacies associations) reflect fluctuating inner to outer sublittoral paleoenvironments. Five principal transgressive deposits (Piscataway, middle Potapaco, Piney Point, Old Church, and lower Calvert) are separated by regressive deposits or unconformities. Peridelta environments developed during late Potapaco and Woodstock time, and coastal upwelling produced an association of opportunistic species during Calvert time.

INTRODUCTION

PREVIOUS STUDIES

Foraminifera from the central and western parts of the Salisbury embayment (Coastal Plain of Virginia, Maryland, and Delaware; fig. 1) have been studied by many workers during the past 40–50 years. Important comprehensive studies of Cenozoic assemblages were published in the late forties when three deep wells in Maryland were thoroughly analyzed (locations 4–6 in fig. 1; Cushman, 1948a, 1948b; Dorsey, 1948) and the first detailed analysis of outcropping Aquia assemblages were published (Shifflett, 1948). Since then, the most pertinent published works have been those of Nogan (1964), McLean (1966), and Gibson and others (1980) in Virginia and Maryland. In addition, several important papers contain analyses of related assemblages from New Jersey (Olsson, 1960, 1970; Youssefnia, 1978; Charletta, 1980), North Carolina (Katrosh and Snyder, 1982; Jones, 1983; Waters, 1983; Snyder and others, 1988), the central Atlantic Coastal Plain (Gibson, 1982, 1983a, 1983b), and the adjacent offshore region (Poag, 1984, 1985c; Poag and Low, 1987).

METHODS

Twenty-five whole-core samples 2–4 inches (in) (5–10 centimeters (cm)) long, taken from near the principal lithostratigraphic boundaries and near other important lithologic changes (see Mixon and others, chap. A, this vol.), establish the broad biostratigraphic and paleoenvironmental framework of the Haynesville section (two core holes approximately 150 feet (ft) (30 meters(m)) apart, altitude at surface 72 and 87 ft (22 and 27 m) above sea level[1], respectively). The samples were soaked in a solution of warm water and Calgon (to disperse the clays) and then wet-sieved on a 74-micrometer (μm) screen. After drying, foraminiferal assemblages were separated from the remaining sedimentary residue by floating with tetrachloroethylene. From these floated samples, I recorded the identifiable adult planktonic species. I then used a microsplitter to separate the foraminiferal assemblages into aliquots of approximately 300 specimens for statistical analysis (benthic percentage). An additional aliquot of approximately 300 benthic specimens provided values of generic predominance and generic richness. In addition, I examined the unfloated sediment residues for

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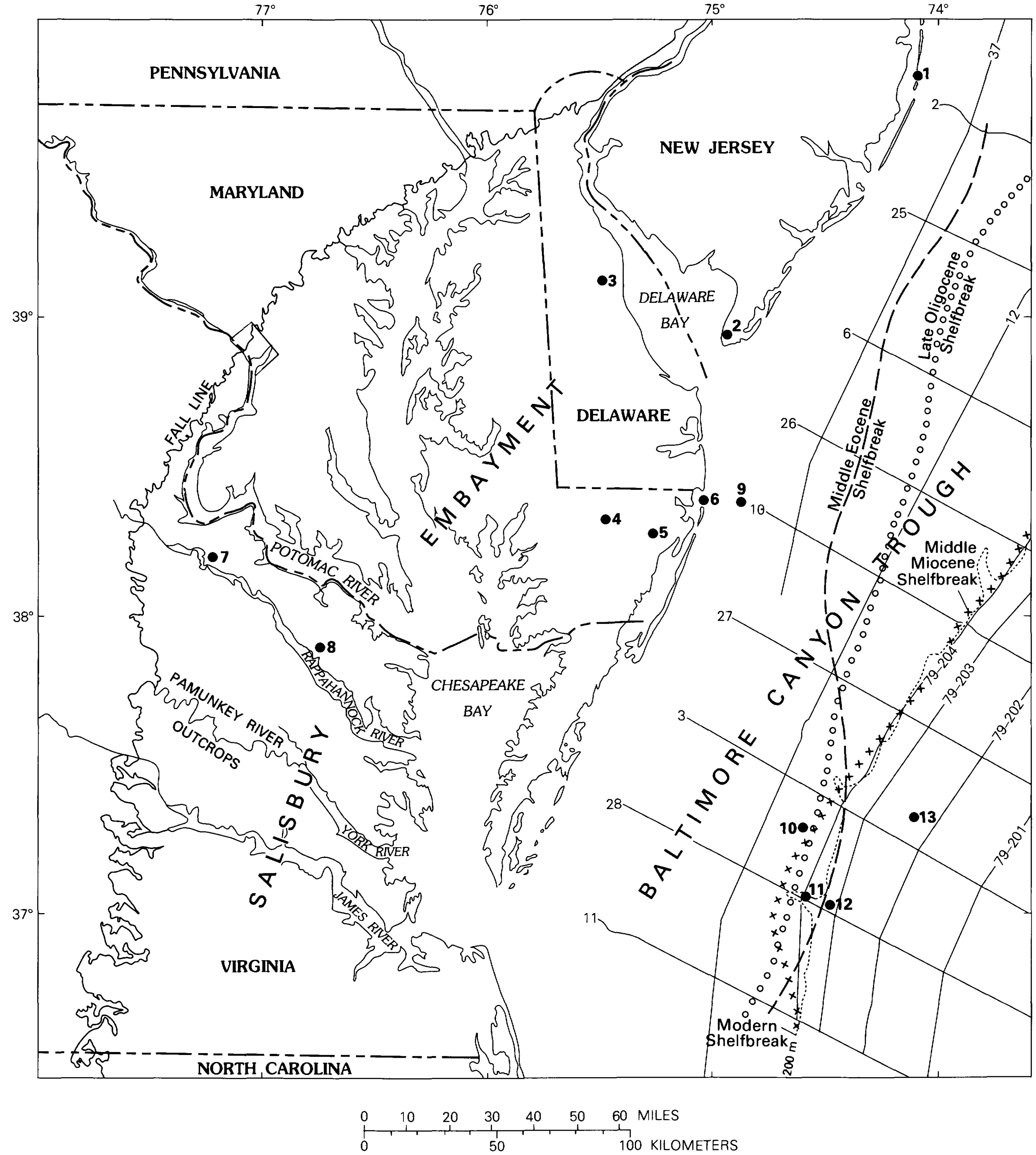
[1] *Sea level*: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.



Bold numbers represent borehole locations (see Poag, 1985c)--1, USGS Island Beach No. 1; 2, Anchor Gas Dickinson No. 1; 3, Dover Air Force Base, Je 32-04; 4, Ohio Oil, L.G. Hammond No. 1; 5, Socony-Vacuum Oil, J.D. Bethards No. 1; 6, Standard Oil of New Jersey, Maryland Esso No. 1; 7, USGS Oak Grove No. 1; 8, USGS Haynesville Nos. 1 and 2; 9, USGS AMCOR No. 6008; 10, USGS AMCOR No. 6007; 11, Exxon, Chevron, Gulf, Mobil ASP No. 10; 12, Exxon, Chevron, Gulf, Mobil ASP No. 22; 13, Exxon, Chevron, Gulf, Mobil ASP No. 23

Light numbers designate multichannel seismic reflection profiles--1 through 28 are USGS lines; 79-201 through 79-204 are Bundesanstalt fur Geowissenschaften und Rohstoffe lines

FIGURE 1.—Location of study area and pertinent boreholes of the Salisbury embayment and the Baltimore Canyon trough. Positions of ancient shelfbreaks derived from an analysis of offshore boreholes and extrapolations of stratigraphy along a grid of multichannel seismic reflection profiles (Poag, 1987; Poag and Low, 1987).

significant lithic constituents and recorded the less abundant planktonic and benthic species that appeared to have significant stratigraphic or paleoenvironmental distribution. Selected benthic species are illustrated in plates 1–5. Planktonic biozone identification and nomenclature is based principally on the extensive work of Blow (1969, 1979), with modifications drawn from Bolli and others (1985) and Kennett and Srinivasan (1983). Correlation of the biozones to an age-stage framework follows Berggren and others (1985).

PALEOENVIRONMENTAL ANALYSES

A large body of published data has established general relationships between modern benthic foraminiferal assemblages and their environments; these relationships can be used as analogs to help interpret ancient depositional conditions. Modern analogs off the central Atlantic States have been summarized in the work of Poag and others (1980) and Culver and Buzas (1980). More generalized data of particular value come from Murray (1973) and Poag (1981). From these and other published sources I have selected the following five faunal attributes on which to base assessments of the Haynesville strata.

1. Species richness.—This attribute is defined as the number of species recorded in a sample (Dodd and Stanton, 1981; Levinton, 1982). I use it to assess the planktonic components of each sample (see Phleger, 1960). Under normal circumstances, low values of planktonic species richness (e.g., 0–5) generally indicate shallow water (a thin water column) in which (1) only near-surface species can maintain reproducing populations, (2) mainly juveniles, representing nonreproducing populations, are present, or (3) the influence of freshwater excludes most planktonic species (which are stenohaline). Relatively high rates of sediment deposition also may contribute to the low planktonic species richness of shallow-marine deposits. High values of planktonic species richness (e.g., 10–20) generally indicate deeper, normal marine waters that support large reproducing populations over a wide range of water depths. Relatively lower sediment deposition rates contribute to higher planktonic-species-richness values in these deeper waters.

2. Generic richness.—This attribute is defined as the number of genera represented in a sample (Poag, 1981). I use it (it mimics species richness) to assess the benthic component of each sample. Under normal circumstances, low values of benthic richness (e.g., 1–15) indicate generally shallow-marine to brackish waters in which seasonal and diurnal environmental stress is relatively great. High values of benthic richness (e.g., 20–30) indicate deeper, normal marine waters characterized by relatively low environmental stress.

3. Generic predominance.—This attribute is defined as the benthic genus (or genera) in a given sample that constitutes the most abundant specimens in an aliquot of approximately 300 specimens (or in the total assemblage, if fewer than 300 specimens constitute an entire sample; Poag, 1981). Generic predominance patterns in modern oceans clearly delineate environmental characteristics, such as relative bathymetry and substrate composition (e.g., Walton, 1964; Poag, 1981) and have been used to estimate depositional settings of fossil assemblages (e.g., Poag and Low, 1980, 1987; Poag, 1986). Under normal conditions, two or three genera predominate in most samples (Poag, 1981).

4. Benthic percentage.—This attribute is defined as the number of benthic specimens present relative to the total number of specimens (benthic plus planktonic) in a sample. Under normal circumstances, low benthic percentage (e.g., 0–30 percent) generally indicates deeper, normal marine waters supporting rich planktonic populations. High benthic percentages (e.g., 80–100 percent) are characteristic of shallow-marine or brackish environments. Often, however, diagenesis or other taphonomic processes may produce high benthic percentages by eliminating or reducing the more fragile and more easily dissolved planktonic components.

5. Biofacies associations.—An abundance of one or more groups of specialized or opportunistic benthic species may indicate distinctive environmental conditions. Two such groups are present in the Haynesville samples (see pls. 1–5) and are used to help interpret the paleoenvironments. The first group is characteristic of biotopes rich in organic carbon and low in dissolved oxygen content (e.g., oxygen-minimum zones, upwelling zones, or peridelta environments). Genera characteristic of this group are *Bolivina*, *Globobulimina*, *Florilus*, *Fursenkoina*, *Epistominella*, and *Uvigerina* (all with living representatives) and their extinct homeomorphs, *Caucasina*, *Pyramidina*, *Virgulinella*, and *Pseudouvigerina* (Phleger and Soutar, 1973; Douglas and Heitman, 1979; Leutenegger and Hansen, 1979; Casey and others, 1981; Poag, 1981, 1985b; Sen Gupta and others, 1981; Miller and Lohmann, 1982; Snyder and others, 1988). The second group is characterized by low-trochospiral, planoconvex tests, which in life are attached by the planar side to firm substrates, such as mineral grains, mollusk shells, algae, and sea grasses (e.g., Murray,. 1973). Haynesville taxa falling into this category are *Cibicides*, *Cibicidina*, *Hanzawaia*, *Rosalina*, *Gavelinella*, and *Anomalinoides*.

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STRATIGRAPHY AND PALEOENVIRONMENTS

PALEOCENE STRATA

AQUIA FORMATION

Piscataway Member

Three samples were taken from the Piscataway Member of the Aquia Formation (tables 1, 2; figs. 2–4), two adjacent samples near the middle of the member and one near the top. The lowest two samples (samples 1, 2) came from an olive-gray, glauconitic, clayey, silty sand containing scattered small clams (*Gryphaeostrea*). The sand-size fraction retained for foraminiferal studies contains principally rounded quartz and glauconitic grains, cemented bioclastic debris, and a rich assemblage of foraminifera. Benthic specimens constitute 39 and 41 percent of the total foraminiferal assemblage in samples 1 and 2, respectively. Twenty-three and twenty-two benthic genera, respectively, were observed, and the number of indigenous planktonic species is 13. These planktonic suites constitute two of the three richest indigenous planktonic assemblages encountered in the Haynesville core holes (fig. 2). The occurrence together of *Planorotalites pseudomenardii*, *Subbotina triloculinoides*, *S. velascoensis*, *Morozovella pusilla pusilla*, *M. angulata*, *M. acuta*, *M. conicotruncata*, *M. aequa*, and *Muricoglobigerina mckannai* indicates that the section belongs to zone P. 4 of the upper Paleocene (Thanetian). The presence of a few older species (e.g., *Morozovella trinidadensis*) indicates reworking of early Paleocene (Danian) sediments as old as zone P. 1d or P. 2.

In the lowest sample, the predominant benthic species (fig. 3) belong to five different genera (tables 1, 2): *Cibicidoides* (12.2 percent), *Cibicidina* (11.2 percent), *Fissurina* (11.2 percent), *Pyramidina* (10.7 percent), and *Spirobolivina* (10.2 percent). Four genera (*Cibicidoides*, 12.4 percent; *Fissurina*, 10.9 percent; *Spirobolivina*, 11.9 percent; and *Gyroidinoides*, 10.4 percent) dominate the next to lowest sample.

This combination of attributes indicates that deposition took place in relatively deep (middle to outer sublittoral) conditions, where firm substrates provided attachment surfaces for *Cibicidoides* and *Cibicidina*. The water column was deep enough to support rather complete late Paleocene planktonic assemblages (probably at least 100–150 m deep; fig. 4).

The uppermost Piscataway sample (sample 3, table 2) is quite different from the lowest two. It was taken from a much clayier sand containing iron-stained quartz grains and smooth, rounded, very coarse grains of goethite(?). The washed foraminiferal residue contains rounded quartz grains and orange glauconite grains. The total unsplit microfossil assemblage contains notably fewer specimens than that of the lowest two Piscataway samples (table 1), and the percentage of benthic foraminiferal specimens per aliquot rises to 65 (fig. 4). The number of identified planktonic species (13) is nearly identical, however, and they are the same taxa as those in the lower two samples, indicating zone P. 4 (upper Paleocene). The 21 recorded benthic genera are dominated by *Cibicidoides* (24.1 percent, table 2). Less abundant genera constituting more than 10 percent of the assemblage are *Pyramidina* (16.5 percent) and *Epistominella* (10.3 percent).

This combination of attributes suggests that the water depth was somewhat less (~50–100 m) than during deposition of the lowest two samples (~100–150 m, fig. 4). An abundance of firm substrates is indicated by the dominance of *Cibicidoides*; the secondary abundance of *Pyramidina* and *Epistominella* indicates relative enrichment in organic carbon and relatively low dissolved oxygen near the sediment-water interface. The faunal attributes of this sample may have been altered somewhat by subaerial exposure or ground-water percolation, as suggested by the iron-stained sediments and the close proximity of an unconformity (fig. 4; see Mixon and others, chap. A, this vol.).

Paspotansa Member

Five samples were taken for foraminiferal analysis from the Paspotansa Member—two near the base, two near the middle, and one near the top of the section (tables 1, 2; figs. 2–4). All the samples came from olive-gray, glauconitic, quartz sands whose washed foraminiferal residues are chiefly subrounded to angular quartz grains and glauconite. In the lower two samples, the glauconite is dark green; the middle two samples contain weathered (orange) glauconite; the glauconite in the uppermost samples also is predominantly orange, and some quartz grains are iron stained as well.

In the lowest two samples (samples 4 and 5, table 2), the benthic foraminiferal assemblage comprises 19 and 26 genera, respectively, and constitutes 93 percent of the total assemblage (fig. 4; table 1). Identified indigenous planktonic species (seven to eight species) include some of the Piscataway taxa, but three new species are introduced (fig. 2). Of these three, *Morozovella apanthesma* and *M. marginodentata* do not range below zone P. 5. I interpret this to mean that these samples belong to zone P. 5 (upper Paleocene) and that the older planktonic specimens are reworked. The benthic foraminiferal assemblage of the lower two Paspotansa samples contains predominantly *Pseudouvigerina* (23.3 and 23.6 percent) and *Cibicidoides* (17.3 and 20.7 percent) (tables 1, 2).

This combination of attributes suggests that the water shoaled (~40 m?) relative to late Piscataway time (fig. 4). The predominance of *Cibicidoides* and *Pseudouvigerina* suggests firm substrates and lower than normal dissolved oxygen near the bottom.

In the middle two Paspotansa samples (samples 6 and 7, table 2), the benthic foraminiferal percentages decrease to 75 and 77 and the number of indigenous planktonic species identified ranges from 7 to 10. The overlap of *Morozovella apanthesma* and *M. marginodentata* (zones P. 5–7) with *M. velascoensis* (zones P. 4–5) confirms assignment to zone P. 5. Reworking of older specimens is still prominent, however (fig. 2). *Pseudouvigerina* is strongly predominant (28.9 percent) in sample 6 but is reduced to 10 percent in sample 7 (tables 1, 2), where *Cibicidoides* is predominant (21.0 percent), followed in abundance by *Gyroidinoides* (15.7 percent) and *Gavelinella* (14.6 percent).

These attributes suggest that inner sublittoral paleoenvironments (~40 m) during deposition of samples 6 and 7 were similar to those during deposition of samples 4 and 5 (fig. 4). The strong reduction of *Pseudouvigerina* in sample 7, however, may indicate a return to more normal values for dissolved oxygen. The presence of relatively abundant *Gavelinella* in sample 7 probably indicates an environmental change as well, but its particular significance is not known.

Faunal attributes change considerably in the uppermost Paspotansa sample (sample 8, table 2). Benthic percentage is about the same as below (75 percent, fig. 4, table 1), but the generic richness value drops to 14 (fig. 4, table 1) and the number of indigenous planktonic species identified drops to 2 (fig. 2). The continued presence of *Morozovella velascoensis*, however, suggests no change in planktonic zonal assignment (still zone P. 5).

The relatively large number (6) of co-predominant genera (tables 1, 2; *Cassidella*, 16.2 percent, *Pyramidina*, 15.6 percent, *Pulsiphonina*, 13.0 percent, *Epistominella*, 12.3 percent, *Gavelinella*, 11.7%, *Gyroidinoides*, 11.7%) is unusual, particularly because *Cassidella* is predominant in only this sample. Proximity to (<1 m (3 ft) below) a regional unconformity, however (see also Mixon and others, chap. A, this vol.), may account for this unusual attribute. Sample 8 is highly weathered, and only 154 benthic specimens were extracted. *Cassidella* also occurs in sample 9, immediately above the unconformity (and in only one other sample (sample 12)); *Gavelinella* is predominant in sample 9 (35.1 percent), and *Pyramidina* is also abundant. These relationships suggest that the unusual number of co-predominant genera represented in sample 8 is the result of faunal mixing by the downward reworking of *Cassidella*, *Gavelinella*, and *Pyramidina* in the filling of burrows that extend below the unconformity. The predominant indigenous genera of sample 8, therefore, appear to be *Pulsiphonina* and *Epistominella*.

The high benthic percentage, the low benthic-richness value, and the co-predominance of *Epistominella* and *Pulsiphonina* suggest that inner sublittoral paleoenvironments (~40 m) were maintained at the Haynesville site during deposition of sample 8, and that dissolved oxygen was deficient at the sea floor.

EOCENE STRATA

NANJEMOY FORMATION

Potapaco Member

Five samples were taken from the Potapaco Member for foraminiferal analysis—two near the base, two near the middle, and one near the top of the member (tables 1, 2, figs. 2–4).

The basal foraminiferal assemblage (sample 9, table 2), taken from lithic unit A of the Potapaco (Mixon and others, chap. A, this vol.), is significantly different from the others. It was taken from a section of interbedded greensand and greenish-gray clay-silt layers. The level at which the sample was taken contains abundant glauconite-filled burrows, and the washed foraminiferal residue contains chiefly subrounded quartz grains and abundant dark-green glauconite. Benthic percentage is quite high (85 percent, fig. 4), 21 benthic genera are present, and only seven indigenous planktonic species were identified. Of these seven planktonic species, three make their first appearance in the core hole. *Morozovella acuta*, *M. occlusa*, *M. aequa*, and *M. apanthesma* range upward into zone P. 6b, whereas *Planorotalites wilcoxensis* first appears in zone P. 6b. Thus I assign sample 9 to zone P. 6b of the lower Eocene. Specimens of the three remaining planktonic species are reworked from older strata. The predominant benthic genus in sample 9 is *Gavelinella* (35.1 percent); *Gyroidinoides* (15.0 percent) and *Pyramidina* (12.6 percent) are the only other genera representing more than 10 percent of the assemblage.

TABLE 1.—*Census of benthic specimens, by genera, identified from the Haynesville core holes*

[Data derived from two counting processes. "Total specimens" includes counts of planktonic and benthic forms; these figures were used to calculate "Percent benthic." Numbers of benthic specimens were derived from a separate aliquot; these figures were used to calculate percentages in table 2. Datum is altitude. Asterisk indicates that specimens belonging to this taxon are reworked from older strata or are contaminants from younger strata and are not indigenous to the sample in which they are now found]

Formation	Aquia								Nanjemoy							Piney Point		Old Church		Calvert					
Altitude (ft)	−434′	−434′	−420′	−413′	−412′	−378′	−376′	−331′	−328′	−322′	−307′	−304′	−283′	−260′	−244′	−213′	−191′	−185′	−182′	−175′	−171′	−161′	−136′	−124′	−101′
Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Alabamina	15	12	16	12	15	4	17	-	-	-	-	1	-	-	2	1	2	-	-	-	-	-	-	-	1*
Anomalinoides	3	6	6	22	-	12	26	1	-	5	1	7	-	4	-	-	-	-	-	-	-	-	-	-	-
Asterigerina	-	-	-	-	-	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bolivina	1	-	-	-	4	1	-	2	-	-	4	-	8	25	10	-	1	-	8	5	8	28	12	15	25
Bolivinita	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
Buccella	-	-	-	-	-	3	1	-	-	-	-	-	-	-	-	-	1	1	7	-	3	-	-	-	4
Bulimina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-	-	-	-
Buliminella	-	-	-	-	1	-	-	-	1	-	-	-	-	-	-	-	2	1	10	2	2	12	9	11	2
Cancris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Cassidella	-	-	-	-	-	-	-	25	3	-	-	-	-	-	-	-	-	-	-	-	1*	-	-	-	-
Cassidulina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	76	30	8	10	-	-	-	-
Caucasina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8	4	41	12	235	124	33	52
Charltonina	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cibicidina	23	17	21	17	14	8	1	3	5	2	26	14	3	28	7	9	1	9	3	1	-	-	-	-	-
Cibicides	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-
Cibicidoides	25	25	54	47	64	41	59	6	2	49	65	71	11	45	17	314	36	65	18	6	19	-	-	-	-
Dentalina	4	1	-	1	3	-	1	-	-	-	-	-	-	-	-	-	8	-	-	-	-	-	-	-	-
Discorbitura	3	1	-	-	-	-	-	-	-	-	-	-	1	-	1	-	-	1	-	-	-	-	-	-	-
Ehrenbergina	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2
Elphidium	-	-	-	-	-	-	-	-	-	-	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Epistominella	17	13	23	4	12	8	-	19	28	28	7	-	2	-	-	-	2	6	-	10	-	41	21	5	2
Fissurina	23	22	2	-	1	-	-	-	1	-	2	-	-	-	1	-	5	3	3	11	3	-	3	-	4
Florilus	-	-	-	-	-	-	-	-	2	2	2	5	-	5	-	-	6	4	6	75	30	17	29	43	105
Fursenkoina	-	-	-	-	1	1	-	-	-	-	-	3	-	31	-	-	9	3	2	-	3	3	3	-	-
Gaudryina	-	-	-	-	-	-	-	-	-	-	1	3	-	-	-	-	-	-	-	-	-	-	-	-	-
Gavelinella	7	3	11	21	21	14	41	18	117	2	-	-	3	8	-	-	-	-	-	-	-	-	-	-	4*
Globobulimina	-	1	1	3	3	-	-	-	2	-	-	-	-	-	-	-	-	1	8	-	-	-	-	-	-
Globulina	7	9	3	15	21	14	17	-	3	-	18	18	2	13	6	17	145	-	8	-	-	1	-	-	-
Guttulina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-
Gyroidinoides	8	21	4	6	17	22	44	18	50	-	11	45	-	21	2	4	3	-	-	-	4	-	-	-	-
Hanzawaia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12	5	32	39	3
Lagena	-	-	3	-	-	3	-	-	2	-	-	-	1	-	1	-	20	2	1	6	5	2	1	1	-
Lankesterina	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
Lenticulina	2	2	5	3	5	5	3	-	5	-	7	8	-	-	-	-	6	5	4	1	1	-	-	-	-
Loxostomum	4	7	-	-	-	-	-	5	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Marginulina	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Melonis	-	-	6	11	16	8	4	-	1	3	17	13	-	-	2	-	4	-	1	-	1	-	-	-	-
Neoeponides	-	-	-	7	7	2	2	11	18	3	20	22	3	3	6	26	-	-	-	-	1	-	-	-	-
Nodosaria	-	-	-	3	1	1	-	-	-	-	-	2	-	-	-	2	3	-	-	1	-	-	-	-	-
Nonion	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	23	17	-	2	-	-	-	-

TABLE 1.—*Census of benthic specimens, by genera, identified from the Haynesville core holes*—Continued

Formation	Aquia								Nanjemoy							Piney Point		Old Church		Calvert					
Altitude (ft)	−434′	−434′	−420′	−413′	−412′	−378′	−376′	−331′	−328′	−322′	−307′	−304′	−283′	−260′	−244′	−213′	−191′	−185′	−182′	−175′	−171′	−161′	−136′	−124′	−101′
Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Nonionella	3	3	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	45	30	-	15	-	-	-	-
Oridorsalis	-	-	-	-	1	-	4	-	-	-	3	3	-	-	-	-	-	-	-	-	-	-	-	-	-
Planulina	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pseudopolymorphina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
Pseudouvigerina	-	-	16	63	73	74	28	-	-	-	33	17	-	2	1	-	-	-	-	-	-	-	-	-	1*
Pullenia	2	2	-	-	-	1	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
Pulsiphonina	1	-	-	-	-	-	3	20	22	18	55	28	-	-	-	-	-	-	-	-	-	-	-	-	-
Pyramidina	22	18	37	9	10	3	3	24	42	20	2	5	3	2	-	-	-	-	-	-	-	-	-	-	10*
Quinqueloculina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	-	4	-	-	-	-	-	-	-
Rosalina	-	-	-	-	-	-	-	-	6	-	2	24	-	24	12	1	3	10	-	55	76	6	55	118	52
Sigmomorphina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	-	-	-	-
Siphogenerina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	3	3
Siphonina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Spirobolivina	21	24	4	16	10	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	2*	-	-	-	1*
Spiroplectammina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40	1	-	50	40	30	25	67	-	20	-
Stilostomella	-	2	4	1	1	1	3	-	5	3	6	1	-	1	-	-	3	-	1	-	8	-	-	2	-
Tappanina	7	7	4	10	5	-	-	1	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-	1*
Textularia	5	5	-	-	2	16	9	-	-	-	1	-	-	10	-	4	1	15	-	20	12	10	4	37	-
Trifarina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	6	-	-	-	-	-	-
Turrilina	1	-	1	-	1	9	15	1	1	15	72	35	3	47	15	-	8	-	-	-	-	-	-	-	-
Uvigerina	-	-	-	-	-	-	-	-	-	-	5	-	-	-	-	-	-	14	45	41	95	4	1	13	1
Virgulinella	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40	-	-	-	-	-
Total specimens	600	550	470	286	333	341	368	204	393	195	455	310	189	445	164	389	297	400	386	345	415	460	344	356	274
Percent benthic	39	41	65	93	93	75	77	75	85	77	42	68	68	61	73	100	91	87	66	36	43	94	85	96	100
Number indigenous benthic specimens	205	202	224	271	310	256	281	154	333	150	373	325	43	270	126	389	270	350	256	355	354	432	294	340	257
Number indigenous benthic genera	23	22	21	19	26	24	19	14	21	12	24	20	13	17	18	13	22	23	23	19	23	14	12	13	13

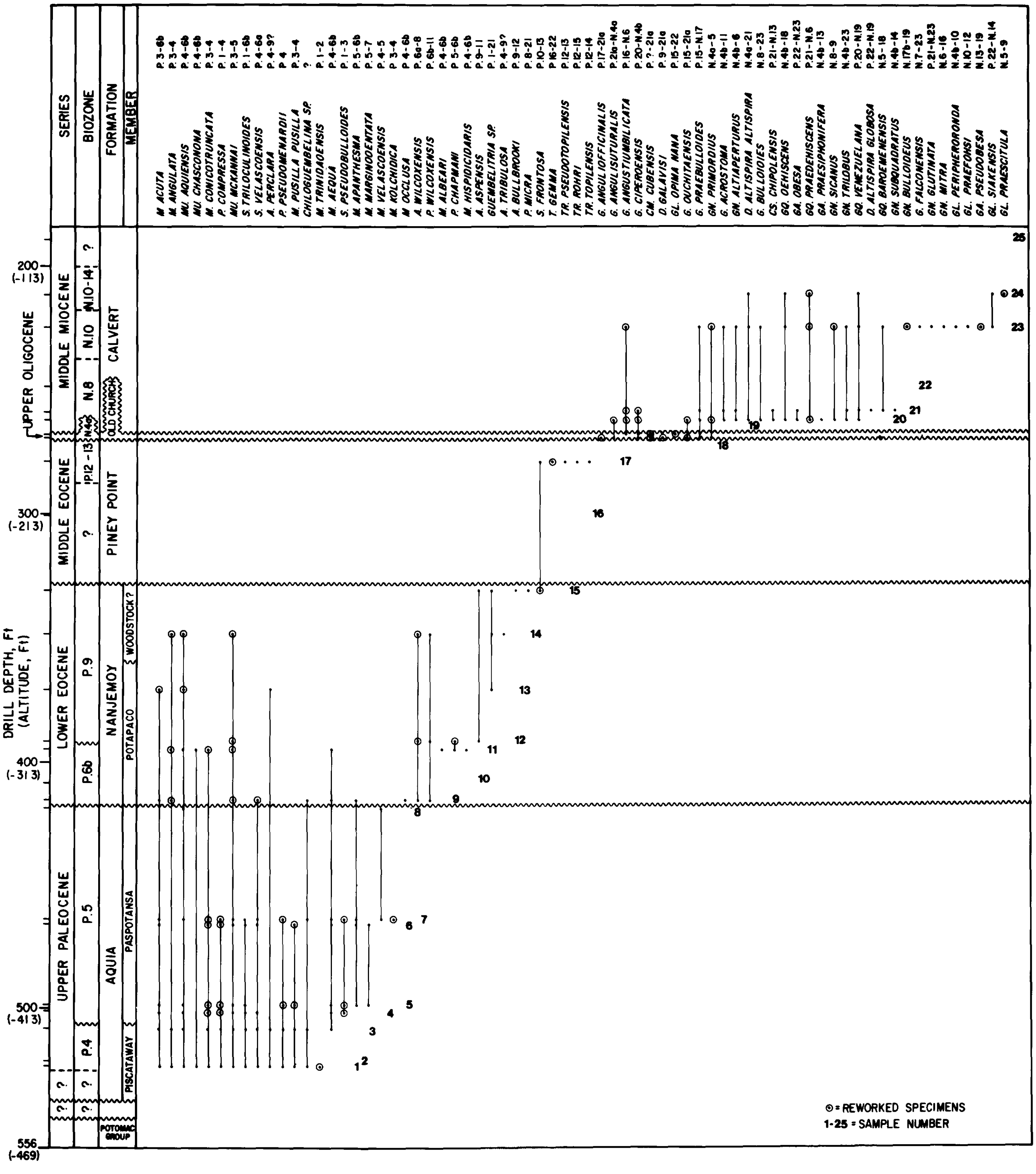

FIGURE 2.—Stratigraphic distribution of selected planktonic foraminifera in the Haynesville core holes. P. and N. numbers refer to planktonic foraminiferal zones (see Blow, 1969, 1979; Kennett and Srinivasan, 1983; Berggren and others, 1985; Bolli and others, 1985).

This assemblage, appears to have originated in inner sublittoral paleoenvironments (~40 m).

The second lowest Potapaco sample (sample 10, table 2) was taken from an olive-gray bed of clay-silt (from the

FIGURE 3.—Stratigraphic distribution of selected benthic foraminifera in the Haynesville core holes. See plates 1–5 for illustrations of these species. ▶

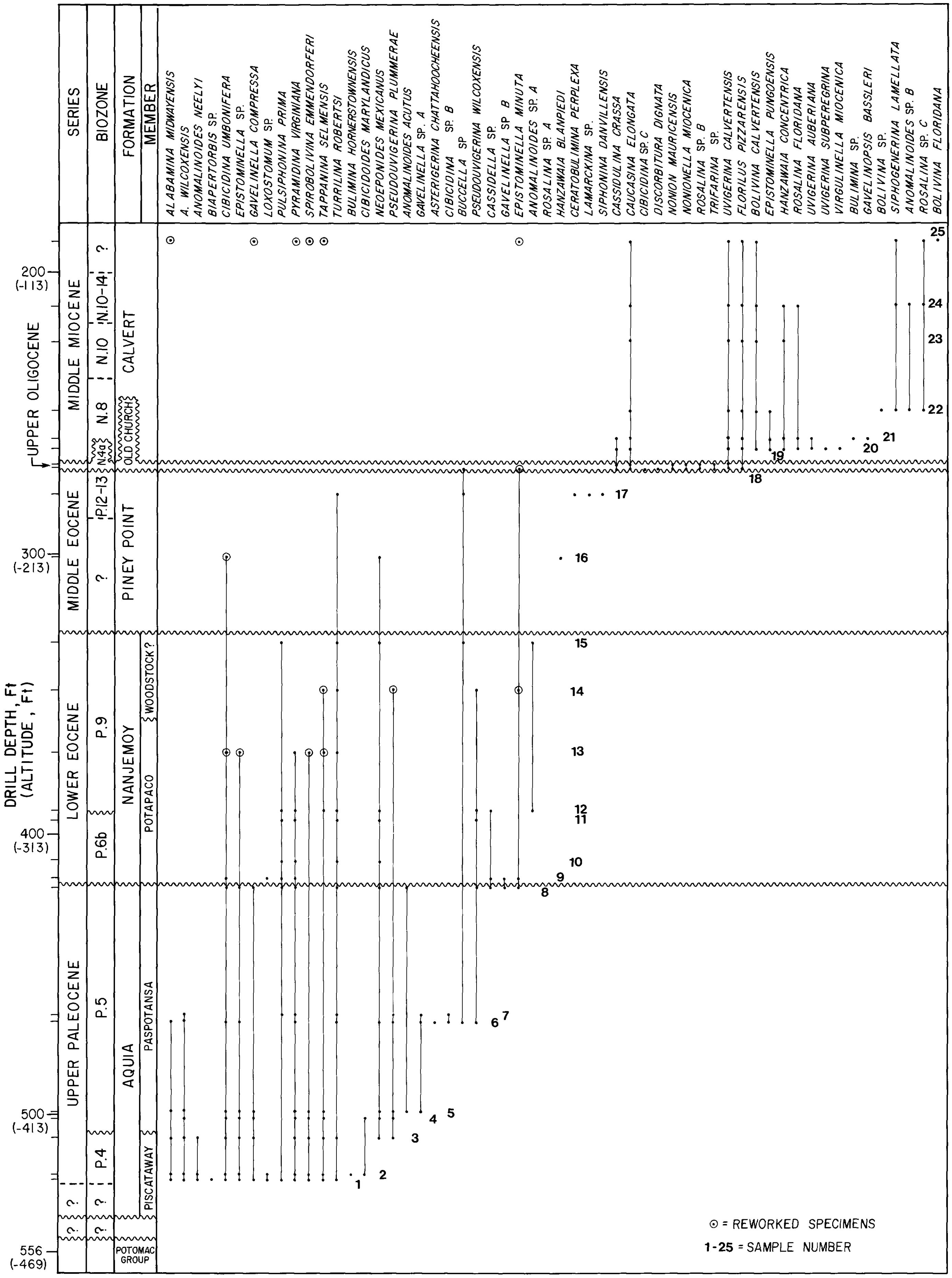
SERIES
BIOZONE
FORMATION
MEMBER
ALABAMINA MIDWAYENSIS
A. WILCOXENSIS
ANOMALINOIDES NEELYI
BIAPERTORBIS SP.
CIBICIDINA UMBONIFERA
EPISTOMINELLA SP.
GAVELINELLA COMPRESSA
LOXOSTOMUM SP.
PULSIPHONINA PRIMA
PYRAMIDINA VIRGINIANA
SPIROBOLIVINA EMMENDORFERI
TAPPANINA SELMENSIS
TURRILINA ROBERTSI
BULIMINA HORNERSTOWNENSIS
CIBICIDOIDES MARYLANDICUS
NEOEPONIDES MEXICANUS
PSEUDOUVIGERINA PLUMMERAE
ANOMALINOIDES ACUTUS
GAVELINELLA SP. A
ASTERIGERINA CHATTAHOOCHEENSIS
CIBICIDINA SP. B
BUCCELLA SP.
PSEUDOUVIGERINA WILCOXENSIS
CASSIDELLA SP.
GAVELINELLA SP. B
EPISTOMINELLA MINUTA
ANOMALINOIDES SP. A
ROSALINA SP. A
HANZAWAIA BLANPIEDI
CERATOBULIMINA PERPLEXA
LAMARCKINA SP.
SIPHONINA DANVILLENSIS
CASSIDULINA CRASSA
CAUCASINA ELONGATA
CIBICIDINA SP. C
DISCORBITURA DIGNATA
NONION MAURICENSIS
NONIONELLA MIOCENICA
ROSALINA SP. B
TRIFARINA SP.
UVIGERINA CALVERTENSIS
FLORILUS PIZZARENSIS
BOLIVINA CALVERTENSIS
EPISTOMINELLA PUNGOENSIS
HANZAWAIA CONCENTRICA
ROSALINA FLORIDANA
UVIGERINA AUBERIANA
UVIGERINA SUBPEREGRINA
VIRGULINELLA MIOCENICA
BULIMINA SP.
GAVELINOPSIS BASSLERI
BOLIVINA SP.
SIPHOGENERINA LAMELLATA
ANOMALINOIDES SP. B
ROSALINA SP. C
BOLIVINA FLORIDANA
DRILL DEPTH, Ft
(ALTITUDE, Ft)
200
(-113)
300
(-213)
400
(-313)
500
(-413)
556
(-469)
MIDDLE MIOCENE
UPPER OLIGOCENE
MIDDLE EOCENE
LOWER EOCENE
UPPER PALEOCENE
?
N.10-14
N.10
N.8
N.4a
P.12-13
?
P.9
P.6b
P.5
P.4
?
?
CALVERT
OLD CHURCH
PINEY POINT
NANJEMOY
WOODSTOCK?
POTAPACO
AQUIA
PASPOTANSA
PISCATAWAY
POTOMAC GROUP
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
⊙ = REWORKED SPECIMENS
1-25 = SAMPLE NUMBER

TABLE 2.—*Stratigraphic distribution of genera that constitute 10 percent or more of the benthic assemblage in at least one sample from the Haynesville core holes*

[Numbers are percentages. Solid dots indicate that taxon is present but constitutes less than 10 percent of benthic assemblage; R, reworked from older strata (not indigenous to sample)]

SERIES	UPPER PALEOCENE								LOWER EOCENE							MIDDLE EOCENE		UPPER OLIGOCENE		MIDDLE MIOCENE					
FORMATION	AQUIA								NANJEMOY							PINEY POINT		OLD CHURCH		CALVERT					
MEMBER	PISCATAWAY			PASPOTANSA					POTAPACO					WOODSTOCK											
COREHOLE	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	1	2	2	2	1	1	1	1
DRILL DEPTH	521' 6-10"	521' 2-6"	507' 0-2"	500' 0-3"	499' 0-4"	465' 0-4"	463' 5-9"	418' 9-11"	415' 0-4"	409' 6-9"	394' 11" to 395' 1"	391' 0-4"	370' 0-3"	347' 1-3"	316' 7-10"	285' 5-7"	268' 1-4"	257' 0-2"	269' 3-6"	262' 10" to 263' 2"	258' 8-10"	233' 3-7"	208' 3-5"	196' 4-6"	173' 10" to 174' 2"
ALTITUDE	-434' 6-10"	-434' 2-6"	-420' 0-2"	-413' 0-3"	-412' 0-4"	-378' 0-4"	-376' 5-9"	-331' 9-11"	-328' 0-4"	-322' 6-9"	-307' 11" to -308' 1"	-304' 0-4"	-283' 0-3"	-260' 1-3"	-244' 7-10"	-213' 5-7"	-181' 1-4"	-185' 0-2"	-182' 3-6"	-175' 10" to -176' 2"	-171' 8-10"	-161' 3-7"	-136' 3-5"	-124' 4-6"	-101' 10" to -102' 2"
SAMPLE NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CIBICIDINA	11.2	●	●	●	●	●	●	●	●	●	●	●	●	10.4	●	●	●	●	●	●					
CIBICIDOIDES	12.2	12.4	24.1	17.3	20.7	16.0	21.0	●	●	32.7	17.4	21.8	25.6	16.7	13.5	80.7	13.3	18.6	●	●	●				
FISSURINA	11.2	10.9	●		●				●		●				●		●	●	●	●	●		●		●
PYRAMIDINA	10.7	●	16.5	●	●	●	●	15.6	12.6	13.3	●	●	●	●											R
SPIROBOLIVINA	10.2	11.9	●	●	●								●								R				R
GYROIDINOIDES	●	10.4	●	●	●	●	15.7	11.7	15.0		●	13.8		●	●	●	●				●				
EPISTOMINELLA	●	●	10.3	●	●	●		12.3	●	18.7	●		●				●	●		●		●	●	●	●
PSEUDOUVIGERINA			●	23.3	23.6	28.9	10.0				●	●			●										R
GAVELINELLA	●	●	●	●	●	●	14.6	11.7	35.1	●			●	●											R
CASSIDELLA								16.2	●												R				
PULSIPHONINA	●						●	13.0	●	12.0	14.8	●													
TURRILINA	●		●		●	●	●	●	●	10.0	19.3	10.8	●	17.4	11.9		●								
BOLIVINA	●				●	●		●			●		18.6	●	●		●		●	●	●	●	●	●	●
FURSENKOINA					●	●						●		11.5			●	●	●			●	●		
ROSALINA									●		●	●		●	●	●	●	●		15.5	21.5	●	18.7	34.7	20.2
SPIROPLECTAMMINA															31.8	●		14.3	15.6	●	●	15.5		●	
GLOBULINA	●	●	●	●	●	●	●		●		●	●	●	●	●	●	53.7		●			●			
UVIGERINA											●							●	17.6	11.6	26.8	●	●	●	●
NONIONELLA	●	●	●												●			12.9	11.7		●				
CASSIDULINA															●			21.7	11.7	●	●				
VIRGULINELLA																				11.3					
FLORILUS									●	●	●	●		●			●	●	●	21.1	●	●	10.0	12.6	40.9
CAUCASINA																		●	●	11.6	●	54.4	42.2	●	20.2
HANZAWAIA																●					●	●	10.9	11.5	●
TEXTULARIA	●	●			●	●	●				●			●		●	●	●		●	●	●	●	10.9	

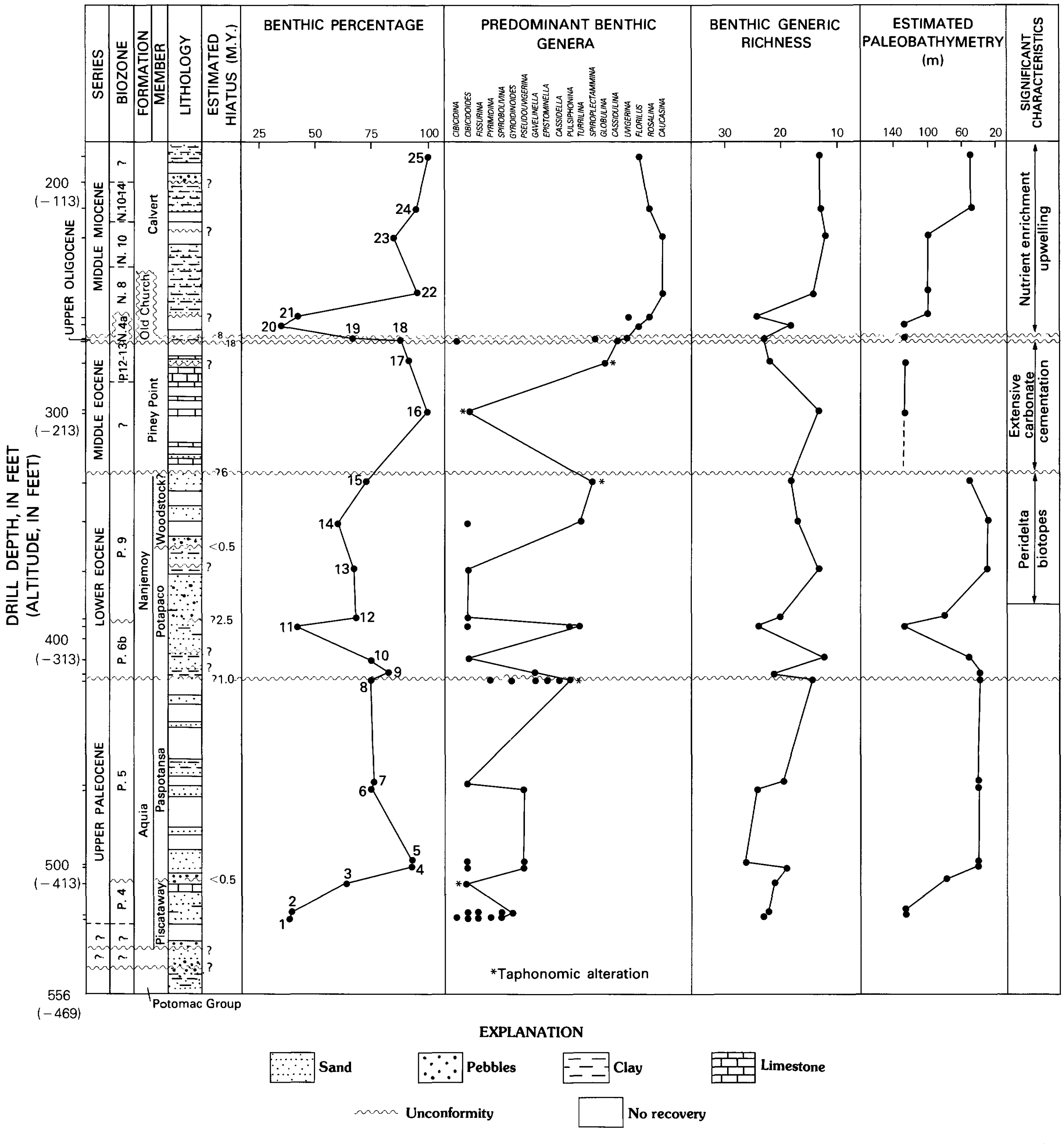

FIGURE 4.—Summary of stratigraphy, lithology, selected faunal attributes, and estimated paleobathymetry based on 25 samples from the Haynesville core holes. Blanks in lithology column indicate intervals of no core recovery. Solid line connecting dots in column for predominant benthic genera emphasizes the introduction of new predominant genera (indicating paleoenvironmental, taphonomic, and evolutionary change) upward through the stratigraphic column at the Haynesville site. Dashed line indicates projected paleobathymetry (no sample).

upper part of lithic unit B of the Potapaco; Mixon and others, chap. A, this vol.). The washed foraminiferal residue contains mainly dark-green glauconite grains; subangular to angular quartz grains and siderite(?)

grains are subordinate. Benthic percentage decreases to 77, 12 benthic genera are present, and no adult planktonic specimens were identified. The benthic assemblage is dominated by *Cibicidoides* (32.7 percent, tables 1, 2); *Epistominella* (18.7 percent), *Pyramidina* (13.3 percent), *Pulsiphonina* (12.0 percent), and *Turrilina* (10.0 percent) are the other genera representing 10 percent or more of the assemblage.

These relationships suggest inner sublittoral paleoenvironments (~40–60 m, fig. 4) with firm substrates and oxygen deficiency at the sea floor. A low foraminiferal number (only 195 specimens) suggests a rapid depositional rate and also biases the census data.

The third lowest Potapaco sample (sample 11, table 2) came from a sandy, gray clay containing burrows filled with quartz, glauconite, and phosphate(?) grains (upper part of lithic unit C of the Potapaco; Mixon and others, chap. A, this vol.). The washed foraminiferal residue contains chiefly angular to subangular quartz and sparse dark-green to black glauconite grains. The benthic percentage is low (42 percent), but the number of benthic genera is relatively high (24), and the number of identified indigenous planktonic species is low (6). Of the six planktonic forms, three, *Morozovella albeari*, *M. hispidicidaris*, and *Planorotalites chapmani*, are introduced for the first time in the Haynesville section; each ranges no higher than zone P. 6b. *Muricoglobigerina aquiensis*, *Mu. chasconona*, and *Morozovella aequa* also range into zone P. 6b, so sample 11 is assigned to zone P. 6b. Three other species are reworked older forms.

Three benthic genera predominate in sample 11 (tables 1, 2; fig. 4): *Turrilina* (19.3 percent), *Cibicidoides* (17.4 percent), and *Pulsiphonina* (14.8 percent). The low benthic percentage (42 percent) and the introduction of *Turrilina* as the predominant form signal a significant change from older paleoenvironments. *Turrilina* is an extinct Paleogene genus which appears to be related to the modern buliminids and caucasinids (see pl. 2, figs. 4–7; also see Revets, 1987). Thus its predominance may reflect muddy substrates with lowered dissolved oxygen contents. Modern buliminids are predominant in relatively deep water (>100 m), so the abundance of *Turrilina*, along with the relatively high percentage of planktonic specimens, suggests deepening waters (100–150 m) relative to the paleoenvironments of samples 9 and 10 (fig. 4).

The fourth lowest Potapaco sample (sample 12, table 2) was taken near the base of a dark-gray, medium to coarse, glauconite sand (base of lithic unit D of the Potapaco; Mixon and others, chap. A, this vol.). The washed foraminiferal residue contains chiefly dark-green glauconite; subordinate grains include subrounded quartz and siderite(?). The benthic percentage is 68; 20 benthic genera are present, and two indigenous planktonic species are recorded. The introduction of *Acarinina aspensis* (zones P. 9–11) suggests assignment to zone P. 9.

Cibicidoides (21.8 percent) is the predominant genus in sample 12 (tables 1, 2), followed by *Gyroidinoides* (13.8 percent) and *Turrilina* (10.8 percent). The renewed dominance of *Cibicidoides*, the decreased planktonic component, and the reduction in *Turrilina* suggest shoaling waters (60–100 m, fig. 4), firmer (less muddy) substrates, and more normal dissolved oxygen contents compared with sample 11.

The highest Potapaco sample (sample 13, table 2) came from an olive-gray, micaceous, lignitic clay-silt (near the top of lithic unit D of the Potapaco; Mixon and others, chap. A, this vol.). The washed foraminiferal residue contains abundant mica, glauconite, and quartz grains. Fish skeletal debris, lignite, internal casts of gastropods, and a few radiolarians and diatoms also are present. The foraminiferal assemblage is small (only 189 indigenous specimens), and 68 percent are benthic species. The paucity of specimens also is reflected in the low number (13) of benthic genera represented and the presence of only four indigenous adult planktonic specimens. The biostratigraphic value of the scanty planktonic assemblage is low, but the species represented (fig. 2) probably are part of the zone P. 9 association.

Cibicidoides is the predominant benthic taxon in sample 13 (25.6 percent), followed by *Bolivina* (18.6 percent). *Bolivina* is often associated with this type of sediment, in which the abundance of lignite indicates high organic carbon and low oxygen content of the surface sediments during deposition (Poag, 1985c). The abundance of benthic specimens, dominated by *Cibicidoides*, suggests relatively shallow water (20–40 m, fig. 4), perhaps supporting a crop of sea grass that provided attachment surfaces for the benthic foraminifera above the muddy bottom. The lithic and microfaunal attributes of sample 13 are typical of peridelta biotopes.

WOODSTOCK MEMBER

Two samples were taken from the Woodstock Member for foraminiferal analysis, one near the middle and one near the top (tables 1, 2; figs. 2–4). The lower sample (sample 14, table 2) came from a micaceous, glauconitic, quartz sand, which yielded a washed residue of subrounded quartz and dark-green and orange glauconite grains. Many of the quartz grains are also iron stained. Siderite(?) and mica are minor constituents.

The benthic percentage of sample 14 is 61, the number of benthic genera is 17, and the number of identified indigenous planktonic species is three (fig. 2). The presence of *Acarinina tribulosa* suggests that this sample is stratigraphically no higher than zone P. 9 (lower Eocene). Predominant benthic genera are *Turrilina*

(17.4 percent) and *Cibicidoides* (16.7 percent), followed by *Fursenkoina* (11.5 percent) and *Cibicidina* (10.4 percent). These lithic and microfaunal relationships suggest an inner sublittoral paleoenvironment similar to that of sample 13 (20–40 m, fig. 4). The abundance of *Turrilina* and *Fursenkoina* suggests marine waters having lower than normal dissolved oxygen content.

The upper Woodstock sample (sample 15, table 2) came from a micaceous glauconite sand, which yielded a washed residue of abundant mica, iron-stained glauconite, and iron-stained quartz grains. Siderite(?) is a subordinate constituent. The benthic foraminiferal percentage is 73, 18 benthic genera are present, and only four indigenous planktonic species are identified. The sparse planktonic assemblage contains two species that range no lower than zone P. 9, probably indicating assignment to this zone (lower Eocene). *Subbotina frontosa,* which normally ranges no lower than zone P. 10, appears to have been reworked downward by burrowing across the superjacent unconformity.

The unusual benthic assemblage of sample 15 (fig. 3) is strongly dominated by a single species of the agglutinated genus *Spiroplectammina* (31.8 percent; tables 1, 2). *Cibicidoides* (13.5 percent) and *Turrilina* (11.9 percent) are subordinate genera. The lithic and microfaunal attributes recorded suggest an inner sublittoral (40-60 m, fig. 4) environment with firm, sandy substrates. Weathering during the hiatus at the end of Woodstock deposition is reflected by the iron-stained sediments, and, undoubtedly, this has altered the faunal composition somewhat. The dominant taxon, *Spiroplectammina,* was not found in any of the older samples, however, and appears to have been a significant component of the original assemblage.

PINEY POINT FORMATION

Two samples were taken for foraminiferal analysis from the Piney Point section, one near the middle and one near the top (tables 1, 2; figs. 2–4). Both samples came from intervals of carbonate-cemented, shelly, glauconitic, quartz sands interbedded with loose, sandy strata of the same constituents.

The lower Piney Point sample (sample 16, table 2) produced a washed residue of shelly quartz sand having relatively little glauconite (both weathered and dark-green grains are present). Calcite-cemented lithoclasts are common, and spar-filled cavities are abundant. No foraminiferal specimens floated from this residue because of the calcite infilling air spaces within the tests. Therefore, I examined the entire washed residue. The foraminiferal assemblage therein contains only benthic specimens (fig. 4), of which 80.7 percent belong to *Cibicidoides.* No other genus represents 10 percent or more of the assemblage, although 13 genera are present (table 1). Many specimens are severely dissolved, broken, or thickly coated with overgrowths of sparry calcite (see Collen and Burgess, 1979, for a detailed discussion of the effects of this diagenetic process on benthic foraminifera). This is a severely altered assemblage, in which chiefly the more robust tests have survived. The total number of species (14) and the taxonomic makeup of the entire assemblage (tables 1, 2) indicates, however, that the original environment of deposition was probably a normal marine biotope (fig. 4). The lack of planktonic species precludes precise zonal assignment.

The washed residue of the upper Piney Point sample (sample 17, table 2) is similar to that of the lower sample, but a more complete foraminiferal suite is present and a large number of specimens floated from the residue. The benthic percentage is still high (91 percent), but 22 genera are represented (table 1) and four indigenous planktonic species are identified (fig. 2). The planktonic suite contains three species that appear for the first time in the Haynesville section. The co-occurrence of *Truncorotaloides rohri* (zones P. 12–15), *Tr. topilensis* (zones P. 12–14), and *Subbotina frontosa* (zones P. 10–13) indicates that this sample probably belongs to zone P. 12–13 of the middle Eocene (Lutetian).

The floated benthic assemblage of sample 17 is strongly dominated (53.7 percent) by *Globulina* rather than *Cibicidoides* (which dominated sample 16), but an examination of the washed residue revealed that a large portion of the residual foraminiferal assemblage (mainly *Cibicidoides*) did not float off, owing to extensive recalcification. Furthermore, dissolution and recalcification have altered this assemblage and reduced the number of fragile and thin-wall forms (such as planktonic species). The statistical analysis, therefore, does not accurately reflect the original assemblage, but the general taxonomic composition of the altered assemblage, the relatively high generic richness (table 1), and the well-developed (large) planktonic specimens indicate that outer sublittoral (100–150 m), normal marine paleoenvironments probably existed during its accumulation (fig. 4).

OLIGOCENE STRATA

OLD CHURCH FORMATION

Two samples were taken for foraminiferal analysis from the thin section of the Old Church Formation (tables 1, 2; figs. 2–4), one (sample 18) from the base and one (sample 19) near the top. The Old Church section consists of calcareous, shelly, poorly sorted, muddy, very fine to coarse sand containing scattered granules and fine pebbles (see Mixon and others, chap. A, this vol.). The washed residues contain angular to subangular quartz sand, echinoid debris, mollusk fragments, and barnacle plates, as well as rich foraminiferal assemblages. Benthic foraminifera constitute 66–87 percent of the assemblages, 23 genera are represented in each sample, and 10 planktonic species are identified.

The biozonation based on planktonic species is difficult to determine precisely, although a middle to late Oligocene age is certain. Four species (*Chiloguembelina cubensis*, *Globigerina angulioffficinalis*, *G. ouachitaensis*, and *Dentoglobigerina galavisi*) normally range no higher than zone P. 21a, and one of the most abundant species (*G. angulisuturalis*) ranges no lower than P. 21a. This overlap suggests assignment to zone P. 21a, of latest early Oligocene age. On the other hand, three species (*G. angulisuturalis*, *G. ciperoensis*, and *Globorotalia opima nana*) range as high as zone N. 4a, whereas *Globigerinoides primordius* ranges no lower than the upper part of zone N. 4a, which is of latest Oligocene age (Kennett and Srinivasan, 1983). Part of the problem is that the Old Church section is only about 1 m (3 ft) thick, and reworking upward and downward is so prevalent in these updip Coastal Plain strata that positive zonal assignment is difficult. I tentatively assume that *Gn. primordius* is in place, and that the Old Church section belongs to the late Oligocene zone N. 4a (of Kennett and Srinivasan, 1983), having a moderate but significant suite of reworked early Oligocene forms. This opinion is based on consideration of the regional stratigraphic and depositional history derived from other boreholes (Poag, 1985a, 1985b, 1987), which indicates that lower Oligocene strata have been removed from broad areas of the U.S. Atlantic margin during a sea-level fall in the early part of the late Oligocene. In addition, the absence of *Globorotalia kugleri*, which is normally abundant high in zone N. 4a and in zone N. 4b, suggests that the upper part of zone N. 4a is missing. Furthermore, the distinctly Miocene elements of the overlying Calvert Formation are not present in the Old Church samples, indicating that *Globigerinoides primordius*, which elsewhere does range into the early Miocene (zone N. 5), is probably indigenous to the Old Church.

The benthic assemblage of the lower Old Church sample (sample 18, table 2) contains predominantly *Cassidulina* (21.7 percent), *Cibicidoides* (18.6 percent), *Spiroplectammina* (14.3 percent), and *Nonionella* (12.9 percent). In the upper Old Church sample (sample 19, table 2), the suite of predominant taxa is nearly the same: *Uvigerina* (17.6 percent), *Spiroplectammina* (15.6 percent), *Cassidulina* (11.7 percent) and *Nonionella* (11.7 percent). These assemblages are taxonomically quite different from older assemblages (introduction of abundant *Cassidulina*, *Uvigerina*, and *Nonionella* and 10 new benthic species; figs. 3, 4), reflecting, in part, evolutionary changes in the benthic foraminiferal community. The predominant genera, benthic generic richness, and planktonic species richness characterizing these assemblages suggest outer sublittoral environments (100–150 m), having abundant organic carbon and reduced dissolved oxygen at the sea floor.

MIOCENE STRATA

CALVERT FORMATION

Seven samples were taken from the Calvert Formation for foraminiferal analysis (tables 1, 2; figs. 2–4)—three near the bottom, two near the middle, and two near the top of the section. The lower two samples (samples 20 and 21, table 2) came from a shelly, clayey, silty sand, which yielded a washed residue of subangular quartz, fish skeletal debris, echinoid spines, mollusk fragments, and siderite(?). The foraminiferal contents of these lower two samples are quite different from the higher Calvert samples (samples 22–25). In the lowest sample (sample 20, table 2), the benthic assemblage constitutes only 36 percent of the foraminifera and 18 benthic genera are represented. Twelve indigenous planktonic species are identified, 11 of which appear for the first time in the Haynesville section (fig. 2).

The planktonic assemblage is a distinctly Miocene one, though some species range into the Oligocene and Pliocene. The stratigraphically limiting species are *Globigerinoides altiaperturus* and *Gn. sicanus* (fig. 2), whose overlapping ranges suggest assignment to zone N. 8 of the middle Miocene (Langhian). A few reworked older species (e.g., *Globigerina angulisuturalis*, *Globigerinoides primordius*, and *Globoquadrina praedehiscens*) are also present.

The predominant benthic foraminifera in sample 20 are *Florilus* (21.2 percent) and *Rosalina* (15.5 percent); subordinate genera are *Caucasina* (11.6 percent), *Uvigerina* (11.6 percent), and *Virgulinella* (11.3 percent). Except for *Uvigerina*, each of these genera is represented by a single species (fig. 3; pls. 4, 5). This assemblage is not encountered lower in the Haynesville section. It reflects a peculiar set of circumstances that were rather widespread along the U.S. Atlantic margin during the middle Miocene. All the predominant genera (species), except perhaps *Rosalina*, are indicators of high-nutrient/low-oxygen conditions associated with shallow-water delta margins or areas of coastal upwelling. In fact, 7 of the 19 genera represented (including *Epistominella* and *Buliminella*, table 1) in this assemblage are generally prominent in such conditions. In this case, the presence of an abundant and species-rich planktonic assemblage and the lack of lignite in the sediments suggest that upwelling, not terrigenous deltaic deposition, was the source of nutrient enrichment. The abundance of fish skeletal debris, which is also common in regions of upwelling (Diester-Haass, 1978), supports this conclusion. Palmer (1986) found that radiolarian assemblages in lower Calvert strata (Fairhaven Member) also suggest the influence of coastal upwelling. The other attributes suggest outer sublittoral paleoenvironments (100–150 m) having muddy substrates (fig. 4).

In sample 21 (table 2), the foraminiferal assemblage changes to 43 percent benthics (including 24 indigenous benthic genera) and contains 10 indigenous planktonic species. The planktonic assemblage is similar to that of sample 20, but three new species are introduced into the section (fig. 2). No change in biozonation is suggested by this assemblage.

The predominant benthic genera in sample 21 are *Uvigerina* (26.8 percent) and *Rosalina* (21.5 percent), which, along with the other assemblage attributes, suggests a paleodepth of ~100 m and continued nutrient enrichment and low oxygen values in the bottom water (fig. 4). The other genera characteristic of high-nutrient/low-oxygen conditions are still present (except for *Buliminella*), but each constitutes less than 10 percent of the assemblage.

In sample 22, a distinct lithologic change takes place. The washed sample contains residual lumps of diatom-radiolarian clay with a few angular quartz grains and scattered skeletal remains of fish. The benthic percentage ascends to 94, but only 14 benthic genera are represented. No adult planktonic specimens are identified. A single species, *Caucasina elongata* (an opportunist that, like some species of *Bolivina* [Phleger and Soutar, 1973; Poag, 1985a], proliferated in high-nutrient, sublittoral environments), forms more than half (54.4 percent) the benthic assemblage. *Spiroplectammina* (15.5 percent) is the only other genus constituting more than 10 percent of the assemblage. The other forms characteristic of high-nutrient/low-oxygen conditions are still present, however. The abundance of diatoms and radiolarians is, in itself, evidence of high rates of primary productivity brought about by nutrient-enriched waters. The dominance of *Caucasina elongata* corroborates the presence of high-nutrient/low-oxygen conditions. The high benthic percentage and low generic richness would seem to suggest relatively shallow waters for deposition of sample 22, but I interpret these attributes, in this case, to reflect the opportunistic proliferation of *Caucasina elongata* and the reduction of planktonic foraminifera by relatively large populations of siliceous plankton (radiolarians and diatoms), a common attribute of upwelling regions (Diester-Haass, 1978). Sample 22 probably represents a mid-sublittoral (~100 m) paleoenvironment.

Diatoms and radiolarians are even more abundant in the washed residue of sample 23; *Caucasina elongata* is again strongly predominant (42.2 percent), and the benthic percentage remains high (85 percent). Six of the familiar high-nutrient/low-oxygen genera are represented among the total of 12 benthic genera present. An assemblage of 15 indigenous planktonic species introduces a significant new suite of 8 new species to the Haynesville section (fig. 2). The stratigraphically most reliable species in this new suite are *Globorotalia peripheroronda* and *Gl. praefohsi*, whose overlap indicates assignment to zone N. 10 of the middle Miocene (lower Serravallian). Several of the other species are reworked from older strata. These lithic and microfaunal attributes suggest continued deposition in a mid-sublittoral (~100 m) paleoenvironment characterized by upwelling nutrients.

Another change in lithology and microfossil content takes place in sample 24. The washed sample yielded residual lumps of micaceous clay and echinoid spines; radiolarians and diatoms are much less abundant than in samples 22 and 23. The benthic foraminiferal component reaches 96 percent, although only 13 benthic genera were recorded (table 1, fig. 4). The planktonic assemblage consists of only four indigenous species, all of which are long ranging (fig. 2). The introduction of *Globorotalia siakensis* suggests, however, that the section is stratigraphically no higher than zone N. 14 of the middle Miocene (middle-Serravallian).

The benthic foraminiferal assemblage is strongly dominated by *Rosalina* (34.7 percent), which is not one of the high-nutrient/low-oxygen indicators, though it often occurs with them. However, six species of the high-nutrient group are still present in low numbers (fig. 3; pls. 4, 5). These attributes suggest an inner sublittoral paleoenvironment having firm substrates for *Rosalina* attachment and water depths of 40–60 m (fig. 4). The composition of the microfauna indicates that the influence of upwelling had diminished at the Haynesville site during deposition of sample 24.

Only the lower of the upper two Calvert samples contained foraminifera. The washed residue of sample 25 yielded small lumps of diatomaceous clay containing fish skeletal debris. The benthic component constitutes 100 percent of the foraminiferal assemblage. Thirteen indigenous genera are represented (table 1), and at least six additional genera are represented by reworked older specimens, principally derived from Paleocene and Eocene strata (e.g., *Tappanina selmensis*, *Alabamina midwayensis*, *Gavelinella compressa*, *Pyramidina virginiana*; table 1; fig. 3). The dominant indigenous taxon is *Florilus* (40.9 percent), followed by *Caucasina* (20.2 percent and *Rosalina* (20.2 percent). This sample represents another interval of inner sublittoral deposition

(40–60 m) under the influence of nutrient enrichment due to upwelling (fig. 4). The benthic species represented here are known to range as high as the Pliocene (Poag, 1984), but their relative abundance and the absence of species restricted to the Pliocene suggest that the sample is still of Miocene (probably middle Miocene) age (see Poag, 1984).

GENERAL DEPOSITIONAL FRAMEWORK

The Haynesville core site (two core holes, 150 ft (30 m) apart) is approximately 70 kilometers (km) (43 miles (mi)) downdip (eastward) from the inner edge of the Virginia Coastal Plain (Fall Line) and 40–50 km (25–30 mi) downdip from the Oak Grove core site (Gibson and others, 1980; Reinhardt and others, 1980) and from the Pamunkey River outcrops (Ward, 1984), where similar but shallower water sedimentary sections have been reported. Drilling at the Haynesville site penetrated the Cenozoic section on the southwestern flank of the Salisbury embayment, a landward extension of the Baltimore Canyon trough (fig. 1). Extensive stratigraphic studies offshore (Poag, 1987; Poag and Low, 1987) have shown that the shelfbreak, during the principal depositional phases of the Cenozoic, was approximately 200 km (~125 mi) offshore (eastward) from the Haynesville site. Thus we know that the Cenozoic sediments at Haynesville accumulated in an inner-shelf paleophysiographic setting. This knowledge helps to constrain the relative paleodepths of the sampled microfossil assemblages. It should be emphasized, though, that paleodepth is not necessarily a direct function of paleophysiography. For example, bathyal depths (>200 m) can develop on a continental shelf if sea level rises coincident with basin subsidence (e.g., the continental shelf of Antarctica, today). Such a condition appears to have developed in the Baltimore Canyon trough during the middle Eocene (Poag and Low, 1987), which is characterized by the greatest paleodepths of the Cenozoic, along the Virginia-New Jersey margin. Taphonomic alteration of microfossil assemblages, however, has obscured the record of this regional deepening in the deposits of the Haynesville cores.

What we see in the depositional succession of the Haynesville cores is a series of inner sublittoral (20–40 m) to outer sublittoral (100–150 m) marine sedimentary sequences separated by erosional unconformities (fig. 4; see Mixon and others, chap. A, this vol.). The generally shallow water origin of the strata and the reworking of older strata by erosion and of younger strata by burrowing have created difficulties in determining which planktonic zonal markers are indigenous in some of the units (fig. 2). Interpretations are, in some cases, based on a general assessment of the regional stratigraphic and depositional framework (fig. 5; Poag, 1987). They represent the most logical conclusions allowed by the limited data at hand, but they should be considered tentative interpretations subject to revision as new data are gathered from more complete, deeper marine sections.

The duration of hiatuses shown in figure 4 (identified by lithostratigraphic or biostratigraphic discontinuities) is estimated by using the biochronology of Berggren and others (1985). If an unconformity should fall within as single biozone, or between two consecutive biozones (as often is the case), the duration of the hiatus is given as an arbitrary fraction of the biochron. The accuracy of hiatal estimates is, therefore, variable, depending on the position of the unconformity relative to the biochronologic scale. The stratigraphic positions of the four principal unconformities (fig. 4) and the hiatuses represented by them, however, fit well into the regional framework (fig. 5), which supports their general reliability.

Taphonomic changes in the benthic assemblages (such as reworking upward and downward, selective dissolution, and secondary calcification) also have impeded paleoenvironmental reconstruction. Because of these problems, statistical faunal attributes (e.g., species richness, planktonic/benthic ratio) that are widely applied in deeper marine biotopes (outer sublittoral, bathyal, abyssal) are often inaccurate when applied to foraminiferal assemblages deposited in shallower water strata of the coastal plain. It is critical, therefore, to place the Coastal Plain foraminiferal data in the context of the regional lithologic, geochemical, and depositional/erosional framework in order to draw the most reasonable paleoenvironmental inferences. As only the broad-scale regional relationships are well known in the study area (Poag, 1987), the more detailed aspects of paleoenvironmental reconstruction presented herein must be considered preliminary. However, the cyclic pattern of five principal transgressive sequences (Piscataway, middle Potapaco, Piney Point, Old Church, and lower Calvert; figs. 4, 5) separated by regressive sequences or unconformities, appears to be firmly supported by the evidence at hand. Also, the inference of perideltaic paleoenvironments for the upper Potapaco and Woodstock sections and of high primary productivity (due to upwelling) during Calvert deposition appears to be valid.

CONCLUSIONS

Analysis of 25 foraminiferal assemblages taken from five Cenozoic formations encountered in two adjacent core holes near Haynesville, Va., yields the following principal conclusions regarding the Haynesville stratigraphic section:

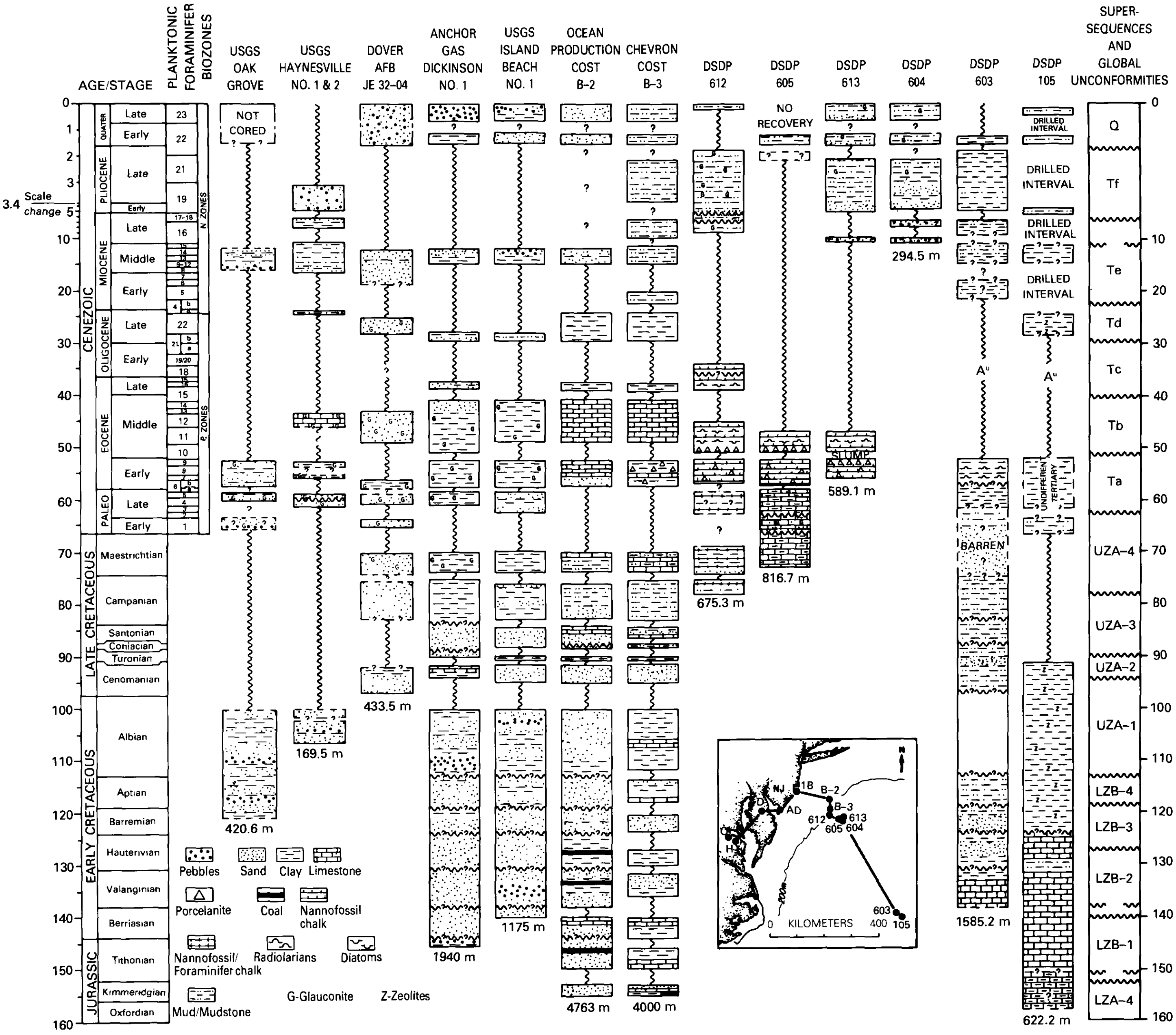

FIGURE 5.—Comparison of stratigraphy of core holes at the Haynesville site with that of other boreholes in the Salisbury embayment, the Baltimore Canyon trough, and the North American basin and with depositional supersequences and global unconformities of the Vail model (Vail and others, 1977; Vail and Mitchum, 1979; Haq and others, 1987). Time scale for Cenozoic from Berggren and others (1985) and for Mesozoic from Kent and Gradstein (1985). Total depths listed represent thickness of stratigraphic column. Modified from Poag (1987).

1. On the basis of planktonic foraminifera, the lowest sample from the Piscataway Member of the Aquia Formation is placed in zone P. 4 of the upper Paleocene. A local unconformity (hiatus of probably less than 0.5 m.y.) separates the Piscataway from the Paspotansa Member, which belongs to zone P. 5, also of the upper Paleocene (fig. 4).

2. A regional unconformity representing a hiatus of about 1 m.y. separates the Paspotansa Member from the Potapaco Member of the Nanjemoy Formation (figs. 4, 5). The basal section of the Potapaco belongs to zone P. 6b of the lower Eocene; the upper section belongs to zone P. 9, and the two sections are separated by a local unconformity (hiatus estimated to be about 2.5 m.y.; fig. 4). The overlying Woodstock Member of the Nanjemoy also belongs to zone P. 9, but it is separated from the Potapaco by a local unconformity (hiatus estimated to be less than 0.5 m.y.; fig. 4).

3. The top of the Woodstock Member is an unconformable surface of regional extent, representing a hiatus that could be as long as 6 m.y. (fig. 4, 5). The upper part of the overlying Piney Point Formation belongs to zone P. 12 of the middle Eocene. Assignment of 6 m.y. to the hiatus assumes that the base of the Piney Point also belongs to zone P. 12.

4. The thin section of the Old Church Formation, which overlies the Piney Point, belongs to zone N. 4a of the upper Oligocene, thereby indicating that an hiatus of 18 m.y. is represented by the regional unconformity at its base (figs. 4, 5).

5. Another regional unconformity separates the Old Church from the overlying Calvert Formation (figs. 4, 5). A hiatus of 8 m.y. is indicated by the superposition of zone N. 8 (middle Miocene) on zone N. 4a (upper Oligocene). The middle and upper parts of the Calvert section belong to zones N. 10–14 (middle Miocene).

6. Benthic foraminifera indicate that inner to outer sublittoral paleoenvironments were prevalent during the Cenozoic at the Haynesville site (fig. 4). The shelfedge, as determined from seismostratigraphic analysis (Poag, 1987), lay well to the east of the Haynesville sites during the middle Eocene, late Oligocene, and middle Miocene (fig. 1). The shelfedge positions for the Paleocene and early Eocene were also well to the east, but their precise locations are difficult to determine from available seismic data. Deepest water conditions at the Haynesville locality developed during deposition of the Piscataway, middle Potapaco, Piney Point, Old Church, and lower Calvert sections.

7. During late Potapaco and all of Woodstock time, the Haynesville site accumulated lignitic, micaceous sediments whose benthic foraminifera suggest the high-nutrient/low-oxygen conditions typical of peridelta biotopes (fig. 4).

8. An association of opportunistic benthic foraminifera (adapted to high-nutrient/low oxygen conditions) and rich planktonic assemblages (especially diatoms and radiolarians) occupied the Haynesville site during Calvert time, indicating the strong influence of coastal upwelling (fig. 4).

9. Reworking (both upward and downward) is prevalent in the Haynesville section (especially near the unconformable contacts) and complicates identification of indigenous assemblages (figs. 2, 3). Carbonate diagenesis is also a significant taphonomic process in parts of the section (especially prevalent in the Piney Point Formation) and has altered the original foraminiferal assemblages of several samples.

10. The Haynesville section fits well into the regional stratigraphic and paleoenvironmental framework of the Salisbury embayment and Baltimore Canyon trough (figs. 1, 5). The only unusual aspect is the presence of foraminifera belonging to probable upper Oligocene zone N. 4a, which have not been reported previously from the subsurface of the western margin of the Salisbury embayment. The Old Church Formation, which contains similar N. 4a assemblages, is known, however, farther updip (to the southwest), where it crops out along the Pamunkey River (fig. 1; Ward, 1984; Ward and Strickland, 1985).

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PLATES 1–5

[Contact photographs of the plates in this report are available, at cost, from the U.S. Geological Survey Photographic Library, Federal Center, Denver, CO 80225]

PLATE 1

[Scale bar=50 μm; specimens without scale bars are same magnification as preceding specimen]

FIGURES 1–3. *Alabamina midwayensis* Brotzen, 1948. Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft 2–6 in). Piscataway Member, Aquia Formation. 1, umbilical view; 2, edge view; 3, spiral view.

4–6. *Alabamina wilcoxensis* Toulmin, 1941. Haynesville core hole 2, 499 ft 0–4 in (altitude −412 ft 0–4 in). Paspotansa Member, Aquia Formation. 4, umbilical view; 5, edge view; 6, spiral view.

7–9. *Anomalinoides neelyi* (Jennings, 1936). Haynesville core hole 2, 521 ft 6–10 in (altitude −434 ft 6–10 in). Piscataway Member, Aquia Formation. 7, spiral view; 8, edge view; 9, umbilical view.

10–12. *Biapertorbis* sp. Haynesville core hole 2, 521 ft 6–10 in (altitude −434 ft 6–10 in). Piscataway Member, Aquia Formation. 10, umbilical view; 11, edge view; 12, spiral view.

13–15. *Cibicidina umbonifera* (Schwager, 1883). Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft 2–6 in). Piscataway Member, Aquia Formation. 13, spiral view; 14, edge view; 15, umbilical view.

16–18. *Epistominella* sp. Haynesville core hole 2, 500 ft 0–2 in (altitude −413 ft 0–2 in). Paspotansa Member, Aquia Formation. 16, spiral view; 17, edge view; 18, umbilical view.

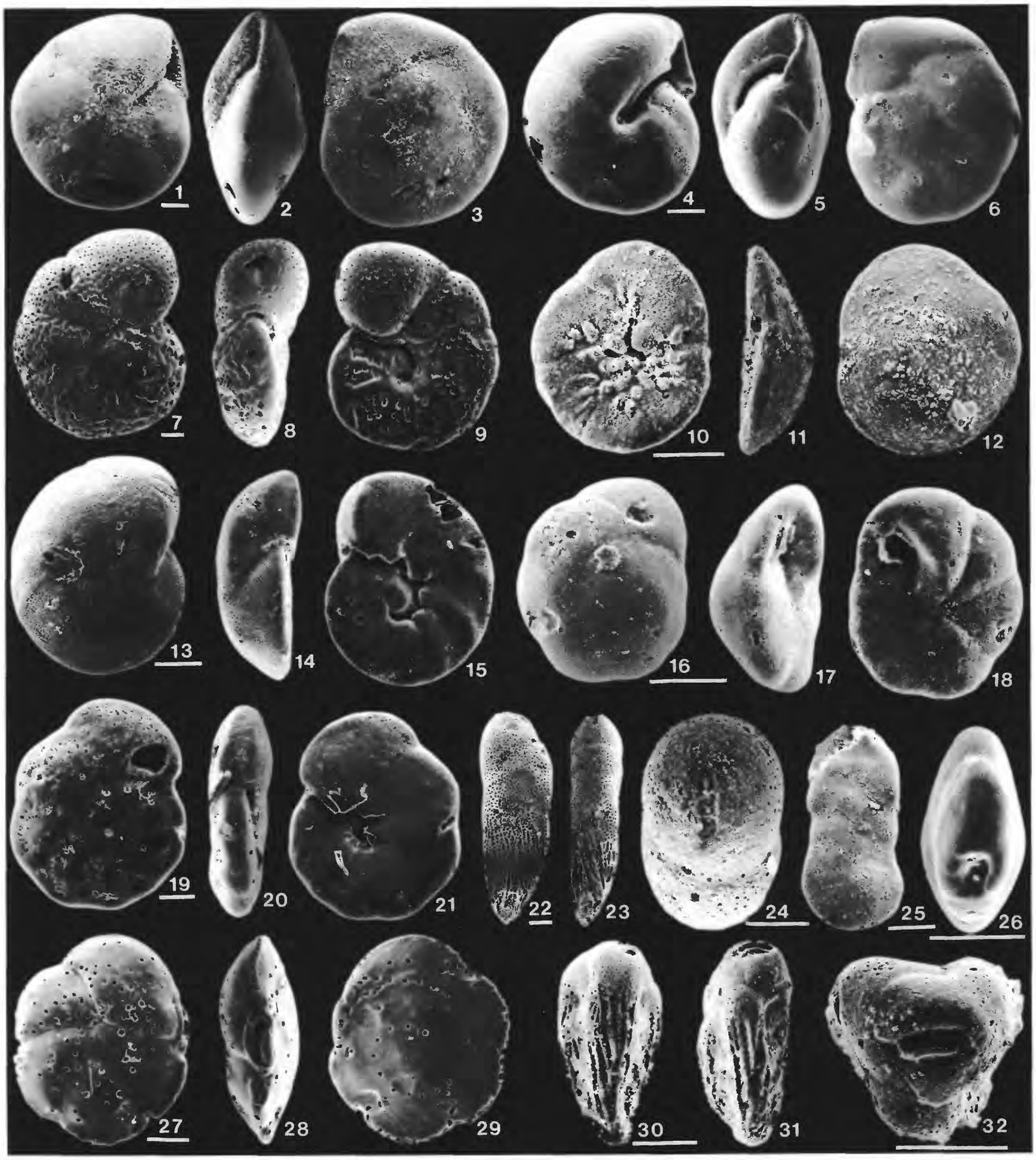
19–21. *Gavelinella compressa* (Olsson, 1960). Haynesville core hole 2, 507 ft 0–2 in (altitude −420 ft 0–2 in). Piscataway Member, Aquia Formation. 19, spiral view; 20, edge view; 21, umbilical view.

22–24. *Loxostomum* sp. Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft 2–6 in). Piscataway Member, Aquia Formation. 22, lateral view; 23, edge view; 24, apertural view.

25, 26. *Spirobolivina emmendorferi* (Jennings, 1936). Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft, 2–6 in). Piscataway Member, Aquia Formation. 25, lateral view; 26, apertural view.

27–29. *Pulsiphonina prima* (Plummer, 1926). Haynesville core hole 2, 463 ft 5–9 in (altitude −376 ft 5–9 in). Paspotansa Member, Aquia Formation. 27, umbilical view; 28, edge view; 29, spiral view.

30–32. *Pyramidina virginiana* (Cushman, 1944). Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft 2–6 in). Piscataway Member, Aquia Formation. 30, 31, lateral views; 32, apertural view.



ALABAMINA, *ANOMALINOIDES*, *BIAPERTORBIS*, *CIBICIDINA*, *EPISTOMINELLA*, *GAVELINELLA*, *LOXOSTOMUM*, *SPIROBOLIVINA*, *PULSIPHONINA*, AND *PYRAMIDINA*

PLATE 2

[Scale bar=50 µm; specimens without scale bars are same magnification as preceding specimen]

FIGURES 1–3. *Tappanina selmensis* (Cushman, 1933). Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft 2–6 in). Piscataway Member, Aquia Formation. 1, edge view; 2, lateral view; 3, apertural view.

4–7. *Turrilina robertsi* (Howe and Ellis, 1939). Haynesville core hole 2. 4, lateral view; 5, apertural view; 409 ft 6–9 in (altitude −322 ft 6–9 in), Potapaco Member, Nanjemoy Formation. 6, lateral view; 7, apertural view; 347 ft 1–3 in (altitude −260 ft 1–3 in), Woodstock Member, Nanjemoy Formation.

8, 9. *Bulimina hornerstownensis* Olsson, 1960. Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft 2–6 in). Piscataway Member, Aquia Formation. 8, lateral view; 9, apertural view.

10–12. *Cibicidoides marylandicus* (Shifflett, 1948). Haynesville core hole 2, 521 ft 2–6 in (altitude −434 ft 2–6 in). Piscataway Member, Aquia Formation. 10, spiral view; 11, edge view; 12, umbilical view.

13–15. *Neoeponides mexicanus* (Cushman, 1925). Haynesville core hole 2, 500 ft 0–3 in (altitude −413 ft 0–3 in). Paspotansa Member, Aquia Formation. 13, umbilical view; 14, edge view; 15, spiral view.

16, 17. *Pseudouvigerina plummerae* (Cushman, 1927). Haynesville core hole 2, 500 ft 0–3 in (altitude −413 ft 0–3 in). Paspotansa Member, Aquia Formation. 16, lateral view; 17, apertural view.

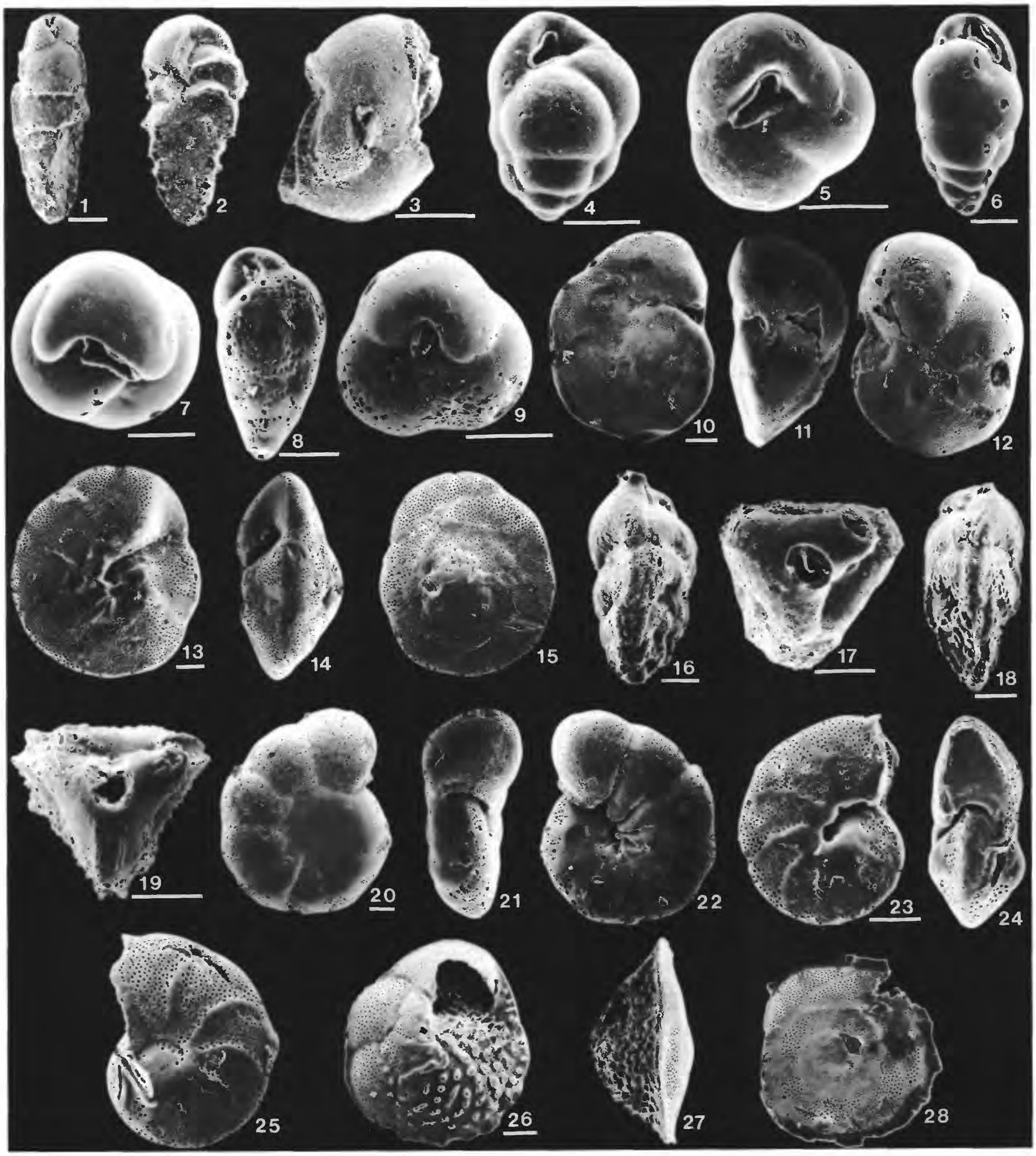
18, 19. *Pseudouvigerina wilcoxensis* Cushman and Ponton, 1932. Haynesville core hole 2, 391 ft 0–4 in (altitude −304 ft 0–4 in). Potapaco Member, Nanjemoy Formation. 18, lateral view, neck broken; 19, apertural view, neck broken.

20–22. *Gavelinella* sp. A. Haynesville core hole 2, 463 ft, 5–9 in (altitude −376 ft 5–9 in). Paspotansa Member, Aquia Formation. 20, spiral view; 21, edge view; 22, umbilical view.

23–25. *Gavelinella* sp. B. Haynesville core hole 2, 418 ft 5–9 in (altitude −331 ft 5–9 in). Paspotansa Member, Aquia Formation. 23, umbilical view; 24, edge view; 25, spiral view.

26–28. *Asterigerina chattahoocheensis* Oman, 1965. Haynesville core hole 2, 465 ft 0–4 in (altitude −378 ft 0–4 in). Paspotansa Member, Aquia Formation. 26, umbilical view; 27, edge view; 28, spiral view.

PLATE 2



TAPPANINA, TURRILINA, BULIMINA, CIBICIDOIDES, NEOEPONIDES, PSEUDOUVIGERINA, GAVELINELLA, AND *ASTERIGERINA*

PLATE 3

[Scale bar=50 μm; specimens without scale bars are same magnification as preceding specimen]

FIGURES 1–3. *Cibicidina* sp. B. Haynesville core hole 2, 463 ft 5–9 in (altitude −376 ft 5–9 in). Paspotansa Member, Aquia Formation. 1, umbilical view; 2, edge view; 3, spiral view.

4–6. *Buccella* sp. Haynesville core hole 2, 269 ft 3–6 in (altitude −182 ft 3–6 in). Old Church Formation. 4, spiral view; 5, edge view; 6, umbilical view, final chamber broken.

7–9. *Anomalinoides acutus* (Plummer, 1927). Haynesville core hole 2, 507 ft 0–2 in (altitude −420 ft 0–2 in). Piscataway Member, Aquia Formation. 7, spiral view; 8, edge view; 9, umbilical view.

10–12. *Cassidella* sp. Haynesville core hole 2, 418 ft 9–11 in (altitude −331 ft 9–11 in). Paspotansa Member, Aquia Formation. 10, lateral view; 11, apertural view; 12, edge view.

13–15. *Epistominella minuta* Olsson, 1960. Haynesville core hole 2, 507 ft 0–2 in (altitude −420 ft 0–2 in). Piscataway Member, Aquia Formation. 13, spiral view; 14, edge view; 15, umbilical view.

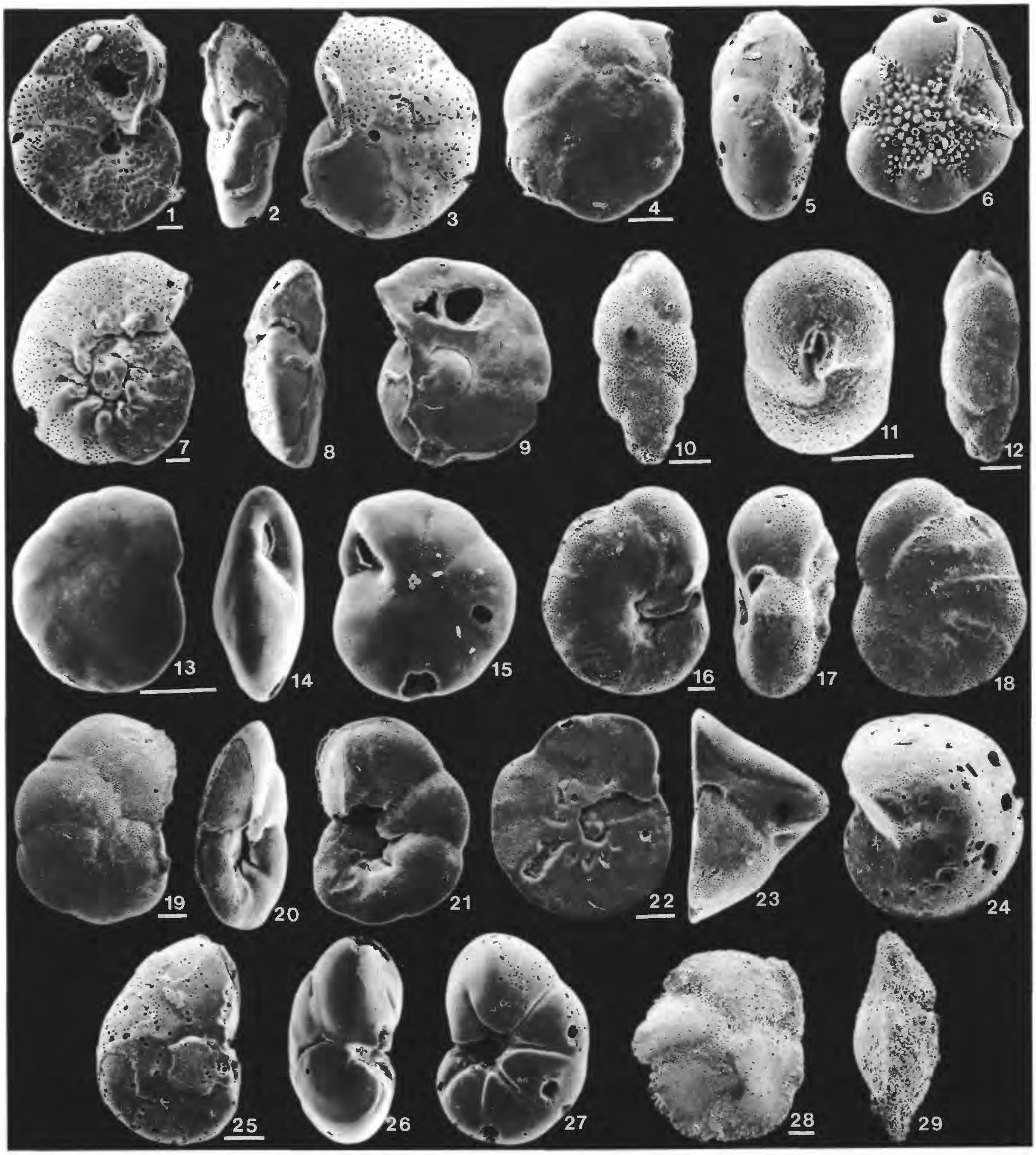
16–18. *Anomalinoides* sp. A. Haynesville core hole 2, 391 ft 0–4 in (altitude −304 ft 0–4 in). Potapaco Member, Nanjemoy Formation. 16, umbilical view; 17, edge view; 18, spiral view.

19–21. *Rosalina* sp. A. Haynesville core hole 2, 347 ft 1–3 in (altitude −260 ft 1–3 in). Woodstock Member, Nanjemoy Formation. 19, spiral view; 20, oblique edge view; 21, umbilical view.

22–24. *Hanzawaia blanpiedi* (Toulmin, 1941). Pamunkey River, Va. Stop 13, bed 8 (of Ward, 1984), Piney Point Formation. 22, umbilical view; 23, edge view; 24, spiral view.

25–27. *Ceratobulimina perplexa* (Plummer, 1927). Pamunkey River, Va. Stop 13, bed 8 (of Ward, 1984), Piney Point Formation. 25, spiral view showing spalling aragonitic wall; 26, edge view; 27, umbilical view.

28, 29. *Siphonina danvillensis* Howe and Wallace, 1932. Haynesville core hole 2, 278 ft 1–4 in (altitude −191 ft 1–4 in). Piney Point Formation. 28, umbilical view; 29, edge view, aperture obscured by secondary growth of calcite crystallites.



CIBICIDINA, BUCCELLA, ANOMALINOIDES, CASSIDELLA, EPISTOMINELLA, ROSALINA, HANZAWAIA, CERATOBULIMINA, AND *SIPHONINA*

PLATE 4

[Scale bar=50 μm; specimens without scale bars are same magnification as preceding specimen]

FIGURES 1, 2. *Cassidulina crassa* d'Orbigny, 1839. Haynesville core hole 2, 269 ft 3–6 in (altitude −182 ft 3–6 in). Old Church Formation. 1, edge view; 2, lateral view.

3–7. *Caucasina elongata* (d'Orbigny, 1846). 3, lateral view; 4, lateral view; 5, lateral view; Haynesville core hole 1, 233 ft 3–7 in (altitude −161 ft 3–7 in). Calvert Formation. Note short spines at base and bordering early chambers of specimen 5. 6, lateral view; 7, spiral view showing proloculus and four chambers of the initial whorl; Haynesville core hole 2, 262 ft 10 in to 263 ft 2 in (altitude −175 ft 10 in to −176 ft 2 in). Calvert Formation.

8, 9. *Nonion mauricensis* Howe and Ellis, 1939. Haynesville core hole 2, 270 ft 0–4 in (altitude −183 ft 0–4 in). Old Church Formation. 8, lateral view; 9, edge view.

10–12. *Nonionella miocenica* Cushman, 1926. Haynesville core hole 2, 269 ft 3–6 in (altitude −182 ft 3–6 in). Old Church Formation. 10, spiral view; 11, edge view; 12, umbilical view.

13–15. *Rosalina* sp. B. Haynesville core hole 1, 257 ft 0–2 in (altitude −185 ft 0–2 in). Old Church Formation. 13, spiral view; 14, oblique edge view; 15, umbilical view.

16, 17. *Trifarina* sp. Haynesville core hole 2, 270 ft 0–4 in (altitude −183 ft 0–4 in). Old Church Formation. 16, lateral view; 17, apertural view.

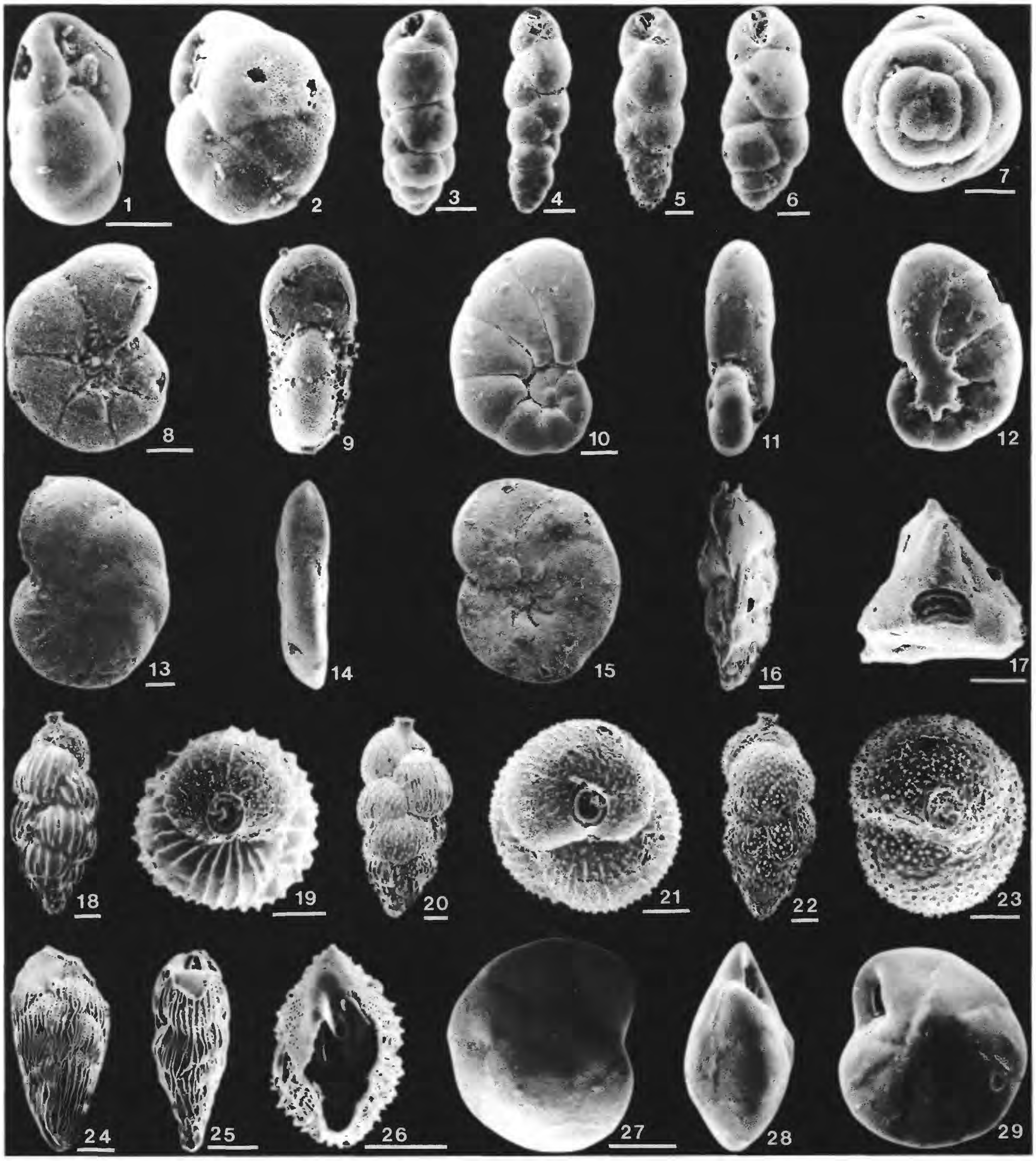
18, 19. *Uvigerina calvertensis* Cushman, 1948. Haynesville core hole 2, 262 ft 10 in to 263 ft 2 in (altitude −175 ft 10 in to −176 ft 2 in). Calvert Formation. 18, lateral view; 19, apertural view.

20, 21. *Uvigerina subperegrina* Cushman and Kleinpell, 1934. Haynesville core hole 2, 262 ft 10 in to 263 ft 2 in (altitude −175 ft 10 in to −176 ft 2 in). Calvert Formation. 20, lateral view; 21, apertural view.

22, 23. *Uvigerina auberiana* d'Orbigny, 1839. Haynesville core hole 2, 262 ft 10 in to 263 ft 2 in (altitude −175 ft 10 in to −176 ft 2 in). Calvert Formation. 22, lateral view; 23, apertural view.

24–26. *Bolivina calvertensis* Dorsey, 1948. Haynesville core hole 1, 233 ft 3–7 in (altitude −161 ft 3–7 in). Calvert Formation. 24, lateral view, final chamber broken away; 25, edge view, final chamber broken away; 26, apertural view, final chamber broken away.

27–29. *Epistominella pungoensis* Gibson, 1983. Haynesville core hole 1, 233 ft 3–7 in (altitude −161 ft 3–7 in). Calvert Formation. 27, spiral view; 28, edge view; 29, umbilical view.



CASSIDULINA, CAUCASINA, NONION, NONIONELLA, ROSALINA, TRIFARINA, UVIGERINA, BOLIVINA,
AND *EPISTOMINELLA*

PLATE 5

[Scale bar=50 μm; specimens without scale bars are same magnification as preceding specimen]

FIGURES 1, 2. *Florilus pizzarensis* (Berry, 1928). Haynesville core hole 2, 262 ft 10 in to 263 ft 2 in (altitude −175 ft 10 in to −176 ft 2 in). Calvert Formation. 1, edge view; 2, lateral view.

3–6. *Hanzawaia concentrica* (Cushman, 1918) forma *strattoni*. Haynesville core hole 1, Calvert Formation. 3, spiral view; 4, edge view; 5, umbilical view, 208 ft 3–5 in (altitude −136 ft 3–5 in); 6, edge view showing incipient development of inperforate keel and angulate periphery seen in well-developed specimens of forma *typica*, 196 ft 4–8 in (altitude −124 ft 4–8 in).

7–10. *Rosalina floridana* Cushman, 1930. Haynesville core hole 1, 196 ft 4–8 in (altitude −124 ft 4–8 in). Calvert Formation. 7, spiral view; 8, edge view; 9, umbilical view, broken umbilical flaps exposing deep umbilicus; 10, umbilical view, umbilical flaps covering umbilicus.

11, 12. *Virgulinella miocenica* (Cushman and Ponton, 1931). Haynesville core hole 2, 262 ft 10 in to 263 ft 2 in (altitude −175 ft 10 in to −176 ft 2 in). Calvert Formation. 11, lateral view showing final chamber broken away; 12, spiral view showing penultimate aperture within broken rim of final chamber.

13, 14. *Bulimina* sp. Haynesville core hole 2, 258 ft 8–10 in (altitude −171 ft 8–10 in). Calvert Formation. 13, lateral view, final chamber broken; 14, apertural view.

15–17. *Gavelinopsis bassleri* (Cushman and Cahill, 1933). Haynesville core hole 2, 258 ft 8–10 in (altitude −171 ft 8–10 in). Calvert Formation. 15, spiral view; 16, edge view; 17, umbilical view.

18–21. *Bolivina* sp. Haynesville core hole 1, 233 ft 3–7 in (altitude −161 ft 3–7 in) Calvert Formation. 18, lateral view; 19, edge view; 20, apertural view; 21, lateral view.

22, 23. *Siphogenerina lamellata* Cushman, 1918. Haynesville core hole 1, 196 ft 4–8 in (altitude −124 ft 4–8 in). Calvert Formation. 22, lateral view, neck broken; 23, apertural view, final chamber and neck broken.

24–26. *Anomalinoides* sp. B. Haynesville core hole 1, 208 ft 3–5 in (altitude −136 ft 3–5 in). Calvert Formation. 24, umbilical view showing imperforate umbilical boss; 25, edge view; 26, spiral view.

27–29. *Bolivina floridana* Cushman, 1918. Haynesville core hole 1, 173 ft 10 in to 174 ft 2 in (altitude −101 ft 10 in to −102 ft 2 in). Calvert Formation. 27, lateral view; 28, edge view; 29, apertural view, final chamber broken.

FLORILUS, HANZAWAIA, ROSALINA, VIRGULINELLA, BULIMINA, GAVELINOPSIS, BOLIVINA, SIPHOGENERINA, AND *ANOMALINOIDES*