COMMONWEALTH OF VIRGINIA
DEPARTMENT OF CONSERVATION
AND ECONOMIC DEVELOPMENT
DIVISION OF MINERAL RESOURCES

POST-MIOCENE STRATIGRAPHY AND MORPHOLOGY, SOUTHEASTERN VIRGINIA

ROBERT Q. OAKS, JR. AND
NICHOLAS K. COCH

BULLETIN 82

VIRGINIA DIVISION OF MINERAL RESOURCES
James L. Calver

Commissioner of Mineral Resources and State Geologist

CHARLOTTESVILLE, VIRGINIA
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POST-MIOCENE STRATIGRAPHY AND MORPHOLOGY, SOUTHEASTERN VIRGINIA

By

Robert Q. Oaks, Jr.[1] and Nicholas K. Coch[2]

ABSTRACT

Detailed study of stratigraphy and morphology of post-Yorktown (post-Miocene) units in southeastern Virginia between the Fall Line and the Atlantic Ocean clarifies earlier work, and establishes the presence of ten units or formations. Surfaces of unconformity separate the ten post-Yorktown units into six groups deposited during submergent-emergent cycles, as follows: (1) Sedley-Bacons Castle; (2) "Moorings;" (3) Windsor; (4) Great Bridge-Norfolk-Kempsville; (5) Londonbridge-Sand Bridge; and (6) Holocene sediments. Comparisons with present coastal sediments and morphology indicate that all stratigraphic units except the Bacons Castle were deposited in marine, beach, lagoonal, and estuarine environments.

Interbedded sand, silt, and clay of the Sedley formation were deposited in estuaries and in the sea at least as far west as Surry. The Bacons Castle Formation resulted from widespread fluvial deposition of gravel, sand, and silt east of the Fall Line during the emergent episode following Sedley time.

The "Moorings" unit was deposited as a barrier sand along the Surry scarp while lagoonal silt accumulated in protected areas to the west.

Beach sand of the lower member of the Windsor Formation was deposited along the base of the Surry scarp and eastward at least to the Suffolk scarp; lagoonal clay, silt, and sand of the upper member subsequently accumulated in areas between the two scarps.

The Great Bridge Formation, lying entirely east of the Suffolk scarp, consists of a lower, fluvial member of gravel, sand, and peat which fill channels in the Yorktown, overlain by lagoonal silt and clay that interfinger with barrier sand in the subsurface just west of the present shoreline. Beach sand and gravel of the Norfolk Formation was deposited along the Suffolk scarp; equivalent estuarine sediments and lagoonal clay and silt accumulated locally westward, while offshore

[1]Department of Geology, Utah State University, Logan, Utah 84321.
[2]Department of Earth and Environmental Sciences, Queens College of City University of New York, Flushing, New York 11367.

sand and silt accumulated eastward. Beach sand and gravel of the Kempsville Formation were deposited along the Hickory scarp.

Beach sand and gravel of the Londonbridge Formation was deposited along Oceana ridge and the Diamond Springs scarp, while equivalent lagoonal silt and clay was deposited in low areas westward nearly to the Suffolk scarp. The Sand Bridge Formation consists of a lower sand member, of marine origin east of the Hickory scarp, and an upper member of lagoonal clay and silt west of equivalent ridges of barrier sand near the present coast.

Holocene sediments are presently being deposited in barrier and backbarrier coastal environments, near streams, and as peat in the Dismal Swamp.

Weathering characteristics and relative dissection of depositional morphology suggest a Pliocene and/or early Pleistocene age for the Sedley and Bacons Castle, an early or middle Pleistocene age for the "Moorings," and a middle Pleistocene age for the Windsor. The five younger, pre-Holocene units are so little weathered or modified by erosion that all probably are no older than Sangamon, yet no younger than mid-Wisconsin, an interpretation supported by Uranium-series ages of 62,000 to 86,000 years B.P. for the Norfolk and Kempsville, and radiocarbon ages greater than 40,000 years B.P. for the Sand Bridge.

INTRODUCTION

This report summarizes a geologic study of the stratigraphy and morphology of post-Miocene sediments in the Coastal Plain of southeastern Virginia (Figure 1), and includes part of Prince George, Surry, Isle of Wight, and Nansemond counties and Chesapeake, Portsmouth, and Virginia Beach cities. The mapped area encompasses nearly 1200 square miles, and is generally bounded on the west by the Fall Line,

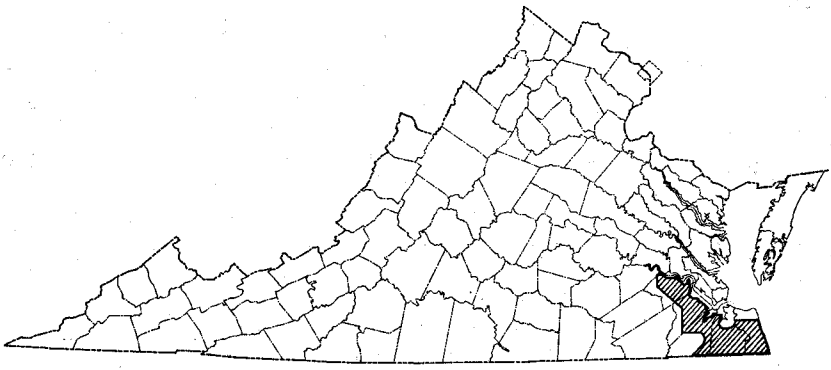

Figure 1. Index map showing location of area of study.

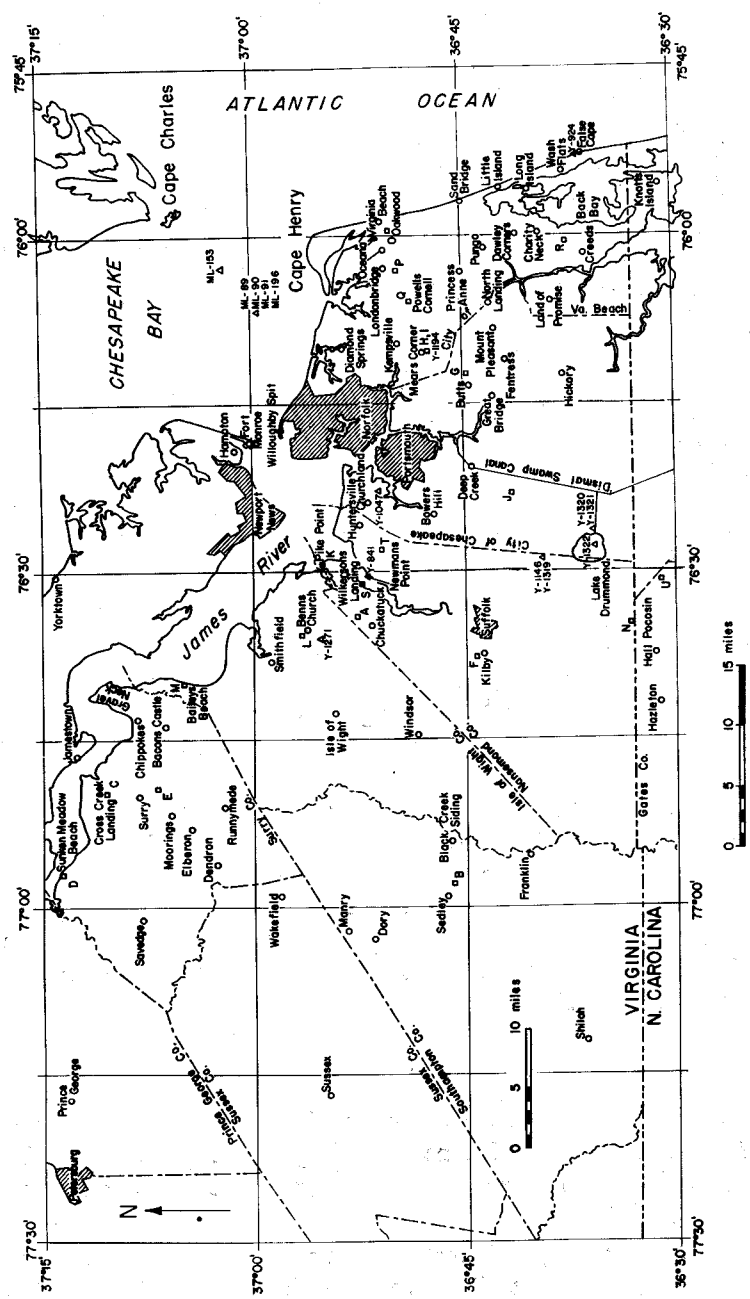

Figure 2. Index map showing physical features, political boundaries, text localities, type-section locations, reference sections (squares, letters), and locations of samples for radiocarbon dates (triangles, numbers).

on the north by the James River and Norfolk city, on the east by the Atlantic Ocean, and on the south by the Virginia-North Carolina state line (Figure 2). It is located between parallels 36°30′ and 37°15′ north latitude and meridians 75°45′ and 77°30′ west longitude (Plates 1 and 2). Access to the area is by Interstate Highways 64, 264, and 464; U. S. Highways 17, 58, 60, 258, and 460; State Highways 10, 32, 40, 165, and 168; and numerous hard-surfaced State roads.

The investigation was initiated under Contract NONR 609(40), Task Order NR 388-064, between the United States Navy, Office of Naval Research, Geography Branch, and the Department of Geology, Yale University, during 1961-63 (J. E. Sanders and R. F. Flint, Principal Investigators). In consultation with Flint, Sanders supervised the overall project through 1963. The program was financed by the Virginia Division of Mineral Resources during 1963-69. The area was chosen for study because morphologic features and stratigraphic units of post-Miocene age are clearly defined and well preserved and because conflicting stratigraphic interpretations by earlier workers needed to be resolved.

PURPOSE OF INVESTIGATION

The purpose of this investigation was to determine the post-Miocene geologic history and paleogeography of southeastern Virginia along a mapping strip extending the entire width of the Coastal Plain. Detailed geologic mapping, the establishment of a stratigraphic framework by subsurface methods, and determination of the relation between stratigraphy and morphology were primary objectives. Emphasis was placed on evidence of former positions of the shoreline and of sea level in space and in time. The need to develop criteria for recognizing depositional environments and their relation to sea level made the study of morphology and sediments of existing coastal environments an important additional objective.

PRESENT INVESTIGATION

This report consists of material derived from the doctoral dissertations of Coch and Oaks, plus newer stratigraphic data obtained by Coch from mapping and drilling in 1965 through 1968 (Coch, 1968; Bick and Coch, 1969).

Coch (1965) investigated post-Yorktown sediments lying between the Suffolk scarp and the Fall Line, herein designated the *Inner Coastal Plain,* and in the roughly triangular area between the Suffolk scarp and the Western Branch of the Elizabeth River (Plate 1). Oaks

(1965) investigated sediments southward and eastward of the Western Branch of the river (Plate 2) entirely within the herein-designated *Outer Coastal Plain* that lies between the Suffolk scarp and the Atlantic Ocean. He also studied morphology and sediments of existing coastal environments.

In May, 1962, progress was summarized in two papers (Sanders and others, 1962a; Sanders, Flint, and Oaks, 1962). A progress report (Sanders and others, 1962b) was subsequently modified and published by Oaks and Coch (1963). Studies of morphology and sediments of the continental shelf, made to facilitate the recognition of older shelf deposits onshore and to evaluate the effect of submergence and emergence on barrier shorelines were summarized by Sanders. Flint (1966) compared the Pleistocene history of Virginia with foreign interglacial sequences. Coch and Oaks (1966) described the "terrace-formation concept" previously used in the Atlantic Coastal Plain, and Oaks and Coch (1966) evaluated evidence for post-Sand Bridge, pre-Holocene slightly eastward tilting in southeastern Virginia.

Coch spent 45 weeks in detailed reconnaissance mapping of the Inner Coastal Plain in the summers of 1961, 1962, and 1963, under the auspices of the Office of Naval Research. He spent 27 weeks during the summers of 1965 and 1966 in detailed mapping of the Benns Church, Smithfield, Windsor, and Chuckatuck 7.5-minute quadrangles for the Virginia Division of Mineral Resources. He also spent 10 weeks in detailed mapping of the Bacons Castle and part of the Hog Island 7.5-minute quadrangles for the Division during the summer of 1967 (Bick and Coch, 1969). Additionally, Coch completed detailed mapping of the Newport News South and Bowers Hill 7.5-minute quadrangles during the summers of 1969 and 1970 (Coch, 1971). The results of the latter work are not included in the present report. Relatively small changes in the outcrop patterns and stratigraphic relationships resulted from the new mapping; however, the regional post-Miocene stratigraphy and morphology are not significantly changed. Locations, density, and types of stratigraphic control points used in mapping the Inner Coastal Plain during 1961-67 are shown in Plate 1. The 768 control points consist of 241 exposures, 187 shallow hand-auger and plastic-tube borings, 264 exposures plus shallow borings, and 76 deep test borings (split-spoon samples).

Oaks spent 33 weeks during the summers of 1961, 1962, and 1963 in detailed reconnaissance mapping of the Outer Coastal Plain, and 7 weeks studying existing coastal and swamp environments. Field work in 1963 was supported by the Virginia Division of Mineral Resources. The 927 control points used for mapping consist of 65

exposures, 292 shallow hand-auger and plastic-tube borings, 120 deep jet-rig borings, and approximately 450 logs of test borings (split-spoon samples) from the Norfolk area and along Interstate Highways 64 and 264. Locations, density, and types of stratigraphic control points used in mapping the Outer Coastal Plain during 1961-63 are shown on Plate 2.

Techniques used are described in detail and evaluated by Coch (1965), Oaks (1965), and Shier and Oaks (1966). Elevations of stratigraphic contacts and of the ground surface along profiles of closely spaced borings were obtained by: (1) reversed-sighting hand-level surveys from bench marks and surveyed intersections; (2) U. S. Coast and Geodetic Survey tide tables near tidally influenced bodies of water; (3) interpolation between contour intervals of 5 feet; (4) plane-table surveys; and (5) survey altimeter. Excellent 15-minute topographic quadrangle maps of the U. S. Geological Survey were available for the entire area.

Because of scarce outcrops, mapping was done mainly by means of borings in the Outer Coastal Plain and in undissected parts of the Inner Coastal Plain, whereas in more dissected places mapping of outcrops was possible. Also, stratigraphic units east of the Suffolk scarp are distinctive and persistent through large areas, whereas older units in the Inner Coastal Plain are less persistent laterally and somewhat less distinct. Depositional morphology in the east has hardly been altered, whereas dissection has affected much of the Inner Coastal Plain. Therefore, a direct comparison of mapping accuracy between east and west and even within the same region is difficult to make. Mapping of contacts from exposures is considerably more rapid and precise than the use of borings, but accuracy in recognition and tracing of units depends largely on the distinctness of each unit rather than on the method of mapping.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge, in addition to the financial support, the encouragement, suggestions, and administrative aids rendered by Evelyn Pruitt and Louis Quam of the Office of Naval Research, by J. E. Sanders and R. F. Flint of Yale University, by Dr. James L. Calver and staff of the Virginia Division of Mineral Resources, and by D. W. Thorne, J. S. Williams, and C. T. Hardy of Utah State University.

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Technical assistance by specialists has included: (1) identifications and ecologic data on macrofossils, by G. H. Johnson, College of William and Mary, and by H. G. Richards, Philadelphia Academy of Natural Sciences, the latter under U. S. Office of Naval Research Contract NONR (G-0019-63); (2) analysis of microfossils by R. H. Benson, University of Kansas, and James D. McLean, Jr.; (3) identification and ecologic data on decapod (crab) remains by H. B. Roberts, U. S. National Museum; (4) collection and analysis of bird and seal remains by C. E. Ray, Alexander Wetmore, and D. H. Dunkle, U. S. National Museum, and Paul Drez, then a student at Old Dominion College; (5) X-ray mineralogical analyses of clay samples by J. L. McAtee, Jr., Baylor University, and S. S. Greenberg, then with the Virginia Division of Mineral Resources; (6) electron-microscope analyses and interpretation of quartz-grain surface features by D. H.

Krinsley, Queens College; (7) radiocarbon dates by Minze Stuiver, Yale Geochronometric Laboratory; (8) uranium-series dates by D. E. Shier and Kenneth Osmund, Florida State University, and by John Goddard, Queens College; (9) some of the size analyses, J. H. Kravitz, Malcolm McConnell, and Ed Keefe in the Yale Sedimentology Laboratory.

MORPHOLOGY

The generalized morphology of the mapped area in southeastern Virginia is typical of the Atlantic Coastal Plain, which is known for its "stair-step" appearance (Shattuck, 1901, 1906), consisting of wide, gently eastward-sloping plains separated by linear, steeper, eastward-facing scarps. Earlier workers called these features, respectively, *benches* or *terraces* and *scarps* or *escarpments.* The plains are successively lower and less dissected from west to east; thus it was inferred that the higher western plains are older. The plains slope eastward at less than 2 feet per mile, whereas the scarps have slopes of as much as 50 to 450 feet per mile through short distances.

The Inner Coastal Plain is characterized by elevations of 20 to 175 feet above mean sea level and by relief of 20 to 50 feet away from major streams (Figure 3). Maximum local relief reaches 130 feet near the James River. Broad and flat undissected tracts, locally called *pocosins,* form poorly drained areas between major streams.

In contrast, the Outer Coastal Plain is characterized by low elevations and relief (Figure 3). Although dunes at Cape Henry are as high as 85 feet above sea level, few places are above 25 feet. Relief of as much as 20 feet occurs locally along the Nansemond and James rivers. Several flat areas up to 5 miles across, with less than 5 feet of relief and little natural drainage, closely resemble the pocosins of the Inner Coastal Plain.

Depositional topography predominates east of the Suffolk Scarp, but fluvial erosion has destroyed large portions of the original depositional surfaces of the Inner Coastal Plain. Overall, the topography has a north-south trend that is closely related to the depositional morphology of ancient barrier-and-lagoonal environments. Several major stream valleys cut across this regional trend, but most others follow original depositional lows parallel to the regional trend. The stream valleys are partially filled by fluvial and fluvial-estuarine sediments, which have flat surfaces and locally form terraces along major streams.

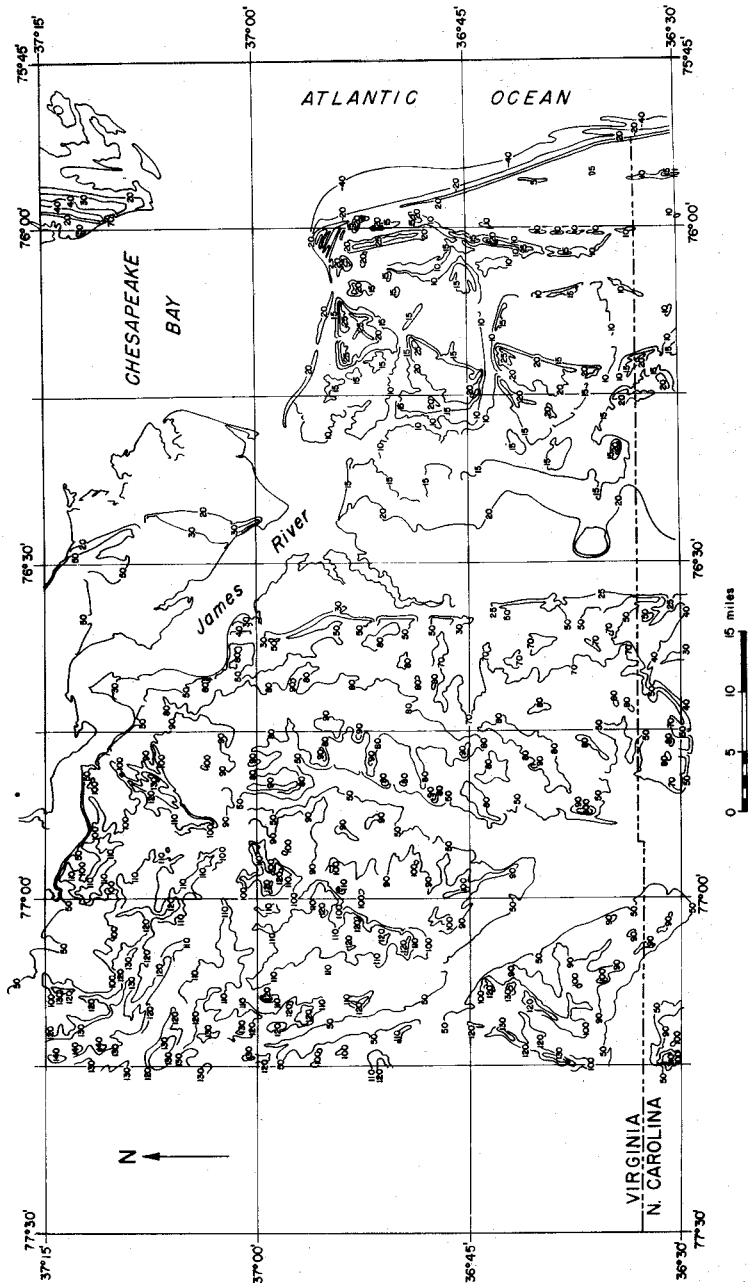


Figure 3. Generalized topography of southeastern Virginia; contours in feet above mean sea level.

DRAINAGE

Two major river systems, the James and the Chowan-Blackwater, drain the area (Figure 4). Short, northward-flowing streams, emptying

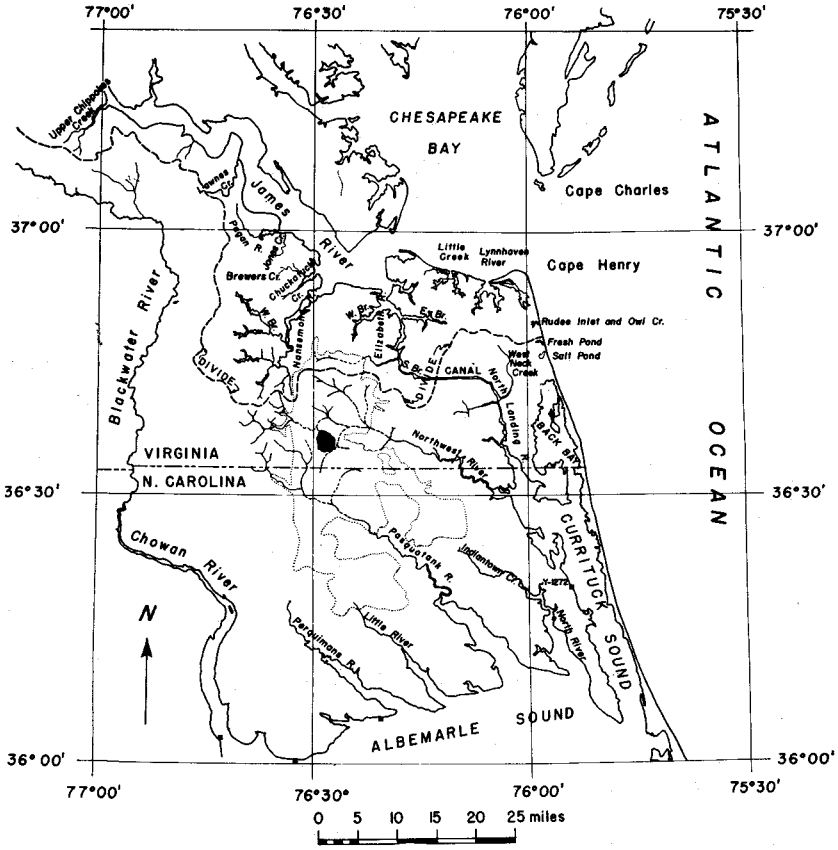


Figure 4. Drainage of southeastern Virginia and adjacent North Carolina; dots outline Dismal Swamp; pre-peat drainage shown within swamp is based on Figure 33.

into the James River or Chesapeake Bay, characterize the northern part of the area and include Chippokes Creek, Pagan River, Chuckatuck Creek, Nansemond River, Elizabeth River, Little Creek, and Lynnhaven River, respectively from west to east. Southward-flowing streams are longer, and include: (1) West Neck Creek, North Landing River, Northwest River and its tributaries from the Dismal Swamp, and minor drainage into Back Bay, all of which empty into Currituck Sound; (2) Dismal Swamp drainage into Albemarle Sound, *via* the

Pasquotank River, Little River, and Indiantown Creek; and (3) Blackwater River and its major tributaries, the Nottoway and Meherrin rivers, which combine to form the Chowan River and empty into Albemarle Sound. The closest opening to the sea for the southern drainage is Oregon Inlet, 56 miles south of the Virginia-North Carolina boundary.

The divide separating James and Chowan-Blackwater drainage lies within a few miles of the James River between the Fall Line and a point near Lawnes Creek, then trends southward toward a point near Suffolk, and then eastward to the Atlantic Ocean. The northward asymmetry and the right-angle bends of the divide and the Chowan-Blackwater River form the most striking features of the drainage systems (Figure 4). Remnants of a former, small, eastward-flowing drainage network is present near Virginia Beach. These include Rudee Inlet, Owl Creek, Salt Pond, and Fresh Pond, which are parts of a once larger system that has been nearly destroyed by headland retreat of the coast.

PREVIOUS MORPHOLOGIC SUBDIVISIONS

The morphology of southeastern Virginia has been studied by Rogers (1884), Shaler (1890), Clark and Miller (1906, 1912), and Wentworth (1930). Rogers (1884, p. 252) described two plains south of the James River, a higher and more dissected *Western bench* that extended to the Fall Line and was separated from a lower *Eastern bench* by a distinct eastward-facing scarp just east of Suffolk. Rogers inferred that this scarp represented a former shoreline, but he did not name the feature.

Shaler independently recognized the same three features. He proposed (1890, p. 314, 326) the name *Nansemond bench* for the plain at elevations of 60 to 70 feet that lies directly west of the scarp, which he in turn called the Nansemond escarpment (now Suffolk scarp), but he did not name the lower area to the east. Shaler also inferred that a shoreline formerly existed at the scarp.

Clark and Miller (1906, 1912), following the "terrace-formation concept" of Shattuck (1901, 1906), subdivided the Inner Coastal Plain into the higher *Sunderland terrace* in the west and the lower *Wicomico terrace* in the east, separated by a low but distinct scarp near Surry; the Wicomico terrace extended from this scarp to a second scarp near Suffolk. The area below an elevation of 25 feet east of Suffolk was termed the *Talbot terrace*. Stephenson (1912, 1926) subdivided the Talbot terrace in North Carolina into the Chowan terrace in the west, between elevations of 40 and 50 feet, and the

Pamlico terrace in the east, below 25 feet. Each terrace was presumed to be underlain by a terrace formation of marine origin that terminated at the next landward scarp.

Topographic maps (1919-1927) permitted more extensive morphologic subdivisions by Wentworth (1930), who named the Suffolk and Surry scarps and retained the Sunderland and Wicomico terraces, but divided the Pamlico terrace into the Dismal Swamp terrace in the west and the Princess Anne terrace in the east and north.

Wentworth (1930, p. 69) described the surface of the Dismal Swamp terrace as sloping gently seaward from 25 feet of elevation at the toe of the Suffolk scarp to between 15 and 18 feet near the coast. The Princess Anne terrace was described as a low, flat plain close to 12 feet north of Diamond Springs and entirely east of a prominent northward-trending ridge at Oceana, except for a small

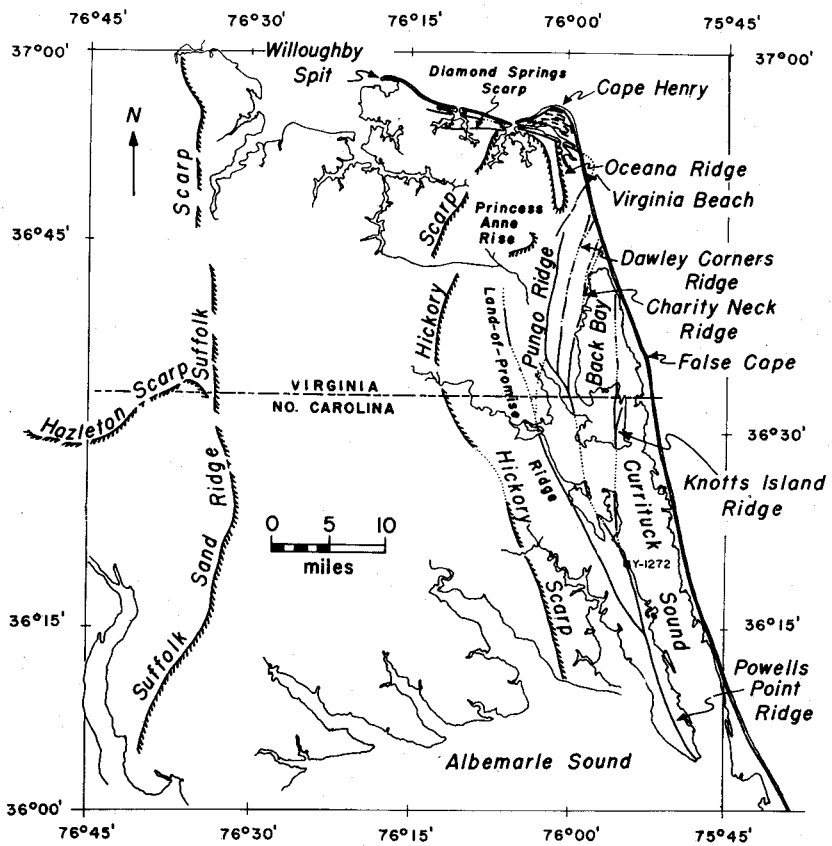


Figure 5. Scarps and ridges in southeastern Virginia and adjacent North Carolina.

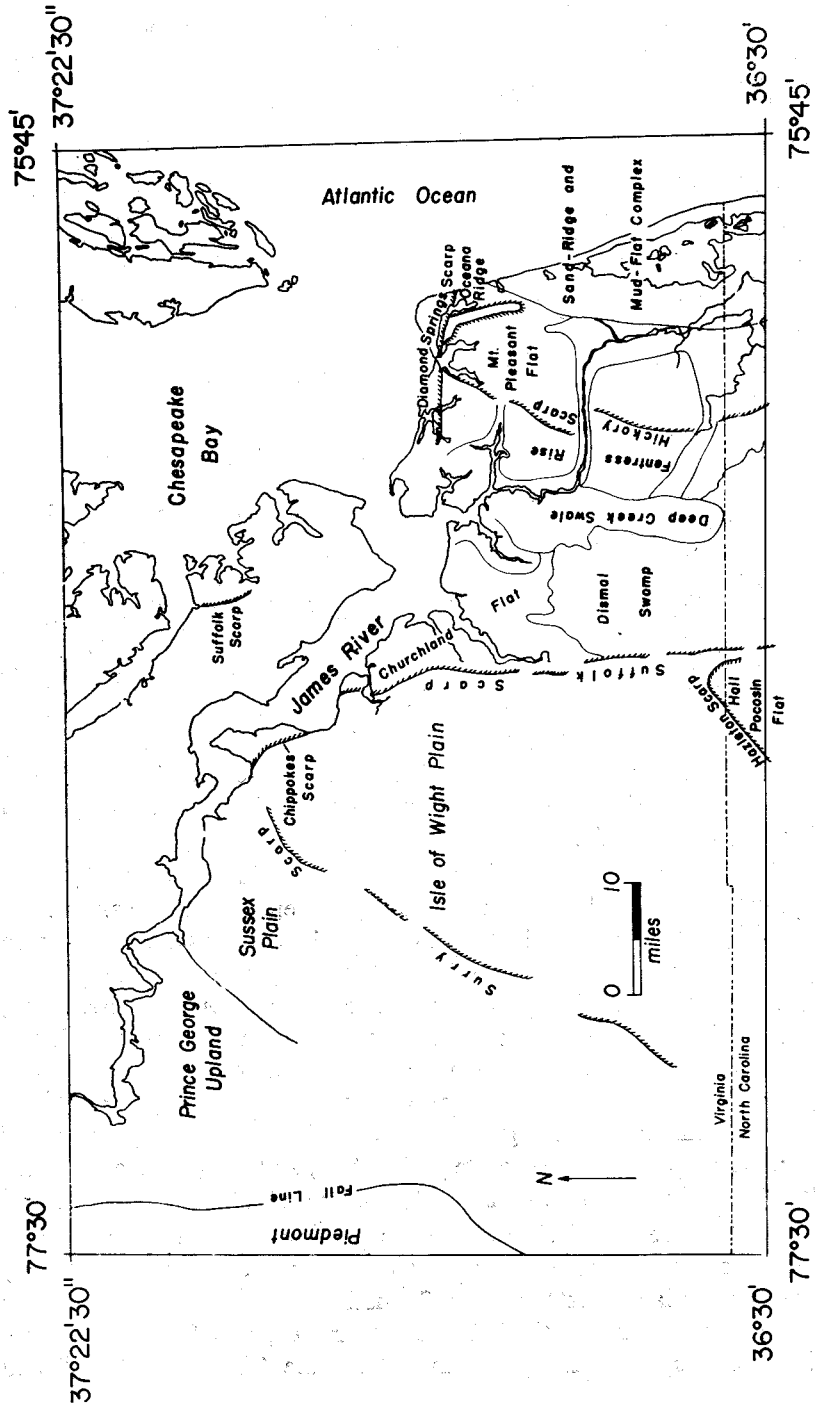


Figure 6. Major morphologic subdivisions of southeastern Virginia.

reentrant that extended westward in the vicinity of the community of Princess Anne (Wentworth, 1930, p. 81). Wentworth named the ridge at Oceana the Princess Anne scarp, but the features he described and illustrated (1930, Figures 5, 24) actually are two intersecting ridges of different ages (Oceana ridge and Pungo ridge) (Figures 3, 5, 6). Wentworth (1930, p. 63, Figure 62) also extended the Chowan terrace of Stephenson (1912) from North Carolina into Virginia, and described a portion of it between 35 and 45 feet above sea level just east of Hazleton (Figure 2) between the Wicomico terrace and the Suffolk scarp.

PRESENT MORPHOLOGIC SUBDIVISIONS

Most previous morphologic subdivisions are here abandoned because of their incorrect stratigraphic implications or confused definitions and because they insufficiently describe the existing morphology. The names Surry and Suffolk have been retained for the western scarps. The names Sunderland, Wicomico, and Chowan are not used in this report because the original genetic interpretation of these "terraces" by Shattuck (1901, 1906) and Stephenson (1912) is not supported by the data from southeastern Virginia (Moore, 1956; Oaks and Coch, 1963). The names Dismal Swamp terrace, Princess Anne terrace, and Princess Anne scarp have been abandoned because of their confused definitions (Wentworth, 1930, p. 30, 81) and because they fail to describe the morphology in the detail required by the present study.

For the foregoing reasons descriptive terms without definite genetic implication are employed in this report. Different sets of names have been applied to morphologic features and to stratigraphic units in order to emphasize the distinction between them, except for peat of Holocene age in the Dismal Swamp. The terms *plain, flat, rise, swale, ridge, scarp,* and *upland* are used. *Plain* and *flat* refer to broad, undissected areas of low relief that are respectively eastward-sloping and virtually horizontal. *Rise* refers to a westward-sloping surface. A *swale* is a linear low. *Ridge* and *scarp* distinguish the morphology of steep-sided features that separate *plains, flats,* and *rises* lying at different elevations. An *upland* is a dissected, rolling surface.

West of the Suffolk scarp, the Surry scarp and the following new subdivisions are adopted (Figure 6): Prince George upland (west) and Sussex plain (east) for the Sunderland "terrace" of Wentworth; Isle of Wight plain for the Wicomico "terrace"; and Chippokes scarp, Hazleton scarp, and Hall Pocosin flat for the Chowan "terrace" and

its landward scarps. East of the Suffolk scarp the following subdivisions are adopted: Churchland flat, Dismal Swamp (restricted to the swamp itself), Deep Creek swale, Fentress rise, Hickory scarp, Mount Pleasant flat, Land-of-Promise ridge, Princess Anne rise, and several minor features for the Dismal Swamp "terrace" of Wentworth; Oceana ridge, Diamond Springs scarp, and Sand-ridge and Mud-flat complex for the Princess Anne scarp and Princess Anne "terrace" of Wentworth; present coastal areas, and the offshore area (Oaks, 1965; Coch, 1965). Relationships of the morphologic subdivisions are shown by topography along geologic sections on Plates 1 and 2; the locations of ridges and scarps are shown in Figures 5 and 6.

PRINCE GEORGE UPLAND

The Prince George upland, which is named for Prince George County (Figure 2), is bordered on the west by the Fall Line and on the east by a southwestward-trending line along the axis of Upper Chippokes Creek (Figure 4). It is about 20 miles wide near the James River (Figure 6) and 10 miles wide near the Virginia-North Carolina boundary. Its gently rolling surface slopes eastward at an average of 2.5 feet per mile from an elevation of approximately 175 feet near Petersburg to approximately 130 feet near Savedge. The plain is dissected by tributaries of the Chowan-Blackwater and James rivers; relief of 50 feet is common locally even in areas away from the rivers. This surface is underlain by fluvial sediments of the Bacons Castle Formation.

SUSSEX PLAIN

The Sussex plain is named for Sussex County (Figure 2). It is bordered on the west by the Prince George upland and on the east by the Surry scarp (Figure 6). The Sussex plain is approximately 15 miles wide near the James River and 10 miles near the Virginia-North Carolina boundary. It has an eastward slope that averages 1 foot per mile from an elevation of approximately 130 feet near Savedge to 120 feet near the Surry scarp. The Sussex plain is less dissected than the Prince George upland, and maximum local relief of areas away from major streams is only 25 feet. Higher parts of this surface are underlain by clay and silt believed equivalent to sand of the "Moorings unit" exposed in the Surry scarp, whereas lower areas along streams are underlain by the stratigraphically lower and older Bacons Castle Formation. Low areas just west of the Surry scarp possibly are underlain locally by remnants of clay and silt of the Windsor Formation.

SURRY SCARP

The Surry scarp was named by Wentworth (1930, p. 57) for the town of Surry, Surry County, which lies slightly west of the scarp (Surry 7.5-minute quadrangle). It is a linear, eastward-facing escarpment that has a slope varying from 0.5 degree at Elberon (Figure 2) to about 0.75 degree easterly from Surry. Elevations along the scarp crest vary from 128 feet in the area east of Surry to 116 feet at Elberon. It was studied in detail only from the James River to Elberon; however, it can be traced readily on topographic maps from Surry

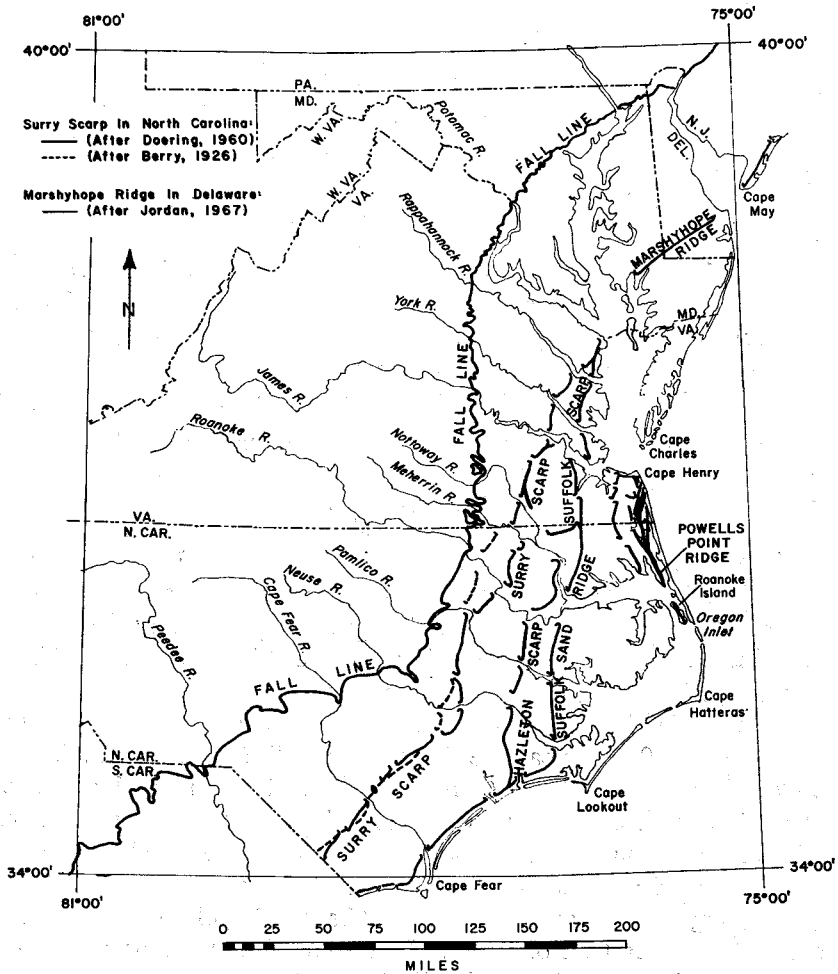


Figure 7. Major scarps and ridges of the Atlantic Coastal Plain in Maryland, Delaware, Virginia, and North Carolina.

southwestward nearly to North Carolina (Figure 3), and it is well developed near Wakefield, Manry, Dory, and Shiloh (Figure 2). Flint (1940) traced the Surry scarp about 375 miles, discontinuously, from near Surry to a point northeast of the Savannah River in South Carolina. North of the James River the Surry scarp can be traced northward to a point just south of the Potomac River, where it is intersected by the younger Suffolk scarp (Figure 7). The Surry scarp is underlain by sand of the "Moorings unit" in Virginia south of the James River.

ISLE OF WIGHT PLAIN

The Isle of Wight plain, named for Isle of Wight County (Figure 2), lies east of the Surry scarp and west of the Suffolk and Hazleton scarps (Figure 6). It is approximately 15 miles wide near the James River, and 30 miles near the Virginia-North Carolina boundary. It slopes eastward at an average of 2 feet per mile from an elevation of 100 feet at the toe of the Surry scarp to between 60 and 70 feet at the crest of the Suffolk and Hazleton scarps. It is only slightly less deeply dissected than the Sussex plain; however, large undissected tracts occur along the divide between the James and Chowan-Blackwater rivers. Undissected portions of the Isle of Wight plain are underlain by probable lagoonal sediments of the upper member of the Windsor Formation, whereas remnants of older units are exposed in lower areas along streams.

CHIPPOKES SCARP

The Chippokes scarp is named for the community of Chippokes, which lies at the crest of this scarp in Surry County (Hog Island 7.5-minute quadrangle). It is a linear, northeastward-facing escarpment 5 miles long with a slope of 3 degrees that separates the Isle of Wight plain from the lower flat area between 40 and 50 feet of elevation, which is known as Gravel Neck (Figure 2). The scarp is river-cut and separates the Isle of Wight plain from slightly dissected fluvial-estuarine sediments of the Norfolk Formation in the lower area.

HAZLETON SCARP

The Hazleton scarp is named for the community of Hazleton, which lies at its crest in Gates County, North Carolina (Corapeake 7.5-minute quadrangle). The scarp slopes eastward from the Isle of Wight plain to the Hall Pocosin flat at slightly less than 2 degrees. It trends southeastward for 7 miles south of the North Carolina state line,

then turns toward the west and parallels a linear segment of the Chowan-Blackwater River (Figures 3, 5), where it appears to be river-cut.

HALL POCOSIN FLAT

The Hall Pocosin flat is named for Hall Pocosin, Gates County, North Carolina (Corapeake 7.5-minute quadrangle). It is 4 miles wide at the Virginia state line, and lies at the eastern toe of the Hazleton scarp (Figure 6). In North Carolina it lies directly west of a sandy ridge that passes into the Suffolk scarp just south of the Virginia state line (Sinha, 1959, Figures 10, 16, 19). The Hall Pocosin flat is dissected to about the same degree as the Isle of Wight plain. Undissected portions, at an elevation of 35 to 45 feet, are directly underlain in Virginia by lagoonal sediments of the Norfolk Formation.

SUFFOLK SCARP

The Suffolk scarp was named by Wentworth (1930, p. 63) for the town of Suffolk, Nansemond County, which occupies a reentrant in the scarp made by the Nansemond River (Suffolk 7.5-minute quadrangle). The Suffolk scarp is much more distinct than the Surry scarp; it trends nearly north-south and has an easterly slope between 1 and 3.5 degrees in the area studied. Except for offsets at major rivers, the Suffolk scarp can be traced continuously for at least 210 miles, from the Potomac River at the Virginia-Maryland boundary south to the Neuse River in North Carolina (Flint, 1940). It intersects the Surry scarp just south of the Potomac River (Figure 7). The toe of the scarp lies between 20 and 30 feet of elevation through this distance. Its undissected crest lies at 60 to 70 feet in southeastern Virginia. The Suffolk scarp is underlain by beach sand of the Norfolk Formation except where later erosion has exposed the older underlying units.

CHURCHLAND FLAT

The Churchland flat is named for the community of Churchland, City of Chesapeake (Newport News South 7.5-minute quadrangle). It lies north of the Dismal Swamp, east of the Suffolk scarp, south of the James River, and west of the Elizabeth River (Figure 6). It varies in width from 7 miles in the north to 10 miles in the south, and is approximately 20 miles long in a northwesterly-southeasterly direction. The Churchland flat lies between 18 and 25 feet. It is well drained by tributaries of the James River, but is considerably less dissected than the higher Isle of Wight plain in the west. The Churchland flat oc-

cupies the northwestern part of the Dismal Swamp "terrace" of Wentworth (1930). It is underlain by lagoonal-estuarine sediments of the upper member of the Sand Bridge Formation, although the older Norfolk and Yorktown formations are exposed in lower areas along some streams.

DISMAL SWAMP

The name Dismal Swamp originated in colonial days for the swampy, undrained area that lies east of the Suffolk scarp, west of the Deep Creek swale, and south of the Churchland flat (Figure 6). The Dismal Swamp occupies the southwestern part of the Dismal Swamp "terrace" of Wentworth (1930), but the name is here restricted to the boundaries of that swamp. It extends from a point east of Suffolk to an irregular southern boundary that reaches into North Carolina for several miles (Figure 4). In Virginia the swamp is 10 to 11 miles wide, east to west, and 15 miles long, north to south. Its surface slopes gently eastward at 1 foot per mile from an elevation of 25 feet at the toe of the Suffolk Scarp to 15 feet at the Deep Creek swale in the east. Lake Drummond occupies a large oval depression 2 to 3 miles in diameter in the undissected surface of the swamp. Several short valley systems that begin in the Isle of Wight plain abruptly terminate at the swamp; other streams have their heads along the east and south edges. Between 1959 and 1962 the swamp was extensively ditched to provide better drainage, access, and fire control. Freshwater peat of Holocene age underlies the surface to depths of as much as 13 feet.

DEEP CREEK SWALE

The Deep Creek swale is named for the community of Deep Creek, City of Chesapeake (Deep Creek 7.5-minute quadrangle). Its axis trends north-south, and the land surface rises westward to the Dismal Swamp and eastward to the Fentress rise (Figure 6). The swale lies between elevations of 10 and 15 feet, and opens northward into a flat area at the same level beneath Portsmouth and Norfolk (Figure 3). Higher parts of the Deep Creek swale are underlain by lagoonal sediments of the upper member of the Sand Bridge Formation; lower parts near streams are underlain by sand of the lower member of the same formation.

FENTRESS RISE

The Fentress rise is named for the community of Fentress, City of Chesapeake (Fentress 7.5-minute quadrangle). It consists of five large remnants of a gently westward-sloping surface that rises eastward from the Deep Creek swale to a flat crest with an elevation between

20 and 25 feet (Figure 6). The remnants are separated by four east-west-trending valleys, which are from north to south: (1) Eastern Branch of Elizabeth River; (2) Southern Branch of Elizabeth River; (3) Northwest River; and (4) Indiantown Creek (North Carolina). Three of these remnants lie entirely within Virginia, and are herein called, respectively, the northern, central, and southern segments. The fourth segment continues into North Carolina; both it and the fifth segment can be followed southward on soil maps and aerial photographs as far as Albemarle Sound (Figure 5). The original width of the Fentress rise in southeastern Virginia was 5 to 6 miles, but this has been reduced in several places by erosion along the western side. The Hickory scarp forms the eastern boundary of the Fentress rise; the east-west-trending Diamond Springs scarp forms the northern side of the northern segment.

Higher parts of the Fentress rise are underlain by marine sediments of the Norfolk Formation, and locally in the east and along rivers by beach sand and lagoonal sediments of the Kempsville Formation. Lagoonal sediments of the upper member of the Sand Bridge Formation occur along the western edge of the Fentress rise, and beach sand of the Londonbridge Formation occurs along the northern edge of the northern segment. The Fentress rise occupies the central third of the "Dismal Swamp terrace" of Wentworth (1930).

HICKORY SCARP

The Hickory scarp is named for the community of Hickory, which lies at the crest of the scarp in the City of Chesapeake (Fentress 7.5-minute quadrangle). It forms the eastern boundary of the Fentress rise at an elevation of 20 to 25 feet, and the western limit of the Mount Pleasant flat at 10 to 17 feet. The scarp is low and indistinct in the field. Its slope varies from only 0.75 degree to less than 0.10 degree, yet the scarp is apparent on soil maps and aerial photographs, and in mapping. The Hickory scarp trends northwesterly in North Carolina, but it curves to a northeasterly trend in Virginia, and lies in line with the trend of the Eastern Shore Peninsula (Figures 3, 5, 7). It is offset 2.5 miles to the west just north of the Intracoastal Waterway and directly east of Suffolk, where a similar offset of one mile occurs in the Suffolk scarp. The Hickory scarp is underlain by beach sand of the Kempsville Formation.

MOUNT PLEASANT FLAT

The Mount Pleasant flat is named for the community of Mount Pleasant, City of Chesapeake (Fentress 7.5-minute quadrangle). In

Virginia it forms a broad, generally undissected area 5 to 9 miles wide from east to west, and 18 to 20 miles long from north to south. This flat lies east of the Hickory scarp, south of the Diamond Springs scarp, and west of the Sand-ridge and Mud-flat complex (Figure 6). It includes the area between the shore and Oceana ridge north of the Sand-ridge and Mud-flat complex, and it can be traced south into North Carolina at least to Albemarle Sound (Figure 5).

The surface of the Mount Pleasant flat lies between 10 and 17 feet above sea level. Slightly higher areas, at 15 to 17 feet, include a subsequent feature and five linear areas, as follows: (1) Princess Anne rise, a gently westward-sloping area 2.5 miles by 2 miles in diameter at Princess Anne; (2) Land-of-Promise ridge, a north-south feature 3 miles long and less than 0.5 mile wide, just west of North Landing River; (3) an unnamed linear feature 2 miles long that trends east-west just south of the Intracoastal Waterway; (4) an unnamed linear feature just east of Kempsville, 2.5 miles long, that trends southeasterly; (5) a narrow band along the west and south sides of Oceana ridge; and (6) a low north-south ridge between Oceana ridge and the shore (Figure 3). The narrow swale between the south end of Oceana ridge and the Sand-ridge and Mud-flat complex may be the small reentrant of the Princess Anne "terrace" that Wentworth (1930, p. 81) said extended into the Dismal Swamp "terrace". The portion of the flat east of Oceana ridge corresponds to the northern part of the Princess Anne "terrace" of Wentworth along the Atlantic Coast.

The Mount Pleasant flat is incompletely dissected and poorly drained although broad stream valleys traverse it. The surface is so flat over large areas that it has been ditched extensively to provide drainage. Lagoonal sediments of the upper member of the Sand Bridge Formation form the surface over most of the flat. However, beach sand of the lower member underlies Land-of-Promise ridge, Princess Anne rise, and probably the small ridge east of Oceana ridge, and barrier washover sand of the Londonbridge Formation probably underlies most of the flat along the west side of Oceana ridge. Deep ditches in the Mount Pleasant flat commonly expose sand of the lower member of the Sand Bridge Formation, and, rarely, lagoonal clay of the older Londonbridge Formation.

OCEANA RIDGE

Oceana ridge is named for the community of Oceana, City of Virginia Beach (Princess Anne 7.5-minute quadrangle). The ridge is 1.5 miles wide and 7 miles long, and trends S. 10° E. from the

Diamond Springs scarp in the north to a point directly west of Fresh Pond (Figure 4). Its crest is as much as 25 to 30 feet above sea level, and its eastern toe lies at 12 to 17 feet. The west slope is only slightly more gentle and less linear than the distinct east face, which slopes as much as 2 degrees (Figure 3). Oceana ridge is underlain by beach sand of the Londonbridge Formation.

SAND-RIDGE AND MUD-FLAT COMPLEX

The Sand-ridge and Mud-flat complex consists of linear ridges of sand and intervening, lower-lying mud flats situated east of the Mount Pleasant flat and North Landing River (Figure 6). The area in Virginia is triangular in shape, with a base line 10 miles wide at the Virginia-North Carolina boundary, and two sides, each approximately 20 miles long, formed by the present coastal barrier in the east and Pungo ridge in the west (Figure 5). The present coastal barrier trends N. 15° W. whereas Pungo ridge trends N. 15° E.; these two ridges intersect in the north just south of Virginia Beach. The area extends into North Carolina at least to Albemarle Sound and probably to Roanoke Island. In Virginia much of the area is occupied by the Back Bay lagoon.

The sand ridges of the complex generally trend parallel to Pungo ridge, the westernmost one. Their widths vary from a few hundred feet to a thousand feet, and they generally decrease in width and in height toward the north. The rounded ridge crests rise 5 to 15 feet above the lower-lying flats. From west to east, the names of the ridges in the Back Bay area of Virginia and typical elevations of their crests between Creeds and Pungo, Virginia (Figure 2), are: Pungo Ridge (18 to 21 feet); Dawley Corners ridge (10 to 12 feet); Charity Neck ridge (4 to 5 feet); and Knotts Island ridge (5 feet). At Knotts Island itself the elevation of the ridge crest is 14 to 16 feet. In ground plan the middle two sand ridges bifurcate to the north. Similar north-opening bifurcations characterize Powells Point ridge and Knotts Island ridge in North Carolina (Figure 5).

The aspect of the lower-lying flats is varied, depending on location with respect to present water bodies. West of the Back Bay lagoon, fresh-water swamps occur along streams, tidal marshes adjacent to lagoonal shores, and low-lying, ditched, better-drained areas.

The complex is underlain by beach-ridge sand and lagoon-flat sediments of the upper member of the Sand Bridge Formation, and corresponds only to the southern part of the Princess Anne "terrace" of Wentworth (1930, Figure 24).

DIAMOND SPRINGS SCARP

The Diamond Springs scarp is named for the community of Diamond Springs, City of Chesapeake (Ocean View 7.5-minute quadrangle). The scarp is a distinctive east-west feature that forms the north face of the Fentress rise and of Oceana ridge. Three lower, ridge-like extensions occur for short distances between these two features and past them on either side, both east and west (Figure 3). The elevation of the crest of the scarp ranges from 20 to 25 feet; the toe lies at 10 to 15 feet north of the Fentress rise and from sea level to 15 feet north of Oceana ridge (Cape Henry 7.5-minute quadrangle). In the latter area the scarp locally is as steep as 45 degrees; elsewhere, slopes of 3 to 8.5 degrees are common.

The Diamond Springs scarp corresponds to the east-west portion of the Princess Anne scarp of Wentworth (1930, p. 69); however, it extends east of the limit that Wentworth (1930, Figure 24) inferred for the latter scarp. The crest of the Diamond Springs scarp is underlain by beach sand of the Londonbridge Formation, and the base by beach sand of the younger Sand Bridge Formation.

PRESENT COASTAL AREAS

Present coastal areas consist of: (1) tidal and non-tidal marsh; (2) barrier beach and dunes south of Virginia Beach; (3) mainland beach at Virginia Beach; (4) Cape Henry; and (5) Willoughby Spit (Norfolk North, Ocean View, Cape Henry, Virginia Beach, North Bay, and Knotts Island 7.5-minute quadrangles).

Tidal marshes occur along tidal shores of river mouths, bays, and lagoons; farther inshore the tidal marshes grade to fresh-water marshes and are flanked and finally replaced by swamps. The largest original areas of salt-water marsh surrounded the Back Bay lagoon, but these are progressively changing to fresh-water marshes through man's efforts to prevent storm washovers and tidal inlets by maintaining a high dune ridge along the coastal barrier. The main beaches face the ocean, but a few small sand and shell lag deposits occur locally along the shores of Back Bay and some of its islands.

The False Cape barrier is 0.5 to 2 miles wide and extends unbroken from just south of Salt Pond to Oregon Inlet, North Carolina, a distance of 69 miles. Two linear chains of dunes border the barrier beach along most of the coast. In Virginia these dunes have been stabilized since 1938 by means of fences made of brush, slats of wood, and netting. The elevations of dune crests typically range from 20 to 25 feet; a few solitary dunes south of False Cape reach 40 feet.

The mainland beach at Virginia Beach is slowly migrating landward through erosion and littoral-drift removal of the older unconsolidated sediments under direct wave attack. Combined beach and dune areas are as much as 0.3 mile wide. This segment of the shoreline is approximately 8 miles long and extends from the Diamond Springs scarp in the north almost to Sand Bridge in the south.

Cape Henry is situated north of Virginia Beach, at the mouth of Chesapeake Bay. It consists of a series of convex sand ridges whose crests have elevations of 20 to 85 feet; the ridges are separated by marshy flats lying between sea level and 5 feet. Willoughby Spit, 0.3 to 0.5 mile wide and 12 miles long, extends west from Cape Henry and Lynnhaven River into the mouth of the James River just north of Norfolk. Its dune crest at one time locally had an elevation of 50 feet (Cape Henry 15-minute quadrangle).

OFFSHORE AREA

The offshore area includes the shore face of the modern barrier (nearshore-marine environment) and the continental shelf (offshore-marine environment). The shore face is characterized by its steep slope, and the continental shelf by linear, discontinuous, north-south sand ridges separated by lower, nearly flat areas underlain by finer-grained sediments. Slope of the bottom immediately offshore is directly comparable with the slope of the Suffolk and Surry scarps (Plates 1 and 2). Like the latter two features, the shore face is relatively steep, 20 feet in the first 900 to 2400 feet offshore (0.5 to 1.25 degrees) and 30 to 40 feet in the first 2700 to 12,000 feet offshore (Figure 3). The shore face then slopes considerably less steeply, modified by ridges, to —60 feet between 3.8 and 12.5 miles offshore (USCGS Chart 1227). The offshore bottom from Sand Bridge south is steeper than in the area north of Sand Bridge, probably because the existing barrier spit becomes progressively farther away from the youngest previous shoreline in the Sand-ridge and Mud-flat complex. Additionally, sand from borrow pits inland periodically is added to the beach at Virginia Beach to maintain good bathing conditions, and this procedure lessens the offshore slope there (U. S. Army Corps of Engineers, 1953, 1959).

MORPHOLOGY AND ENVIRONMENTS

Several conclusions are justified by the depositional morphology that is present in existing coastal and offshore environments, which were studied by Oaks (1965) and by Sanders (personal communica-

tion). These conclusions should be applicable to the morphology of former sedimentary coastal areas not influenced strongly by deltas.

First, natural slopes across a depositional shoreline (Figure 8, Plate 2), from land to sea are, successively: (1) gently seaward (older sediments) to steeply seaward (intracoastal scarp); (2) flat, with major irregularities in restricted low areas (back-barrier sediments deposited as much as two feet above mean high water and drained by tidal channels); (3) gently landward (back-dune flat; washover apron); (4) steeply landward, irregular, and steeply seaward in a discontinuous, narrow zone (dune chain broken by inlets); (5) gently seaward but irregular in a narrow zone (berm and foreshore); (6) steeply seaward (shore face); and (7) gently seaward in a broad plain broken by pre-existing irregularities (continental shelf). Therefore, in sedimentary coastal areas, extensive plains and flats can form both in back-barrier environments (Sussex plain, Isle of Wight plain, Hall Pocosin flat, Churchland flat, Mount Pleasant flat) and in offshore environments (Fentress rise).

Conversely, plains and flats may be underlain by extensive, freshwater peat deposits (Dismal Swamp), or fluvial-estuarine sediments graded to a certain position of sea level (Gravel Neck). Flat surfaces might also consist of exposed, wave-eroded platforms of gently dipping strata; however, such features are less likely to occur in the post-Miocene sediments of southeastern Virginia than in more consolidated sediments. Plains also can originate by subaerial erosion of widespread, flat-lying sediments of different compositions, or even by stream aggradation (Prince George upland). Because of these various possibilities, it is imperative to study in detail the sediments of plains and flats to determine their individual origins (Johnson, 1932, 1944a). Inferences based on morphology alone are neither sufficient nor conclusive.

Persistent linear scarps can be formed by marine erosion of headlands, by lagoon-shore erosion of headlands, by both in succession (Suffolk scarp, Hickory scarp) or by erosion along linear rivers (east-west part of Hazleton scarp; paired scarps 40 miles in length along a straight stretch of Pamlico River, North Carolina).

A distinct, persistent, narrow, linear ridge probably can form only as a barrier (Surry scarp, Suffolk sand ridge in North Carolina, Oceana ridge, ridges of Sand-ridge and Mud-flat complex), whereas a less persistent feature might form as a longitudinal dune related only to source and wind conditions, or even by differential preservation of more resistant fluvial-channel sediments through subaerial erosion.

Swales may be areas of erosion, of lesser deposition, or of differen-

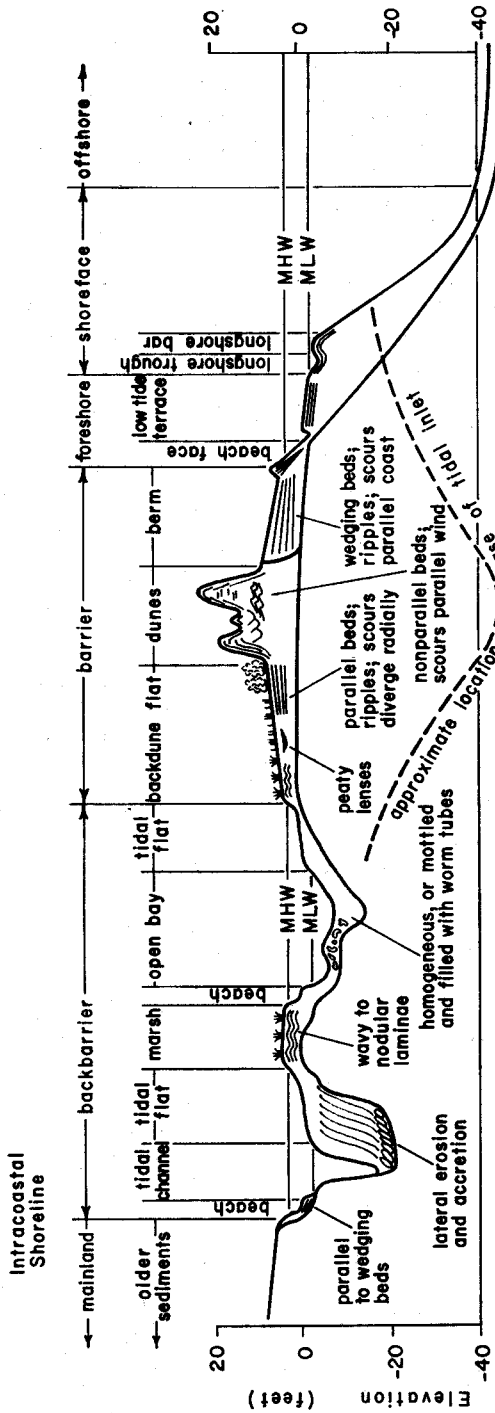


Figure 8. Schematized section through existing barrier and backbarrier environments, Virginia Costal Plain; vertical scale greatly exaggerated.

tial compaction. Again stratigraphic evidence is necessary to confirm inferences derived from studies of swale morphology. Structural origins of ridges, scarps, and swales are possible also.

Morphology of the present coast indicates a steep nearshore slope from just below low-tide level to water depths of 30 to 40 feet. Such a configuration shows that sea-level positions inferred from the elevations of the toe of a scarp or ridge in areas of abundant sediment supply and unconsolidated sediments probably are incorrect and far too low.

DISTINGUISHING FLUVIAL AND COASTAL SEDIMENTS

Characteristics of fluvial and coastal-barrier sediments are summarized in Table 1. These were derived from the study of modern and Pleistocene coastal sediments in Virginia and Texas, Pleistocene fluvial strata in Virginia, Mesozoic and Cenozoic fluvial rocks in central Utah, Mesozoic and Paleozoic barrier rocks in the Four Corners area (Colorado, Utah, Arizona, New Mexico) and northern Utah, various published articles, and numerous discussions with colleagues, especially Charles V. Campbell.

Criteria that appear to be diagnostic of coastal environments include: (1) montmorillonite in clays and true glauconite in sands; (2) high degree of roundness of sand grains; (3) pyramidal, V-shaped indentations (littoral) and long, meandering, intersecting conchoidal fractures (eolian) in quartz-grain surfaces; (4) abundant marine fossils such as corals and echinoderms, especially varied assemblages; (5) parallel stratification in sand of berm, foreshore, and shoreface; (6) asymmetric, steplike morphology from back-barrier area to offshore area, wherein fine-grained sediments underlie flat areas and sand underlies the steeper slope separating the flat areas.

Characteristics common in coastal environments and rare in fluvial environments include: (1) good to excellent sorting of most sand deposits; (2) bluish-gray color and general lack of oxidation of sediments, including sand, below sea level; (3) vertical decrease in grain size downward in progradational sequences. Boulders are uncommon in beach deposits except very close to a source; and kaolinite is rare within the marine environment. No single criterion will be diagnostic, nor even usable, in every instance; however, evaluation of several characteristics simultaneously should permit the correct identification of depositional environment in many cases.

Table 1.—Characteristics of fluvial and barrier environments expected in a humid-subtropical coastal plain with a source similar to the Appalachian region.

Criterion	Fluvial	Barrier	Comment
Grain Size	Sand and gravel in channels and in braided streams; silt and sand in point bars, levees, and flood plains near channels; clay and silt in oxbow and other lakes and back-swamp parts of flood plains.	Sand and gravel in estuary channels and back barrier tidal channels, inlets, berm, foreshore; silt and sand in dunes, back dune flat, and shore face; clay and silt in back barrier bays, tidal flats, and offshore.	Size-frequency curves of both environments possibly are characteristic. Boulders are uncommon in coastal sediments.
Composition	Highly dependent on source area; commonly varied; feldspar locally abundant; large amounts of kaolinite and vermiculite diagnostic; percentage of heavy minerals generally low.	Commonly quartzitic with little feldspar; kaolinite rare; montmorillonite and true glauconite diagnostic unless abundant in source area; percentage of heavy minerals generally high.	Can be suggestive or diagnostic.
Degree of Sorting	Highly variable within channels, dependent on position in channel and abundance of clay; poor elsewhere.	Good in inlets, berm, foreshore, dunes, and back dune flat; good to intermediate in shore face, back barrier tidal channels, and some estuary channels; intermediate to poor in back barrier areas, offshore, and near sources of abundant mud supply.	Excellent sorting is uncommon in most fluvial facies unless derived from equigranular source.
Degree of Rounding	Commonly good for gravel, poor for sand unless derived from source; larger particles round more rapidly than smaller ones.	Good for pebbles; can also be good for sand; rounding more rapid than in fluvial environment; dune sand more rounded than sand in foreshore.	Rounding of sand possibly is diagnostic.

Table 1.—Continued

Criterion	Fluvial	Barrier	Comment
Quartz-Grain Surface Features	Pyramidal indentations seldom present; definite diagnostic patterns uncommon.	Foreshore sand grains characterized by small pyramidal indentations that appear as V-shapes; eolian sand grains characterized by meandering ridges that result from intersections of curved, conchoidal surface.	Beach and eolian features appear to be diagnostic (Krinsley and Takahashi, 1962).
Oxidation	Commonly oxidized above water table in levees and flood plains near channels, in channel and braided streams, and in point bars wherever vegetation is slight or oxygenated groundwater is present; can be inherited. Unoxidized in stagnant lakes and backswamp parts of flood plains.	Deposits of dunes and foreshore oxidized; deposits of shore face, inlets, and back dune flats oxidized or unoxidized depending on local conditions; deposits of back barrier bays and tidal flats and of offshore commonly unoxidized except in upper few inches. High energy of beach likely to clean grains of inherited oxidation features. Frosting of dune sand common.	Bluish-gray color is characteristic of submerged environments.
Fossils	Vascular plant fragments and large pieces of wood; freshwater microfossils such as hystrichosphaerids and diatoms, fresh water pelecypods and pulmonate gastropods; marine fossils derived from eroded marine beds within drainage basin. Carbonate fossils largely destroyed through oxidation and leaching by groundwater.	Small vascular plant fragments in back barrier areas and in offshore areas near river mouths; brackish-water microfossils such as arenaceous foraminifers in the same localities; corals and echinoderms and diverse fauna in open-marine conditions. Preservation dependent on subsequent diagenetic conditions.	Diagnostic in most cases where fossils are present.

Table 1.—Continued

Criterion	Fluvial	Barrier	Comment
Sedimentary Structures	Trough-shaped scours in channels; sediment in scours fines upward to base of succeeding scour; overall decrease in grain size upward; ripples associated with fine sand; dunes, with coarser sand and small gravel; both planar and festoon cross-strata present; bedding generally not persistent laterally and exhibits distinct pinch-and-swell; discoid cobbles have upstream dip; elongate grains in ripple trough perpendicular to current, those in ripple crests parallel to current; angular chunks of clay common in channels; flat-topped ripples on point bars. Original thin bedding of backswamps disrupted by plant roots and burrowing animals.	Trough-shaped scours and angular chunks of clay restricted to areas of channeled flow such as inlets, tidal channels, tide rips, locally on berms, and perhaps, estuaries; characteristic seaward-dipping parallel beds in berm, foreshore and shore face laterally continuous for more than 50 feet; thin, parallel, gently landward-dipping back shore beds (washover fan); sediment fines and bedding thins downward in progradational sequences; flat-topped ripples on low-tide terrace and sandy tidal flats; separation of elongate and discoid cobbles in beach face because the latter fail to roll; discoid cobbles dip offshore; concentration of opaque minerals along bedding surfaces and throughout dunes. Finely laminated sand, silt, and clay, interlayered, in back barrier marshes and tidal flats and offshore; wavy, indistinct laminae in salt-grass marsh; small clay chips common offshore; mottles and worm tubes common in back barrier bays with marine salinities.	Trough-shaped scours uncommon in barriers; parallel beach stratification is diagnostic, although pseudo-parallel stratification occurs parallel to fluvial flow in channels and in braided streams.

Table 1.—Continued

Criterion	Fluvial	Barrier	Comment
Stratigraphic Pattern of Facies	Lateral and vertical changes in grain size commonly extreme to rather marked through short distances, especially in braided channels; changes both gradational and sharp, can be symmetrical with respect to channel; sand bodies U-shaped in cross section, surrounded by fine-grained flood plain sediment, and generally perpendicular to coastline; pattern of coarsest sediment both linear and anastomsing.	Systematic and gradational lateral and vertical changes in grain size in most barrier environments; marked changes laterally and vertically in inlets, tidal channels, and estuaries; facies asymmetric with respect to barrier, having coarsest sediments on seaward side; triangular shape of barrier in cross section, but sheet-like if progradational; except in inlet areas; in general, facies trend parallel to coastline.	Overall facies pattern is diagnostic where control is sufficient.
Relation of Facies to Morphology	Base of channel lower than flood plain; low, linear levee ridges can flank one or both sides of channel; curving, ridge-and-swale topography of point bars, and plan-view U-shape of oxbow lakes where present; lakes and bays of irregular shape in low-relief flood plain; scarps along entrenched channels; depositional surface commonly more irregular than that of most barrier-associated environments.	Step-like morphology, with 40 to 60 feet of relief between offshore and back barrier areas. Low relief in back barrier area, tendency for deposition to near sea level throughout; low relief with slight landward slope in back dune flat; constructional dune ridges with closed depressions, irregular shapes and slopes, and as much as 100 feet of relief locally; inlet channels as much as 80 feet deep; backshore nearly flat; steep seaward slope of foreshore and shore face, with minor irregularities at low-tide terrace and shore face bars; low relief and gentle seaward slope of inner continental shelf, broken locally by preexisting features.	Diagnostic in most cases.

REGIONAL GEOLOGY

The Atlantic Coastal Plain area, south from New Jersey to Georgia, consists of deformed and consolidated pre-Jurassic "basement" rocks that are overlain by unconsolidated and semiconsolidated wedges of Mesozoic and Cenozoic sediments that thicken and dip gently eastward (Stephenson, 1928; Brown, 1958). "Basement" rocks include downfaulted Triassic strata and Paleozoic igneous and metamorphic rocks that are similar to those exposed in the Piedmont province west of the Coastal Plain province (Rodgers, 1952; Dietrich, 1960).

At the Fall Line, thin Cretaceous and Tertiary strata nonconformably overlie pre-Jurassic rocks of the Piedmont province, whereas near the present coast of Virginia, more than 75 miles eastward, the crystalline basement is overlain by 2000 to 3000 feet of Cretaceous, Tertiary, and Quaternary sediments (Cederstrom, 1945b; Ewing, Crary, and Rutherford, 1937). The Cretaceous and Tertiary strata that overlie the basement consist of marine, coastal, and alluvial sediments that extend from the Fall Line eastward beneath the continental shelf (Drake, Ewing, and Sutton, p. 1-59).

Sediments of probable Pliocene and early Pleistocene age cover much of the higher portions of the Coastal Plain, whereas those of middle and late Pleistocene age form a thin blanket, 15 to 100 feet thick, over much of the lower, more seaward portions. These post-Miocene sediments underlie the scarps, plains, flats, and other morphologic features. The assemblages of heavy minerals indicate that post-Miocene sediments in southeastern Virginia were derived from the plutonic and high-grade metamorphic rocks of the Piedmont and Blue Ridge provinces (Coch, 1965).

Regional structures that affect sediments of the Atlantic Coastal Plain are broadly divisible into those that parallel, and those that trend at a large angle to Appalachian structural trends. Differential movement of the basement has localized most, if not all, of these regional structures.

From the Fall Line eastward at least to the vicinity of the coast, the top of the basement exhibits three distinct segments that approximately parallel Appalachian structural trends (Prouty, 1946; Berry, 1948; Richards and Straley, 1953). From west to east, slopes of the segments are successively 10 to 45 feet per mile, 120 to 125 feet per mile, and 100 feet per mile. The westernmost segment is an inferred erosional surface of pre-Cretaceous age, and has a known subsurface relief of 200 to 300 feet within 0.5 mile locally (Ewing and others, 1939; Johnson and Straley, 1953). The monoclinal aspect of the

three segments suggests structural control in part, although erosional origins also have been proposed (Dietrich, 1960).

The Cretaceous and Cenozoic strata overlying the basement also have been affected by major, southeast-trending basement arches and basins (Figure 9) that cut across the regional Appalachian trend at

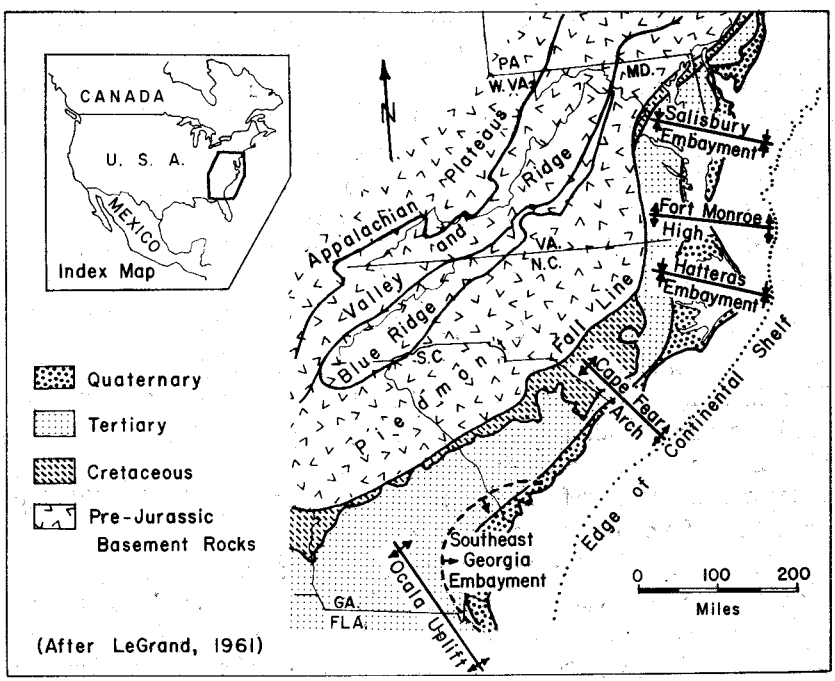


Figure 9. Major structural features in the Atlantic Coastal Plain.

a large angle (Straley and Richards, 1948; Ewing, Wollard, and Vine, 1939, 1940; Cederstrom, 1945a; Spangler and Peterson, 1950; Spangler, 1950; LeGrand, 1961; and Richards, 1967). Differential vertical movements along these structures have influenced considerably depositional history and stratigraphic patterns since at least Cretaceous time.

Major structural features involving the basement in or adjacent to the area of study are the Hatteras embayment in northeastern North Carolina and the Fort Monroe high in southeastern Virginia, which intersect Appalachian trends at a large angle, and possible north-south basement features that intersect Appalachian trends at a small angle. Two minor east-facing monoclines or faults that involve Eocene and Miocene strata also trend north-south, but it is not known whether the basement is involved in these structures (Cederstrom, 1939).

The present study shows that the eastward slope of the top of the Yorktown Formation decreases from about 2.5 feet/mile in the area between Petersburg and the Suffolk scarp to about 1 foot/mile from the Suffolk scarp to near the present coast. There the slope increases abruptly again (Plates 1 and 3). The decrease in slope of the top of the Yorktown Formation suggests a north-south anticlinal structure with an axis east of the Suffolk scarp. Such a structure would explain the slope changes in the top of the Yorktown Formation, and would coincide with a major north-south-trending Bouguer gravity high along the Deep Creek swale, close to the slope break in the top of the basement near the subsurface –2500-foot contour (Oaks, 1965). Such evidence suggests slight structural uplift along a north-south trend in southeastern Virginia during post-Miocene time, perhaps during the most recent domal uplift of the Appalachians in Pliocene or early Pleistocene time (Potter, 1955).

STRATIGRAPHY

The exposed and near-surface stratigraphic units east of the Fall Line in southeastern Virginia consist of thin, widespread, and rather flat-lying unconsolidated sediments that range in age from Miocene to Holocene. The top of the upper Miocene Yorktown Formation is a convenient basal reference surface as it has a distinctive lithology from that of younger units in most places.

The top of the Yorktown Formation slopes gently eastward from the Fall Line, and east of the Dismal Swamp and Churchland flat the formation lies entirely below sea level. Above its deeply dissected surface lie 10 stratigraphic units that record a complex history of relative sea-level changes and shoreline evolution (Figures 10, 11, Table 2).

RECOGNITION OF STRATIGRAPHIC UNITS

Each post-Yorktown unit in the Outer Coastal Plain, and most units in the Inner Coastal Plain, contain at least one widespread facies, generally of lagoonal or nearshore-marine origin, with a combination of physical properties by which it can be identified readily in outcrop or in vertical sequence. These properties include color, mineralogy, grain size, sorting, sedimentary structures, fossils, and compactness (Tables 2, 3, 4). Stratigraphic subdivision is here based on differences in these characteristics and on the presence of unconformities. Unconformities were recognized in outcrop by the presence of covered paleosols, lag concentrates, and channeling. Subsurface unconformities were recognized by contouring the top of each unit; evidence for subaerial erosion was found in some, but not all, cases. Oxidation at the top of a subsurface unit was taken to indicate subaerial ex-

posure unless such oxidation could reasonably be explained by original depositional conditions or subsequent groundwater conditions (Table 5).

Where a characteristic facies disappeared in the subsurface, a profile of closely spaced borings established interfingering, gradational, or overlapping stratigraphic relationships between facies or different units. Relative ages were determined from superposition of units, amount of dissection, and degree of weathering including alteration of soluble heavy minerals, enrichment in secondary clay, and etching of quartz-grain surfaces.

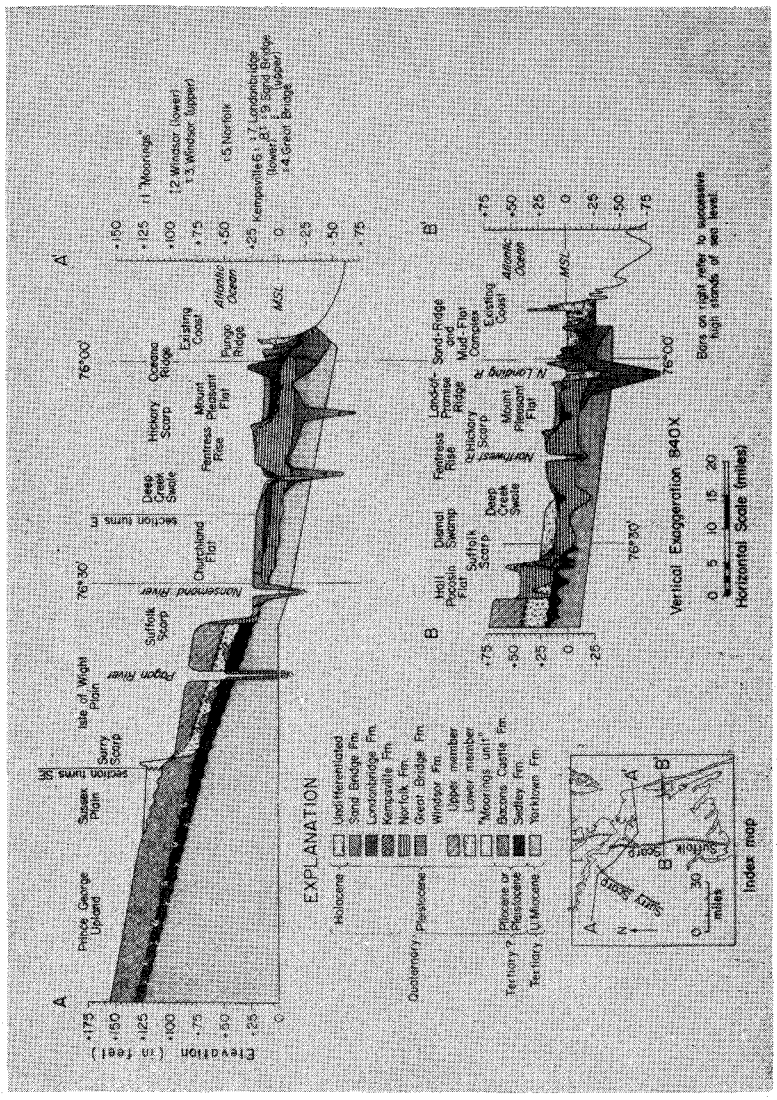


Figure 10. Diagrammatic geologic sections showing relations of post-Yorktown stratigraphic units in southeastern Virginia.

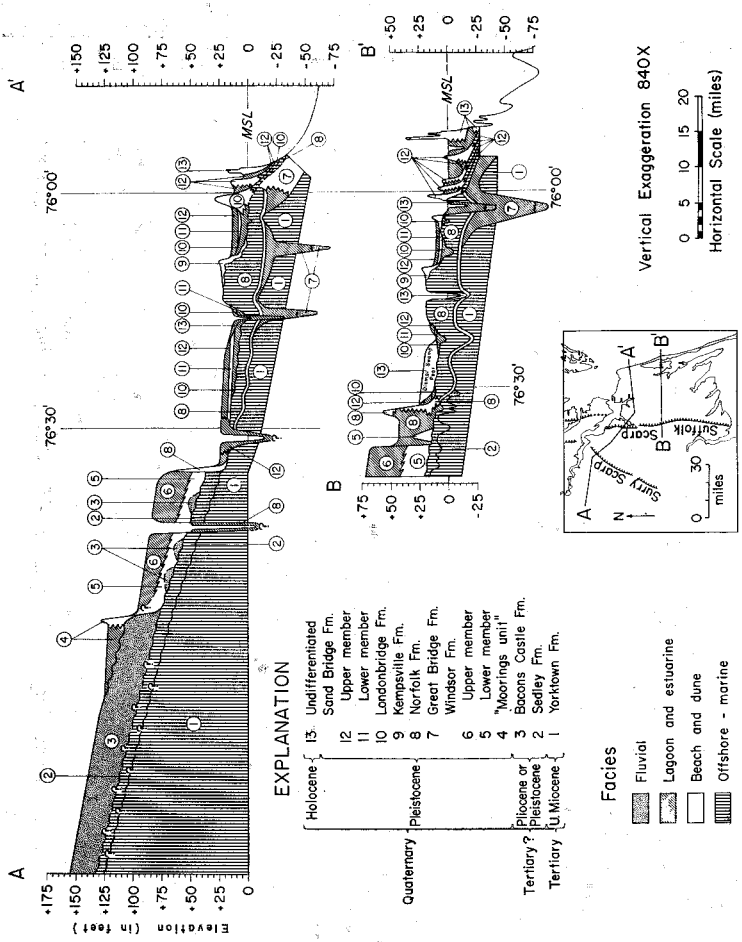


Figure 11. Diagrammatic geologic sections showing facies of post-Yorktown stratigraphic units in southeastern Virginia.

Table 2.—Post-Miocene geologic formations in southeastern Virginia.

Age	Name			Character	Generalized thickness in feet
Holocene	Undivided sediments			Dune and beach sand and fine gravel, lagoonal clay and silt; peat, alluvial silt.	20
	Dismal Swamp Peat			Freshwater peat (underlain by lake clay and fluvial sand).	7
Pleistocene	Sand Bridge Fm.	Upper member	Western area	Lagoonal clay and silt; tidal-delta and tidal-channel sand and clayey sand.	4
			Sand-ridge and Mud-flat complex	Variable lagoonal sand and clay and barrier sand.	18
		Lower member		Clean to clayey and silty fine or fine to medium sand.	5
	London-bridge Fm.	Clayey-silt facies		Lagoonal clay and silt.	5
		Sand facies		Dune and beach sand and gravel with shells.	30
	Kempsville Formation			Beach sand, gravel, and shells; lagoonal peaty clay (restricted).	10
	Norfolk Fm.	Upper member		Lagoon clay, silt and sand, and dune and beach sand and gravel in west; variable sand, silty to clayey sand, and sandy silt in east.	20
		Lower member		Beach sand and fine gravel.	4
	Great Bridge Fm.	Upper member		Open-bay lagoonal clay, silt, and silty fine sand, some shells, peaty locally.	20
		Lower member		Fluvial sand and gravel, freshwater peat.	15
	Windsor Fm.	Upper member		Lagoonal clayey and silty sand and silty clay.	15
		Lower member		Beach and nearshore sand and fine gravel.	15

Table 2.—Continued

Pleistocene	"Moorings" unit	Fine sand facies	Dune and beach(?), silty fine sand.	25
		Clayey silt facies	Lagoonal clay, silt, and fine sand.	10
Pliocene and/or Pleistocene	Bacons Castle Fm.	Silt facies	Floodplain clay, silt, and fine sand.	5
		Sand facies	Fluvial channel silt, sand, fine gravel, and cobbles	8
	Sedley formation		Marine and estuarine clay, silt, and fine sand.	13
Miocene (and Pliocene?)	Yorktown Formation		Marine clay, silt, sand, and coquinite.	37 (maximum exposed)

Table 3.—Heavy minerals of selected post-Yorktown stratigraphic units.

Heavy Minerals*	Sedley formation	Bacons Castle Formation	"Moorings unit" sand facies	Windsor Formation, upper member	Norfolk Fm., coarse-sand facies	Sand Bridge Fm., upper mbr., clayey-sand facies
Rutile	1	1	2	3	tr.	tr.
Zircon	11	8	6	16	8	17
Tourmaline	1	1	2	tr.	2	1
Monazite	—	—	—	—	—	1
Garnet	—	tr.	—	—	tr.	tr.
Biotite	—	—	—	—	—	tr.
Opaques	75	77	73	62	67	51
Staurolite	tr.	5	5	6	3	1
Kyanite	1	3	2	4	2	3
Epidote	5	3	tr.	tr.	1	tr.
Hornblende	2	—	1	1	9	16
Sphene	tr.	tr.	tr.	1	2	1
Sillimanite	3	3	8	7	5	8
Orthopyroxene	tr.	—	1	tr.	1	1
Total Percent	99+	99+	100	100	100	100
Number of Samples	3	6	11	6	4	6

*Heavy minerals listed in order of decreasing persistence (Pettijohn, 1956, p. 506). Data from Coch (1965, 1968).

Table 4.—Percentages of minerals in clay-sized fractions of Yorktown Formation and selected younger stratigraphic units.

Clay-sized Minerals / Stratigraphic Units	Quartz	Amphibole	Feldspar	Gypsum	Goethite	Hematite	Siderite	Calcite	Vermiculite	Kaolinite or Chlorite	Montmorillonite	Illite or Muscovite	Number of samples	Identified by
Recent lagoon, marine salinity	40-60	—	5-10	—	—	—	—	—	—	5-10+	T-5	<15-35	3	JLM
Sand Bridge Fm. upper member	60-80	A-10	T-20	—	—	—	—	—	A-20	T-20	5-30	T-20+	8	JLM SSG
silty-clay facies	20+	—	T-5	—	—	—	—	—	20+	A-T	—	T-20	2	SSG
silty-sand facies														
lower member	20+	—	5-20+	—	—	—	—	—	—	5-20	T	20+	2	SSG
Londonbridge Fm. clayey-silt facies	50-60	A-10	T-20+	T	—	—	—	—	—	10-20+	A-10	5-20+	7	JLM SSG
Norfolk Fm. upper member silty-sand facies	20+	—	T-20	—	—	—	—	—	—	5-20	T-20	20+	3	SSG
clayey-sand facies	20+	—	A-20	—	—	—	—	—	T-20+	T-20	T-20	T-20+	6	SSG
Great Bridge Fm. upper member clayey-silt facies	20+	A-T	5-20	A-T	—	—	—	—	A-20+	T-20	A-20+	T-20+	3	JLM SSG
Bacons Castle Fm.	20+	—	5-20	—	—	—	—	—	—	T	—	5-20	1	SSG
Sedley fm.	5-20+	—	A-T	—	5-20+	T	A-20	—	A-T	A-20	5-20+	T-20	3	SSG
Yorktown Fm.	5-20+	—	5-20	—	—	A-20	A-20+	—	5-20+	T-20	5-20	T-20	2	SSG

T, trace; A, absent; JLM, J. L. McAtee, Baylor University; SSG, S. S. Greenberg, Va. Div. Min. Resources.

Table 5.—Weathering characteristics and relation to lithology in post-Yorktown stratigraphic units.

Unit	Facies exposed at present	Parent material	Depth of oxidation (feet)	Color in weathered zone	Alteration of quartz-grain surface features	Alteration of soluble heavy minerals	Degree of soil development	Depth of clay enrichment (feet)
Holocene	existing barrier	quartz sand	to water table	virtually unweathered	none	virtually none	thin humus at surface where plants abund. behind dunes	0.25
Sand Bridge Fm. upper mbr.	sand facies in ridges (barrier)	quartz sand	3 to 6 (grades to lighter colors at base of clay enrichment)	lightly limonitic	ND	very slight	moderately developed; A horizon approx 1 foot thick	3 to 5, in Pungo Ridge; less in more eastern ridges
	silty-clay facies (lagoon)	quartz, minor feldspar, clay	0.5 foot; mottled throughout	grays and browns, light limonitic mottling	ND	very slight	very slight	silt concentrated in uppermost foot
	clayey-sand (Nansemond) facies (tidal channel)	quartz, feldspar, clay	3 to 8	moderately limonitic, mottled hematitic	very slight	very slight	moderately developed	NA

Table 5.—Continued

Unit	Facies exposed at present	Parent material	Depth of oxidation (feet)	Color in weathered zone	Alteration of quartz-grain surface features	Alteration of soluble heavy minerals	Degree of soil development	Depth of clay enrichment (feet)
	silty-sand facies (river-influenced lagoon)	quartz, clay, feldspar	2 to 3	lightly limonitic	ND	ND	moderately developed	2 to 3
lower mbr.	sand# (beach)	quartz sand	commonly throughout	lightly limonitic* NA?	very slight	very slight	no soil at top	NA
Londonbridge Fm.	sand facies in Oceana Ridge (barrier)	quartz sand	3 to 6 (grades to lighter colors at base of clay enrichment)	lightly limonitic	ND	very slight	well developed; A horizon approx 1 foot thick	3 to 6
	clayey-silt facies+ (lagoon)	quartz, minor feldspar, clay	unoxidized	NA	ND	ND	NA	NA
Kempsville Fm.	sand facies in Hickory Scarp (beach)	quartz sand	3 to 4 (grades to lighter colors at base of clay enrichment)	lightly limonitic	very slight	ND	well developed; A horizon approx 1 foot thick	3 to 4

Table 5.—Continued

Unit	Facies exposed at present	Parent material	Depth of oxidation (feet)	Color in weathered zone	Alteration of quartz-grain surface features	Alteration of soluble heavy minerals	Degree of soil development	Depth of clay enrichment (feet)
Norfolk Fm. upper mbr.	coarse-sand facies in Suffolk Scarp (beach-barrier)	quartz sand	3 to 5 (grades to lighter colors at base of clay enrichment)	limonitic	moderate; distinguishable from younger units; less than Windsor; considerably less than pre-Windsor units	moderate	well developed; A horizon approx 2 feet thick	3 to 4
	clayey-sand facies (fluvial-estuarine)	quartz, mica, feldspar, clay	3 to 4	limonitic	ND	ND	well developed; A horizon approx 2 feet thick	3 to 4
	silty-clay facies (lagoon)	quartz, clay, mica, feldspar	3 to 6 avg. up to 19 near Suffolk Sand Ridge	limonitic	ND	ND	NA	NA
	silty-sand facies+ (river-influenced offshore)	quartz, mica, feldspar, clay, fossils	2 to 5	limonitic	ND	ND	NA	NA

Table 5.—Continued

Unit	Facies exposed at present	Parent material	Depth of oxidation (feet)	Color in weathered zone	Alteration of quartz-grain surface features	Alteration of soluble heavy minerals	Degree of soil development	Depth of clay enrichment (feet)
	medium-sand+ facies (nearshore)	quartz, chert, clay, fossils	upper surface removed by later erosion	NA	ND	ND	NA	NA
	silt facies* (iocal offshore)	quartz, mica, fossils	NA	NA	ND	ND	NA	NA
	sand facies* (local offshore)	quartz, fossils	NA	NA	ND	ND	NA	NA
	fine-sand facies (offshore)	quartz sand, mica, minor feldspar, fossils	3 to 5	limonitic	ND	*	well developed; forest podzol at top 1 foot thick	2 to 3
lower mbr.	sand (beach)*	quartz sand and gravel	NA	NA	ND	ND	NA	NA
Great Bridge Fm. upper mbr.	sand facies* (barrier)	quartz sand, rock fragments	unoxidized	NA	ND	ND	NA	NA

Table 5.—Continued

Unit	Facies exposed at present	Parent material	Depth of oxidation (feet)	Color in weathered zone	Alteration of quartz-grain surface features	Alteration of soluble heavy minerals	Degree of soil development	Depth of clay enrichment (feet)
	clayey-silt facies* (lagoon)	quartz, feldspar, clay	unoxidized	NA	ND	ND	NA	NA
lower mbr.	sand* (fluvial)	quartz sand, rock fragments, freshwater peat	oxidized in places	white with brownish tinge in places	ND	ND	NA	NA
Windsor Fm. upper mbr.	silty sand and silty clay (lagoon)	quartz sand, mica, minor feldspar(?), clay	5 to 7	limonitic; mottled hematitic	ND	moderately heavy	well developed; A horizon approx 4 feet thick	4 to 8
lower mbr.	sand and gravel# (beach)	quartz	NA	NA	NA	ND	NA	NA
"Moorings unit"	fine-sand facies in Surry Scarp (barrier?)	quartz; minor feldspar, mica, opaques	max. 14	strongly limonitic; mottled hematitic	heavy	heavy	well developed; A horizon approx 5 feet thick	max. 14

Table 5.—Continued

Unit	Facies exposed at present	Parent material	Depth of oxidation (feet)	Color in weathered zone	Alteration of quartz-grain surface features	Alteration of soluble heavy minerals	Degree of soil development	Depth of clay enrichment (feet)
	clayey-silt facies (lagoon?)	quartz, clay	more than 8	strongly limonitic; mottled hematitic	ND	heavy	well developed; A horizon approx 2 feet thick	silt concentrated in uppermost foot
Bacons Castle Fm.	silt facies (flood plain)	clay, quartz	more than 8	hematitic, some limonitic mottles, unoxidized clay plates	ND	heavy	well developed; A horizon approx 2 to 3 feet thick west of Savedge	NA
	sand facies (fluvial channel)	quartz, clay	more than 8	hematitic, limonitic	severe	very heavy	NA(?)	NA
Sedley fm.	sandy silt (offshore?) (fluvial-estuarine in part?)	quartz, clay, glauconite, ferrous oxide	10 to 15	hematitic; deep red grades down into reddish orange	ND	very heavy (megascopic)	no soil at top	NA

Table 5.—Continued

Unit	Facies exposed at present	Parent material	Depth of oxidation (feet)	Color in weathered zone	Alteration of quartz-grain surface features	Alteration of soluble heavy minerals	Degree of soil development	Depth of clay enrichment (feet)
Yorktown Fm.	coquinite (beach along Suffolk Scarp)	broken shell, quartz sand	upper surface removed by later erosion	NA	ND	ND	NA	NA
	clay and silty sand (offshore) in east; sand (nearshore) in west	quartz sand, feldspar, mica, clay, glauconite	5 to 20	hematitic; deep red to yellowish orange	ND	ND	saprolite at top up to 20 feet thick; well developed	max. 20

Data from Coch (1965, 1968); Oaks (1965)

*Not exposed at present and probably not exposed since deposition.

+Rarely exposed at present and probably not exposed immediately after deposition.

#Exposed at present in outcrop but probably not exposed immediately after deposition.

NA-Not applicable. ND-No data available

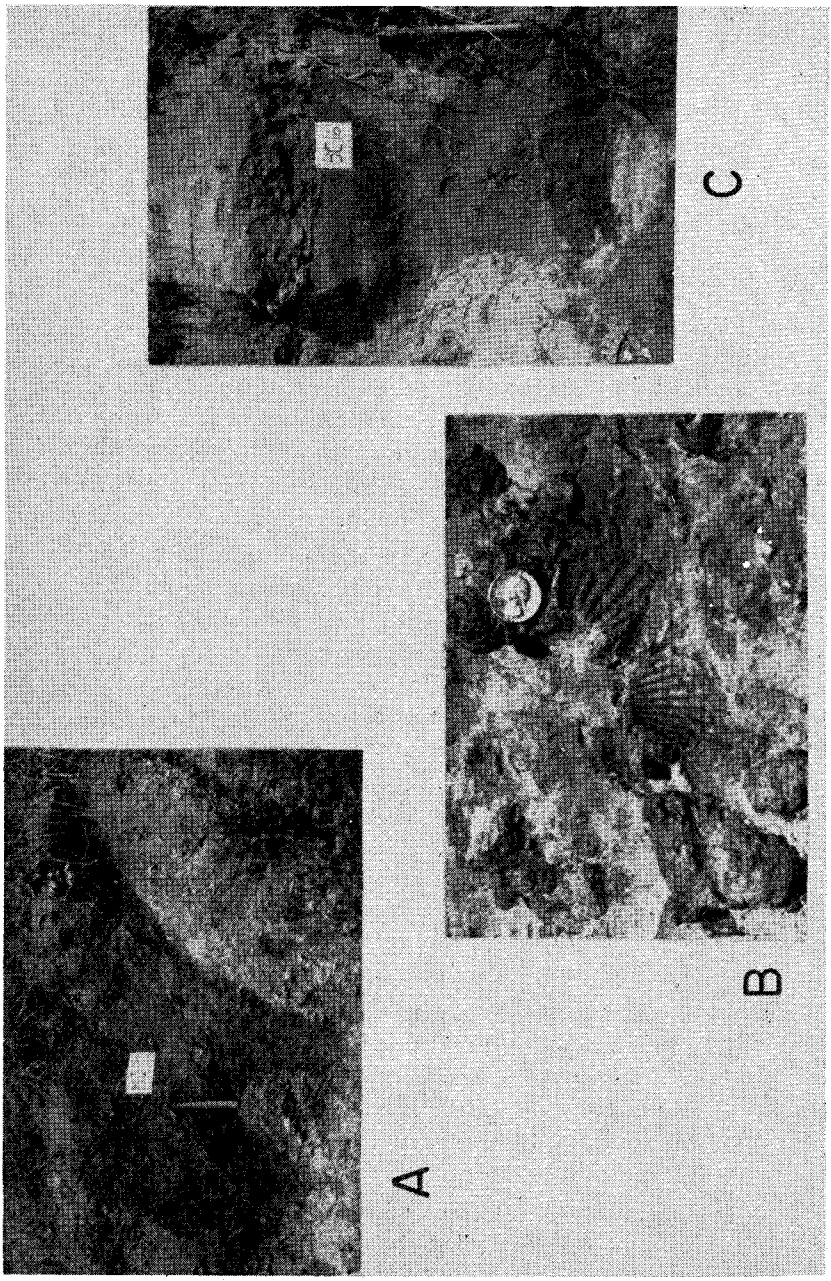
MIOCENE (AND PLIOCENE?) SERIES

YORKTOWN FORMATION

The Yorktown Formation was named by Clark and Miller (1906) for marine clay, sand, and shell, comprising the youngest unit of the Miocene Series, exposed in bluffs of the York River near Yorktown, Virginia. It is present throughout the area of study, although locally it may be absent due to subsequent erosion east of the Suffolk scarp (Figure 10). The formation is unconformably overlain by various younger stratigraphic units (Plates 1 and 2). The upper part of the Yorktown in outcrop is characterized by yellowish-orange to orangish-red and dark reddish-brown saprolite 5 to 10 feet thick and locally, near the Nansemond River, 20 feet thick (Figure 12, A). Where this conspicuous saprolite has been removed by erosion, the formation is medium blue, and is difficult to distinguish from younger units of similar color.

In core and jet-rig borings, the top of the Yorktown is recognized by abrupt changes in compaction, composition, degree of oxidation, and kinds, abundance, and mode of preservation of fossils. It is noticeably more compact than most of the overlying units, especially those east of the Suffolk scarp (Coch, 1965, 1968; Harrison, 1962). Glauconite is common in the Yorktown Formation, whereas it is uncommon in overlying sediments, except locally near the base of the Sedley formation. Except along the Nansemond River, no oxidation occurs at the top of the Yorktown Formation more than two miles east of the Suffolk scarp. Also, oxidation is not always present at the top of this unit beneath interfluves west of the Suffolk scarp.

The Yorktown Formation is characterized by its abundant, varied fauna (McLean, 1966, p. 34). In contrast, post-Yorktown stratigraphic units are characterized by less diverse, commonly sparse, fossil assemblages consisting of only brackish to nearshore species. Additionally, the Yorktown Formation contains "guide fossils" that are not present in younger units. Such fossils include wide-grooved pectens, corals other than *Astrangia* sp., *Turritella variabilis* Conrad, *Glycymeris* sp., and *Cardita granulata* Say, all of which evolved subsequently or did not occur so far north in later epochs (Gardner, 1943, 1948; Richards, 1950, 1962, personal communication). In addition, tests of *Elphidium* sp. of Miocene age commonly have a yellowish tinge compared to specimens of the same genus from post-Windsor units (Oaks, 1965). Post-Yorktown units of the Inner Coastal Plain are uniformly non-fossiliferous with the exception of the Sedley formation.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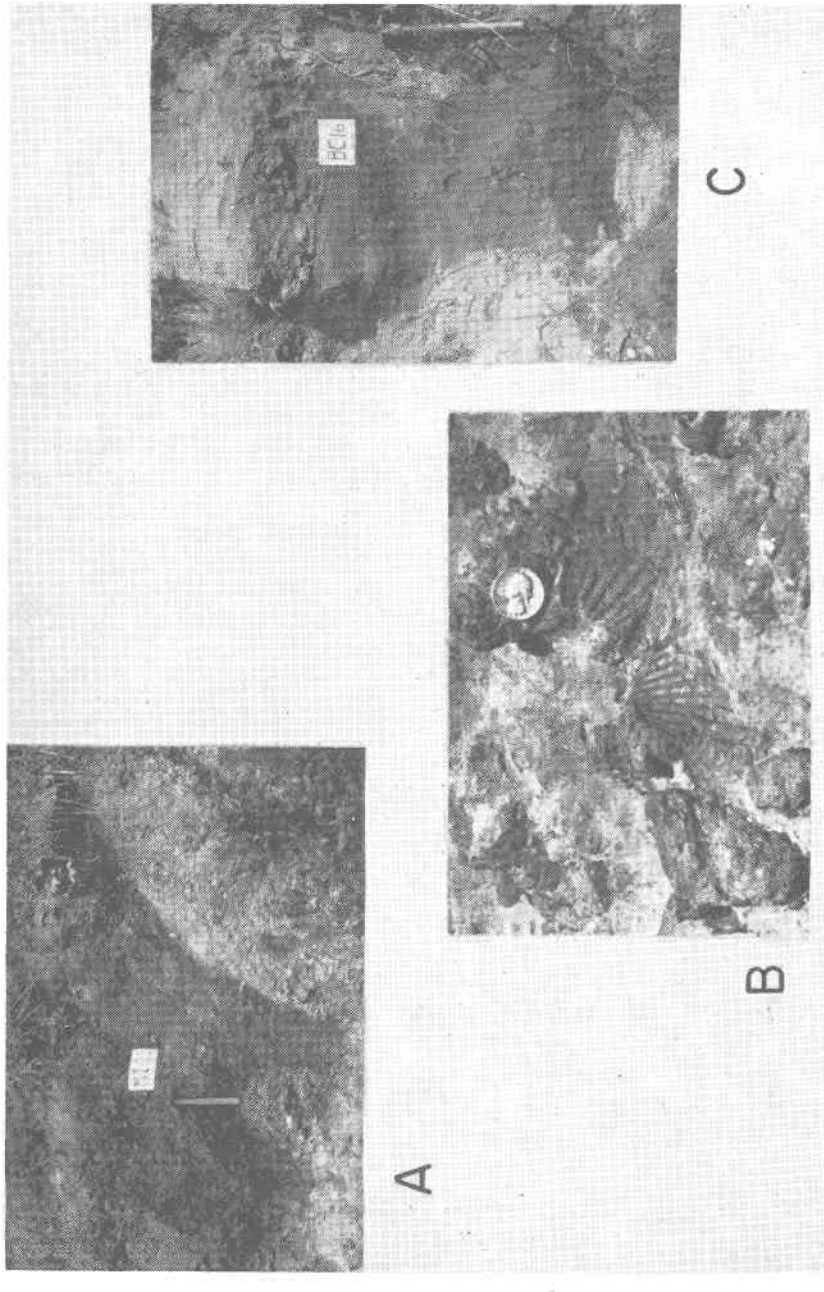
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C

The Yorktown Formation unconformably overlies the Miocene St. Marys Formation (Gardner, 1943); the contact is exposed locally west of Gravel Neck along the south side of the James River. The Yorktown is approximately 150 feet thick; it dips gently eastward in the area studied (Roberts, 1932, p. 21). West of the Suffolk scarp, it is unconformably overlain at different places by the Sedley, Bacons Castle, Windsor, or Norfolk formations (Figure 10). East of the Suffolk scarp, the Yorktown is unconformably overlain at various places by the Great Bridge, Norfolk, Londonbridge, or Sand Bridge formations (Plate 2). For a short distance east of the Suffolk scarp, Windsor and older units locally overlie the Yorktown.

The very irregular, upper surface of the Yorktown Formation slopes gently eastward from about 130 feet near Petersburg to below sea level east of the Nansemond River and Lake Drummond (Figure 13). Buried channels in the top of the formation have more than 70 feet of relief locally, and Harrison (1962) reported 90 to 120 feet of relief beneath both the lower James River and the mouth of Chesapeake Bay. Such channels have controlled subsequent drainage, as present drainage systems have developed upon thick fills, and thus have come to lie directly above such older channels (Figure 10). However, not all of the important older channels were followed by later streams. Because topographic lows in the tops of all post-Yorktown units are also coincident with those in the top of the Yorktown Formation, drainage lines must have been reestablished in approximately the same locations during every emergent episode following Yorktown time.

Although detailed study of characteristics of the Yorktown Formation is beyond the scope of this report, broad patterns of sediment facies nevertheless were apparent in the upper part of the unit. These facies include: (1) clean, well sorted, fine to medium sand with leached shell imprints beneath the Sussex plain (possibly St. Marys Formation): (2) fossiliferous clayey sand, silt, and clay beneath the Isle of Wight plain and Churchland flat; (3) silty, fine sand beneath Portsmouth

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Figure 12. A. Saprolite at top of Yorktown Formation beneath Isle of Wight plain; hammer 10 inches long; exposure at end of farm road west of State Road 676, 0.5 mile north of State Highway 10, Isle of Wight County.

B. Imprints of *Pecten* sp. and round ferricrete nodules in Sedley formation beneath Sussex plain; coin (25-cent piece) gives scale; exposure on north side of State Road 627, 0.1 mile west of State Road 628, Surry County.

C. Glauconite zone at base of Sedley formation, beneath Isle of Wight plain; shovel handle 20 inches long; exposure in east bank of Cypress Creek 0.6 mile south of State Highway 10 bridge over Cypress Creek, Isle of Wight County.

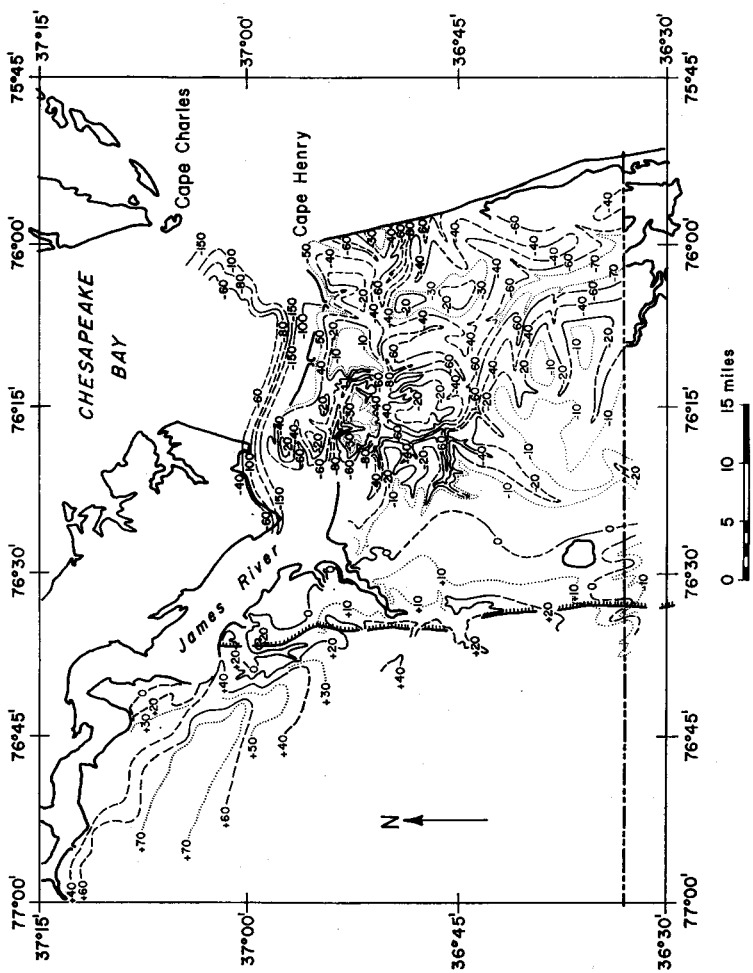


Figure 13. Topography of top of Yorktown Formation, southeastern Virginia. Contour interval: above -100, 20 feet; below -100, 50 feet; supplementary contours at intervals of 10 feet.

and Norfolk; (4) fossiliferous clay with minor layers of sand and coquina south and east of Portsmouth and Norfolk; and (5) current-deposited coquina (Appendix I, Section A) in discontinuous patches slightly east of, and parallel to, the Suffolk scarp between Chuckatuck and the James River. The coquina was studied and described in detail by Coch (1968). Similar coquina is exposed in the cliffs along the York River at Yorktown farther north (Roberts, 1932, p. 21), and beneath younger sediments in the Dismal Swamp near the Virginia-North Carolina boundary.

Since its initial description by Clark and Miller (1906) the Yorktown Formation has been considered by most workers to be late

Miocene in age, based on its macrofauna. Recently, however, McLean (1966, p. 28) noted that the upper part of the formation contains a microfauna of possible Pliocene age. Also, vertebrate fossils from the Yorktown have been identified by the U. S. Geological Survey (1965, p. A71) as being possibly Pliocene.

PLIOCENE AND/OR PLEISTOCENE SERIES

SEDLEY FORMATION

The Sedley formation was named by Moore (1956) for the sands, sandy clays, and clays that overlie the Yorktown Formation and underlie a coarse-grained unit that he called the Kilby formation. The Sedley is a distinct and mappable unit in the area of the present report, so the name is here used as originally proposed by Moore. A typical section is described in Appendix I, Section B.

The Sedley formation has been traced on the surface and in the subsurface from Petersburg eastward to the Suffolk scarp and from the James River southward to the Virginia-North Carolina boundary. In several places subsequent erosion has removed the Sedley, and younger units lie directly on the Yorktown Formation. East of the Suffolk scarp, the Sedley is present only as thin, isolated remnants that extend less than a mile eastward in the subsurface.

The Sedley formation unconformably overlies the Yorktown Formation. The surface of contact is irregular, and channels with relief of 25 feet are evident in exposures near the James River. The base of the Sedley generally is marked by a glauconite zone that weathers dark reddish brown (Figure 12, C). The sharp upper contact of the Sedley formation (Figure 14) is marked by the conspicuously coarser grain size of the overlying Bacons Castle Formation. Where the Bacons Castle Formation has been removed by later erosion, especially beneath the Isle of Wight plain, the Sedley formation is overlain unconformably by the lower member of the Windsor Formation. Along tributaries of the James River, remnants of the Sedley formation are overlain by the clayey-sand (fluvial-estuarine) facies of the Norfolk Formation. Along the Suffolk scarp, the unit is overlain by the coarse-sand (beach) facies of the Norfolk Formation, the silty-clay (lagoonal) facies of the Norfolk Formation, the silty-clay (lagoonal) facies of the upper member of the Sand Bridge Formation, or rarely, by the clayey-silt (lagoonal) facies of the Londonbridge Formation (Plates 1 and 2).

Thickness of the Sedley formation ranges from less than 1 foot just east of the Suffolk scarp to more than 30 feet north of Surry; average thickness is between 10 and 15 feet (Figure 15). The thickness,

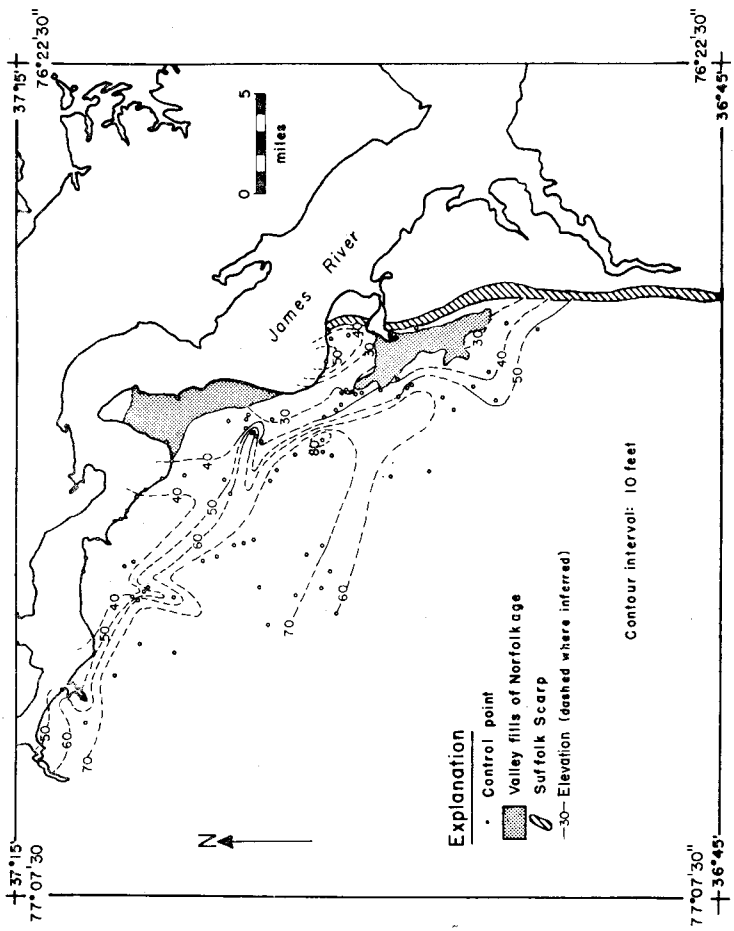


Figure 14. Topography of top of Sedley formation, southeastern Virginia; control on top of Yorktown Formation used where Sedley is absent.

continuity, and coarseness of the unit increase markedly toward major streams, and the top of the unit also slopes toward such streams. Figure 15 indicates that the Sedley sediments fill linear depressions cut into the top of the Yorktown Formation. Beneath the Isle of Wight plain the formation consists of sandy silt and fine sand with thin layers of silty clay. It coarsens to clayey, fine to medium sand with organic matter near major streams, and it also distinctly coarsens westward to fine sand with minor layers of silty clay beneath the Sussex plain.

Heavy minerals in the formation consist of opaques, zircon, epidote, sillimanite, hornblende, kyanite, sphene, rutile, tourmaline, orthopyroxene, and staurolite, in decreasing order of abundance (Coch, 1968;

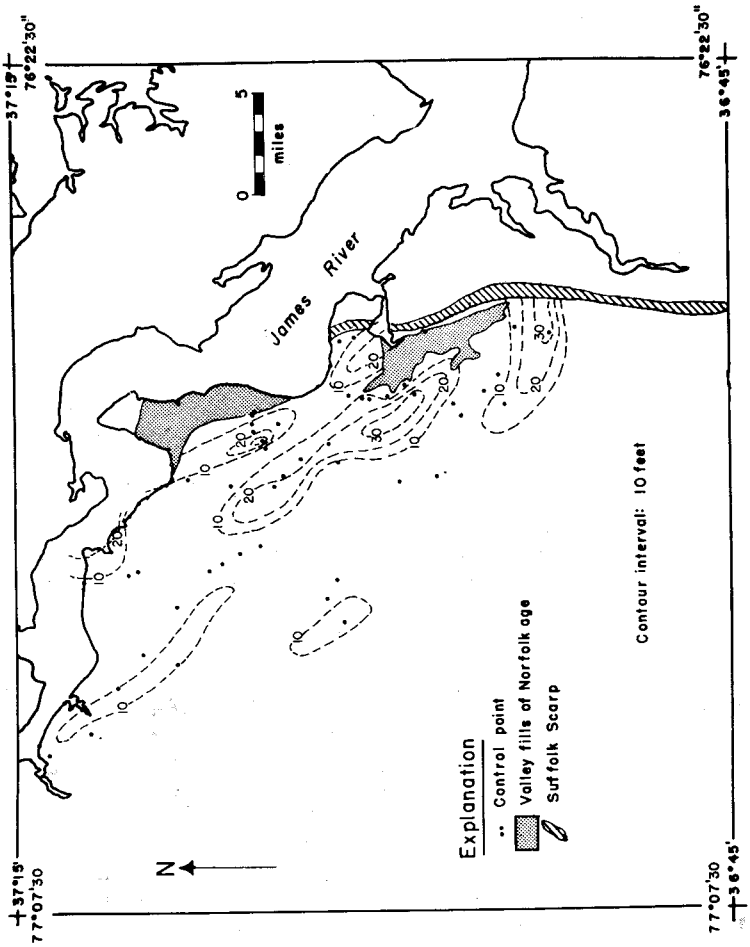


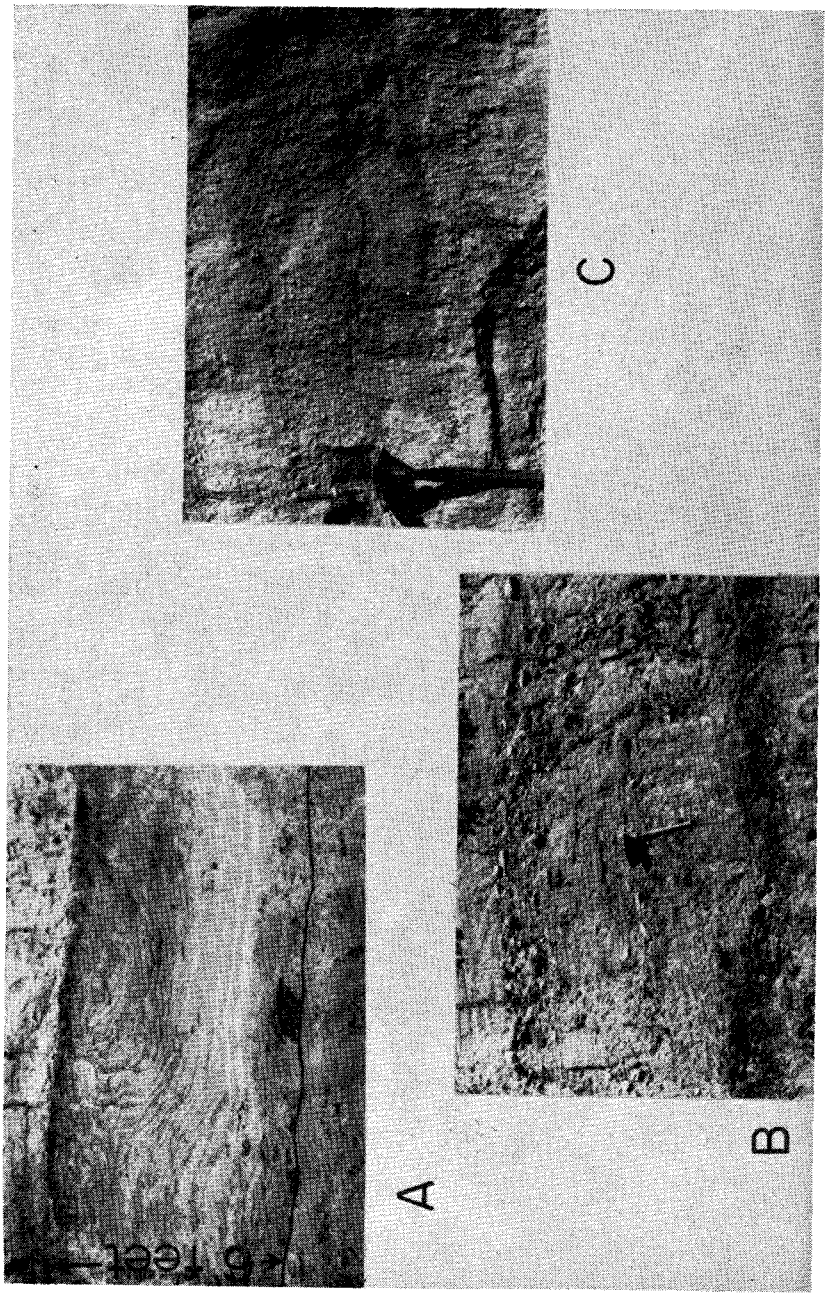
Figure 15. Isopachous map of Sedley formation, southeastern Virginia.

Table 3). The clay-sized fraction consists of chlorite, montmorillonite, illite, goethite, siderite, and feldspar in amounts up to 20 percent each, hematite in amounts less than 5 percent, and 40 to 80 percent quartz (written communication, S. S. Greenberg; Table 4).

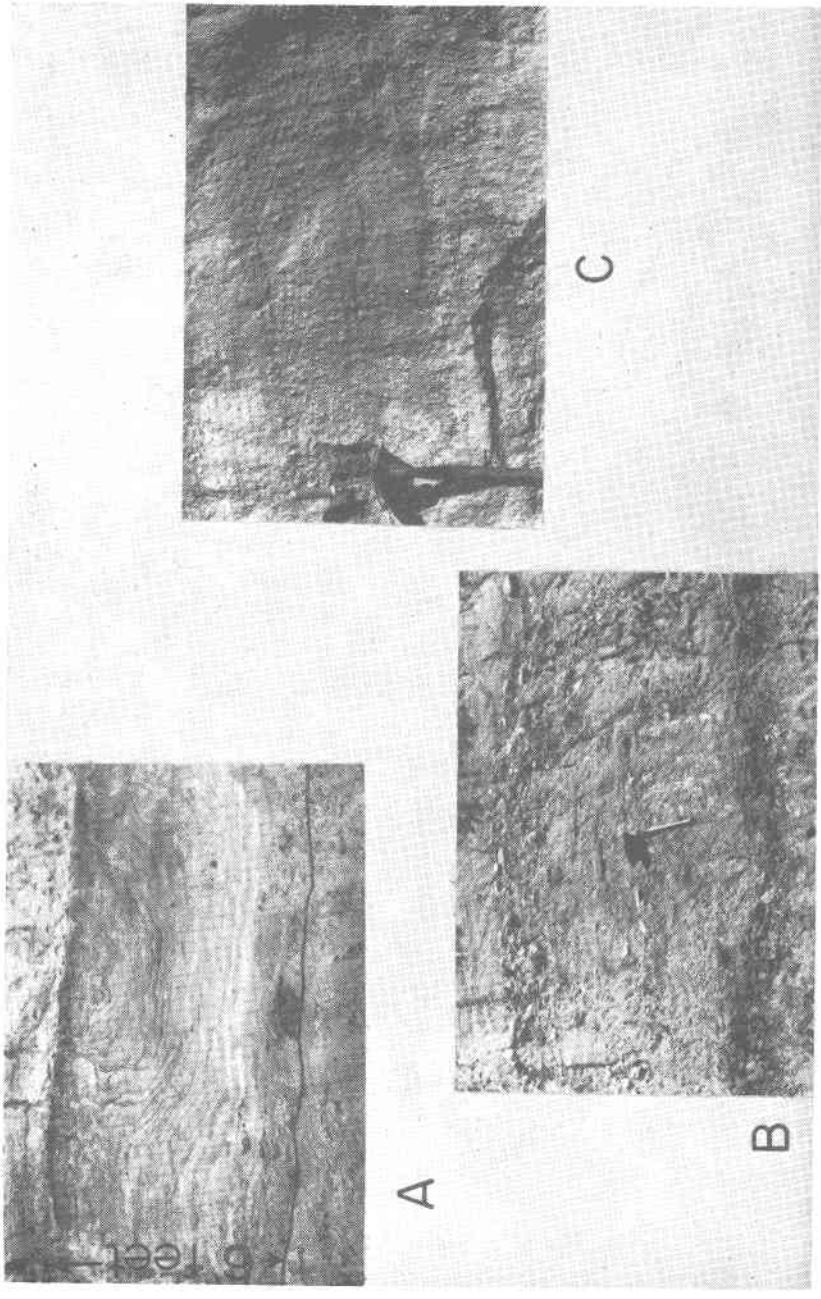
A resistant, spongy iron oxide coats many grains, even after extensive chemical and ultrasonic cleaning (Coch, 1968). Mineral grains show well-developed solution features and jagged coxcomb terminations indicative of intrastratal solution (Bradley, 1957). Siliceous overgrowths occur on some of the quartz grains and on a few of the heavy minerals, especially kyanite (Coch, 1968).

Near the James and Pagan rivers, at elevations below 60 feet, the Sedley formation is oxidized moderate red to light brown by

hematite to a maximum depth of 15 feet. It contains casts and molds of shells, Liesegang structures (Figure 16, A), and ferricrete nodules



hematite to a maximum depth of 15 feet. It contains casts and molds of shells, Liesegang structures (Figure 16, A), and ferricrete nodules



(areas in which the grains are cemented by a matrix of iron oxide; term originated by Lamplugh, 1907). Beneath the oxidized zone, non-weathered Sedley sediments are grayish blue. In contrast, the top part of the Sedley higher than elevations of 60 feet, beneath interfluve areas of the Isle of Wight plain, is oxidized moderate-reddish orange only to a depth of 3 feet. Such differences in depths of weathering probably result from the coarsening of the Sedley formation and the removal by erosion of the nearly impermeable upper member of the overlying Windsor Formation near the James and Pagan rivers.

Coch (1965, 1968) noted that the Sedley formation occurs both across interfluves and above elevations of 60 feet in southeastern Virginia. The formation contains a few marine fossils, and it both coarsens and rises westward. These observations suggest that the shoreline was west of the Sussex plain and that relative sea level was above 75 feet during maximum submergence. Parts of the coarser, thicker, and more organic portions of the Sedley formation along major streams could be fluvial-estuarine in origin, formed either as the sea rose to the maximum position of submergence, or as it later retreated.

The age of the Sedley formation is uncertain. A Pliocene or early Pleistocene age is suggested by (1) its stratigraphic position between the late Miocene (and possibly early Pliocene) Yorktown Formation and the Bacon's Castle Formation and (2) its fossils. The fossils and degree of weathering of the Sedley Formation itself suggest an age not younger than early Pleistocene. The few macrofossils that occur in the Sedley formation are chiefly casts and molds of *Pecten* spp., and are very fragile (Figure 12, B). One form, *Pecten madisonius* Say, is believed definitely to be Miocene in age (written communication, H. G. Richards), but it could have been reworked from older sediments; however, microfossils from the Sedley were assigned a post-Yorktown

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Figure 16. A. Liesegang banding in Sedley formation beneath Isle of Wight plain; dark line marks top of Yorktown Formation; exposure on east side of State Road 677, just south of Canal Run, Isle of Wight County.

B. Sand facies of Bacons Castle Formation beneath Sussex Plain (type locality); well developed channel occurs in upper right corner; coarse cobble gravel grades upward into cross-stratified clayey sand; dark bank marks top of Sedley formation; shovel handle 20 inches long; exposure on north side of State Road 609, at Sunken Meadow Beach, Surry County.

C. Intersecting, trough-shaped cross-strata in sand facies of Bacons Castle Formation. Shovel handle approximately 17 inches long; exposure in borrow pit in Sussex plain, 200 feet northeast of State Road 609, 0.4 mile southwest of State Road 626, Surry County.

age by J. L. McLean, Jr. (personal communication). Hence, the formation is given a probable age assignment of Pliocene or early Pleistocene or both.

Other units in the Atlantic Coastal Plain in a similar stratigraphic position, which may be correlative in age, include the North Keys Sand described by Hack (1955) in Maryland, and the Duplin Formation described in central South Carolina by Johnson and DuBar (1964). Another possible equivalent of the Sedley formation is the fossiliferous, marine James City Formation of presumed Pliocene age, recognized along the Neuse River west of the Suffolk Sand Ridge in North Carolina by DuBar and Solliday (1963, p. 228, 232).

BACONS CASTLE FORMATION

The Bacons Castle Formation was named by Coch (1965, 1968) for clayey sand, silty sand, pebble gravel, and cobble gravel that unconformably overlie the Sedley and Yorktown formations, and are, in turn, unconformably overlain by the "Moorings unit" and Windsor Formation. The name, here formally used, is derived from the community of Bacons Castle, Surry County (Bacons Castle 7.5-minute quadrangle; Figure 2). Type sections of its two facies are described in Appendix I, sections C and D.

The Bacons Castle Formation has been traced on the surface and in the subsurface from Petersburg eastward to the Suffolk scarp and from the James River southward to the Virginia-North Carolina boundary. Beneath the Isle of Wight plain the formation is present only as isolated remnants. It is not present east of the Suffolk scarp.

The Bacons Castle Formation overlies the Sedley and Yorktown formations along a generally irregular, channeled contact which is commonly marked by a sharp increase in grain size upward. On a regional scale this contact slopes eastward and also toward major rivers. Beneath the Sussex plain the Bacons Castle is overlain by the clayey-silt (lagoonal?) facies of the "Moorings unit" and in the Surry scarp by the fine-sand (beach) facies of the "Moorings." Where the silt facies of the Bacons Castle Formation directly underlies the clayey-silt facies of the "Moorings," or directly overlies the Sedley formation, west of the Surry scarp, the units are difficult to separate. The top of the Bacons Castle is sharply truncated and overlain just east of the Surry scarp by the Windsor Formation (Plate 1). Beneath the Isle of Wight plain only small remnants of the Bacons Castle persist, chiefly along major rivers, and the unit is difficult to separate from

the unconformably overlying lower member of the Windsor, except by differences in sorting and in degree of weathering. At the Suffolk scarp, remnants of the Bacons Castle are sharply overlain locally by the coarse-sand (beach) facies of the Norfolk Formation.

Maximum thickness of the Bacons Castle is 28 feet; it thickens towards major streams. The sand facies has a maximum thickness of 20 feet, and consists of clayey sand, pebble gravel, and cobble gravel (Figure 16, B). Coarser fragments commonly are concentrated near the base. Sedimentary structures include channels (Figure 16, C), and trough-type cross laminae. The sand facies becomes coarser from east to west across the area and also near major rivers; it grades upward and laterally into the silt facies. The silt facies has a maximum thickness of 18 feet, and consists of sandy silt and silty sand with clay partings. Because the silt facies occurs at the top in most cases, it is rarely preserved east of the Surry scarp, where later erosion has removed much of the Bacons Castle. No macrofossils or microfossils were found in the formation, except for worn, redeposited Miocene foraminifers and a few enigmatic burrows(?).

Heavy minerals of the Bacons Castle Formation include opaques, zircon, staurolite, kyanite, sillimanite, epidote, tourmaline, rutile, garnet, and sphene in decreasing order of abundance (Coch, 1968; Table 3); this assemblage is characterized by the absence of unstable minerals such as pyroxenes and amphiboles. The clay-sized fraction consists of illite and feldspar in amounts up to 20 percent each, chlorite in amounts less than 5 percent, and 50 to 80 percent quartz (Table 4). Sillimanite and several other heavy minerals have jagged coxcomb terminations characteristic of intrastratal solution (Bradley, 1957); quartz grains are deeply etched (written communication, D. S. Krinsley).

The Bacons Castle Formation is oxidized yellowish orange, moderate red, and reddish brown by hematite to a maximum depth of 15 feet. The silt facies commonly is more thoroughly oxidized than the sand facies, probably because of the higher amounts and smaller sizes of opaque minerals in the silt facies.

A fluvial environment of deposition for the Bacons Castle sediments by aggrading streams is indicated by the complex intertonguing of facies, lack of fossils, oxidation, eastward-dipping cross laminae, westward coarsening, and thickening and coarsening near present major streams. Other origins are not consistent with all the features observed, especially the wide occurrences of both facies.

The sand facies probably represents fluvial-channel deposits, whereas the silt facies likely corresponds to floodplain deposits of aggrading

streams. Clay platelets in the silt facies could result from erosion of dessicated floodplain deposits nearby. Lateral channel shifting, possibly in braided channels, would account for complex interfingering of the two facies. During deposition sea level must have been below 20 feet, the lowest known remnant of the Bacons Castle Formation.

The age of the Bacons Castle Formation is uncertain. Its wide distribution suggests a protracted period of deposition following Sedley time. Evidence of a post-Miocene age of the Sedley formation indicates a probable Pliocene or Pleistocene age for the Bacons Castle. The iron oxide in the Bacons Castle and Sedley formations is hematite, rather than limonite that is characteristic of weathered zones in younger stratigraphic units. Deep oxidation, etching of mineral grains, weathering, and absence of unstable minerals indicate that considerable time elapsed before deposition of the Windsor Formation. On this basis, the Bacons Castle Formation is assigned a Pliocene and/or early Pleistocene age. The Bacons Castle Formation corresponds in fluvial origin and stratigraphic position with the Brandywine Formation in Maryland (Hack, 1955) and the Okefenokee Formation in South Carolina (Colquhoun, 1965).

PLEISTOCENE SERIES

"MOORINGS UNIT"

The "Moorings unit" is here used informally for a linear body of fine sand in the Surry scarp that overlies the Bacons Castle Formation and underlies the Windsor Formation (Appendix I, section E). The name is derived from the community of Moorings in Surry County (Runnymede, 7.5-minute quadrangle; Figure 2). The fine-sand facies of the "Moorings unit" at the Surry scarp interfingers westward with a thin clayey-silt facies beneath the Sussex plain (Coch, 1965). At first it was believed that these two facies were equivalent to the Windsor Formation (Elberon formation of Coch, 1965) east of the Surry scarp, but further work indicates that both "Moorings" facies probably are older than either member of the Windsor Formation.

Remnants of the "Moorings unit" have not been recognized east of the Surry scarp; additionally, the fine-sand facies at the scarp has been removed entirely in some places by later erosion. The clayey-silt facies exists as thin remnants that form the surface of small, undissected parts of the Sussex plain. These extend westward to the Prince George upland in the vicinity of Savedge (Figures 2 and 6). Both facies have been traced from near the James River southward to Dendron (Figure 2).

The "Moorings" fine-sand facies sharply overlies the silt facies of the Bacons Castle Formation at the Surry scarp along a smooth and flat surface near an elevation of 105 feet (Plate 1). At the scarp, facies of these two units are readily distinguished by differences in oxidation and in grain size. At the contact, unoxidized, white, fine sand of the basal part of the fine-sand facies sharply overlies the deeply weathered silt facies of the Bacons Castle Formation. The fine-sand facies in turn is overlain unconformably by the Windsor Formation along the east side of the Surry scarp.

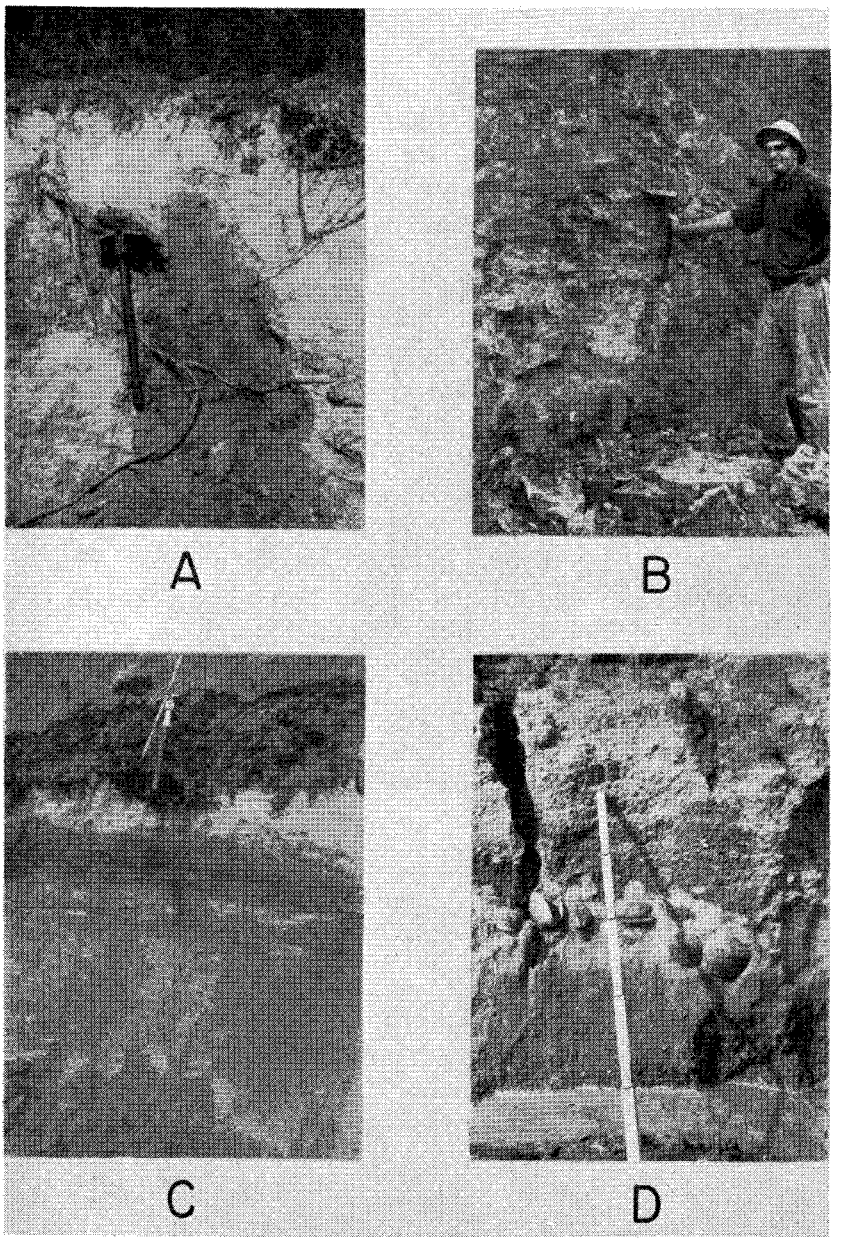
The fine-sand facies, ranging in thickness from 0 to 30 feet, consists of unfossiliferous, fine, slightly silty sand. In cores cross laminae outlined by concentrations of opaque minerals have dips as much as 22°. The facies has a maximum elevation of approximately 128 feet just south of Surry.

Heavy minerals include opaques, sillimanite, zircon, staurolite, rutile, tourmaline, kyanite, hornblende, orthopyroxene, sphene, and epidote, in decreasing order of abundance (Table 3). Heavy-mineral grains are somewhat less etched and pitted than those in the pre-"Moorings" units. Hornblende and pyroxene occur in amounts slightly greater than those of older units, and somewhat less than amounts in younger units. Quartz grains are less deeply etched than those in the Bacons Castle Formation, but considerably more etched than those in the coarse-sand facies of the Norfolk Formation (written communication, D. S. Krinsley).

The fine-sand facies is oxidized and enriched in clay to a maximum depth of 14 feet. Limonite causes a pale yellowish-brown color in the upper 4 feet, and hematitic mottling imparts a yellowish-brown to moderate-red color at greater depth. Clay enrichment in the oxidized zone probably results from decomposition of ferromagnesian and opaque minerals (Coch, 1965).

The clayey-silt facies, ranging from 5 to 20 feet in thickness, consists of silt with about equal amounts of clay and fine sand (Figure 17, A). Grain-size distribution in this facies is similar to that in the lagoonal facies of the Windsor, Great Bridge, Norfolk, Londonbridge, and Sand Bridge formations (Coch, 1965; Oaks, 1965). Patches of clayey sand are present locally. The facies is faintly mottled and lacks visible stratification. Erosion has separated the clayey-silt facies into numerous small remnants that are difficult to map in detail. The facies is oxidized to a maximum depth of 7 feet. Color in the zone of oxidation is dark-yellowish orange with irregular streaks of moderate red, caused by limonite with hematite mottles.

Barrier and lagoonal environments of deposition are inferred for the fine-sand and clayey-silt facies of the "Moorings unit," respectively, on the basis of distribution and interfingering of facies, ridge-like morphology of the fine-sand facies in the Surry scarp with depositional



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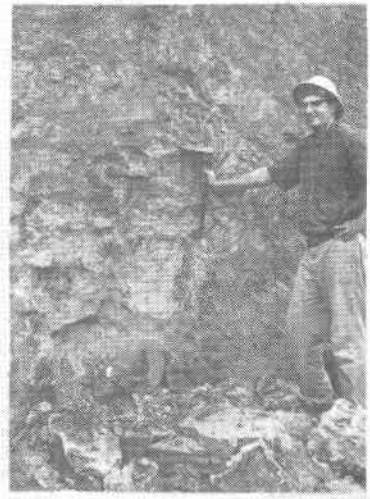
A



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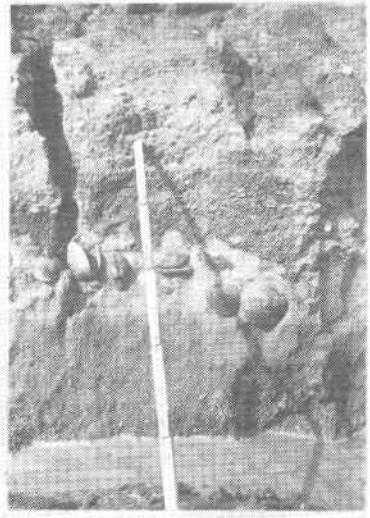

D

flats westward, and resemblance of grain sizes and structures of facies to younger deposits of known barrier and lagoonal origin. The thinness and irregular basal contact of the clayey-silt facies suggest deposition in low areas of the pre-existing topography on the underlying fluvial Bacons Castle Formation. Sedimentary structures in the fine-sand facies resemble those in modern coastal dunes, and quartz-grain surface features are believed characteristics of beach action superposed on a pattern characteristic of glacial action (written communication, D. S. Krinsley; Krinsley and Takahashi, 1962). Lenses of clayey sand in the clayey-silt facies could represent tidal-channel deposits. The maximum position of sea level during "Moorings" time, inferred from the highest undissected occurrences of the clayey-silt facies, was between an elevation of 120 and 125 feet, based on the assumption that the clayey-silt facies is equivalent to the fine-sand facies.

The age of the "Moorings unit" is uncertain, although probably Pleistocene. Deep oxidation, hematitic mottling, solution and etching of grains, and paucity of unstable minerals in the "Moorings unit" contrast with the shallow limonitic weathering and other characteristics of post-"Moorings" units, but are only slightly less intense than similar features in the Bacons Castle Formation. A considerable period of exposure following "Moorings" time also is suggested by: (1) removal of the unit and part of the underlying Bacons Castle Formation east of the Surry scarp; (2) more complete dissection of the Sussex plain compared to the Isle of Wight plain; and (3) indistinctness of the

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Figure 17. A. Clayey-silt facies of "Moorings unit" beneath Sussex plain; shovel handle 20 inches long; exposure just northwest of intersection of State Roads 609 and 610, Surry County.

B. Cohesive, clayey silty sand, upper member of Windsor Formation; exposure in west wall of borrow pit, 4 to 12 feet below surface of Isle of Wight plain, 0.1 mile west of State Roads 10 and 32, 2.5 miles north of U. S. Highway 460, Nansemond County.

C. Blocky silty-clay facies of upper member of Sand Bridge Formation, overlying beach and dune sand of Kempsville Formation (type locality) along irregular and slightly gradational contact shown just below shovel handle (20 inches long). Exposure in northwest corner of Womack borrow pit, along Hickory scarp, 0.1 mile southwest of State Road 603, 0.35 mile southwest of Bonneys (Mears) Corner, City of Virginia Beach.

D. Fine-sand facies of upper member of Norfolk Formation (type locality) sharply overlain by beach sand of Kempsville Formation along Hickory scarp. Broken shell fragments oriented along stratification in Kempsville Formation; articulated shells of *Mercenaria mercenaria* L. in living position in upper 6 inches of Norfolk Formation. Bioherm of serpulid worm tubes in lower right corner. Scale in inches. Southwest side of Womack borrow pit, City of Virginia Beach.

Surry scarp. Hence, an early, or perhaps middle, Pleistocene age of the "Moorings unit" appears most likely.

The "Moorings unit" is significant in that it is the highest and westernmost marine stratigraphic unit of probable Pleistocene age in the coastal plain of southeastern Virginia (Coch and Oaks, 1966). West of Savedge, where the clayey-silt facies of the "Moorings unit" thins to a feather edge, only fluvial sediments of the older Bacons Castle Formation crop out.

WINDSOR FORMATION

The Elberon formation was named by Coch (1965) for the community of Elberon, Surry County (Dendron, 7.5-minute quadrangle). He defined the formation as composed of three facies: a silty-clay facies (lagoonal) west of the Surry scarp, a fine-sand facies (barrier) along the Surry scarp, and a silty-sand facies (nearshore marine) east of the Surry scarp. Subsequently, detailed mapping by Coch (1968) and reconnaissance of the area farther west indicated the need for redefinition of the Elberon formation. Coch (1968) therefore gave the name Windsor Formation to the silty-sand facies of the proposed Elberon formation, and formally designated the type section of the Windsor at core boring W-1211 (Appendix I, section F; Figure 2) about 6.5 miles east-southeast of the town of Windsor (Chuckatuck 7.5-minute quadrangle). The remaining facies included in the original definition of the Elberon formation (Coch, 1965) are informally designated the "Moorings unit" in this report.

The Windsor Formation has been traced on the surface and in the subsurface from the Surry scarp eastward to the Suffolk scarp and from the James River southward to the Virginia-North Carolina boundary. It also has been mapped in the York-James Peninsula (Bick and Coch, 1969). The Windsor has not been identified west of the Surry scarp nor east of the Suffolk scarp. The formation nearly corresponds in distribution to the Wicomico "terrace-formation" of Clark and Miller (1906, 1912) and of Wentworth (1930). Moore (1956, 1957) included it as part of his Kilby Formation.

The Windsor Formation unconformably overlies the "Moorings unit" at the Surry scarp; it unconformably overlies erosional remnants of the Bacons Castle Formation and the Sedley and Yorktown formations beneath the Isle of Wight plain. The Windsor in turn is overlain unconformably by the coarse-sand (beach) facies of the Norfolk Formation or the silty-clay (lagoonal) facies of the upper member of the Sand Bridge Formation in the Suffolk scarp, and by the clayey-

sand (estuarine) facies and the silty-clay (lagoonal) facies of the Norfolk Formation along the Pagan River and in the Hazleton scarp, respectively.

The maximum thickness of the formation is about 35 feet; it is thickest near the Suffolk scarp and thins westward to less than 5 feet at the Surry scarp. The unit consists of a coarse-grained lower member that ranges in thickness from less than 5 to about 17 feet and a fine-grained upper member that ranges in thickness from less than 10 to about 25 feet. The contact between the two members is gradational (Appendix I, section F); near the Surry scarp they are indistinguishable.

The lower member consists of light-gray, medium to coarse, unfossiliferous sand and fine pebble gravel. In the lower portion of the member, the sand is well sorted and contains laminae of dark minerals; the pebbles near the base are well rounded. Silt content increases gradually upward, and near the top of the member, platelets and chunks of gray clay are common.

The upper member consists of unfossiliferous, thick-bedded clayey sand, silty sand, and silty clay similar to the silty-sand (estuary-mouth) facies of the Norfolk Formation. At elevations above 80 feet, the lithology is chiefly stiff, purplish-gray, silty clay with about 15 percent fine to medium sand; below 80 feet, it is chiefly gray, clayey, silty medium sand (Figure 17, B). Its base is slightly irregular, but slopes evenly eastward at 2 feet per mile from an elevation of 85 feet just east of the Surry scarp to 45 feet at the Suffolk scarp.

In areas near present streams, major grain-size changes occur within a few feet, both laterally and vertically, and the upper and lower members grade laterally into thick sections of gray clayey sand, well-sorted medium sand with rounded clay chunks, and beds of laminated silty clay and fine to medium sand.

Heavy minerals of the upper member of the Windsor Formation include opaques, zircon, sillimanite, staurolite, kyanite, rutile, sphene, hornblende, epidote, tourmaline, and a trace of orthopyroxene, in order of decreasing abundance (Coch, 1968). Heavy-mineral grains are considerably less etched and pitted than those in pre-Windsor stratigraphic units, but less altered than those in post-Windsor units. Hornblende, in amounts of 1 to 2 percent, is greater than in pre-Windsor units, but considerably less than in post-Windsor units. Undissected remnants of the upper member at elevations above 80 feet are oxidized to depths of only 2 feet. Where the upper member has been removed by erosion, the lower member is oxidized to dark-yellowish orange with streaks of dusky red by hematite to a maximum depth of 8 feet.

A nearshore-marine environment of deposition for the lower member of the Windsor Formation is proposed on the basis of its unoxidized original color, westward limit at the Surry scarp, and the probable Windsor beach ridges with crests near an elevation of 100 feet that separate from the Surry scarp near the James River and near Franklin (Figures 3 and 18). The good sorting, coarse grain size, good rounding, and opaque-mineral laminae also are consistent with a beach- or nearshore-marine origin for the lower member. Lithology of the upper member indicates quieter depositional conditions or a higher influx of fine-grained sediment, or both, during late Windsor time. A lagoonal

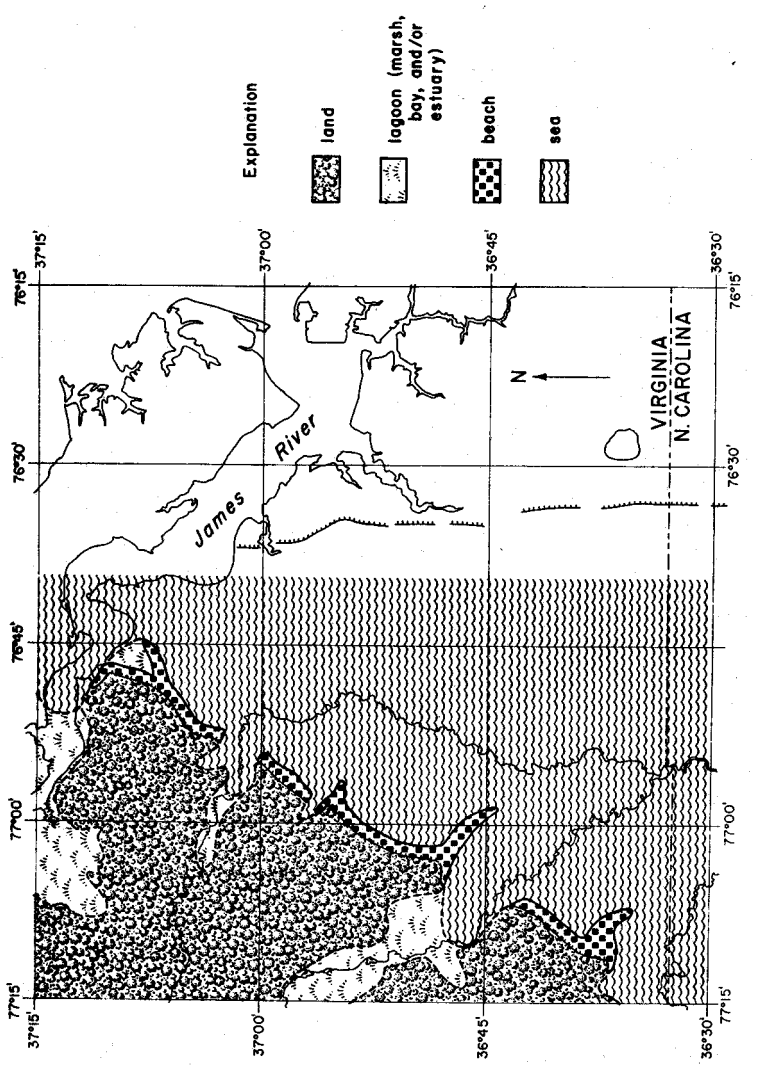


Figure 18. Paleogeography of southeastern Virginia in Windsor time; relative sea level near 95 feet; shoreline at Surry scarp.

environment of deposition is inferred from the flat depositional morphology of this member, its blanket-like distribution, fine grain size, unoxidized aspect, lack of sedimentary structures, and gradation laterally into probable tidal-channel facies that followed pre-existing drainage lows that developed initially between Yorktown time and Sedley time. The change to coarser grain sizes eastward could indicate proximity to the barrier in the east.

Such a hypothesis of origin for the upper member of the Windsor Formation requires the former existence of a barrier island east of the Suffolk scarp, where beach sand of the Norfolk Formation now overlies the truncated upper member of the Windsor Formation. No definite evidence of such a barrier was found during the present study. However, evidence indicates that a protracted period of subaerial erosion after Windsor time was followed by the Great Bridge-Norfolk-Kempsville submergence, during which strong headland retreat of the Suffolk scarp by wave erosion could have removed all evidence of a former Windsor barrier in southeastern Virginia.

A tentative age of middle Pleistocene is assigned to the Windsor Formation. Moderate oxidation, slightly hematitic mottling, moderately heavy etching and solution of grains, and small but finite amounts of soluble heavy minerals indicate that the Windsor Formation is distinctly younger than the "Moorings" and older units and distinctly older than sediments of the Great Bridge and younger units. Similarly, evidence of protracted exposure and subaerial erosion, both before and following Windsor time, is indicated, respectively, by extensive removal of older units beneath the Isle of Wight plain, and by truncation of the Windsor Formation at the Suffolk scarp and its absence east of that scarp. The degree of dissection also suggests an age intermediate between that of the "Moorings unit" and the post-Windsor units. The Isle of Wight plain is nearly as deeply, but not as thoroughly, dissected as the Sussex plain, whereas it is considerably more dissected than areas east of the Suffolk scarp.

The two members of the Windsor Formation, their location east of the Surry scarp, and their stratigraphic position above a fluvial deposit correspond closely with members of the Waccamaw Formation recognized in South Carolina by Johnson and DuBar (1964, Figure 1), Colquhoun (1962, 1965), and Colquhoun and Duncan (1964, 1966) east of a feature they and Flint (1940) correlated with the Surry scarp of Wentworth (1930).

GREAT BRIDGE FORMATION

The Great Bridge Formation, which occurs only in the subsurface, was named by Oaks and Coch (1963) and modified by Oaks (1965,

p. 104). It is formally used here for a clay and sand unit and an underlying sand and gravel unit that overlie the Yorktown Formation and underlie the Norfolk Formation east of the Suffolk scarp. The name is derived from the community of Great Bridge in the City of Chesapeake (Fentress 7.5-minute quadrangle; Figure 2). The formation consists of a coarse-grained lower member and an upper member with three facies.

The Great Bridge has been traced and mapped by means of samples from jet-rig borings from Norfolk southward to the Virginia-North Carolina boundary and from the ocean westward to the Deep Creek swale (Figure 19). Jet-rig boring W-1048, approximately 3 miles northeast of Great Bridge, is here established as the type

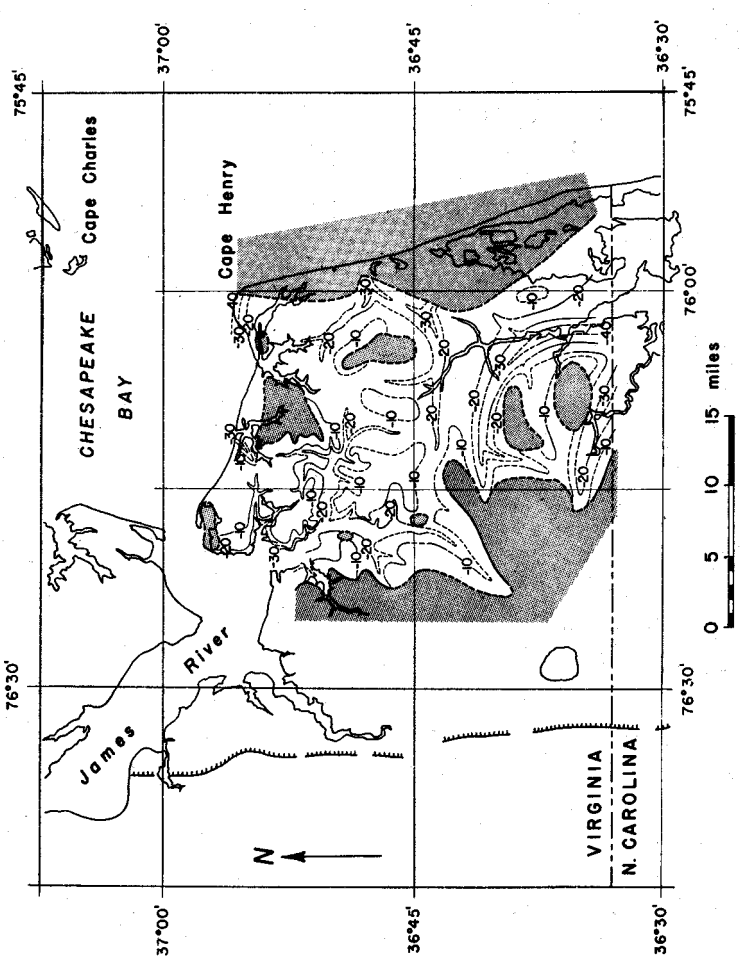


Figure 19. Topography of top of upper member of Great Bridge Formation; stipples show areas where unit is absent; contour interval 10 feet.

section of the lower member (Appendix I, section G); core boring W-778, 2.5 miles south of Kempsville, is designated as the type section of the upper member (Appendix I, section H).

The Great Bridge Formation unconformably overlies the Yorktown Formation along a subaerially eroded contact (Figure 13). It is conformably overlain, in turn, by the Norfolk Formation in most of the mapped area; however, the Londonbridge and Sand Bridge formations unconformably overlie the Great Bridge in several places beneath Oceana ridge and the Sand-ridge and Mud-flat complex (Figure 10). Elsewhere, along major stream systems, sediments of Holocene age unconformably overlie the formations.

In eight jet-rig borings east of the Fentress Rise, problematic sequences of sediments as much as 34 feet thick occur between the Yorktown and Great Bridge formations (designated "Ty?" in Plate 2). The sequences are similar in lithology but intermediate in compactness compared to the overlying and underlying units. Such sequences could be local facies of the Yorktown or Great Bridge, or could include remnants of the Sedley, "Moorings," or Windsor, or offshore equivalents of the Bacons Castle.

The lower member, ranging from 0 to 25 feet in thickness, consists of white to light-gray, fine to coarse sand with minor amounts of pebble gravel. Sand grains are angular to subrounded and are chiefly quartz; pebbles are mainly quartzite and a few other rock fragments. Wood and broken, partly rounded, bluish shell fragments are present. The member interfingers with brown peat containing abundant wood and burr-oak acorn caps; it probably includes the stump from near Churchland (Harrison, 1962) that had a radiocarbon age greater than 47,000 years B.P. (Y-1049). Closely spaced core borings for Interstate Highway 64, 3.5 miles north of Great Bridge, show that the lower member grades laterally and upward into the upper member (Plate 2, section AA-AA′). The lower member is limited to the axes of paleotopographic lows on the Yorktown surface. Its top is as high as –30 feet east of the Fentress rise and –12 feet near the Deep Creek swale.

The upper member consists of three facies: a linear sand facies beneath the Sand-ridge and Mud-flat complex that grades eastward into a silty-sand facies and westward into a clayey-silt facies. Its thickness ranges from 0 to 55 feet; its top is not known to reach higher than –4 feet. This member lies directly on the Yorktown Formation where the lower member is absent. The upper member is widely distributed where the top of the Yorktown lies below –10

to –15 feet (Figure 13), and it is thickest where the top of the Yorktown Formation is lowest (Plate 2).

The sand facies is less than 5 miles wide, and has a linear, curving, north-south trend (Figure 20). It consists of white to light-gray, fine to coarse quartz sand that is angular to rounded, and marine shell

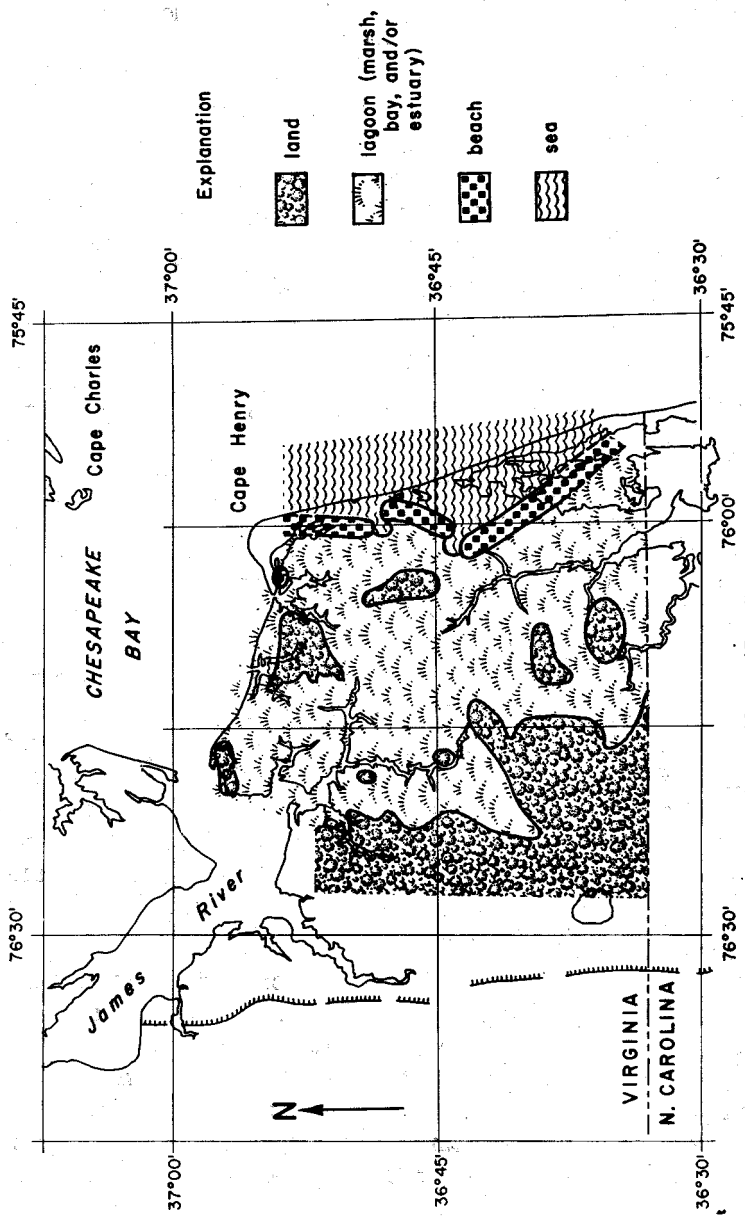


Figure 20. Paleogeography of southeastern Virginia in Great Bridge time; relative sea level near -5 feet; shoreline near present coast.

fragments that are broken and abraded. The silty-sand facies consists of gray to bluish-gray, fine to very fine, micaceous, silty, quartz sand with marine fossils and a few thin clay interbeds.

The clayey-silt facies consists predominantly of gray to bluish-gray, very soft, clayey silt and silty clay that is interlayered locally with fine to very fine silty sand in beds 0.5 to 2 feet thick. Rarely, silty to clean fine sand and fine to medium sand also are interlayered. Thin, very fine silty sand partings are visible in core samples. Where it is both high and thin over high-standing remnants of the Yorktown Formation, this facies commonly grades into peaty clay. The clay-sized fraction consists of montmorillonite, illite, chlorite, and feldspar in amounts up to 20 percent, and considerably more than 20 percent quartz. One sample contained less than 5 percent gypsum and amphibole; another had more than 20 percent vermiculite and no chlorite, (written communication, S. S. Greenberg).

Fossils of the clayey-silt facies include *Mulinia lateralis* Say, *Crepidula fornicata* L., *Olivella mutica* Say, and *Nassarius vibex* Say, all of which live in shallow water today and can tolerate some reduction in salinity below open-marine (DuBar and Chaplin, 1963, p. 141-142). Microfossils include tiny, vascular plant fragments; circular, granular, non-ornamented diatoms and also spoked diatoms; a few *Elphidium* sp. and *Buccella* sp.; a few black internal casts of foraminifers, and, rarely, ostracods.

The top of the Great Bridge Formation shows no evidence of subaerial exposure, such as oxidation, soil development, or erosion, prior to deposition of the overlying Norfolk Formation.

Deposition of most of the Great Bridge Formation within a freshwater-estuarine environment is indicated by the peat of the lower member and the clayey-silt facies of the upper member. Vascular plant fragments in the clayey-silt facies indicate a nearby fluvial influence, perhaps the ancestral James River; the lack of oxidation, general absence of calcareous microfossils, and presence of burrows suggest a slightly reducing depositional environment entirely below water. The linear, fossiliferous, coarse sand facies beneath the Sand-ridge and Mud-flat complex probably represents barrier sediments that grade eastward into offshore-marine sediments of the silty-sand facies (Figure 20). The maximum position of sea level during Great Bridge time, inferred from the highest occurrences of the clayey-silt facies, was between an elevation of –10 to –5 feet.

A tentative age of late Pleistocene is assigned to the Great Bridge Formation. It has a close time relation to the Norfolk Formation, shown by the lack of subaerial erosion and the absence of oxidation

at their contact. The absence of widespread remnants of the Windsor Formation east of the Suffolk scarp, the evidence of deep subaerial erosion of the Yorktown Formation prior to Great Bridge time, and the unconformable contact between the Norfolk and Windsor formations in the Suffolk scarp indicate that Great Bridge time was preceded by a protracted period of emergence and erosion and that the Great Bridge Formation is considerably younger than the Windsor Formation.

The absence of weathering in the top of the Great Bridge Formation prohibits an estimate of relative age based on comparison of degree of weathering of similar materials in other units. The softness and high moisture content of the clayey-silt facies, however, indicate that no long period of dehydration has occurred since deposition and that the Great Bridge Formation has not stood well above sea level for a significantly long time. This in turn suggests a rather recent origin, possibly during Sangamon or mid-Wisconsin time. An age younger than mid-Wisconsin is not supported by evidence from radiocarbon dates of appropriate materials from younger stratigraphic units. Uranium-series dating of six samples of corals from the overlying Norfolk and Kempsville formations, from two localities, gave ages of 62,000 to 86,000 years B. P. These dates also suggest a mid-Wisconsin or perhaps Sangamon age of these two younger units.

NORFOLK FORMATION

The Norfolk Formation, named for Norfolk County by Clark and Miller (1906), was assigned to the Pliocene by them on the basis of shells found in sands, clays, and sandy clays that were dredged from the Dismal Swamp Canal. Elsewhere, they considered the Norfolk to be buried beneath later Pleistocene sediments that obscured its areal extent and thickness. A type section was not designated by Clark and Miller; however Boring RO-9 in the Dismal Swamp was established by Oaks (1965, p. 113) as a reference section (Appendix I, section J); Coch (1968) also described three reference sections in detail. Because of the desirability of designating a fossiliferous exposure that is easily accessible, the type section of the Norfolk Formation is here designated for sediments that are exposed in the Kempsville 7.5-minute quadrangle at the Womack borrow pit, 2.5 miles south-southeast of Kempsville and 0.4 mile southeast of Bonneys (Mears) Corner (Appendix I, section I; Figure 2). Reference sections (Appendix I, sections J through N; Figure 2), are also established here in order to illustrate distinctive, widespread facies of the formation (Figure 21).

The Norfolk Formation unconformably overlies the Sedley and Windsor formations and remnants of the Bacons Castle Formation

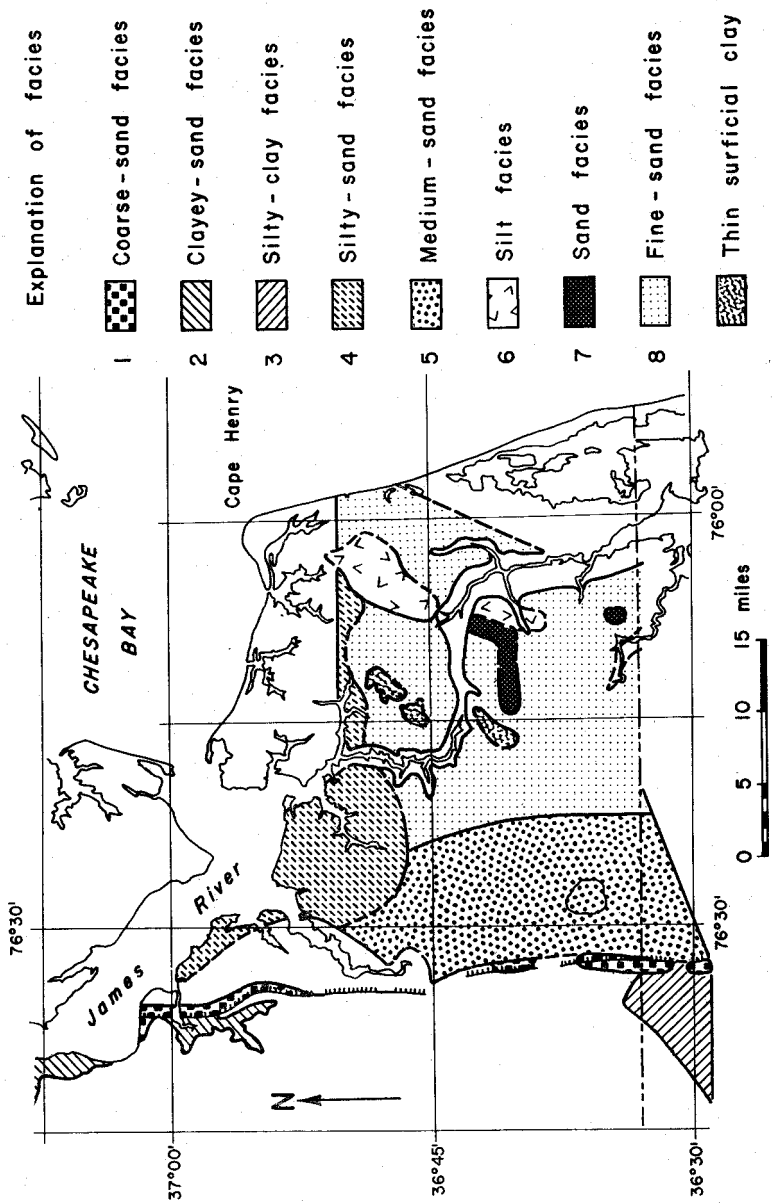


Figure 21. Distribution of major sediment facies of Norfolk Formation, southeastern Virginia.

along a subsurface scarp north of Chuckatuck Creek and south of Suffolk (Plates 1 and 2). The formation unconformably overlies the Yorktown Formation beneath the Churchland flat, the Dismal Swamp, the southern part of the Deep Creek swale, the northern segment of the Fentress rise, through a short distance north of Princess Anne,

and in the southern part of the Mount Pleasant flat (Figure 19). Elsewhere, it conformably overlies the Great Bridge Formation along a contact that is rather flat, but slightly irregular and low in the southeast.

The greatest known thickness of the Norfolk Formation is 45 to 50 feet beneath the Fentress rise, where the top of the Great Bridge Formation is low. More commonly its thickness beneath the Fentress rise is approximately 30 feet; the unit thins both westward and eastward where its top is lower. As in the case of the Yorktown Formation, the modern topography east of the Suffolk scarp is but a subdued reflection of the top of the Norfolk Formation (Figure 22).

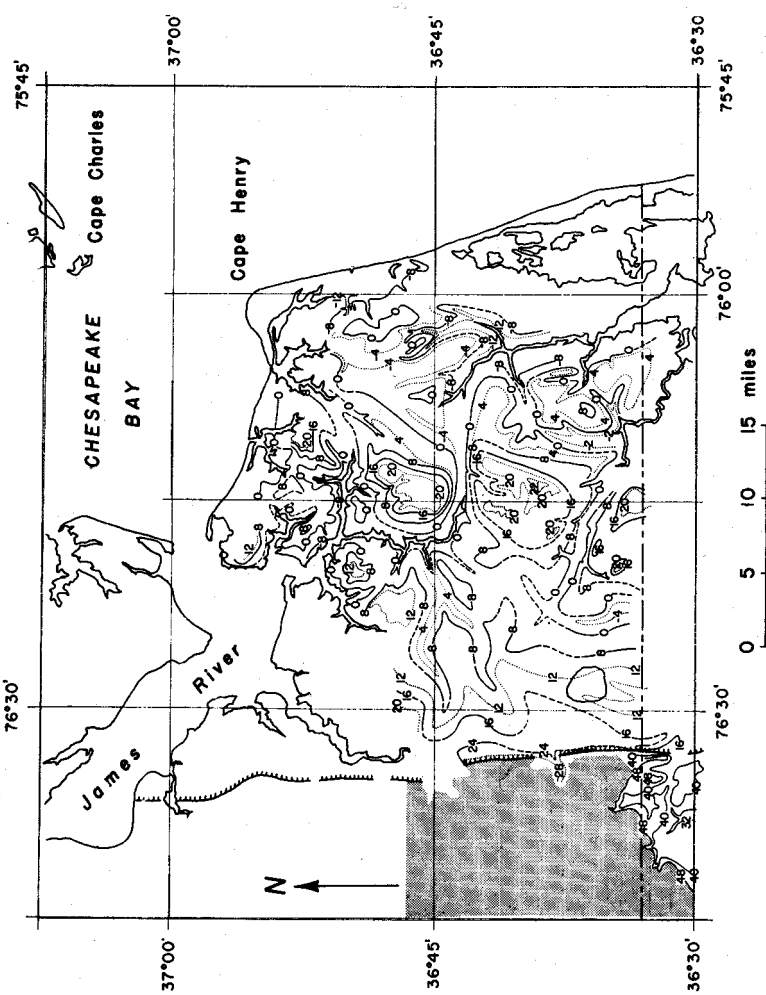


Figure 22. Topography of top of Norfolk Formation, stipples show areas where unit is absent; contour interval 8 feet; supplementary contours at intervals of 2 and 4 feet.

Norfolk sediments are unconformably overlain by the Kempsville Formation along the Hickory scarp; by the Londonbridge Formation in the Deep Creek swale, Dismal Swamp, Mount Pleasant flat, northern segments of the Fentress rise, and Oceana ridge; and by the Sand Bridge Formation in the Churchland flat, westernmost Dismal Swamp, and Sand-ridge and Mud-flat complex, where the Norfolk Formation probably remains only as scattered remnants. Sediments of Holocene age overlie the Norfolk Formation along major streams and in the Dismal Swamp where post-Norfolk units are absent and peat directly overlies the unit.

The Norfolk Formation is composed of a lower member and a variable upper member that is subdivided into eight mappable facies. The lower member consists of bluish-gray, subangular to subrounded, fine to very coarse quartz sand with a trace to 20 percent of fine pebble gravel. It ranges between 1 and 8 feet thick, is gradational with the upper member, and occurs through virtually the entire area where the Norfolk Formation is present east of the Suffolk scarp. As a result, this distinctive lower member forms a very useful stratigraphic marker horizon in the Outer Coastal Plain. Within 2 miles of the Suffolk scarp the coarse lower member becomes indistinguishable from the medium-sand facies of the upper member.

For the upper member a name based on an important or dominant lithology was assigned to each facies (Coch, 1968) to supplement the number system used previously (Oaks, 1965; Coch, 1965). The older number designation for each facies is given in parentheses before the new lithologic names, as follows: (1) coarse-sand facies in the Suffolk scarp (Benns Church sand of Oaks and Coch, 1963); (2) Clayey-sand facies west of the Suffolk scarp near Smithfield; (3) silty-clay facies beneath Hall Pocosin flat; (4) silty-sand facies beneath part of the Churchland flat; (5) medium-sand facies beneath the Dismal Swamp; (6) silt facies beneath a portion of the northern part of the Mount Pleasant flat; (7) sand facies beneath part of the southern segment of the Fentress rise and southern part of the Mount Pleasant flat; and (8) fine-sand facies beneath most of the area east of the Dismal Swamp (Figure 21).

The coarse-sand facies (1) of the upper member crops out at elevations between 25 and 70 feet in a belt less than one mile wide that trends north-south along the Suffolk scarp (Figure 21). It ranges in thickness from a thin veneer, almost completely removed by later erosion, to 50 feet or more in undissected portions of the Suffolk scarp. Coch (1968) described a cored vertical succession through this facies near Benns Church as a fine pebble-gravel 3 to 5 feet thick that grades

upward into medium to coarse sand and very fine pebble gravel 9 feet thick, which was overlain by well-sorted, fine to medium sand with brown bands rich in organic matter. Grains are angular to rounded. Below the weathering zone the color is white to light gray.

Heavy minerals of the coarse-sand facies include opaques, zircon, hornblende, sillimanite, staurolite, tourmaline, kyanite, sphene, epidote, orthopyroxene, garnet, and rutile in decreasing order of abundance (Coch, 1968). The average percentage of hornblende is several times that in the Windsor Formation (Table 3). The Norfolk Formation differs from both older and younger stratigraphic units in its rather high content of staurolite, rutile, and especially hornblende. Heavy-mineral grains are distinctly more etched and pitted than those in sands of the Londonbridge and Sand Bridge formations, and distinctly less etched and pitted than those of the Windsor and older units. No analyses were made of heavy minerals in Kempsville or Great Bridge sands. Quartz-grain surface features of the uppermost sand near Benns Church are characteristic of eolian activity but not in an arid environment; the surface features are moderately etched, considerably less than grains of the "Moorings unit," and distinctly more so than grains of the Kempsville Formation (written communication, D. S. Krinsley). The coarse-sand facies is oxidized yellowish orange and is enriched in clay to an average depth of about 5 feet.

The clayey-sand facies (2) crops out west of the Suffolk scarp as flat-topped remnants at elevations of 45 to 50 feet along the valleys of the James and Pagan rivers (Figure 22). In downstream portions, the facies consists of horizontally bedded silt, fine clayey sand, and clay with thin beds of well-sorted, fine sand. At one locality casts and molds of *Mercenaria mercenaria* L., *Rangia* sp., *Yoldia* sp., and *Mulinia lateralis* Say were found in this facies. This restricted assemblage is characteristic of brackish-water conditions (written communication, H. G. Richards). When traced up tributaries of the James River the facies coarsens, exhibits abrupt lithologic changes, and consists of cross-stratified medium to coarse sand, thin beds of pebble gravel, and clayey medium sand. The clay-sized fraction of the downstream portion of this facies consists of vermiculite, chlorite, illite, and feldspar in amounts between 5 and 20 percent each, and more than 20 percent quartz. The facies has been oxidized orangish yellow to a depth of 4 feet.

The silty-clay facies (3) crops out beneath the Hall Pocosin flat, west of the Suffolk sand ridge near the Virginia-North Carolina boundary (Figure 21). Yellow to white, fine sandy clay, 5 to 7 feet thick, overlies complexly interfingered silty clay, clayey silt, and fine to very fine

sand as much as 40 feet thick. The upper sediments are stiff, but the lower ones are very soft and bluish gray except locally where oxidation has occurred near the present surface. These sediments interfinger eastward with the coarse-sand facies in the Suffolk sand ridge. Where undissected, the upper sediments form a flat surface between elevations of 35 and 45 feet, although they may be 50 feet or slightly higher locally.

The silty-sand facies (4) occurs chiefly in the subsurface beneath the Churchland flat, north of a line that extends approximately southeast from Wilkerson Landing to Bowers Hill and then northeast to Kempsville (Figures 2 and 21). The facies consists of parallel-bedded, soft, bluish-gray, very clayey to very silty fine to very fine sand and clayey sandy silt. It ranges in thickness from 5 and 20 feet and averages approximately 10 feet. Also present are minor amounts of coarse sand, abundant mica, and locally abundant and diverse fossils, including corals. The fauna becomes more restricted toward the northwest and is marked in that direction by the appearance of articulated shells of *Barnea costata* L., a species indicative of brackish water (written communication, H. G. Richards). The clay-sized fraction (Table 4) contains more than 20 percent of both illite and quartz, between 5 and 20 percent chlorite and feldspar, and approximately 5 percent montmorillonite (written communication, S. S. Greenberg).

Locally the silty-sand facies closely resembles sediments of the clayey-silt facies of the Great Bridge Formation and the clayey-silt facies of the Londonbridge Formation. Coincidence of extent of this facies with that of the Great Bridge Formation occurs only northeast of Bowers Hill beneath Norfolk (Figures 19 and 21), and differentiation there was made possible by the intervening coarse lower member of the Norfolk Formation. Coincidence of extent with the Londonbridge Formation occurs beneath both Norfolk and the Churchland flat. Differentiation in the Norfolk area was not possible on the basis of logs of core borings by local drillers.

The medium-sand facies (5) consists of clayey, fine to coarse sand that occurs entirely in the subsurface beneath the Dismal Swamp and grades laterally into the coarse-sand facies near the Suffolk scarp (Figure 21). The facies contains as much as 5 percent angular to subangular black chert as much as 1 mm in diameter, with a trace of fine pebble gravel, but it consists chiefly of angular to subrounded quartz within a matrix of moderate bluish-green clay. Locally, the clay occurs as separate, rounded balls the size of small cobbles and large pebbles; the presence of fragmental Yorktown fossils suggests that the clay was derived by erosion from the Yorktown Formation, which directly underlies this facies beneath the western part of the Dismal Swamp.

The silt facies (6) occurs in the subsurface beneath the eastern part of the Mount Pleasant flat directly west of Oceana ridge (Figure 21). It consists of very compact, light-gray, very fine sandy silt with abundant mica. It is fossiliferous in only a few places, and the assemblages are dominated by *Ensis directus* Conrad. The microfauna is 80 to 90 percent *Elphidium* sp., with some *Buccella* sp. and *Ammonia* sp. Some small vascular plant fragments also are present.

The sand facies (7) occurs in the subsurface in a restricted area beneath the southern segment of the Fentress rise and part of the Mount Pleasant flat (Figure 21). It consists of grap to light-gray, fine to coarse sand. The grain size becomes coarser upward. Fossils of marine origin were encountered in one of five jet-rig borings that penetrated the facies. The greatest thickness of the Norfolk Formation occurs here, and the facies lies above an eastward-trending low in the top of the Great Bridge Formation.

The fine-sand facies (8) predominates over the remainder of the extent of the Norfolk Formation (Figure 21). It crops out only in the central and southern segments of the Fentress rise (Plate 2), at elevations between 17 and 20 feet, and grades laterally into each of the last four facies described. The fine-sand facies consists of light bluish-gray, fine sand to silty, fine to very fine sand, with 3 to 8 percent mica and 1 to 5 percent opaque minerals. Locally, clayey sand and sandy clay are abundant. The composition of this facies is highly variable laterally; very different sections commonly were encountered in borings spaced 500 feet apart. Flat, angular, silty clay plates and layers 0.5 to 2 inches thick, and 1 to more than 2 inches long are very common. Laminae are chiefly horizontal and outlined by opaque minerals, but locally dips of as much as 10 degrees are present. Small vascular plant fragments are common. Three major fossil associations are locally abundant: (1) predominantly *Ensis directus* Conrad and *Mercenaria mercenaria* L.; (2) these two fossils plus many other forms, including *Mulinia, Nassarius, Busycon,* and *Astrangia* spp.; and (3) a serpulid-bioherm fauna (Figure 17, D) consisting of serpulid worm tubes, encrusting bryozoa, *Menippe mercenaria* L., and other forms.

The eastward fining, the unoxidized blue or gray color, and the locally abundant marine fossils indicate deposition of the Norfolk Formation in a shallow-marine environment east of the Suffolk scarp (Figure 23). The thin, coarse, lower member probably was deposited in a beach zone that transgressed rapidly westward as a result of submergence and drowning of the Great Bridge barrier. The white to oxidized coarse-sand facies in the Suffolk scarp resembles modern

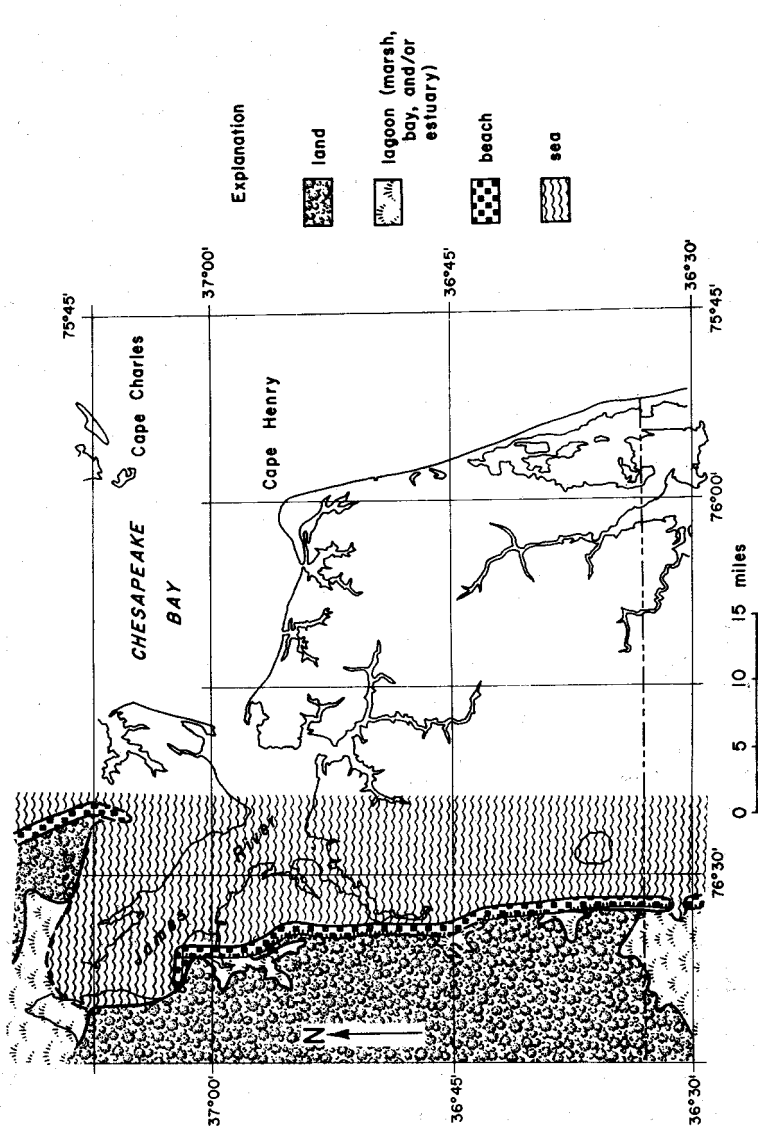


Figure 23. Paleogeography of southeastern Virginia in Norfolk time; relative sea level near 45 feet; shoreline at Suffolk scarp.

beach sand in its high quartz content, degree of rounding, and coarse grain size. Also, the facies lies against an erosional scarp whose linearity, lateral extent, height, and steepness all suggest a beach origin, and it passes laterally to the south into a sand ridge that slopes down to a mud flat westward. Non-arid eolian quartz-grain surface features in the upper part of the coarse-sand facies also suggest a beach origin (written communication, D. S. Krinsley).

The thickness of offshore facies of the Norfolk probably indicates a protracted period of high sea level during deposition. The silty-sand facies beneath the Churchland flat probably represents influx of both sediment and fresh water from the ancestral James River, as indicated by median grain sizes finer than those farther south and by the occurrence of *Barnea costata* Say close to the present mouth of the James River, compared with corals and other marine fossils from the same facies and other facies farther east and southeast. A similar decrease in salinity occurs as the mouth of Chesapeake Bay is approached from the south or southeast at the present time (Joseph, Massman, and Norcross, 1961).

The clayey-sand facies beneath flats at Gravel Neck and near Smithfield probably consists of fluvial and estuarine deposits. These are graded to a level between elevations of 45 and 50 feet. Sediments of the silty-clay facies beneath Hall Pocosin flat resemble open-bay lagoonal deposits in the lower part, and marsh to tidal-flat sediments in the upper part. The morphology of this latter facies also suggests deposition while relative sea level stood between 40 and 50 feet. Evidence of a similar level is recorded by the highest known occurrence of beach sediments in the Suffolk scarp near an elevation of 45 feet. The highest occurrences of marine Norfolk sediments near 20 feet beneath the Fentress rise, when compared with the present coastal offshore slope of 30 to 40 feet in the first 1 to 3 miles, also suggest a relative sea level higher than an elevation of 40 feet during Norfolk time.

The Norfolk Formation probably is of late Pleistocene age. Fossils are of Pleistocene age, and suggest warmer-water conditions than those that occur along the Virginia coast today (written communication, H. G. Richards). Comparison of chemical alteration of quartz-grain surface features suggests a probable age considerably younger than the "Moorings unit" and somewhat older than the Kempsville and Sand Bridge formations. A rather young age is suggested by the moderate degree of limonite oxidation, clay enrichment, soil development, and alteration of soluble heavy minerals. Overall, weathering characteristics of the Norfolk Formation are intermediate between those of the Windsor Formation and those of Kempsville and younger units (Table 5). A period of extensive erosion that followed Norfolk time could represent an entire glacial epoch, or conceivably, only a major fluctuation during a protracted interglacial epoch.

A driftwood sample from the overlying Kempsville Formation gave a radiocarbon age greater than 40,000 years B. P. (Y-1194). Uranium series ages of corals (*Astrangia* spp.) analyzed by D. E. Shier and

Kenneth Osmund at Florida State University gave a "suggested age" of approximately 70,000 years B. P., but the thorium content was anomalously high (written communication, D. E. Shier). J. N. Goddard and N. K. Coch subsequently dated several additional coral specimens from both the Norfolk and Kempsville formations by the same method; their results fell in the range of 62,000 to 86,000 years B. P. If the dates are indeed valid, they would suggest a mid-Wisconsin or perhaps Sangamon age of these two units.

The Norfolk Formation corresponds in origin, in late Pleistocene age, and in stratigraphic position with the Flanner Beach Formation described by DuBar and Solliday (1963) in North Carolina, and to barrier sediments of the Conway Bar (Wando Bar of Johnson and DuBar, 1964) in South Carolina.

KEMPSVILLE FORMATION

The Kempsville Formation was named by Oaks and Coch (1963) and is formally used here for a linear body of sand in the Hickory scarp that overlies the Norfolk Formation and underlies the Londonbridge and Sand Bridge formations. The name is derived from the community of Kempsville in the city of Chesapeake (Fentress 7.5-minute quadrangle; Figure 2). The type section is established at the Womack borrow pit, 2.5 miles southwest of Kempsville and approximately 0.4 mile southeast of Bonneys (Mears) Corner (Appendix I, section I; Figure 2).

The Kempsville Formation crops out between an elevation of 15 and 25 feet along the Hickory scarp and along east-west breaches in the Fentress rise (Plate 2). Locally the formation extends onto the Fentress rise for moderate distances. In the subsurface the unit extends 2 miles east of the Hickory scarp beneath the Mount Pleasant flat just south of Kempsville, but less than 100 yards east of the Hickory scarp just north of the Intracoastal Waterway. No sediments of definite Kempsville age are known from the southern Deep Creek swale or from areas farther west. Stratigraphic units and their relations in the northern Deep Creek swale are obscured by erosion immediately preceding the Holocene Epoch and by the activities of man.

The Kempsville Formation unconformably overlies the Norfolk Formation along an irregular contact (Figure 24), and in turn is overlain sharply by the Londonbridge and Sand Bridge formations along an irregular surface that is erosional in part (Figure 17, C). In the Hickory scarp the Kempsville is as much as 17 feet thick. At that scarp, along most of the southern segment of the Fentress rise, it is abruptly truncated (Figure 24). Opposite the center of the

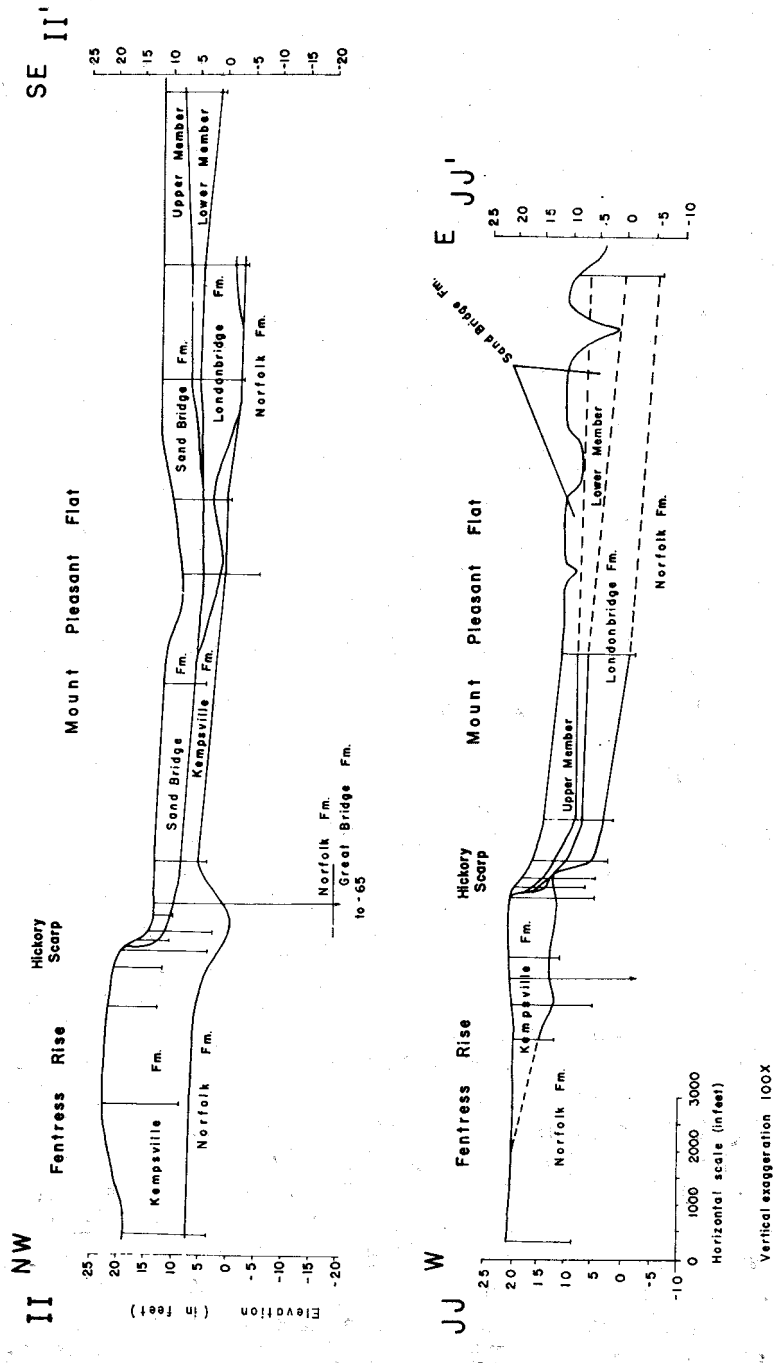


Figure 24. Detailed geologic sections through Hickory scarp; locations of sections shown in Plate 2.

central and southern segments of the Fentress rise the unit is as much as 10 feet thick for approximately 0.5 mile east of the Hickory scarp. In other places where the formation extends east of the scarp, it is only 1 to 4 feet thick.

The Kempsville generally consists of fine to coarse sand with minor amounts of fine pebble gravel. The sand is composed chiefly of angular to subrounded quartz with 1 to 3 percent opaque minerals and with rounded, broken, shell fragments. Locally, along the central and southern segments of the Fentress rise the Kempsville sand interfingers westward with silty, very fine sand, clay, and soft peaty clay. Such sediments may extend as a thin layer over areas of moderate size in the central and southern segments of the Fentress rise (mapped as surficial silty clay in Figure 21).

Fossils of the Kempsville Formation are chiefly *Mactra solidissima* Dilwyn, *Busycon* spp., and *Mercenaria mercenaria* L. The shells are disarticulated, parallel to stratification, and mostly oriented convex-up. *Ophiomorpha* burrows that are diagnostic of shallow water were found in Kempsville sediments of the type section by J. H. Hoyt (oral communication at the locality; see Weimer and Hoyt, 1964). Also, Paul Drez found remains of young seals and shorebirds in the Kempsville Formation at the type section, an indication that both were breeding there (Ray and others, 1968).

Quartz-grain surface features indicate littoral processes with a strong eolian impress. Such surface features are slightly more etched than those of modern beach sands; further, they are less etched than beach and dune sand of Norfolk age, but are altered to the same degree as sediments from both the lower and upper members of the Sand Bridge Formation (written communication, D. S. Krinsley).

The Kempsville Formation is oxidized yellow to reddish-brown to depths of 3 to 4 feet in the Hickory scarp and beneath the Fentress rise. Clay in the weathered upper part acts as a binder and makes the sand very hard when dry. Imprints of leached shells in the unit consist of oxidized thin clay partings with no remaining shell carbonate; the clay follows the shape of the original shell. In the subsurface east of the Hickory scarp, sediments are white to pale-bluish gray. At one point in the borrow pit at the type section, unoxidized, bluish-gray outlines of leached shells are abundant in the pale-blue sands. There leaching appears not to be associated with an oxidizing environment, nor was a clay-like residue formed. Overall, weathering characteristics of the Kempsville resemble those of the Londonbridge and Sand Bridge formations closely, and are slightly less intense than those of the Norfolk Formation (Table 5).

The stratigraphic pattern of the Kempsville Formation is that of oxidized, thicker, and higher sediments of beach, dune, and marsh origin at the Hickory scarp that grade eastward into unoxidized, thinner, and lower nearshore sediments. This stratigraphic pattern is associated with beach structures and shells of marine fossils along a linear, offset scarp with cape- and spit-like areas at east-west breaches in the Fentress rise.

Distribution of the Kempsville Formation suggests that discharge of most of the ancestral James River occurred through the breaches between the southern and central segments of the Fentress rise during Kempsville time, which would have isolated at least the central segment into an island similar to those of coastal Georgia today (Figure 25). Thus, the northern segment of the Fentress rise possibly was connected with the southern part of the Eastern Shore Peninsula during Kempsville time.

The highest known beach sand occurs in the northeastern part of the central segment of the Fentress rise at elevations of 20 to 22 feet; fine-grained dune sand nearby reaches 25 feet. The presence of thin, high-marsh sediments and thin dune sand overlying beach sand locally, suggests a short progradational period during emergence at the end of Kempsville time.

The Kempsville Formation probably is of late Pleistocene age. It contains fossils of Pleistocene age, which may be reworked from the Norfolk Formation in part. A radiocarbon age of greater than 40,000 years B.P. (Y-1194) was determined from a piece of driftwood in beach sand at the type section. The slight development of all weathering characteristics indicates a rather recent origin, and uranium-series dates from the underlying Norfolk Formation and this unit suggest that the Kempsville Formation is either Sangamon or mid-Wisconsin in age.

Erosion prior to Kempsville time created east-west breaches in the Fentress rise and eroded the Norfolk Formation at least as low as –1 foot at the type section. This period of erosion probably was short, because areas west of the Fentress rise and south of the present Elizabeth River were not extensively eroded. Possibly the Kempsville Formation represents only a short still-stand of the sea as it fell from the Norfolk level during renewed glaciation. If so, the breaches in the Fentress rise perhaps were cut by marine processes rather than subaerially.

In contrast, the emergence following Kempsville time was accompanied by removal of the Kempsville beneath much of the Mount

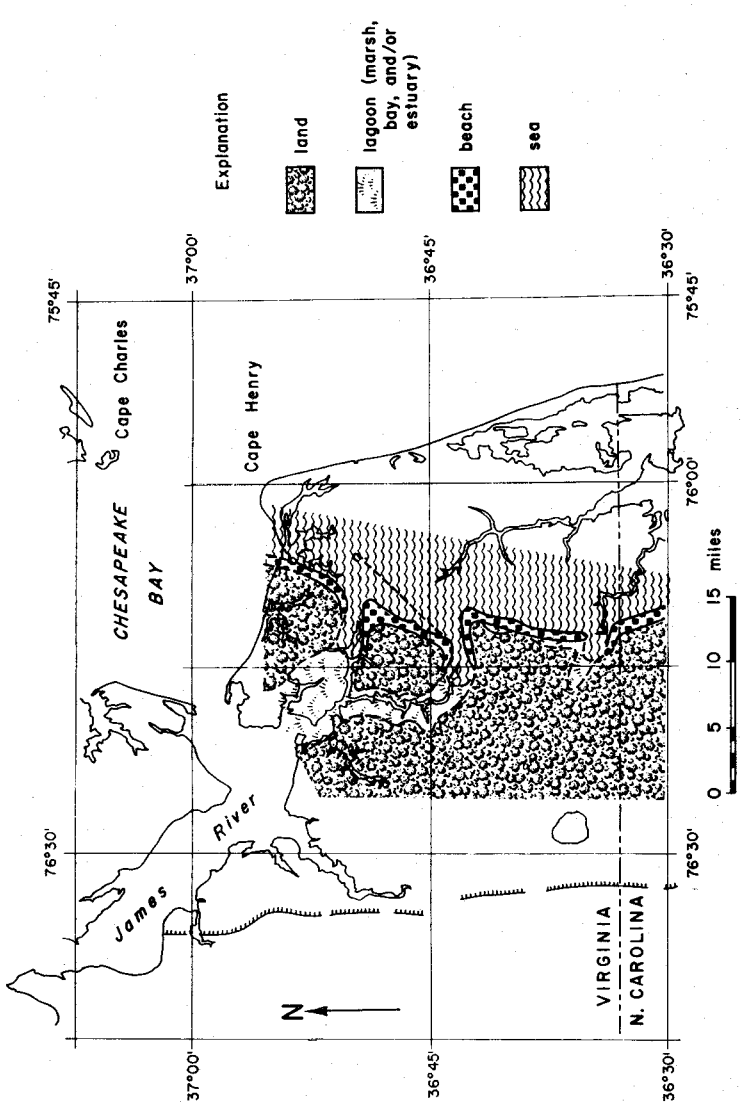


Figure 25. Paleogeography of southeastern Virginia in Kempsville time; relative sea level near 20 feet; shoreline at Hickory scarp; dashed line shows easternmost known extent of Kempsville Formation.

Pleasant flat, entrenchment there of streams below –11 feet, extensive erosion of the Norfolk Formation in the southern Deep Creek swale and Dismal Swamp, and establishment of James River drainage north of the northern segment of the Fentress rise, in about its present location.

The Kempsville Formation corresponds in origin, in late Pleistocene age, and in stratigraphic position with sediments of the Jaluco Delta described by Johnson and DuBar (1964) in South Carolina, and

possibly with sediments deposited between the Awendaw and Cainhoy scarps described by Colquhoun (1965).

LONDONBRIDGE FORMATION

The Londonbridge Formation, named by Oaks and Coch (1963), is here formally used for sand and gravel in Oceana ridge that interfingers westward with soft clayey silt in the subsurface. The name is derived from the community of Londonbridge in the City of Chesapeake (Princess Anne 7.5-minute quadrangle, Figure 2), 4 miles west of Virginia Beach on the west flank of Oceana ridge (Figure 5). Type sections of its two facies are described in Appendix I, sections O and P.

The Londonbridge Formation crops out in Oceana ridge between elevations of 17 and 30 feet, and from Broad Bay westward along the Diamond Springs scarp at least to the area of Diamond Springs. West of Oceana ridge it occurs only in the subsurface, between –5 and 15 feet beneath most of the Mount Pleasant flat, Deep Creek swale, and eastern part of the Dismal Swamp; it also occurs as small isolated remnants in breaches through the Fentress rise. The formation is absent where the Norfolk Formation is high in the Deep Creek swale near Northwest River, across the Fentress rise, beneath the western part of the Dismal Swamp, and at least locally beneath the Sand-ridge and Mud-flat complex (Figure 26).

The Londonbridge consists of a sand facies at Oceana ridge and along the Diamond Springs scarp and a clayey-silt facies farther west that interfingers with the sand facies in the west side of Oceana ridge. It unconformably overlies the Norfolk and Kempsville formations along an irregular and generally sharp contact. The clayey-silt facies is overlain by the lower member of the Sand Bridge Formation along an irregular contact that commonly is gradational through 0.3 foot or less. Elsewhere, especially along the east, south, and west sides of Oceana ridge, the Londonbridge is overlain by the silty-clay facies of the upper member of the Sand Bridge Formation (Figure 27, B). Along pre-Holocene channels in the Dismal Swamp the formation is overlain unconformably by freshwater peat.

Thickness of the sand facies at Oceana ridge ranges from 25 to 47 feet, but the formation thins within a short distance westward, where the clayey-silt facies forms a nearly continuous blanket between 3 and 13 feet thick wherever the top of the Norfolk Formation is low (Figures 22 and 26).

At the Oakwood borrow pit (Appendix I, section O) the sand facies is composed of white to light-yellow, angular to rounded, fine

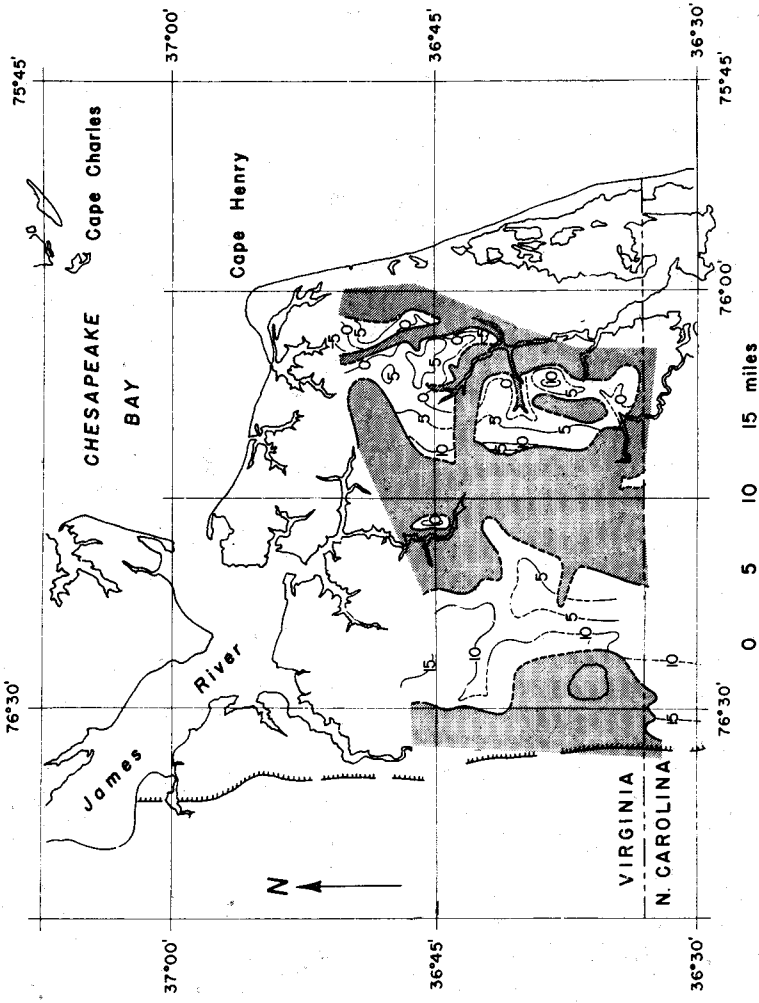
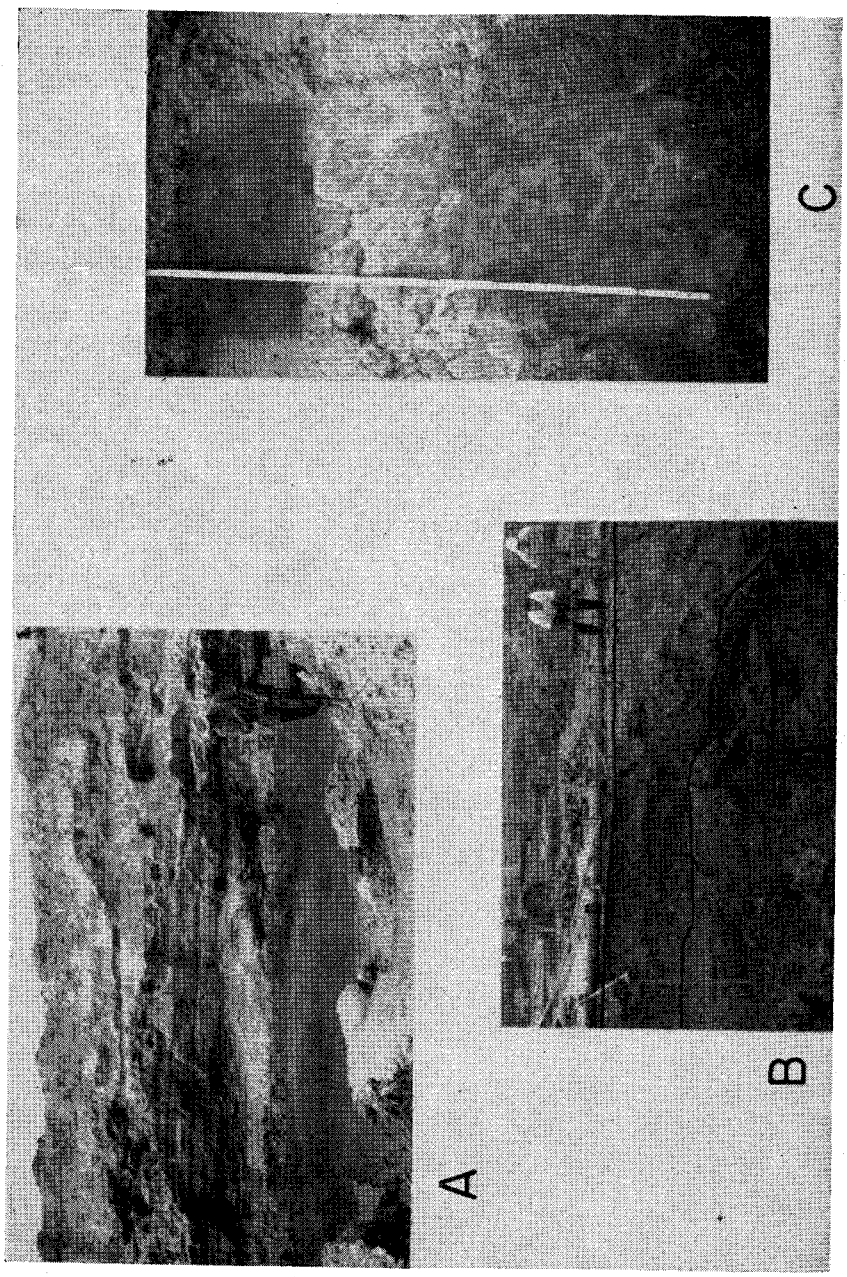


Figure 26. Topography of top of clayey-silt facies of Londonbridge Formation; stipples show areas where facies is absent; contour interval 5 feet.

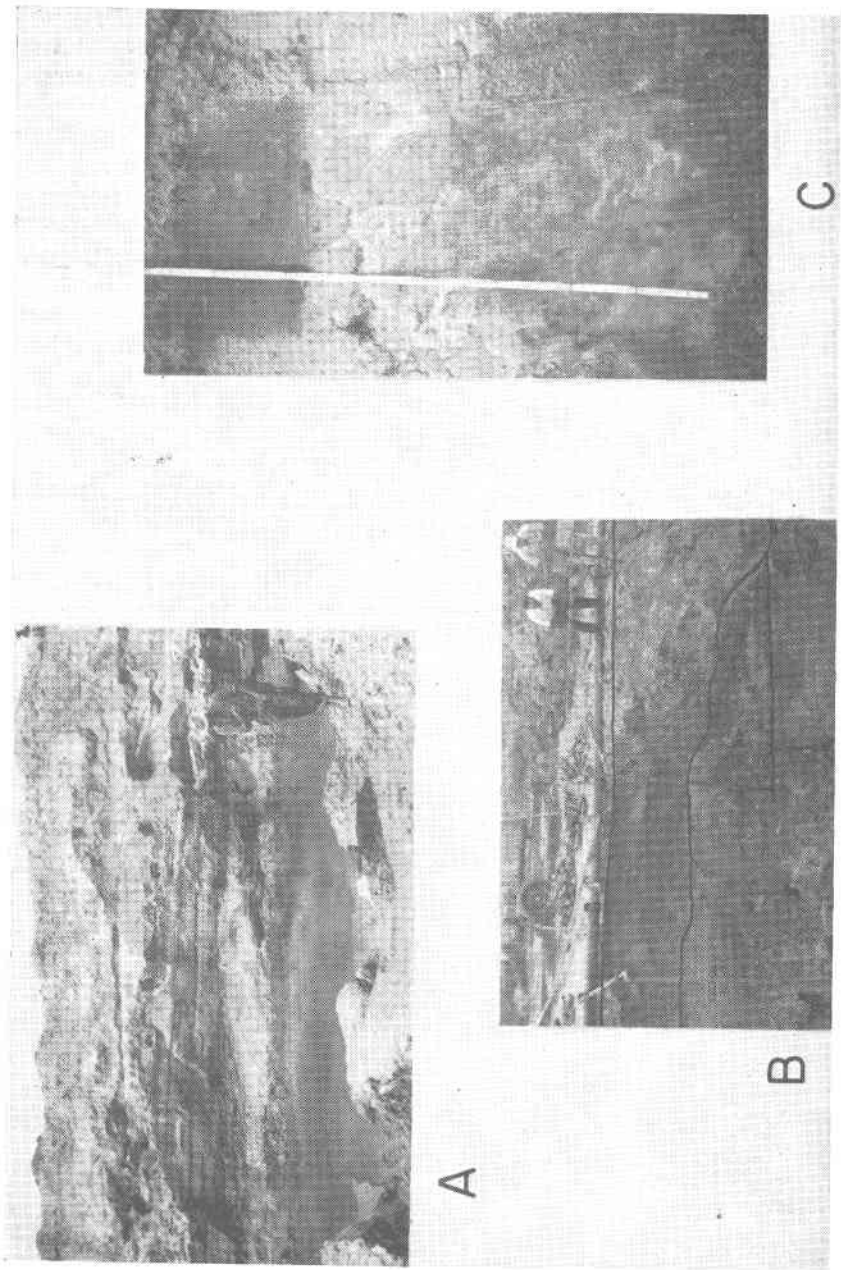
sand and fine to coarse sand with fine pebble gravel consisting of quartz and quartzite, a few rock fragments, and thin beds of soft, gray, clayey silt and clayey sand. Persistent bedding 0.5 to 5 feet thick is common and laterally continuous for 50 feet or more both parallel and perpendicular to the ridge trend. The beds both thin and have dips of 1 to 5 degrees eastward, so that the upper beds dip slightly more steeply than the nearly flat-lying lower ones (Figure 27, A).

The sand facies in Oceana ridge is oxidized from the surface to as deep as –17 feet; more commonly it is oxidized to depths between

0 and –10 feet, beneath which the color is light gray to light-bluish gray. Clay enrichment and deepest oxidation, however, occur in only the uppermost 3 to 6 feet. Imprints of leached shells were found in



0 and –10 feet, beneath which the color is light gray to light-bluish gray. Clay enrichment and deepest oxidation, however, occur in only the uppermost 3 to 6 feet. Imprints of leached shells were found in



the sand facies in each borrow pit in Oceana Ridge; they consist of oxidized thin clay partings with no remaining shell carbonate. Preliminary investigation shows that soluble heavy minerals are altered only slightly, and that some have slight traces of iron-oxide staining.

The clayey-silt facies (Appendix I, section P) consists of soft, gray to bluish-gray, very fine sandy and clayey silt with abundant mica and partings of fine-grained sand. Locally, the facies contains horizontal black laminae or is mottled and contains abundant worm tubes. Disarticulated shell fragments occur in the clayey silt at some localities. Many tiny vascular plant fragments and seed pods, a few *Elphidum* sp., black internal casts of foraminifers, and diatoms are present in microfossil floats. An extensive north-south trending reef of the oyster *Crassostrea virginica* Gmelin, was found in silt near the extreme western limit of the Londonbridge Formation in the eastern part of the Dismal Swamp (Figure 28). The clay-sized fraction (Table 4) contains illite, chlorite, and feldspar in amounts between 5 and 25 percent each, montmorillonite and amphibole in amounts between a trace and 10 percent each, a trace of gypsum, and 50 to 60 percent quartz (written communications, S. S. Greenberg and J. L. McAtee).

The clayey-silt facies is generally unoxidized; however, it is brightly oxidized reddish brown to a depth of 0.5 foot in two localities, and has a thin, peaty, weathered zone in the top at a third locality (oral communication at the locality, by E. E. Gamble).

Figure 27. A. Distinctive berm and foreshore stratification in sand facies of Londonbridge Formation (type locality). View northward. Upper beds both thin and dip eastward; beds near base of exposure are contorted and dip westward. Figure 5.8 feet tall. Exposure in Oceana Ridge at south end of Oakwood borrow pit, 0.1 mile east of State Road 615, 0.6 mile south of Norfolk and Southern Railroad tracks, City of Virginia Beach.

B. Silty-clay facies of upper member of Sand Bridge Formation sharply overlying both truncated, thinly bedded sand of lower member of Sand Bridge Formation (left) and clayey-silt facies of Londonbridge Formation (right). Lines added to show ground surface and stratigraphic contacts. Major creek 200 feet to right (west). Approximately 11 feet exposed. Excavation for storm sewer in new subdivision, Mt. Pleasant Flat, 0.35 mile west of State Road 644, approximately 2 miles south of U. S. Highway 58, City of Virginia Beach.

C. Soil profile developed in sand facies of upper member of Sand Bridge Formation, Sand-ridge and Mud-flat complex. Dark area, 11 inches thick, consists of slightly sandy silty clay; light area, approximately 13 inches thick, consists of clayey fine sand; distinctive mottling characterizes underlying sand; no clay occurs below 37 inches. View to north. Exposure in new ditch 100 feet east of State Road 694, 0.7 mile east of Dam Neck corner at State Road 615, City of Virginia Beach.

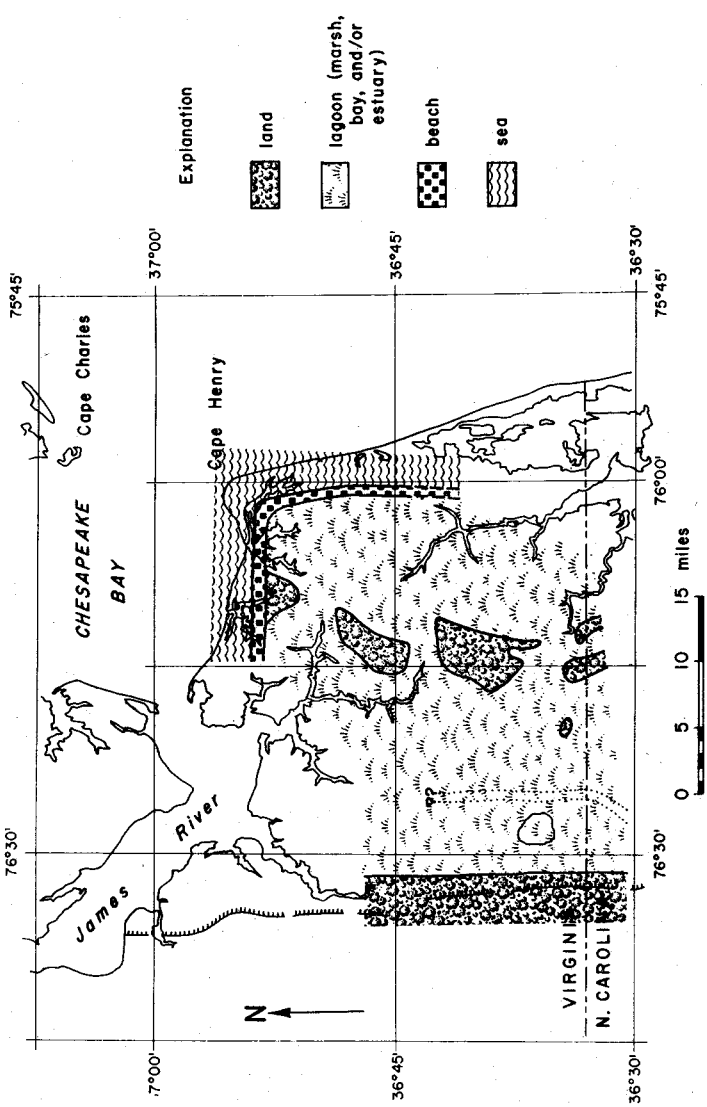


Figure 28. Paleogeography of southeastern Virginia in Londonbridge time; relative sea level near 24 feet; shoreline at Oceana ridge and Diamond Springs scarp. During maximum submergence in latest Londonbridge time, islands in lagoon were shoal areas submerged 5 feet or less, and intracoastal shoreline was probably at Suffolk scarp. Dotted lines show known extent of oyster reef of Londonbridge age.

The sand facies of the Londonbridge probably formed a barrier at Oceana Ridge and a progradational mainland beach along the Diamond Springs scarp, shown by leached shells, laterally continuous seaward-dipping beds, oxidation, coarse grain size, and morphology. An open-bay lagoonal environment is indicated for the interfingered clayey-silt facies, based on the sparse number of fossils, abundance of wood fragments and worm tubes, unoxidized color, softness, fine grain

size, and depositional pattern in topographic lows west of Oceana Ridge. A maximum position of sea level between 22 and 26 feet is inferred from the highest occurrences of beach sand and of lagoonal deposits of the Londonbridge Formation.

The slight degree of weathering of the exposed sand facies, and the Sangamon or mid-Wisconsin age inferred for the older Norfolk and Kempsville formations both suggest a very late Pleistocene age for the Londonbridge Formation.

The formation probably corresponds in origin and stratigraphic position with sediments of the Myrtle Beach Bar and Pine Island Lagoon in South Carolina (Johnson and DuBar, 1964).

SAND BRIDGE FORMATION

The Sand Bridge Formation was named by Oaks and Coch (1963) for a persistent unit that forms the surface of much of the area east of the Suffolk scarp. It is here formally used for a homogeneous lower member of sand and an upper member composed of several different mappable facies that have a complex pattern in the Churchland flat and in the Sand-ridge and Mud-flat complex; elsewhere the upper member is generally uniform. The name is derived from the community of Sand Bridge in the City of Chesapeake (North Bay 7.5-minute quadrangle; Figure 2).

Moore (1956, 1957) informally named the surficial sand, silt, and clay east of the Suffolk scarp as the Nansemond formation. He inferred that the sediments were of lagoonal origin, deposited landward of a barrier at Pungo ridge. Moore referred to an exposure at Newmans Point, on the Nansemond River, but he did not designate a type section nor did he recognize older post-Yorktown units east of the Suffolk scarp. Oaks and Coch (1963) originally believed that Nansemond sediments at Newmans Point formed an offshore facies of the Benns Church sand in the Suffolk scarp, and that both facies were older than the Norfolk Formation and therefore older than the Sand Bridge Formation. Further stratigraphic study showed that Nansemond sediments at Newmans Point actually overlie the Norfolk Formation elsewhere, and grade laterally into other facies of the upper member of the Sand Bridge Formation of Oaks and Coch.

Property owners have prohibited further geological investigations of Newmans Point because of cliff erosion. Therefore, type sections of both the lower and upper members of the Sand Bridge Formation are established at an exposure and boring at Powells Corner in the

Mount Pleasant flat (Appendix I, section Q). A borrow pit subsequently has been opened near the site. Oaks (1965, p. 150) restricted the name Nansemond to the clayey-sand facies of the upper member of the Sand Bridge Formation. For clarity Coch (1968) used the lithologic designation of clayey-sand facies, and that usage is followed here. Reference sections of typical but distinct facies were established at Huntersville, at Wilkerson Landing, and near Creeds by Coch (1965) and Oaks (1965), and are given in Appendix I, sections S, T, and U (Figure 2).

The lower member of the Sand Bridge Formation forms a thin blanket 2 to 8 feet thick beneath lower areas east of the Suffolk scarp (Figure 29). It pinches out near the Suffolk scarp, Fentress rise, and

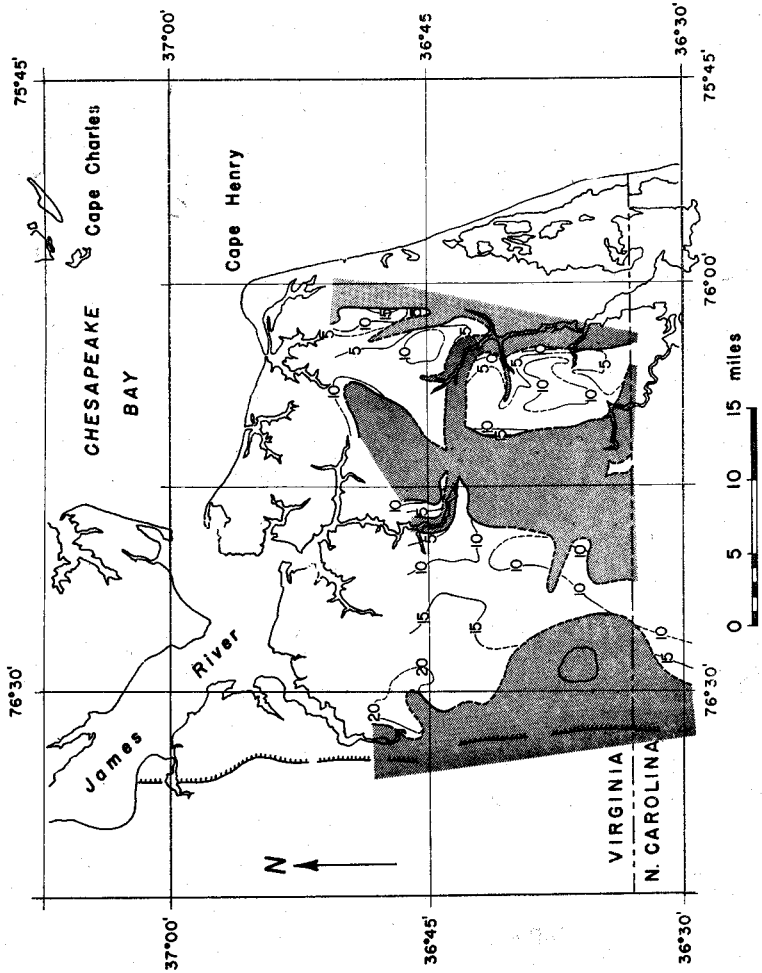


Figure 29. Topography of top of lower member of Sand Bridge Formation; stipples show areas where unit is absent; contour interval 5 feet.

Oceana ridge. It generally overlies and grades downward into the clayey-silt facies of the Londonbridge Formation through a zone commonly less than 0.3 foot thick. In the western Dismal Swamp and western part of the Fentress rise the lower member overlaps Londonbridge sediments to lie unconformably on the Norfolk Formation. In a restricted area near Kempsville and locally along the Hickory scarp, it unconformably overlies the Kempsville Formation. The lower member underlies the upper member along a contact that locally is sharp and shows evidence of channeling (Figure 27, B), but that is generally gradational through a zone 0.5 to 1 foot thick.

The upper member is also sheet-like west of the Sand-ridge and Mud-flat complex, and its average thickness of 2 to 6 feet is completely exposed in many ditches. It is thinnest and, locally, sandy over higher areas, especially Land-of-Promise ridge and Princess Anne rise (Figure 5). The upper member overlaps the lower member so as to overlie the Londonbridge sand facies at Oceana ridge, the Londonbridge clayey-silt facies in the western part of the Mount Pleasant flat and southern part of the Dismal Swamp, the Kempsville Formation in the Hickory scarp, the Norfolk Formation along the western part of the Fentress rise and western part of the Dismal Swamp, and the Yorktown Formation in the extreme northwestern part of the Dismal Swamp and northwestern part of the Churchland flat. The upper member is 10 to 30 feet thick in the Sand-ridge and Mud-flat complex, where it overlies the Great Bridge Formation and remnants of the Norfolk Formation in the south.

The lower member consists of well-sorted, angular to subrounded, fine to medium quartz sand, which is commonly clean but locally clayey or silty. Mica and 1 to 5 percent opaque minerals are present in unoxidized parts of the lower member. At a few exposures low-angle to horizontal stratification 0.2 to 0.5 foot thick occurs, outlined by opaque minerals and laterally continuous for 10 feet or more (Figure 27-B). Two specimens of *Elphidium* were found in six samples; vascular plant fragments and seed pods were somewhat more common. Abundant *Mactra solidissima* Dillwyn and *Anomia simplex* Orbigny and a few *Polynices (Lunatia) heros* (Say) and *Neptunea stonei* (Pilsbry), representing a sublittoral marine assemblage, were found in a borrow pit near the type section by Paul Drez (written communication). The borrow pit is the only extensive exposure of the entire lower member other than a few deep drainage ditches in the Churchland flat; no natural outcrops with steep sides were present in the area studied.

Heavy minerals in the lower member are fresh and unaltered, and contain hornblende in the same high amounts of 10 to 16 percent as the upper member (Coch, 1968). The clay-sized fraction of the lower member (Table 4) consists of more than 20 percent illite, 5 to 20 percent chlorite, 5 to more than 20 percent feldspar, 5 percent montmorillonite, and considerably more than 20 percent quartz (written communication, S. S. Greenberg).

The lower member commonly is slightly oxidized to light yellow, yellowish brown, light olive gray and rarely very dark red. Below a depth of 3 to 4 feet, white to very light gray predominates. Locally, light bluish gray or light brown is present near the base of the unit. Quartz-grain surface features suggest both littoral and eolian transport; such features are etched only slightly more than those of sand from the modern beach and about the same as those of sand from the Kempsville Formation and from the upper member of the Sand Bridge Formation, but less than those of sand from the Norfolk Formation (written communication, D. S. Krinsley).

The upper member consists of four major facies: (1) a clayey-sand facies in the northwestern part of the Churchland flat and along the Western Branch of the Elizabeth River (Nansemond lithofacies); (2) a silty-sand facies beneath the eastern part of the Churchland flat; (3) a silty-clay facies beneath the Dismal Swamp, extreme western part of the Churchland flat, Deep Creek swale, and Mount Pleasant flat; and (4) a linear, repeated series of fine sand in ridges and silty clay beneath flats in the Sand-ridge and Mud-flat complex. Local deposits of fine to coarse sand occur just east of Suffolk and along the south side of the Intracoastal Waterway (Figure 30).

The clayey-sand facies grades laterally into the silty-sand facies in the northeastern and northern parts of the mapped area and into the silty-clay facies in the western and southeastern parts (Figure 30). Composition of the clayey-sand facies ranges from clayey sand, silt, and clay, to well-sorted, fine to medium sand. The facies follows present creeks and estuaries, and upstream becomes coarser and more variable laterally. The base of the clayey-sand facies slopes toward present streams, so that the minimum total thickness of this facies, exposed above sea level, is 25 to 30 feet near present streams. Low-angle, planar cross laminae occur in sandier parts of the facies, together with plates and angular chunks of clay. Thickness of beds is highly variable, and ranges from 0.2 to 8.0 feet. No fossils and only one imprint of a leached shell were found.

Heavy minerals of the clayey-sand facies are typical of the Sand Bridge Formation, and consist of opaques, zircon, hornblende, silli-

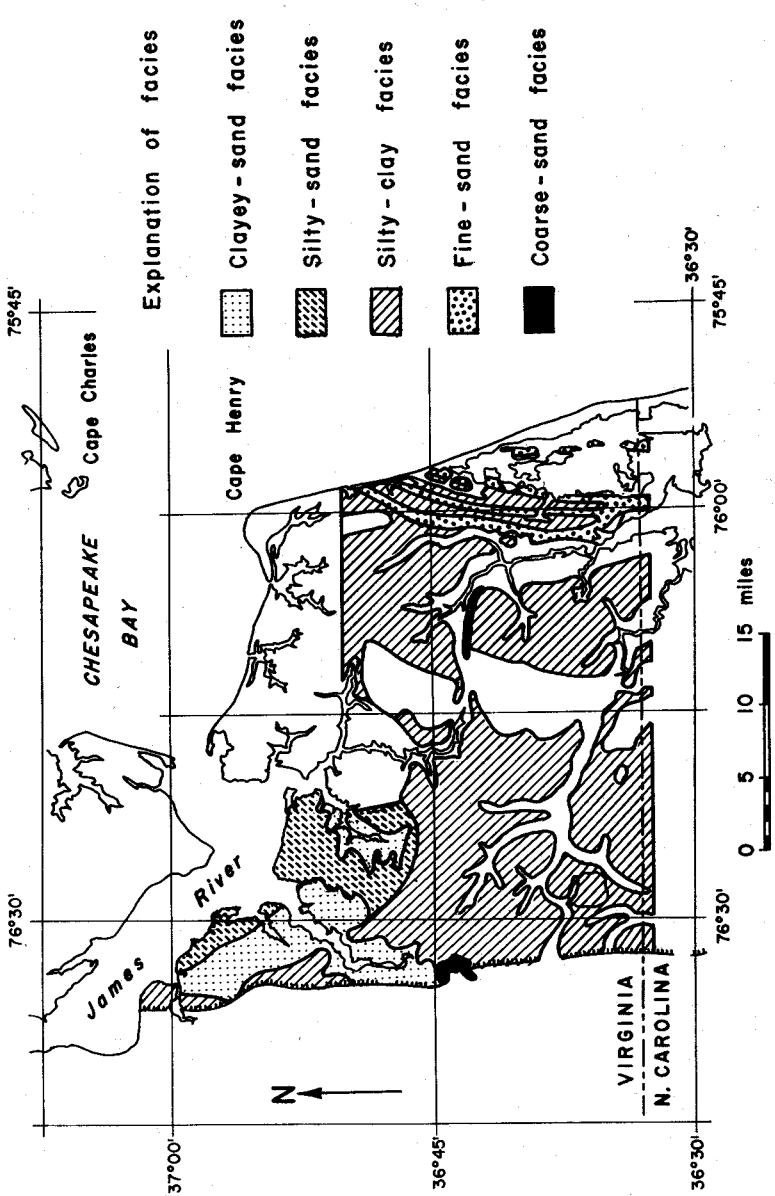


Figure 30. Distribution of major sediment facies of upper member of Sand Bridge Formation, southeastern Virginia.

manite, kyanite, staurolite, sphene, tourmaline, monazite, orthopyroxene, epidote, and traces of rutile, garnet, and biotite, in decreasing order of abundance (Table 3). The large amount of hornblende is twice that in the Norfolk Formation and approximately 15 times or more

than that in any of the pre-Norfolk stratigraphic units (Coch, 1965, 1968).

The clayey-sand facies is oxidized yellowish orange to depths of 3 to 8 feet, below which yellowish green, light gray, or bluish white predominate. Quartz-grain surface features are only slightly more etched than those of modern beach sands, and are etched to the same degree as those from the lower member and from the Kempsville Formation (written communication, D. S. Krinsley).

The silty-sand facies (Figure 30) consists of fine to medium sand with 20 to 30 percent silt. It lacks obvious stratification, sedimentary structures, and fossils. This facies is 5 to 8 feet thick, and its top lies entirely above 18 feet. The clay-sized fraction (Table 4) includes more than 20 percent vermiculite, 5 to 20 percent illite, 5 to 10 percent feldspar, and considerably more than 20 percent quartz (personal communication, S. S. Greenberg). The silty-sand facies is somewhat less deeply oxidized than the clayey-sand facies, and oxidation extends only 2 to 3 feet below the surface.

The silty-clay facies (Figure 30) consists of approximately equal amounts of clay and silt with 10 to 15 percent fine to medium sand, especially near its base. Isolated pebbles and small cobbles occur in the clay and silt near the Suffolk scarp, and isolated pebbles are present locally as far east as Bonneys (Mears) Corner (Figures 2 and 17, C). No microfossils were found in the silty-clay facies, but small vascular plant fragments are common, and decayed vegetation also is locally present (oral communication, E. S. Gaffney). The silty-clay facies in many places has a blocky, massive texture without stratification, and is cohesive (Figures 17, C and 27, B); locally, however, rather continuous but irregular wavy beds 0.1 to 0.3 foot thick are present. Unoxidized color varies from dark gray to very light gray. Yellowish-brown limonitic mottling is common in many places. The clay-sized fraction (Table 4) consists of vermiculite, chlorite, illite, and feldspar in amounts of less than 5 to 20 percent each, 5 to 30 percent montmorillonite, and 60 to 80 percent quartz (written communications, J. L. McAtee and S. S. Greenberg).

In the Sand-ridge and Mud-flat complex, ridges are underlain by linear bodies of white to light gray, fine to very fine quartz sand with a trace of silt, and 3 to 6 percent mica, which overlies compact, light-yellow to yellowish-brown, fine to coarse quartz sand with 1 to 5 percent fine pebble gravel. Oxidized imprints of pelecypod shells are common in the lower sand body; the upper sand has a characteristic dry, fluffy feel similar to that of modern dune sand (Oaks, 1965, p. 50), and it interfingers with the silty-clay facies in the western part of Pungo

ridge. Stratification in cores is low-angle, 0.5 to 2 inches thick, and marked by concentrations of opaque minerals in both sand bodies. Light yellow and yellowish-brown oxidation and clay enrichment (Figure 27-C) extend to depths of 3 to 6 feet in the upper sand body (Table 5).

In the Sand-ridge and Mud-flat complex, flats between ridges are underlain by a thin layer of silty clay and clayey silt 2 to 6 feet thick, which is identical in color and in nearly all of its other properties to the silty-clay facies west of Pungo ridge. This surficial unit is underlain by at least five additional sediment subtypes that exhibit lateral interfingering and vertical gradation within short distances: (1) soft, bluish-gray clayey silt with abundant vascular plant fragments and a hydrogen sulfide odor; (2) brown, organic, clayey, fine to medium sand with a sticky, granular, mealy feel; (3) white to yellowish-brown, fine to medium sand up to 10 feet thick, with rounded wood fragments and thin clay partings that parallel horizontal or low-dipping laminae; (4) light bluish-gray, compact, fine to very fine sand up to 10 feet thick, with opaque minerals and mica outlining laminae; (5) white to yellowish-brown, thinly laminated, fine to coarse sand in sheets 1 to 4 feet thick that extend from the lower sand body of one ridge to the upper sand body of the next ridge to the west.

The lower member west of the Fentress rise was deposited in a shallow, sandy lagoon with local eolian environments; east of the Fentress rise it was deposited in a shoal, open-marine environment where a sand supply coming from offshore entered the Deep Creek swale and areas to the west through breaches in the Fentress rise.

A barrier-lagoonal environment of deposition for the upper member of the Sand Bridge Formation is indicated by characteristic lithologies and sedimentary structures, and by the morphology and stratigraphic patterns (Figure 30). Facies west of Pungo ridge were deposited in various backbarrier environments (Figure 31). The clayey-sand facies probably was deposited in a series of broad tidal channels that now are occupied by modern creeks and estuaries. Such an origin would explain upstream coarsening, abrupt lateral sediment changes, and channel-like morphology of the base of this facies. The silty-sand facies parallels the present James River and is coarser than other major backbarrier facies of the upper member. The evidence suggests lagoonal deposition with an influx of sand from the James River, similar to conditions in shallow parts of Albemarle Sound today. Because of its lithology, irregular wavy laminae, abundant vascular plant fragments and seed pods, distribution only in lower areas, flat depositional upper surface, and interfingering relations with barrier

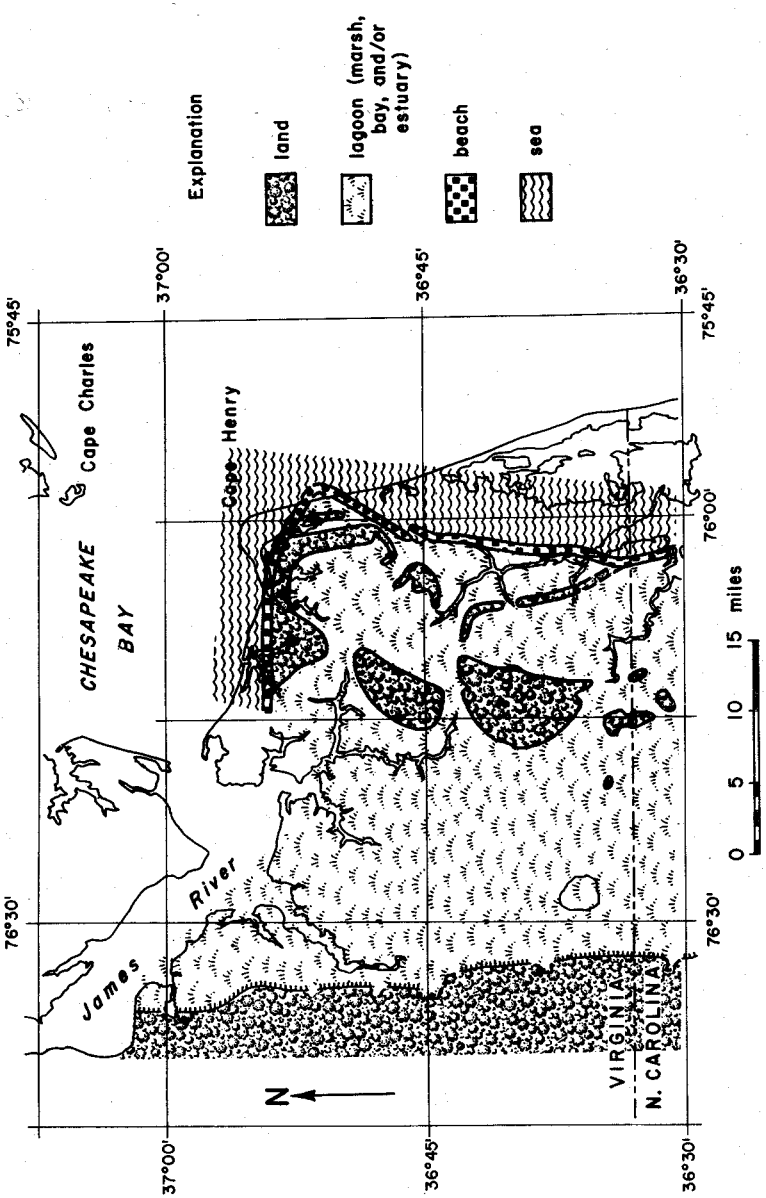


Figure 31. Paleogeography of southeastern Virginia in earliest late Sand Bridge time; relative sea level near 13 feet; shoreline at Pungo ridge.

sand in Pungo ridge, the silty-clay facies is believed to be of marsh and tidal-flat origin.

In the Sand-ridge and Mud-flat complex, the upper sand body along each ridge crest probably is of dune origin, whereas the oxidized

underlying coarse-grained sand with leached shells probably is of beach origin. Deposits between ridges exhibit a variety of backbarrier origins. The stiff surficial clayey silt and silty clay probably are marsh to tidal-flat deposits, and the soft unoxidized subsurface clay is undoubtedly of open-bay origin. The brown, organic, clayey sand with a mealy feel has an exact counterpart in the sandy Arzell soil type that exists along present lagoonal shores of Back Bay that are exposed to long wind fetch (greater than one mile). The sand deposits as much as 10 feet thick between ridges probably represent tidal-channel sediments formed at different distances from inlets. The oxidized sheet of sand that extends from the lower sand body of one ridge to the upper sand body of the next ridge to the west closely resembles storm-washover sediments on flats behind the modern barrier. A maximum position of sea level between 11 and 15 feet is inferred from the highest occurrences of beach sand in Pungo ridge and lagoonal sediments of the Sand Bridge Formation immediately westward.

The Sand Bridge Formation is of late Pleistocene, pre-Holocene age. Separation in time between deposition of the Sand Bridge and Londonbridge formations could not have been great, and both probably belong to the same major submergent episode, as indicated by: (1) lack of oxidation or extensive erosion of the top of the Londonbridge clayey-silt facies; (2) probable shoal-marine origin of the lower member of the Sand Bridge Formation and simultaneous erosion of the southern part of the Londonbridge barrier; (3) similar slight weathering characteristics; and (4) suggested Sangamon to mid-Wisconsin age of the Norfolk and Kempsville formations. Pungo ridge is distinctly younger than Oceana ridge; its crest is consistently lower and its width is consistently less than that of Oceana ridge. Furthermore, the silty-clay facies of the upper member occurs east of Oceana ridge and through a small gap between that ridge and Pungo ridge (Plate 2).

The Sand Bridge Formation is older than unconformably overlying Holocene sediments by virtue of the immature zonal soils of its sand ridges (Figure 27, C), the minor drainage that has developed across the sand ridges in several places, and the truncation of the sand ridges by the present coast. A radiocarbon age of wood from a peat bed in Powells Point Ridge at Aydlett, North Carolina (Figure 5) was greater than 40,000 years B. P. (Y-1272). Because Powells Point Ridge probably is the southern extension of Knotts Island Ridge, and also of other ridges in the Sand-ridge and Mud-flat complex, the Sand Bridge Formation must be at least as old as mid-Wisconsin.

HOLOCENE SERIES

COASTAL SEDIMENTS

Coastal sediments in Virginia are divisible into those of barrier environments and backbarrier environments. Barrier environments include foreshore, berm, dunes, backdune flat, and inlets (Shepherd, 1963; Fisk, 1959). Backbarrier environments include marshes, swamps, small beaches, tidal flats, and open bays (Figure 8).

Barrier Environments

Barriers are offshore ridges of sand or coarser sediment separated from the mainland by a marsh and/or lagoon (Gilbert, 1885, 1890; Shepard, 1960). Barrier environments are controlled by several factors: winds, fetch, swell, and currents, which determine the direction of net littoral drift; tides and storms, including hurricanes; and sediment supply (Bascom, 1963). Together these factors determine the steepness and configuration of the beach; the spacing or absence of cusps and rip currents; the migration of inlets; the shape and orientation of the shoreline and dunes; the size of dune fields or washover fans on the backdune flat; and the sediment size, structures, and composition of each barrier environment.

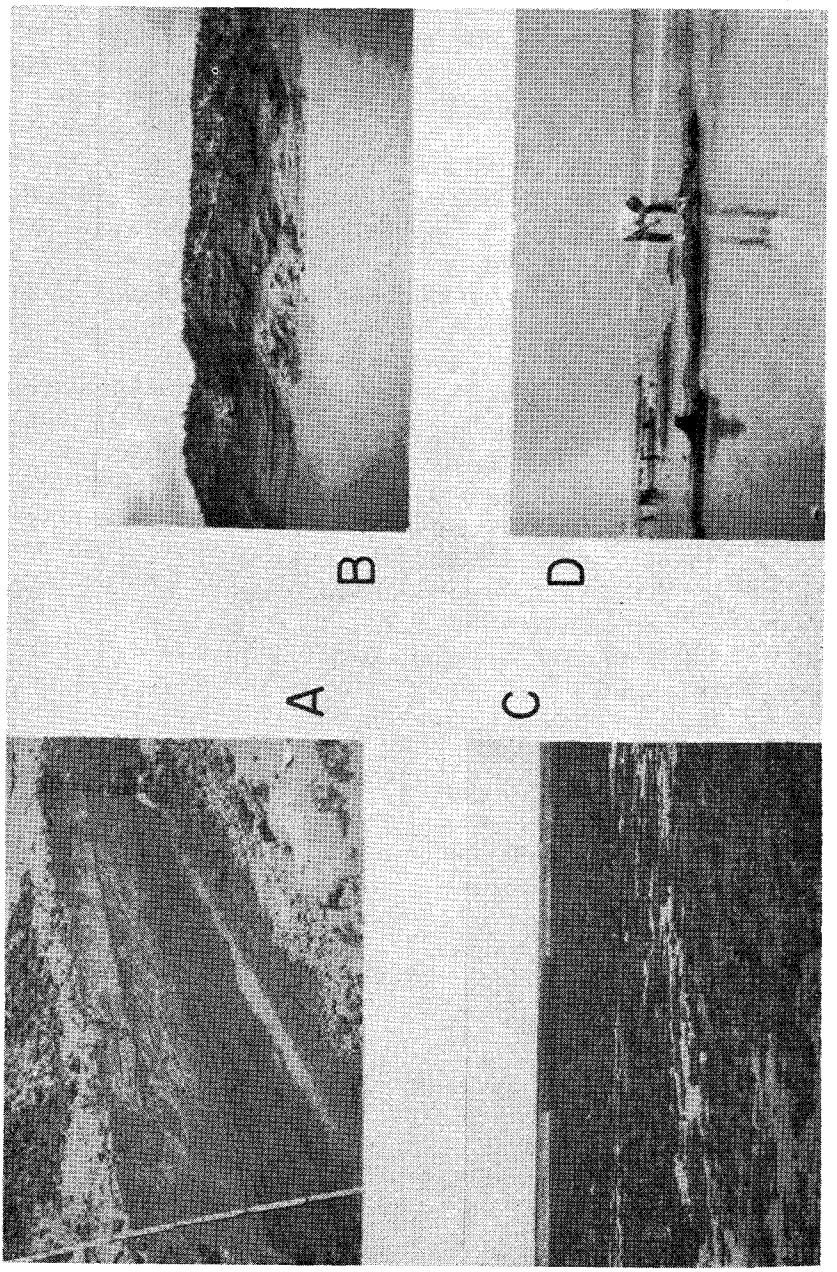
In southeastern Virginia the foreshore consists of a flat, seaward terrace emergent at low tide (Figure 32, D), and a steeper, landward beach face covered by wave uprush at high tide (Figure 8). Sediments consist of white to light-brown, fine to coarse quartz sand with some fine pebble gravel, small amounts of mica, and locally, abundant shell fragments. In the low-tide terrace, horizontal laminae, ripples, and trough-shaped scours occur within parallel beds 0.1 - 0.5 foot thick. Opaque minerals commonly outline stratification. Coarser-grained sand commonly increases with depth, and possibly represents sediments deposited during or at the end of erosional storms.

In the beach face, stratification commonly slopes seaward at 15 degrees, but its angle reaches as much as 35 degrees. Near the surface, stratification parallels the surface and commonly truncates lower layers, especially those of the berm. Thin individual laminae appear to be deposited during each tide cycle. An accretionary period results in deposition of a single seaward-sloping parallel bed with low-angle cross laminae that slope seaward from the top of the bed to the base of the bed through a distance of 10 to 25 feet. Single distinctive foreshore layers of this sort are common near the dunes beneath a cover of younger berm sediments 2 to 5 feet thick and above sediments of the low-tide terrace in a progradational sequence (Figure 32, A).

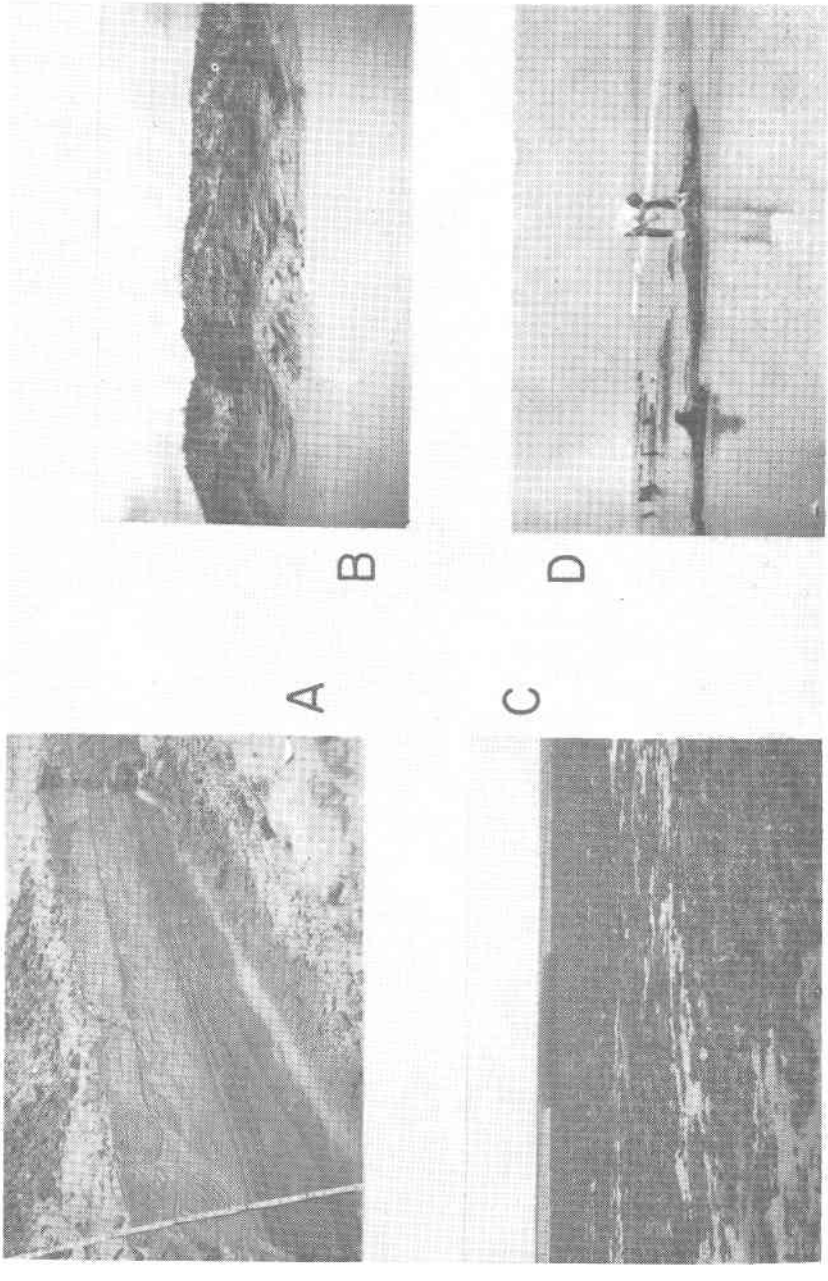
The berm is a nearly flat surface 2 to 5 feet above mean high tide. Sediments of the berm are chiefly pale-yellow to light-brown, fine to medium quartz sand with a few thin, coarse-grained sand layers. A few shells, driftwood, and rounded cobbles and boulders of peat occur locally. Opaque minerals outline small wind-driven ripples within beds of the berm. The most distinctive feature of the berm is the great extent of individual beds, 0.3 to more than 2 feet thick, for distances of 25 to 100 feet or more, both parallel and perpendicular to the beach. Individual beds retain nearly the same thickness, and dip very gently seaward; trough-shaped scours occur parallel to the beach *within* such parallel beds (Figure 32, A). Sediments grade from chiefly wave-deposited at the low, seaward berm ridge and in cusp areas to chiefly eolian over most of the landward part of the berm. The steep erosional scarp present along the seaward face of the dunes extends beneath the landward portion of the berm to an unknown depth, probably 6 to 10 feet.

Dunes along the Virginia coast consist of two indistinct, parallel rows whose crests lie between 18 and 27 feet above sea level where maintained by sand fences; elsewhere, crests of shore dunes are seldom higher than 15 feet. Dune areas are irregular and marked by numerous closed depressions up to 12 feet deep. Because of sand fences and variable winds, little dune migration occurs, and well-developed slip faces are rarely present. Large solitary dunes up to an elevation of 40 feet and 0.2 to 0.4 mile in diameter are present landward of the shore dunes south of False Cape. The shore dunes consist of pale-yellow to light-brown, medium to very fine quartz sand with 1 to 3 percent silt and 1 to 5 percent mica. A few thin layers of medium to coarse sand indicate probable storm-wind deposition. Laminae dipping up to 35 degrees are present where steep, eroded dune faces are present. Elsewhere, dune stratification consists of nearly horizontal laminae that have low-angle pinchouts which make the bedding appear continuous parallel to the beach and to prevailing winds from north and south (Figure 32, B). Above small dunes, laminae tend to be horizontal across flat crests and sloping at low to high angles radially in all directions away from the center.

The backdune flat is a low, narrow strip, mostly 0.1 - 0.3 mile wide that parallels the coast and slopes gently landward from an elevation of about 7 feet near the dunes to about 3 feet along Back Bay, where it grades laterally into swamp or low-marsh environments. Sediments of the backdune flat are dark-brown to pale yellowish-brown, fine to medium sand with variable admixtures of very fine sand, coarse sand, silt, clay, and vascular plant fragments. The abundant mica



probably is blown in from the dunes together with silt. Reedy grass binds the sediments, acts as a baffle to the wind, and adds organic matter to the sediment. Peaty materials accumulate in wet depressions



probably is blown in from the dunes together with silt. Reedy grass binds the sediments, acts as a baffle to the wind, and adds organic matter to the sediment. Peaty materials accumulate in wet depressions

and give the sediment a characteristic sticky, granular, mealy texture. Clay deposited during protracted backbarrier high-water stages forms thin, but distinct, layers for varying distances onto the backdune flat. Intercalated within such sequences, particularly at Wash Flats, are layers of rippled, parallel-bedded, washover-fan sand 1 to 3 feet thick with some shells. In this manner a vertical sequence of thin and thick layers of varying composition forms, wherein more and coarser sand near the dunes grades into sediments with higher clay and organic contents close to the lagoon.

Inlets are areas of rapid currents, deep channels, and shoals that shift rapidly. Single or double tidal deltas with distributaries channel the water flow, which commonly is undirectional and quite rapid (Price, 1963). Such conditions leave fairly large shoal areas of slower currents and sheetflow or of nearly slack water. Juxtaposition of environments with high and low current velocities results in marked sediment variability and in lack of lateral continuity of bedding. Deep closed depressions occur where water-gathering channels join near the back side of a barrier. The bottoms of some of these depressions reach –40 to –60 feet (Figure 8), and are continually filled with coarse sand where channels migrate in response to littoral-drift conditions (U. S. Army Corps of Engineers, 1935, 1947). Locally, sediments undoubtedly resemble those deposited by fluvial processes; however, shell fragments and evidence of current reversal should permit recognition of such deposits in adequate exposures.

Figure 32. A. Progradational stratification exposed in pit dug perpendicular to shore line near center of berm, May, 1966. View northward; Atlantic Ocean to the immediate right (east). Berm stratification consists of two major beds separated by a coast-parallel scour (left). Parallel beach-face laminations are outlined by concentrations of opaque minerals. Low tide-terrace sediments (lower 9 inches) exhibit a coast-parallel scour (left) and a burrow (center). Virginia coast, 5.5 miles south of end of State Road 621 at Sand Bridge, City of Virginia Beach.

B. Stratification exposed in truncated seaward face of dunes at False Cape, Virginia, January, 1962, prior to severe storm of March, 1962. Note sediment-binding grass and nearly horizontal stratification, parallel to predominant winds from the north (right) and prevailing winds from the south (left). Dune face 12 feet high. City of Virginia Beach.

C. Incipient marsh with thick growth of *Spartina* grass, on sandy tidal flat, Chincoteague Inlet. Flat-topped ripples on tidal flat obscured by partial cover *Ulva* sp. (seaweed). Approximately 3 miles southwest of Chincoteague, Virginia. View northwest, grass in background 1.5 feet high.

D. Freshwaster peat exposed on low-tide terrace near low-tide level (-2 feet). Rooted stumps include white pine, juniper, and cypress. Bent-over figure 4 feet high. View northward. Virginia coast, 3.1 miles south of end of State Road 621 at Sand Bridge, City of Virginia Beach.

Backbarrier Environments

Backbarrier environments occupy the area between the backdune flat and older sediments of the mainland. The backbarrier environments are controlled by several interrelated factors: climate; salinity; freshwater and sediment influx of streams; vegetation; lunar tides; wind waves and wind tides; and size, shape, depth, and orientation of submerged areas. Near inlets numerous tidal channels cause a nearly fully oceanic tidal range in the backbarrier area, and wind plays a minor part most of the time. Where broad areas of open bay exist far from inlets, however, wind-driven tides become more important, and salinities commonly are much below marine levels in humid regions, especially where the backbarrier area receives considerable freshwater runoff and also where storm washovers from the sea are few.

Marsh areas generally are best developed in higher-salinity environments, and are divisible into high-marsh and low-marsh subenvironments. The former is covered only during exceptionally high tides, and forms the highest backbarrier areas other than remnants of exposed older sediments. High-marsh sediments in the Wachapreague area consist of very fine sand and silt that are slightly oxidized only near the surface. Wind-blown materials are quantitatively important because of onshore winds. Low and sparse *Spartina* grass and stubby *Salicornia* sp. act as a wind baffle and also bind the sediments thus deposited. Their roots impart a characteristic wavy or "nodular" structure (van Straaten, 1959) to the ubiquitous laminae that exist in the absence of burrowing organisms.

Low marsh near Wachapreague, however, is barely covered at normal high tide and supports a dense growth of high *Spartina* grass similar to that near Chincoteague (Figure 32, C). Shells of *Littorina* sp., *Volsella* sp., and *Emerita* sp. (mole crab) are common on the surface. The sediment is predominantly gray silty clay with minor admixtures of very fine sand and silt. Roots and grass blades make up 10 to 30 percent of the original sediment, and laminae generally are completely disrupted by the plants. The clay-sized fraction (Table 4) includes 30 to 35 percent illite, 10 to 15 percent chlorite, 5 to 10 percent feldspar, a trace of montmorillonite, and 40 to 45 percent quartz (J. L. McAtee, written communication).

Swamps with bushes and low trees commonly replace marshes near high-water level along nearly freshwater lagoons such as Back Bay. Sediments include peat and peaty clay with variable minor admixtures of silt and fine sand, and with abundant roots and wood fragments.

Backbarrier beaches consist of sand and/or shell. Sand beaches occur discontinuously along open-bay shorelines facing areas of long

fetch in Back Bay, and consist of fine to coarse sand containing 2 to 95 percent opaque minerals. Individual laminae dip and thicken toward the bay and are laterally continuous for about 2 to 10 feet. Most beaches in Back Bay are less than 2 feet thick, or 10 feet wide, and rarely reach 100 feet in length. Discontinuous shell beaches occur near high-tide level in the Wachapreague area along deep tidal channels where a narrow tidal flat meets an erosional face cut into high-marsh sediments. Such shell beaches are less than 0.5 foot thick and 50 feet long, and consist chiefly of drilled oyster shells and some shells of *Littorina* sp. and *Volsella* sp.

A tidal flat is a marshy or muddy area lying within the range of lunar tides (Howell, 1960). Tidal flats near Wachapreague consist of soft, very fine, sandy, clayey silt that is oxidized pale yellowish brown in the upper 2 inches, but is bluish gray beneath. The sediments generally are homogeneous to mottled and nonlaminated. Near Chincoteague, however, a broad tidal flat is covered by flat-topped ripples with medium-grained sand concentrated in the flattened crests. Here many pieces of loose seaweed *(Ulva* sp.) litter the surface (Figure 32, C).

Open bays are submerged areas lying below mean low tide, without significant channeled tidal flow, but with direct access to wind-driven or lunar-tidal water. Open bays near Wachapreague and in Back Bay commonly are less than 4 feet deep at low water. Sediments consist of gray, bluish-gray, or black, very soft clayey silt characterized by mottling and total lack of laminae. Where salinity is close to that of marine, shell fragments are present locally, as are abundant annelid worms, tubes, and casting. The clay-sized fraction (Table 4) consists of 15 to 20 percent illite, chlorite and feldspar in amounts of 5 to 10 percent each, traces of montmorillonite, and 60 to 65 percent quartz (written communication, J. L. McAtee).

Shallow tidal channels tributary to the inlet channel near Wachapreague are covered entirely at low tide. Sediments in tidal channels away from the inlet consist chiefly of gray, very fine sandy silt that is thinly laminated. The channels near Wachapreague are practically fixed in position because their headward portions are in extensive marsh areas and migrate very slowly.

The extensive development of marsh and tidal flat near Wachapreague probably resembles closely the backbarrier conditions that are inferred to have existed west of Pungo Ridge during late Sand Bridge time, whereas the extensive tracts of open bays in Back Bay and in Pamlico Sound probably resemble backbarrier conditions west of Oceana Ridge during Londonbridge time.

STREAM-RELATED SEDIMENTS

Along portions of existing streams above tidewater, clean to clayey, fine to medium sand and sandy silt are being deposited. Along portions of streams directly affected by tides, especially the James River, deposits of fine to medium sand with some fragments of oysters and fine pebble gravel are common. Thick fluvial-estuarine valley fills with surfaces near elevations of 1 to 2 feet underlie and/or flank all major tidal rivers and creeks in the area studied. Such deposits fill channels more than 125 feet deep, which are cut into Sand Bridge and older units, and consist chiefly of soft, highly organic silt deposited near or slightly below sea level as the latter rose to its present position (Coch, 1968).

DISMAL SWAMP PEAT

The Dismal Swamp Peat, named by Oaks and Coch (1963), is here formally used for the peat in the swamp. The peat was studied in great detail by Whitehead (1965). The thickest section found by Whitehead (11.5 feet) was on Jericho Ditch, 2.5 miles north of Lake Drummond. The type section is established at a boring on Hamburg Ditch 0.5 mile east of Sherrill Ditch, in North Carolina, an easily accessible point where the peat is 12.8 feet thick (Appendix I, Section U).

The Dismal Swamp Peat is coextensive with the Dismal Swamp, with swamps of valleys tributary to the Swamp from the Isle of Wight plain, and with swamps of Northwest and Pasquotank rivers to tidewater (Figure 4). The surface of the peat slopes gently eastward from a feather edge at the Suffolk scarp near an elevation of 27 feet to a feather edge along the west side of the Deep Creek swale at about 15 feet. Natural drainage is poor, for no streams are well developed. It has been necessary to ditch the area in many places in order to lower the ground-water level below the peat surface.

The thickness of the Dismal Swamp Peat is highly variable even though its surface shows little relief. Peat thicknesses were determined by direct observation where the peat is thin and fully exposed in ditches; and by 187 borings elsewhere (Oaks, 1965; Figure 33). Few data exist for the midsection of the swamp because of general inaccessibility. Moreover, the northeastern part of the swamp was not studied in detail because it had been burned over to depths of as much as 6 feet during a fire in 1930 (oral communication and photographs, William Rogers, Richmond Cedar Works, Portsmouth).

Where the peat is thick the upper foot of underlying sediments commonly consists of two particular lithologies: white, angular, fine

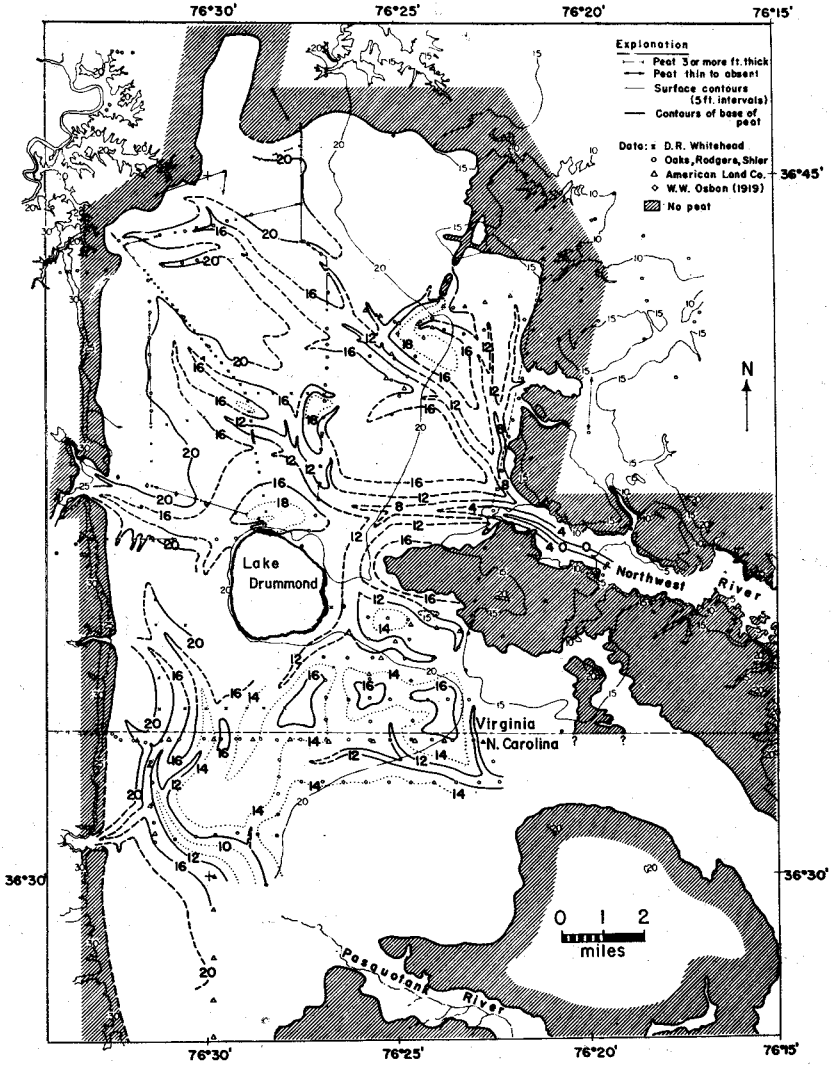


Figure 33. Configuration of base of Dismal Swamp Peat, southern coastal Virginia and adjacent North Carolina. Contour interval 4 feet; supplementary contours at intervals of 2 feet.

to medium sand, presumably of fluvial origin, overlain by soft, light-blue clay with organic fragments and hystrichosphaerids of freshwater origin (written communication, D. R. Whitehead). These two units and the peat unconformably overlie older stratigraphic units, particularly the Sand Bridge, Londonbridge, Norfolk, and Yorktown formations.

Which of the latter flat-lying units lies directly beneath Holocene sediments depends upon the cumulative thickness of the peat, clay, and sand.

The Dismal Swamp Peat consists of a soft, wet, sponge-like mass of decaying organic material, chiefly leaves, twigs, rooted stumps, and fallen logs. The color is commonly dark brown near the surface to brownish black with depth. A thick tangle of logs, stumps, and roots occurs about three feet below the surface through much of the western part of the swamp.

Detailed pollen analysis of the Dismal Swamp Peat by D. R. Whitehead (1965, p. 428; written communication) shows that the peat is entirely of freshwater origin in the northern and western parts of the swamp. The Yorktown Formation undoubtedly has been very important in the development of peat-forming conditions in the Dismal Swamp, where its surface slopes eastward at about 1 foot per mile (Figure 33). The rather impervious clay and the slight slope of the Yorktown Formation make it an ideal unit above which to trap water. In the western part of the swamp the top of the Yorktown Formation is within 10 feet of the surface, and in the eastern part, within 20 feet of the surface. Further, clayey facies of the Sand Bridge and Londonbridge formations help to form impervious layers in the eastern part of the swamp wherever they were not removed by pre-swamp erosion (Figures 26 and 30). The Fentress Rise forms a major barrier to eastward drainage, with breaches only at narrow, transverse, stream valleys; and the Churchland Flat forms an effective barrier to outflow toward the north.

The configuration of the base of the peat (Figure 33) permits the following conclusions to be drawn: (1) the majority of drainage north, northeast, and southeast(?) of Lake Drummond probably discharged through a narrow opening into Northwest River; (2) except near this outlet, where various streams converged, stream gradients were low, on the order of 1 foot per mile; (3) similarly, drainage southwest of Lake Drummond probably discharged through a narrow opening into the Pasquotank River, and possibly into Little River, and/or Indiantown Creek; (4) near the outlet at North Landing River, stream gradients became steeper, up to four feet per mile; similarly, the surface topography is rather steep in the same area compared to flatter areas west of the 20-foot contour.

The greatest radiocarbon age of 5 specimens of Dismal Swamp Peat is 8900 ± 160 years B. P. (Y-1320). Radiocarbon ages of freshwater peats and of oyster shells in clay with brackish-water diatoms, encountered between –70 and –89 feet in borings for the Chesapeake Bay Bridge Tunnel, indicate a relative sea-level position

not higher than –60 to –80 feet between 8135 ± 160 and 15,280 ± 200 years B. P. (Harrison and others, 1965, p. 217-221). Also, where thick, the Dismal Swamp Peat overlies lake clay containing a late-glacial or full-glacial pollen flora that correlates closely with pollen flora from the freshwater peats in Chesapeake Bay studied by Terasmae (written communication, D. R. Whitehead). Therefore, ponding of the Dismal Swamp by natural methods must have occurred while relative sea level was 60 to 70 feet *or more* below its present position.

CONCLUSIONS

The present study clarifies earlier work and establishes a stratigraphic framework for post-Miocene sediments in the Coastal Plain of southeastern Virginia. Other morphostratigraphic interpretations based on the "terrace-formation concept" are erroneous, because three to five formations representing at least two distinct, major submergent episodes underlie each of the four areas previously designated as a terrace, which was presumed to be underlain by a single formation (Clark and Miller, 1906, 1912; Wentworth, 1930).

Detailed geologic mapping and subsurface stratigraphic study show that ten post-Yorktown (post-Miocene) time-stratigraphic units are present east of the Fall Line in southeastern Virginia. Six units east of the Suffolk scarp are younger than four other post-Yorktown units that occur west of the Suffolk scarp. All but one of the units were deposited in coastal and marine environments. The ten units are separated by surfaces of unconformity into six groups that represent successive submergent-emergent cycles, as follows: (1) Sedley-Bacons Castle (2) "Moorings" (3) Windsor; (4) Great Bridge-Norfolk-Kempsville; (5) Londonbridge-Sand Bridge; and (6) Holocene. Positions of shorelines, altitudes of maximum submergences, and emergent episodes are recorded in Table 6. Submergent-emergent cycles probably resulted, at least in part, from glacial-eustatic changes of sea level.

Post-Yorktown pre-Holocene units east of the Suffolk scarp are so little weathered, in terms of oxidation, clay enrichment, soil development, alteration of quartz-grain surface features, and alteration of soluble heavy minerals, that all probably are Sangamon and/or mid-Wisconsin. Such an interpretation is supported by Uranium-series ages of corals from the Norfolk and Kempsville formations between 62,000 and 86,000 years B.P. and radiocarbon ages in excess of 40,000 years B.P. for the Sand Bridge, Kempsville, and Norfolk.

The present study also furnishes evidence of several kinds of shoreline evolution during submergence and emergence. Cliff retreat by

Table 6. Positions of the shoreline and maximum altitudes of sea level during deposition of Yorktown Formation and younger stratigraphic units.

Unit	*Shoreline Position*	*Sea-Level Position*
Yorktown	West of Fall Line	Above +100 feet
Uppermost Yorktown	Just east of Suffolk Scarp	Above +18 feet
Major Emergence	East of Suffolk Scarp	Below —10 feet
1. Sedley	West of Fall Line	Well above +75 feet
Major Emergence	East of Suffolk Scarp	Below +15 feet
2. Bacons Castle	East of Suffolk Scarp	Below +20 feet
3. "Moorings"	Surry Scarp	+120 to +125 feet
Major Emergence	East of Suffolk Scarp	Below +20 feet
4a. Lower Windsor	Surry Scarp	+90 to +100 feet
Minor Emergence(?)	East of Suffolk Scarp(?)	Below +63 feet(?)
4b. Upper Windsor	East of Suffolk Scarp	+80 to +85 feet
Major Emergence	East of present shoreline	Below —80 feet
5. Great Bridge	Just west of present shoreline	—10 to —5 feet
6. Norfolk	Suffolk Scarp	+45 to +50 feet
Minor Emergence(?)	East of Hickory Scarp(?)	Below —1 foot(?)
7. Kempsville	Hickory Scarp	+18 to +22 feet
Major (?) Emergence	East of Oceana Ridge	Below —11 feet
8. Londonbridge	Oceana Ridge	+22 to +26 feet
9a. Lower Sand Bridge	Land-of-Promise Ridge; Princess Anne Rise	+12 to +17 feet
9b. Upper Sand Bridge	Pungo Ridge	+11 to +15 feet
	Dawley Corners Ridge	+4 to +6 feet
	Charity Neck Ridge	+4 to +6 feet
	Knotts Island Ridge	0 to +2 feet
Major Emergence	East of present shoreline	Below —180 feet
10. Holocene	Present shoreline	0 + 3 feet

wave erosion during submergence (Fischer, 1961) took place at the Surry, Suffolk, and Hickory scarps during deposition of the Windsor, Norfolk, and Kempsville formations, respectively. Vertical growth in place during gradual submergence (Fish, 1959) characterized barriers of Great Bridge age and Londonbridge age. Rapid submergence drowned the Great Bridge barrier, and caused landward migration of the shoreline almost to the present Suffolk scarp, a distance of nearly 30 miles. The southern part of the Londonbridge barrier was destroyed, perhaps by littoral drift erosion after sediment supply was diminished by a slight emergence. Progradation during slow emergence took place by means of the seaward construction of successive barrier spits during late Sand Bridge time. These examples indicate the variability possible under different conditions of sediment supply, rate of infilling of lagoons, and rate of submergence or emergence (Lucke, 1934a, 1934b), and afford an improved basis for understanding shoreline evolution in coastal-plain regions.

As was suspected by previous workers, stratigraphy and morphology are closely related; however, scarps and plains are not morphologic features uniquely related to a single coastal environment. Without knowledge of the stratigraphy, therefore, one cannot demonstrate the vertical positions of former sea levels, their number, and their sequence in time. If the post-Miocene history of the Atlantic Coastal Plain is to be fully revealed, future studies must continue to employ subsurface techniques to establish detailed stratigraphic frameworks.

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APPENDIX I

TYPE AND REFERENCE SECTIONS

Type sections of post-Yorktown stratigraphic units in southeastern Virginia and reference sections of their typical facies are here compiled in their entirety for the first time. Each type section is typical of a major facies of each formation. Wherever possible, exposures rather than borings were chosen for type sections. Highway and road designations are those used on county highway maps by the Virginia Department of Highways. Color notations are those of the Munsell Rock Color Chart of the National Research Council (1948).

Test borings were made with an engineer's soils-test rig, using an Acker split-spoon sampler. Numbers preceded by the letter "W" in parentheses (W-1211) designate borings whose samples are on file in the repository of the Virginia Division of Mineral Resources. Jet-rig borings were made by flushing water down a pipe. Samples in the water that was returned to the surface along the outside of the pipe were studied and compared against the "feel" of the sediment, determined by turning the pipe back and forth by hand. Plastic-tube borings were made by pounding plastic tubes into the sediment, until firmly, but not permanently, imbedded. Then, the space above the core was filled with water, the tube corked with a rubber stopper to create a vacuum, the depth measured, and the tube extracted.

SECTION A: YORKTOWN FORMATION
(REFERENCE SECTION, COQUINA FACIES)

Exposure (Coch, 1968, Plate 1, location 7) on north-south face of Lone Star Cement Corporation borrow pit, about 1 mile north of Chuckatuck, Nansemond County, Benns Church 7.5-minute topographic quadrangle (Plate 1), latitude 36° 52′ 42″N., longitude 76° 34′ 37″W. (Figure 2). Elevation at top of section is 26 feet. Lowermost unit of this composite section crops out 200 feet east of above exposure along east-west face. Faunal identification by G. H. Johnson (written communication).

	Thickness Feet
Sand Bridge Formation	
Upper member, silty-clay facies	
Silt, brown, clayey; trace of medium sand; brownish-gray mottled areas; pebble and cobble gravel concentrated near base; gradational basal contact with saprolite developed on Yorktown	3.5
Yorktown Formation, coquina facies	
Upper unit (9.0 feet)	
Coquina, reddish-gray to blue; horizontally bedded; composed of subangular to rounded shell fragments of fine-sand size; trace of quartz sand; abundant whole *Crepidula,* and less abundant microgastropods, *Donax,* barnacles, *Ostrea,* Bryozoa fragments, and echinoid plates and spines; uppermost 1 foot is red sandy silt saprolite developed on coquina	3.0

	Thickness Feet
Coquina, blue to reddish-gray; nearly horizontal beds composed of well-rounded, tabular, water-worn shell fragments of medium-sand size; trace of quartz sand. Diverse fauna includes abundant *Crepidula* and *Donax,* and less abundant *Ostrea, Pecten,* barnacles, echinoid plates and spines, broken pelecypod shells, and microgastropods; disarticulated *Pecten* shells, with convex side up, are concentrated near base; sharp basal contact	6.0
Middle unit (8.5 feet)	
Coquina, bluish-gray; steeply dipping beds (apparent dips 20-35°); composed of thin (0.5 ft. max.), purplish-red indurated coquina with silt matrix and thicker (1.5 ft. max.) beds of tan, friable coquina of medium-sand size; fauna is diverse but not as abundant as in coquina beds above and below; contains abundant *Donax* and *Crepidula;* and less abundant *Polinices,* microgastropods, fragments of Bryozoa, barnacles, echinoid spines and plates; shells and shell fragments are well rounded and abraded; sharp basal contact	8.5
Lower unit	
Coquina, bluish-gray; nearly horizontal beds; friable; composed of shell fragments of medium-sand size; contains abundant *Crepidula* and less abundant *Donax,* barnacles, *Pecten* fragments, and immature *Glycymeris;* finer fraction includes abundant microgastropods, echinoid plates and spines, fragments of Bryozoa, and abraded porcelaneous Foraminifera	3.0 (exposed)

Comments: The three units of the coquina facies merge, to form a thick section of nearly horizontally bedded coquina, about 500 feet east of the northwest corner of the pit (as exposed on August 12, 1967). Cross-bedded strata of the middle unit dips toward the northwest.

SECTION B: SEDLEY FORMATION

Exposure on west side of State Road 637, 0.35 mile south of intersection with State Road 645, just south of Norfolk and Western Railroad, 1.75 miles east of Sedley, Southampton County, Sedley 7.5-minute topographic quadrangle (Plate 1), latitude 36° 46′ 12″N., longitude 76° 55′ 33″W. (Figure 2). Elevation at top of section is 60 feet.

Windsor Formation	
Lower member	
Sand, moderate reddish-brown, medium, clayey; abundant pebble gravel in upper part, grades downward into cobble gravel; sharp and irregular basal contact	4.0

	Thickness Feet
Sedley formation	
Silt, dark-yellowish orange, fine sandy; mottled pale-yellowish brown near base; light brown and dusky red ferruginous crusts in upper 6 feet	8.0 (exposed)

SECTION C: BACONS CASTLE FORMATION (TYPE SECTION, SILT FACIES)

Exposure on east side of State Road 618, 100 feet north of State Road 640, 1.5 miles west of Cross Creek Landing, Surry County, Surry 7.5-minute quadrangle (Plate 1), latitude 37° 10′ 43″N., longitude 76° 51′ 18″W. (Figure 2). Elevation at top of section is 103 feet.

Bacons Castle Formation, silt facies	
Silt and clay, moderate-red; thin streaks of very fine sand; gradational basal contact	6.0
Sand, pale reddish-brown, fine, silty; thin partings of gray, silty clay that outline low-angle (<10°) cross-laminae; gradational basal contact	6.2
Bacons Castle Formation, sand facies	
Sand, moderate-red, medium to coarse, silty; mottled dark yellowish-orange; some pebble gravel; coarsens downward	3.2 (exposed)

SECTION D: BACONS CASTLE FORMATION (TYPE SECTION, SAND FACIES)

Exposure on north side of State Road 609 at Sunken Meadow Beach, Surry County, Claremont 7.5-minute quadrangle, latitude 37° 13′ 08″N., longitude 76° 56′ 09″W. (Figure 2). Elevation at top of section is 71 feet.

Bacons Castle Formation, sand facies	
Sand, moderate-red, medium to coarse; some pebble gravel; irregular streaks of nearly horizontal, pale-olive, sandy silt in upper portions; grades downward and interfingers laterally with underlying unit	8.0
Sand, coarse, clayey; pebble gravel and cobbles up to 0.9 foot long; complexly interfingered with lithology similar to overlying sand bed; coarser rock particles concentrated in distinct channels at base of unit	4.5
Sedley formation? (possibly Yorktown Formation saprolite) (3.5 feet)	
Clay, grayish-red, blocky; sharp basal and upper contacts	3.5
Yorktown Formation (?)	
Sand, fine; trace silt; moderate brown near top and light tan near base; shell imprints throughout section and partly decomposed shells in basal 1.5 feet	11.4

	Thickness Feet
Coquinite; composed chiefly of flat-lying oysters and *Pecten;* matrix of fine sand; irregular but sharp basal and upper contacts	4.9
Sand, grayish-orange, fine; decomposed shells and shell imprints common, with coquinite layer at base	8.4
	(exposed)

SECTION E: "MOORINGS UNIT"

(FINE-SAND FACIES)

Core boring in driveway to farm of J. Seward, 0.1 mile south of intersection of State Roads 626 and 634, 1.7 miles SSE of Surry, Surry County, Runnymede 7.5-minute quadrangle (Plate 1), latitude 37° 06′ 51″N., longitude 76° 49′ 39″W. (Figure 2). Elevation at top of boring is 127 feet.

"Moorings unit"	
Sand, orangish-brown, fine, silty; discontinuous dark red areas	9.0
Sand, orangish-tan, fine to medium; trace of silt	5.0
Sand, fine; some thin beds of grayish-white, medium to coarse sand; noticeable fine opaque minerals; sharp basal contact	10.0
Bacons Castle Formation, silt facies	
Interlaminated reddish-orange, fine to medium sand and red silty clay	15.0
	(base of boring)

SECTION F: WINDSOR FORMATION

(TYPE SECTION, UPPER AND LOWER MEMBERS)

Core boring W-1211 on NE side of farm road 300 feet NW of State Road 634, 0.35 mile NE of U. S. Highway 460, about 6.5 miles ESE of Windsor, Nansemond County, Chuckatuck 7.5-minute quadrangle (Plate 1), latitude 36° 46′ 55″N., longitude 76° 37′ 26″W. (Figure 2). Elevation of top of boring is 76 feet. These sediments were originally designated as the type section of the Windsor by Coch (1968, p. 15, 34).

Windsor Formation	
Upper member	
Sand, gray, medium; trace coarse sand; clayey (40 percent) in top 10 feet; grades downward into gray, medium to coarse, clayey (20 percent) sand with gray clay platelets parallel to stratification; gradational basal contact	18.0
Lower member (17.0 feet)	
Sand, grayish-white, coarse; high percentage of opaque minerals; thin lenses of gray silt; tannish-orange near base; sharp basal contact	17.0

	Thickness Feet
Sedley formation (16.0 feet)	
Silt, dark-blue, clayey; with very thin laminae of fine, slightly clayey sand; upper 0.5 foot is oxidized dark reddish brown with ferricrete crusts; gradational basal contact	10.0
Sand, tan and gray, medium, laminated, slightly clayey; some small chunks of bluish-gray clay; sharp basal contact	6.0
Yorktown Formation	
Silt, blue, sandy; abundantly fossiliferous, mostly small whole shells and shell fragments less than 1 cm wide	4.0 (exposed)

Comment: The lowest part of the upper member and all of the lower member of the Windsor Formation are shown in this core boring.

SECTION G: GREAT BRIDGE FORMATION

(TYPE SECTION, LOWER MEMBER)

Jet-rig boring W-1048 in field 0.1 mile east of State Road 166, 0.95 mile NE of intersection with State Roads 641 and 720 at Butts Station, approximately 3 miles NE of Great Bridge, City of Chesapeake, Fentress 7.5-minute quadrangle (Plate 1), latitude 36° 44′ 53″N., longitude 76° 12′ 28″W. (Figure 2). Elevation of top of boring is 17 feet.

Sand Bridge Formation	
Upper member, silty-clay facies	
Clay, gray, mottled yellowish-brown, stiff; trace of fine sand; grades downward to dark-gray sandy clay	3.0
Lower member (2.0 feet)	
Sand, dark-gray, fine, very clayey	2.0
Kempsville Formation (?) (9.0 feet)	
Sand, light-brown to light-gray, fine; 1 to 3 percent opaque minerals	9.0
Norfolk Formation (25.0 feet)	
Upper member, fine-sand facies (15.0 feet)	
Sand, light-gray, fine, silty; 5 to 6 percent opaque minerals	5.0
Sand, light-gray, fine to medium	2.0
Sand, fine to coarse	2.0
Clay, pale yellowish-brown; silty	0.5
Sand, gray, fine, silty; 5 to 6 percent opaque minerals	5.5
Lower member(?) (10.0 feet)	
Sand, fine to coarse, clayey	4.0
Sand, fine to medium; trace clay(?); sharp basal contact	6.0
Great Bridge Formation (36.0 feet)	
Lower member (36.0 feet)	
Sand, pale-gray, fine to very coarse; wood fragments	1.0
Peat and wood, dark-brown, soft; fresh-water origin	5.0

	Thickness Feet
Clay, light bluish-gray, silty, soft	6.0
Sand, greenish-gray, fine to medium, compact, trace small shell fragments	6.0
Sand, gray, fine to coarse	8.0
Sand, very coarse, and small, angular gravel; some fine to medium sand; interlayered with soft, brown peaty clay and soft, very pale-blue clay	10.0
Yorktown Formation	
Clay and shells, moderate bluish-green, compact; includes *Nuculana, Nassarius,* and *Turritella;* progressively less shells downward	9.0
(base of boring)	

SECTION H: GREAT BRIDGE FORMATION
(TYPE SECTION, UPPER MEMBER, CLAYEY-SILT FACIES)

Test boring W-778 in NE corner of Womack borrow pit, 0.1 mile SW of State Road 603, 0.35 mile SE of Bonneys (Mears) Corner, approximately 2.5 miles SSW of Kempsville, City of Virginia Beach, Kempsville 7.5-minute quadrangle (Plate 1), latitude 36° 47′ 33″N., longitude 76° 10′ 19″W. (Figure 2). Elevation at top of boring is 11 feet.

Sand Bridge Formation	
Upper member, silty-clay facies	
Clay, gray, silty, stiff but plastic	2.0
Kempsville Formation (9.5 feet)	
Sand, white to yellowish-orange, fine to coarse	9.5
Norfolk Formation (23.5 feet)	
Upper member, fine-sand facies (23.5 feet)	
Sand, gray; fine to coarse, silty; fossiliferous; crab claws and marine shell fragments	23.5
Lower member	
Probably present in type section (Section I) of Norfolk Formation 300 feet southeastward, but missed in this test boring during flushing between depths of 35 to 40 feet	up to 5.0
Great Bridge Formation	
Upper member, clayey-silt facies	
Silt, silty clay, and clay, gray to bluish-gray; trace very fine sand; fissile near 75 feet; soft to very soft; few shells, chiefly in beds at depths near 39, 67, and 70 feet, mostly *Mulinia*	minimum 37.0 (up to 42.0)
(base of boring)	

Comments: Upper 3 feet of surficial clay was removed during borrow-pit operations; continuous sampling below 40 feet only.

Thickness
Feet

SECTION I: KEMPSVILLE FORMATION (TYPE SECTION)
NORFOLK FORMATION (TYPE SECTION, UPPER MEMBER, FINE-SAND FACIES)

Composite section of exposure in SE and SW walls of Womack borrow pit, 0.1 to 0.4 mile SW of State Road 603, 0.3 to 0.6 mile SE of Bonneys (Mears) Corner, City of Virginia Beach, Kempsville 7.5-minute quadrangle (Plate 1), latitude 36° 47′ 30″N., longitude 76° 10′ 13″W. (Figure 2). Elevation of top of section is 12 to 15 feet. Adapted from detailed survey in 1967 by Paul E. Drez, Old Dominion College, Norfolk, Virginia.

Sand Bridge Formation

Upper member, silty-clay facies

Clay, silty, and clayey silt; dark-gray to yellowish-brown; trace fine sand with minor gravel near base and locally within unit; stiff but plastic; wavy laminae and mottling; sharp, erosional, basal contact ..... 3 to 5

Kempsville Formation (8 to 11 feet)

Sand, light-brown to light-yellow, fine to very fine; thin lenses of peaty clay locally at base; gradational basal contact ..... 0 to 5

Sand, fine to medium; minor silt, peat, and plant fragments; gradational basal contact ..... 0 to 1

Sand, light-yellow to light bluish-gray, fine to coarse; trace fine gravel; lenses of coarse sand and fine gravel as much as 0.2 foot thick and continuous laterally more than 15 to 20 feet; lenses of gray clay locally at base where in contact with the underlying Norfolk Formation; numerous unoxidized imprints of former pelecypod shells locally at top, disarticulated and oriented convex up, parallel to bedding; sharply overlies Norfolk Formation or else locally gradational at base into next two units described ..... 3 to 11

Sand, white, light gray, and light brown, coarse; fine gravel; coarsens downward; unfossiliferous at top to abundantly fossiliferous below 1.5 feet; shells disarticulated, broken, and abraded, although some articulated shells of burrowing pelecypods occur in the lowermost part in living position; persistent layers of iron oxidation increase in number and thickness westward, where actual cementation occurs; sharp basal contact ..... 0 to 8

Sand, light gray, medium to very coarse; minor gravel; high-angle planar cross laminations outlined by opaque minerals; highly fossiliferous except in west end of pit, where fine sand and silt also appear; articulated shells of burrowing pelecypods; sharp to locally gradational basal contact ..... 0 to 5

Norfolk Formation

Upper member, fine-sand facies (8 to 10 feet)

Sand, light bluish-gray, very fine to fine; very fossiliferous in upper 6 feet; serpulid worm-tube bioherm in uppermost 2 to 4 feet; majority of fossils in living position, complete, and articulated; gradational basal contact ..... 8 to 10

	Thickness Feet
Upper member, silty-sand facies (?)	
Sand, bluish-gray, very fine to fine, silty and clayey, soft; restricted but locally abundant fauna articulated and in living position	3 to 4
	(exposed above water level)

Comment: Spoil from dredging slightly below water level consisted of soft, greenish-brown, silty clay to clayey silt with a very restricted, but locally abundant, fauna (Great Bridge Formation, upper member, clayey-silt facies?) mixed with very fine sand and rarely with gravel (Norfolk Formation, lower member?).

SECTION J: NORFOLK FORMATION
(REFERENCE SECTION, UPPER MEMBER, MEDIUM-SAND FACIES)

Jet-rig boring in bend of Northeast Ditch, 0.9 mile ESE of Portsmouth Ditch, 2.4 miles south of intersection of Big Entry and Portsmouth ditches, City of Chesapeake, Lake Drummond NW 7.5-minute quadrangle (Plate 1), latitude 36° 41′ 33″N., longitude 76° 23′ 13″W. (Figure 2). Elevation at top of boring is 19 feet.

Holocene sediments	
Dismal Swamp Peat	
Peat, dark-brown, very soft, organic; many fragments of rotted bark, wood, and roots; humic odor	4.5
Fluvial (?) sediments	
Sand, white, fine to medium, clayey	1.0
Sand Bridge Formation (4.5 feet)	
Lower member (4.5 feet)	
Sand, very light-gray, fine to medium; 1 to 3 percent opaque minerals; sharp basal contact	4.5
Londonbridge Formation, clayey-silt facies (4.0 feet)	
Clay, light-blue, silty, very soft; sharp basal contact	4.0
Norfolk Formation (11.0 feet)	
Upper member, clayey-sand facies (8.5 feet)	
Sand, light bluish-gray, fine, clayey; fossiliferous (chiefly *Ensis*)	1.0
Sand, bluish-green, fine to medium; trace of coarse sand; many shell fragments; numerous small clusters of opaque minerals	4.5
Sand, bluish-green, fine; trace of medium sand	2.0
Sand, bluish-green, fine to medium, clayey	1.0
Lower member (2.5 feet)	
Sand, grayish- to bluish-green, fine to medium; numerous small clusters of opaque minerals; sharp basal contact	2.5
Yorktown Formation	
Clay, moderate bluish-green, very compact	2.5
	(base of boring)

Thickness
Feet

SECTION K: NORFOLK FORMATION
(REFERENCE SECTION, UPPER MEMBER, SILTY-SAND FACIES)

Exposure on south side of James River at Pike Point, at termination of State Road 1506, Nansemond County, Newport News South 7.5-minute quadrangle (Plate 1), latitude 33° 55′ 11″N., longitude 76° 29′ 10″W. (Figure 2). Elevation at top of section is 21 feet.

Sand Bridge Formation
Upper member, clayey-sand facies
Sand, fine to medium, clayey; pale yellowish-brown in upper half, irregular mottles of dark yellowish-orange in lower half 3.7
Lower member (5.4 feet)
Sand, very pale-orange, fine to medium; trace of silt; irregular mottles of dark yellowish orange 2.6
Sand, dark yellowish-orange, fine to medium, clayey; mottled pale yellowish brown 2.8

Norfolk Formation
Upper member, silty-sand facies
Sand, grayish blue-green to moderate-blue, fine to medium, clayey and silty, moderate-blue; upper half, clayey sand with laminae of blue silt and clay; lower half, clayey sand without stratification, but with abundant shell imprints and fossils 8.8
(exposed)

SECTION L: NORFOLK FORMATION
(REFERENCE SECTION, UPPER MEMBER, COARSE-SAND FACIES)

Plastic-tube boring (Coch, 1968, Plate 1, location 5) just south of house on farm road east of State Highway 10, about 0.6 mile NW of intersection with U. S. Highway 258 at Benns Church, Isle of Wight County, Benns Church 7.5-minute quadrangle (Plate 1), latitude 36° 56′ 42″N., longitude 76° 35′ 27″W. (Figure 2). Elevation of top of boring is 42 feet.

Norfolk Formation
Upper member, coarse-sand facies
Sand, yellowish-orange, medium to coarse; trace of silt in upper 3 feet; gradational basal contact 8.0
Sand, pale yellowish-orange, coarse; trace of pebble gravel; gradational basal contact 3.0
Upper member, silty-sand facies (14.5 feet)
Silt, dark-gray, fine sandy; gradational basal contact 4.0
Sand, moderate-blue, fine, silty, abundantly fossiliferous; sharp basal contact 10.5

Yorktown Formation
Sand, bluish-white, fine, clayey, abundantly fossiliferous 5.0
(base of boring)

Thickness
Feet

SECTION M: NORFOLK FORMATION

(REFERENCE SECTION, UPPER MEMBER, CLAYEY-SAND FACIES)

Exposure, 0.3 mile north of Baileys Beach at termination of State Road 686, 1.3 miles east of State Road 676, Isle of Wight County, Bacons Castle 7.5-minute quadrangle (Plate 1), latitude 37° 05′ 10″N., longitude 76° 39′ 50″W. (Figure 2). Elevation of top of section is 18 feet.

Norfolk Formation

Upper member, clayey-sand facies

Clay, greenish-gray; irregularly jointed; dusky red on joint facies; gradational basal contact	6.0
Sand, pale-olive, fine to medium; slightly clayey; subhorizontal, light brown mottled; thin ferricrete layer at base	2.2
Clay, moderate-yellow, sandy; minor fine pebble gravel; irregularly mottled pale olive	1.9
Clay, grayish-green, sandy; thin laminae of fine sand	3.0
	(exposed)

SECTION N: NORFOLK FORMATION

(REFERENCE SECTION, UPPER MEMBER, SILTY-CLAY FACIES)

Jet-rig boring on west side of State Highway 32, 0.1 mile north of Virginia-North Carolina boundary, Nansemond County, Corapeake 7.5-minute quadrangle, (Plate 1), latitude 36° 34′ 06″N., longitude 76° 34′ 34″W. (Figure 2). Elevation of top of boring is 40 feet.

Norfolk Formation

Upper member, silty-clay facies

Clay, light-gray to pale yellowish-orange, silty, fine sandy; soft; grades downward to very light gray; sand content decreases to a trace at depth of 6.5 feet; gradational basal contact	8.0
Clay, medium-gray, very soft	10.0
Sand, light-gray, fine to very fine, very loose; 3 to 5 percent opaque minerals; sharp basal contact	4.5

Sedley formation (?) (4.5 feet)

Silt, medium-gray, fine sandy, compact; 3 to 5 percent opaque minerals; trace of shells; sharp basal contact	4.5

Yorktown Formation

Sand, fine to medium; compact; some shells	1.0
Coquina, fine sandy, clayey, hard	1.5
Sand, somewhat loose; fine to medium, abundantly fossiliferous with echinoid spines, small pectens, *Glycymeris,* and other shells	1.5
	(base of boring)

Thickness
Feet

SECTION O: LONDONBRIDGE FORMATION

(TYPE SECTION, SAND FACIES)

Exposure and plastic-tube boring in NW corner of Oakwood borrow pit, 0.15 mile ENE of State Road 615, 0.25 mile south of railroad tracks, 0.85 mile SE of Oceana, City of Virginia Beach, Princess Anne 7.5-minute quadrangle (Plate 1), latitude 36° 50′ 05″N., longitude 76° 00′ 36″W. (Figure 2). Elevation of top of section is 25 feet.

Londonbridge Formation, sand facies

Top of exposed section

Silt, black, fine sandy; organic (topsoil)	0.1
Sand, yellowish-brown, fine to medium, clayey; clay content decreases with depth (clay-enriched subsoil)	3.5
Sand, yellowish-brown, medium to coarse; trace of clay; color grades to pale yellow and grain size becomes fine with depth	3.2
Sand, fine to medium; trace of coarse; trace of clay; light-brown to very dusky-red mottling resembles burrows	1.0
Sand, white, medium to coarse; layered with reddish-brown, medium to very coarse sand; trace of clay or organic material; beds 0.1 to 0.5 foot thick	4.9
Sand, pale-yellow; coarse to very coarse; some medium; some very small gravel; well sorted	1.3

Top of boring

Sand, yellowish-brown, fine to coarse; trace of clay	1.3
Clay and fine to coarse sand, yellowish-brown	0.8
Sand, yellowish-brown, medium to coarse; trace of fine; trace of clay	0.5
Sand, light yellowish-gray, medium to coarse; layered with light-yellow, medium to very coarse sand; beds 0.1 to 0.2 foot thick	0.8
Sand, very light-gray, fine to very fine; trace of medium to coarse	3.0
	(base of boring)

SECTION P: LONDONBRIDGE FORMATION

(REFERENCE SECTION, CLAYEY-SILT FACIES)

Exposure and plastic-tube boring in ditch on east side of State Road 632, 0.6 mile south of State Road 635, 0.95 mile SSW of Londonbridge, City of Virginia Beach, Princess Anne 7.5-minute quadrangle (Plate 1), latitude 36° 49′ 43″N., longitude 76° 03′ 10″W. (Figure 2). Elevation at top of boring is 16 feet.

Sand Bridge Formation

Top of exposed section

Upper member, silty-clay facies

Silt, mottled pale yellowish-brown to olive-gray, clayey; fine sandy clayey silt below 2.2 feet; gradational basal contact	4.0

	Thickness Feet
Lower member (4.1 feet)	
Sand, brown, fine to medium, silty, compact; irregular pockets of white, well-sorted fine sand; basal 0.1 foot reddish-brown	2.6
Sand, gray, fine; trace of silt	1.5
Top of boring	
Londonbridge Formation (11.9 feet)	
Sand facies (4.2 feet)	
Sand, orange; medium to coarse	0.9
Sand, gray, fine to medium; trace of clay and silty fine sand, horizontal laminae; two thin (0.2 to 0.3 foot) laminae of yellow, medium to coarse sand with trace of small gravel; gradational basal contact	3.3
Clayey-silt facies (7.7 feet)	
Silt, bluish-gray to light bluish-gray; fine sandy; clayey; and silty clay, thinly interlaminated; very soft; sharp basal contact	7.7
Norfolk Formation	
Upper member, silt facies	
Sand, gray, fine; trace of medium; highly silty; compact	1.7
(base of boring)	

SECTION Q: SAND BRIDGE FORMATION
(TYPE SECTION, UPPER AND LOWER MEMBERS)
NORFOLK FORMATION
(REFERENCE SECTION, UPPER MEMBER, SILT FACIES)

Exposure and plastic-tube boring in ditch on south side of State Road 627, 0.1 mile SE of intersection with State Road 645 (Powells Corner), City of Virginia Beach, Princess Anne 7.5-minute quadrangle (Plate 1), latitude 36° 48′ 44″N., longitude 76° 05′ 48″W. (Figure 2). Elevation of ground surface is 12 feet. A borrow pit was opened a few hundred feet southwest in 1966, where the lower member of the Sand Bridge Formation is fossiliferous (written communication, P. E. Drez).

Sand Bridge Formation	
Top of exposed section	
Upper member, silty-clay facies	
Silt, pale yellowish-brown, clayey, micaceous, massive; grades to fine sandy silt near a depth of 3.0 feet, gradational basal contact	4.2
Lower member (3.8 feet)	
Sand, gray, fine, silty, massive	2.0
Top of boring	
Sand, mottled light bluish-gray and yellowish-brown, fine silty	0.6
Sand, bluish-gray, fine, massive; sharp basal contact	1.2
Londonbridge Formation, clayey-silt facies (4.5 feet)	
Silt, bluish-gray, very fine sandy, massive	0.8
Sand, bluish-gray, fine; trace of silt; 5 to 6 percent opaque minerals	0.2

	Thickness Feet
Silt and fine silty sand, thinly interlaminated, very soft and soft, respectively; bluish-gray to light bluish-gray; sharp basal contact	3.5
Norfolk Formation	
Upper member, silt facies	
Sand, bluish-gray, fine, silty, compact, massive	2.8
(base of boring)	

SECTION R: SAND BRIDGE FORMATION
(REFERENCE SECTION, UPPER MEMBER, SAND FACIES)

Plastic-tube boring on east side of State Road 621, 0.15 mile north of State Road 619, 1.7 miles NE of Creeds, City of Virginia Beach, Creeds 7.5-minute quadrangle (Plate 1), latitude 36° 37′ 29″N., longitude 76° 00′ 36″W. (Figure 2). Elevation of top of section is 10 feet.

Sand Bridge Formation	
Upper member, sand facies	
Sand, brown, fine, silty; trace of clay	2.2
Sand, brownish-gray with oxidized mottles of yellowish-brown, fine, slightly clayey	1.5
Sand, light-yellow, fine; trace of medium; trace of silt; horizontal laminae; white, with 1 to 3 percent opaque minerals, below a depth of 5.0 feet	1.3
Sand, light-brown, fine to medium; trace of coarse, 1 to 3 percent opaque minerals; horizontal laminae 0.5 to 3 inches thick; compact; two thin laminae of light-gray, silty clay between 6.5 and 7.8 feet	2.4
Sand, brown, with orange in two thin, horizontal, fine-grained laminae; fine to coarse	1.5
Sand, brown, fine and fine to coarse, interlayered; 5 to 6 percent opaque minerals; horizontal laminae; oxidized shell imprint	1.6
Sand, brown, fine; horizontal laminae	1.5
Sand, brown, medium to coarse; trace fine, most laminae horizontal, some with low dips; oxidized shell imprints common	1.2
Sand, brown, fine	0.3
(base of boring)	

SECTION S: SAND BRIDGE FORMATION
(REFERENCE SECTION, UPPER MEMBER, CLAYEY-SAND FACIES)

Exposure (Coch, 1968, Plate 4, location 11) at Wilkerson Landing, NE shore of Nansemond River, 1.75 miles SW of Nansemond River Bridge (U. S. Highway 17) Nansemond County; access by private road off State Road 628; Chuckatuck 7.5-minute quadrangle (Plate 1), latitude 36° 52′ 20″N., longitude 76° 31′ 04″W. (Figure 2). Elevation of top of section is 21 feet.

Holocene sediments	
Sand, light olive-gray, silty; numerous burned and disarticulated oyster shells and some Indian artifacts of Early Woodland Culture (written communication, William McCord)	1.7

	Thickness Feet
Sand Bridge Formation (11.1 feet)	
Upper member, clayey-sand facies (11.1 feet)	
Silt, light olive-gray, sandy; irregular yellow mottling	1.0
Sand, yellowish-orange; fine; trace of silt; irregular pale-olive mottling in upper half	8.6
Sand, dusky-yellow, clayey; sharp basal contact	1.5
Yorktown Formation	
Silt, dark red, sandy; well indurated; nodular masses and laminae of ferricrete	1.8
Sand, dark yellowish-orange, fine clayey; very fossiliferous	6.1
	(exposed)

SECTION T: SAND BRIDGE FORMATION
(REFERENCE SECTION, UPPER MEMBER, SILTY-SAND FACIES)

Plastic-tube boring on south side of road leading to Bennetts Creek Nike Site, Nansemond County, just west of State Road 626, 0.85 mile south of U. S. Highway 17, Bowers Hill 7.5-minute quadrangle (Plate 1), latitude 36° 50′ 58″N., longitude 76° 27′ 44″W. (Figure 2). Elevation of top of section is 25 feet.

Sand Bridge Formation	
Upper member, silty-sand facies	
Sand, brownish-gray, medium, silty; light olive-gray and less silty downward; gradational basal contact	2.4
Lower member (3.4 feet)	
Sand, medium; trace of clay, mottles of dark yellowish-orange near base; sharp basal contact	3.4
Norfolk Formation	
Upper member, silty-sand facies	
Silt, greenish-gray, sandy; moderate blue below upper foot	3.1
	(base of boring)

SECTION U: HOLOCENE
(TYPE SECTION, DISMAL SWAMP PEAT)

Boring made with USGS (Davis)-type sampler on north side of Hamburg Ditch, 0.5 mile east of Sherrill Ditch, Gates County, North Carolina, Corapeake 7.5-minute quadrangle (Plate 1) latitude 36° 00′ 47″N., longitude 76° 00′ 52″W. (Figure 2). Elevation of top of section is 23 feet.

Holocene	
Dismal Swamp Peat	
Peat, dark reddish-brown, organic; many roots and fragments of rotted bark; humic odor; very soft; brownish-black below a depth of 5 feet; black layer of organic clay between depths of 9.8 and 10.0 feet	12.0
Peat, black, highly clayey, soft; gradational base	0.8
Lake sediments (?)	
Clay, black, peaty, soft	0.4
Clay, gray, soft	0.8
	(base of boring)

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COMMONWEALTH OF VIRGINIA
DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT
DIVISION OF MINERAL RESOURCES
James L. Calver
Commissioner of Mineral Resources and State Geologist

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C.5

GENERALIZED GEOLOGIC MAP OF INNER COASTAL PLAIN, SOUTHEASTERN VIRGINIA

Base from USGS 15-minute topographic map series, 1927 North American datum.

Geology by Nicholas K. Coch
1961 - 1967

EXPLANATION

(*In geologic sections only, not exposed)

QUATERNARY

HOLOCENE

Qhu — Undivided sediments
Beach, marsh, swamp, and stream sediments

UNCONFORMITY

PLEISTOCENE

Qsb — Sand Bridge Formation
East of Suffolk scarp
Upper member (facies designated by numbers)
(1) Estuarine and tidal-channel: clayey-sand facies.
(2) Fluvial and lagoon: silty-sand facies.
(3) Marsh and tidal-flat: silty-clay facies.
Lower member
Coastal sand, silty sand, and clayey sand (exposed only as narrow bands along streams, combined with upper member on map, but shown separately in cross section as Qsbl).

UNCONFORMITY

Qn — Norfolk Formation
Upper member (facies designated by numbers)
In Suffolk scarp
(1) Beach and dune: coarse-sand facies
West of Suffolk scarp
(2) Fluvial and estuarine: clayey-sand facies.
East of Suffolk scarp
(4) Brackish-marine: silty-sand facies.
*Lower member**
East of Suffolk scarp
Beach sand and gravel.

UNCONFORMITY

Qw — Windsor Formation
Between Suffolk and Surry scarps
Upper member
Lagoon silty sand.
Lower member
Beach- and nearshore-marine sand and gravel (exposed along streams, combined with upper member on map and in cross sections).

UNCONFORMITY

Qm — Moorings unit
(facies designated by numbers)
In Surry scarp
(1) Beach: fine-sand facies.
West of Surry scarp
(2) Lagoon: clayey-silt facies.

UNCONFORMITY

TERTIARY

(PLIOCENE?)

QTbc — Bacons Castle Formation
West of Suffolk scarp
Fluvial channel sand and gravel, floodplain silt.

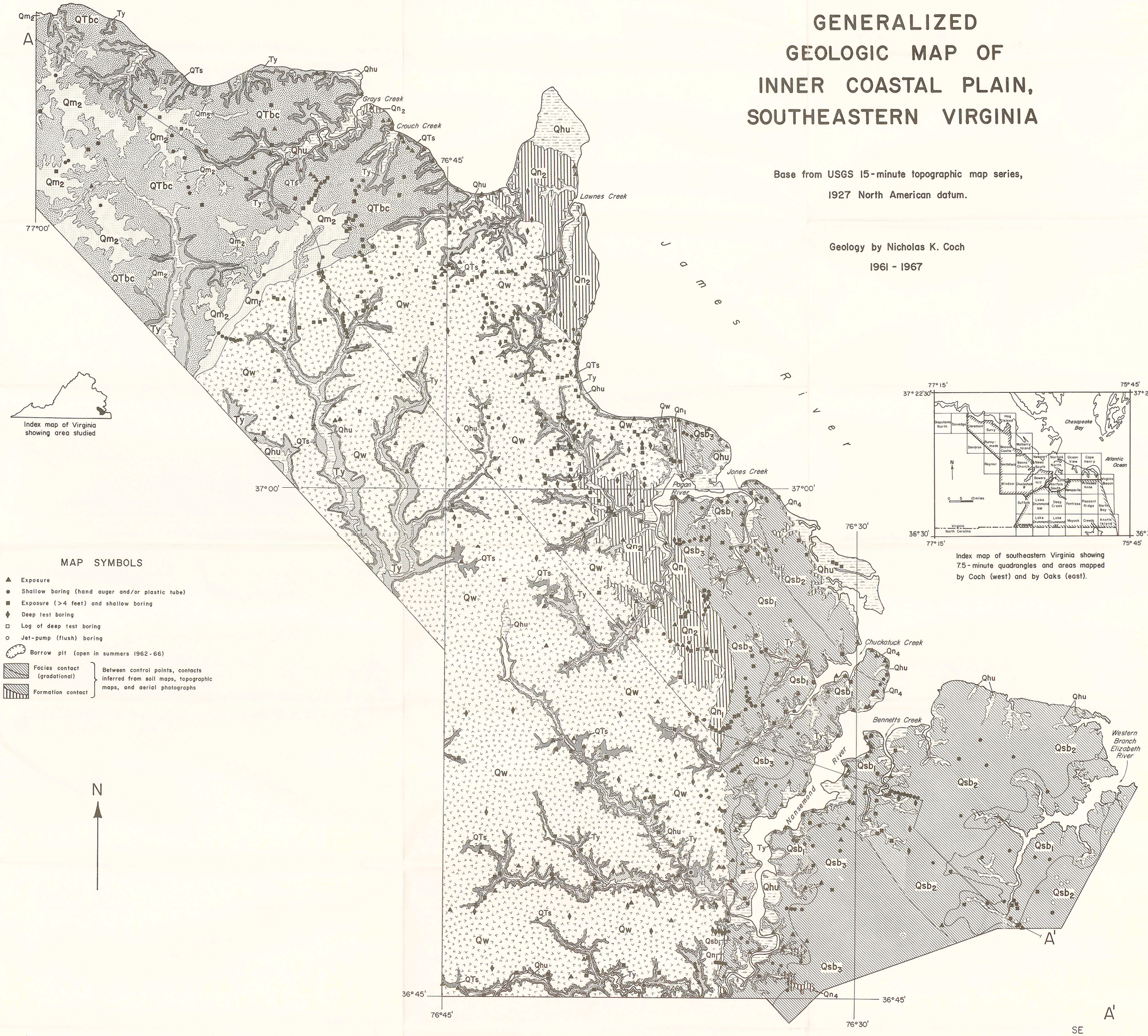
UNCONFORMITY

QTs — Sedley formation
West of Suffolk scarp
Marine and estuarine clay, silt, and fine sand.

UNCONFORMITY

MIOCENE

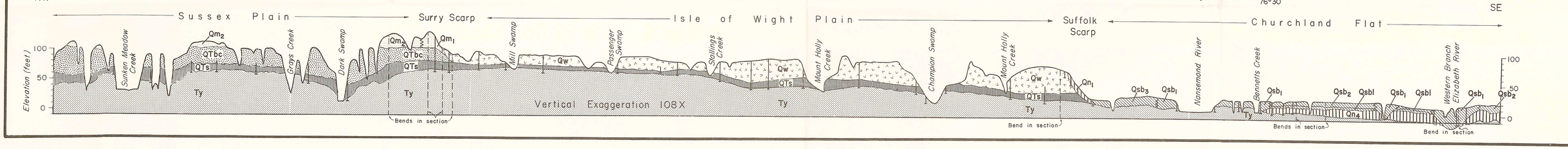
Ty — Yorktown Formation
Fossiliferous marine clay, silt, sand, and coquinite.



MAP SYMBOLS

- Exposure
- Shallow boring (hand auger and/or plastic tube)
- Exposure (>4 feet) and shallow boring
- Deep test boring
- Log of deep test boring
- Jet-pump (flush) boring
- Borrow pit (open in summers 1962-66)
- Facies contact (gradational) / Formation contact — Between control points, contacts inferred from soil maps, topographic maps, and aerial photographs

Index map of southeastern Virginia showing 7.5-minute quadrangles and areas mapped by Coch (west) and by Oaks (east).



COMMONWEALTH OF VIRGINIA
DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT
DIVISION OF MINERAL RESOURCES
James L. Calver
Commissioner of Mineral Resources and State Geologist

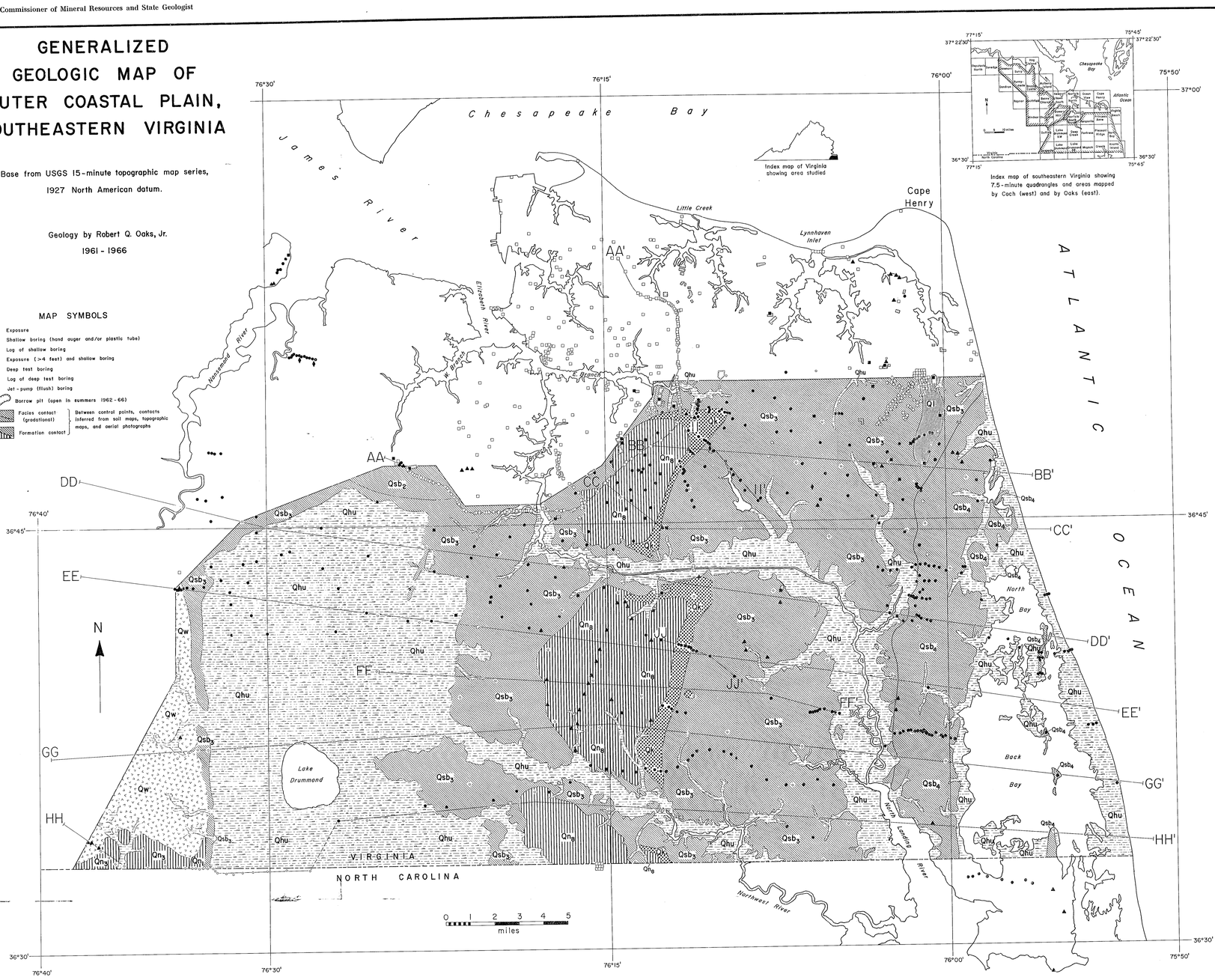
GENERALIZED GEOLOGIC MAP OF OUTER COASTAL PLAIN, SOUTHEASTERN VIRGINIA

Base from USGS 15-minute topographic map series, 1927 North American datum.

Geology by Robert Q. Oaks, Jr.
1961 - 1966

MAP SYMBOLS

- Exposure
- Shallow boring (hand auger and/or plastic tube)
- Log of shallow boring
- Exposure (>4 feet) and shallow boring
- Deep test boring
- Log of deep test boring
- Jet-pump (flush) boring
- Borrow pit (open in summers 1962-66)
- Facies contact (gradational) / Formation contact — Between control points, contacts inferred from soil maps, topographic maps, and aerial photographs



EXPLANATION

(* In geologic sections only, not exposed)

HOLOCENE

Qhu — Undivided sediments
Beach, marsh, swamp, and stream sediments

UNCONFORMITY

QUATERNARY

Qsb — Sand Bridge Formation
East of Suffolk scarp
Upper member (facies designated by numbers)
*(1) Estuarine and tidal-channel: clayey-sand facies.**
(2) Fluvial and lagoon: silty-sand facies.
(3) Marsh and tidal-flat: silty-clay facies.
(4) Barrier: Sand-ridge and Mud-flat complex.
Lower member
Coastal sand, silty sand, and clayey sand (exposed only as narrow bands along streams; combined with upper member on map, but shown separately in cross sections as Qsbl).

UNCONFORMITY (?)

Ql — Londonbridge Formation
Beach and dune sand and gravel in Oceana Ridge; lagoon clayey silt westward nearly to Suffolk scarp.*

UNCONFORMITY

Kempsville Formation
Beach and dune sand and gravel in Hickory scarp; minor marsh clay along west margin of unit.

UNCONFORMITY (?)

PLEISTOCENE

Norfolk Formation
Upper member (facies designated by numbers)
In Suffolk scarp
(1) Beach and dune: coarse-sand facies.
West of Suffolk scarp
(3) Marsh and lagoon: silty-clay facies.
East of Suffolk scarp
*(4) Brackish-marine: silty-sand facies.**
*(5) Shoreface: medium-sand facies.**
*(6) Shelf: silt facies.**
*(7) Shelf: sand facies.**
(8) Shelf: fine-sand facies.
Lower member
East of Suffolk scarp
*Beach sand and gravel (combined with upper member).**

Great Bridge Formation* (Qgb)
East of Suffolk scarp
Upper member (facies designated by numbers in cross sections)
(1) Beach sand and gravel near present coast.
(2) Lagoon silty clay in west.
Lower member
Fluvial sand, gravel, and freshwater peat along channels in top of Yorktown Formation.

UNCONFORMITY

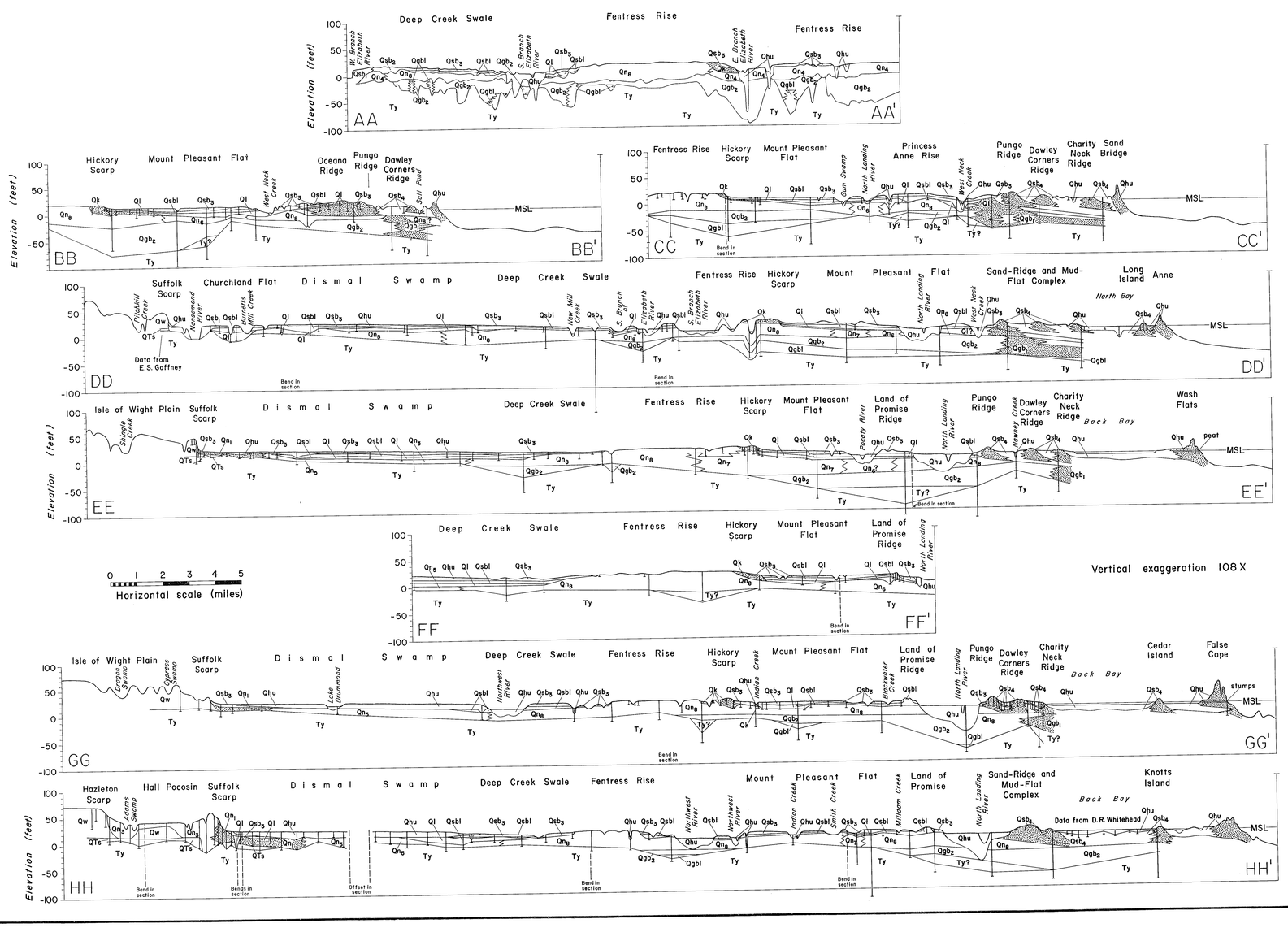
TERTIARY

Qw — Windsor Formation
Between Suffolk and Surry scarps
Upper member
Lagoon silty sand.
Lower member
Beach- and nearshore-marine sand and gravel (exposed along streams; combined with upper member on map, but shown separately in cross sections).

UNCONFORMITY

Sedley formation* (Qts)
West of Suffolk scarp
Marine and estuarine clay, silt, and fine sand.

UNCONFORMITY

MIOCENE (PLIOCENE?)

Yorktown Formation* (Ty)
Fossiliferous marine clay, silt, sand, and coquinite.