Late Mesozoic and Cenozoic Stratigraphic and Structural Framework near Hopewell, Virginia

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LATE MESOZOIC AND CENOZOIC STRATIGRAPHIC AND STRUCTURAL FRAMEWORK NEAR HOPEWELL, VIRGINIA

By JAMES B. DISCHINGER, JR.

ABSTRACT

In the Atlantic Coastal Plain near Hopewell, Va., detailed data acquired by mapping and power augering define a north-striking, east-dipping zone of reverse faults, the Dutch Gap fault zone, extending at least 13 km from the southern boundary of the Hopewell 7 1/2-min quadrangle north to the James River. The fault zone parallels the northward reach of the Appomattox River from Petersburg to Point of Rocks. As much as 20 m of vertical displacement has been recognized on the contact between the Potomac Formation (Cretaceous) and the Aquia Formation (Paleocene). Younger Tertiary units appear to be displaced less than the Paleocene sediments.

One of the faults in the Dutch Gap fault zone has been truncated by a low (3 m) Pleistocene terrace. A second fault has been truncated by a higher (35 m) Pleistocene terrace and by a unit tentatively correlated with the Bacons Castle Formation of Coch (1965) (Pliocene and (or) Pleistocene). The absence of Pleistocene or Pliocene and (or) Pleistocene displacement in these excavated exposures places an upper age limit for movement along these two faults. The age of movement may vary for other en echelon faults in this zone.

The entire Upper Cretaceous section and part of the basal Paleocene are missing in the study area. Locally, this hiatus represents a time span of about 45 m.y. Lower Cretaceous sedimentary rocks assignable to pollen zones II-A (lower Albian) and II-B (lower to middle Albian) as designated by Brenner (1963) and Doyle and Robbins (1977) crop out in the Hopewell area.

Sections of the Aquia (Paleocene) and Nanjemoy (Eocene) Formations that are entirely marine in origin crop out in the central and eastern parts of the study area. Both units and the remainder of the Tertiary marine section were deposited in a sea shallowing westward toward the present Fall Zone. The Marlboro Clay, which separates the Aquia and Nanjemoy greensands, appears to be genetically related to the Aquia Formation, rather than to the Nanjemoy Formation as previously accepted. The Calvert Formation (Miocene) is absent south of the James River in the study area. Sediments of Miocene age locally include a sparsely fossiliferous facies of the "Virginia St. Marys Formation" (see Gibson, 1982). Terrace sediments range in age from Pliocene through Pleistocene. These surficial deposits underlie at least five separate terrace surfaces. The terrace deposits are locally unconformable on all the Cretaceous and Tertiary sedimentary rocks.

INTRODUCTION

PURPOSE OF STUDY

This study was undertaken as part of the U.S. Geological Survey's (USGS) Reactor Hazards Reduction Program. One of the goals of this program is to contribute to the growing recognition and cataloging of Cenozoic faults in the Atlantic Coastal Plain. Once the faults are recognized and cataloged, the stress field and resulting tectonic framework that produced these faults can be determined. This study defines the stratigraphic and structural relationships of a tectonically anomalous area in the vicinity of Hopewell, Va.

REGIONAL SETTING

Hopewell is on the south bank of the James River at its confluence with the Appomattox River (fig. 1). In this area, the regional concurrence of linear topographic features, geophysically determined subsurface lineaments, and Cretaceous outcrops along both rivers at anomalously high altitudes suggest that Cretaceous through late Tertiary deposition and landscape development have been tectonically controlled.

Both the James and the Appomattox Rivers traverse the study area. Each descends the Fall Zone, several miles to the west, and then makes a radical course change upon entering the Coastal Plain province (fig. 1). The James River flows generally southeastward across the Piedmont into Richmond where it turns abruptly and flows southward for nearly 16 km. Downstream from this linear southward reach, the James again trends southeastward through three large meanders before its confluence with the Appomattox River at Hopewell (pl. 1). The Appomattox River likewise trends southeastward across the Piedmont until it crosses the Fall Zone in Petersburg, where it flows through a northward linear reach. About 6.5 km west of City Point, the Appomattox turns eastward before joining the James River.

The aeromagnetic map by Zietz and others (1978) provides data on subsurface rocks in the study area. Generally, the map shows a magnetic low (about 10,500 gammas) trending nearly north-south along the west side of the study area (fig. 2). A magnetic high (about 13,000 gammas) parallels the low along the eastern edge of the study area. The gradient connecting these two features corresponds to the linear belt of topographically anomalously high Cretaceous outcrops and the linear reaches of the James and Appomattox Rivers.

Similar trends are shown by the Bouguer gravity map of Johnson (1977). A negative anomaly (−5 mGal) roughly follows the western edge of the study area whereas a positive anomaly (+30 mGal) lies just to the east (fig. 3).

Ayers and Bollinger (1975, fig. 8), in a study of macroseismic and microseismic ground motions in Virginia, showed an east-west trending, intensity-VI isoseismal along the southern part of the State, with a north-trending, intensity-VI salient along the Fall Zone. They noted that this salient may reflect the contrasting sediment and bedrock lithologies at the contact between the Coastal Plain and the Piedmont geologic provinces.

METHOD OF INVESTIGATION

Detailed mapping of the Coastal Plain stratigraphic units, ranging from Cretaceous through Quaternary, was done at 1:24,000 scale. The mapped area—hereinafter called the study area—includes parts of the Hopewell, Westover, Chester, Dutch Gap, and Drewrys Bluff 7 1/2-min quadrangles. Most of the mapping was done using exposures along the banks of the James and Appomattox Rivers and their tributaries. Additional information was gleaned from quarries and borrow pits. Several lithologic logs from deep water wells were provided by the Virginia Division of Mineral Resources. One auger hole traverse was obtained from a local quarry operator, and 26 power-auger holes were drilled by the author. In addition, two trench sites were excavated (pl. 1) to determine the style of deformation and an upper age limit for movement along the Dutch Gap fault zone.

ACKNOWLEDGMENTS

This study stems from a Master's thesis completed at the University of North Carolina at Chapel Hill (UNC-CH) in 1979 under the direction of Walter H. Wheeler. Many people have added substantially to the accuracy and completeness of this report by contribution and review of material on individual subjects.

I am thankful to Wayne L. Newell (USGS) for his critical review of this manuscript and for his suggestions throughout the project, and to David C. Prowell (USGS) for his review, for his aid in the development of this study, and for his advice in the field concerning faulting styles. Roy L. Ingram (UNC-CH) consulted with me in the field on facies relationships within several of the formations. My thanks go also to John M. Dennison (UNC-CH) for his ideas concerning photographic techniques and the presentation of my cross-section data; to Eugene K.

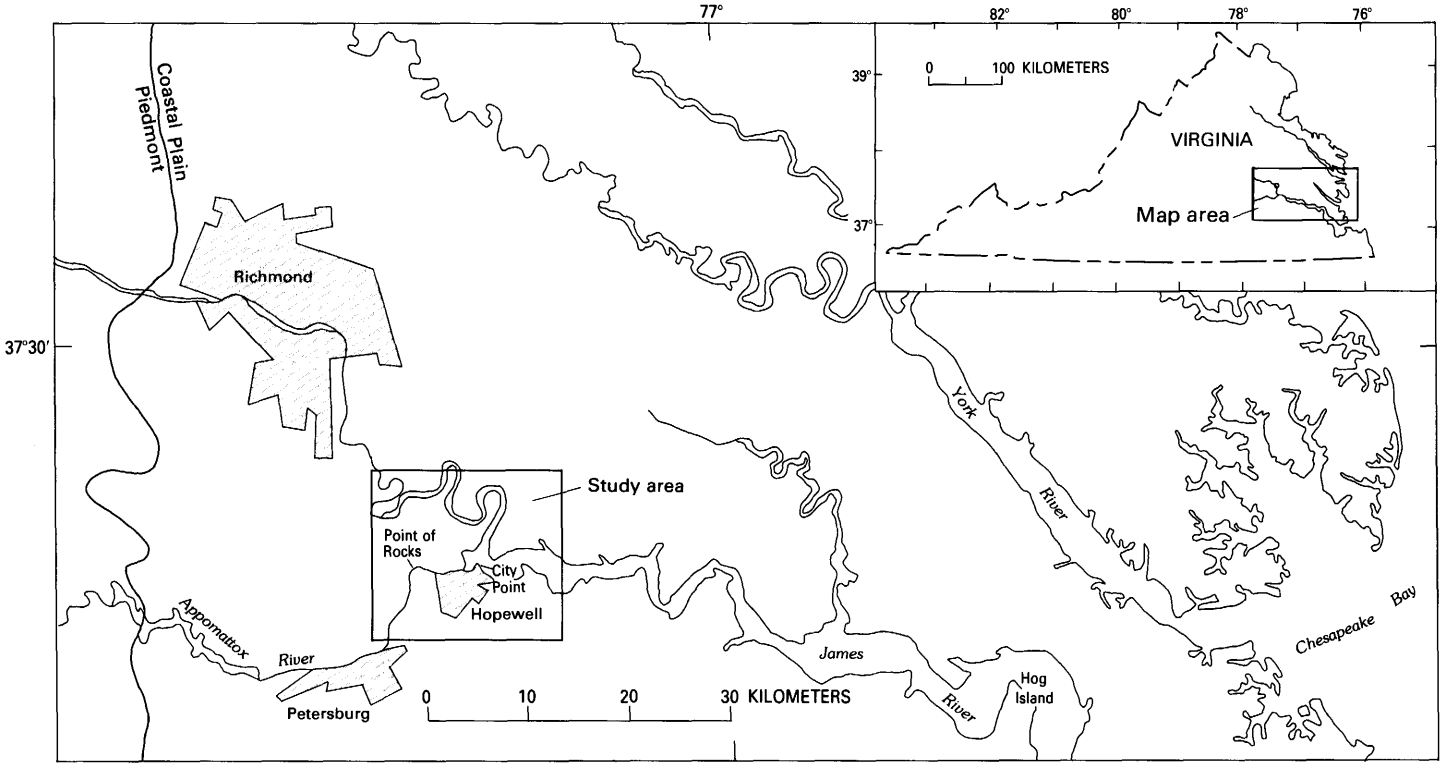

FIGURE 1.—Location of study area.

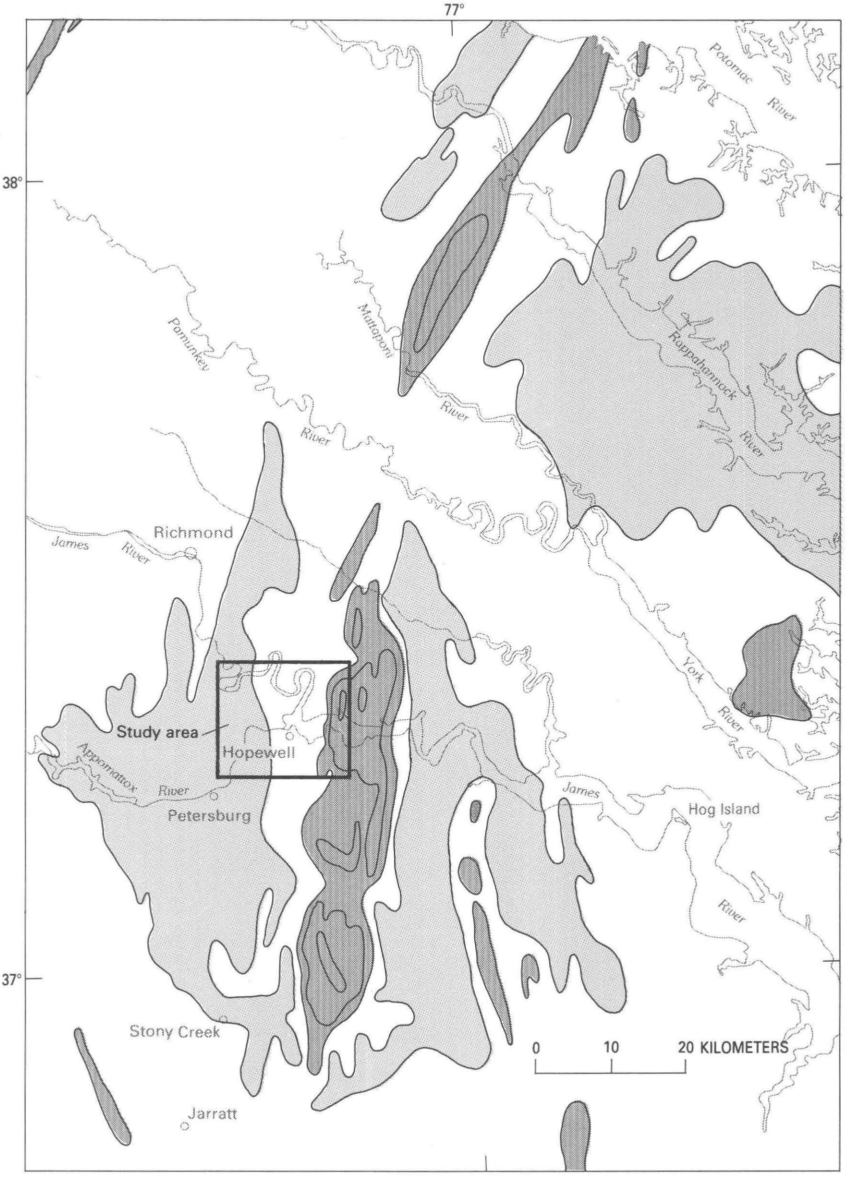

FIGURE 2.—Relation of major aeromagnetic trends to study area. Magnetic highs are dark-shaded, and magnetic lows are light-shaded (modified from Zietz and others, 1978).

Rader (Virginia Division of Mineral Resources) for his assistance in the field and for the use of water well data logged by the Virginia Division of Mineral Resources; to Joseph G. Carter (UNC-CH) for his

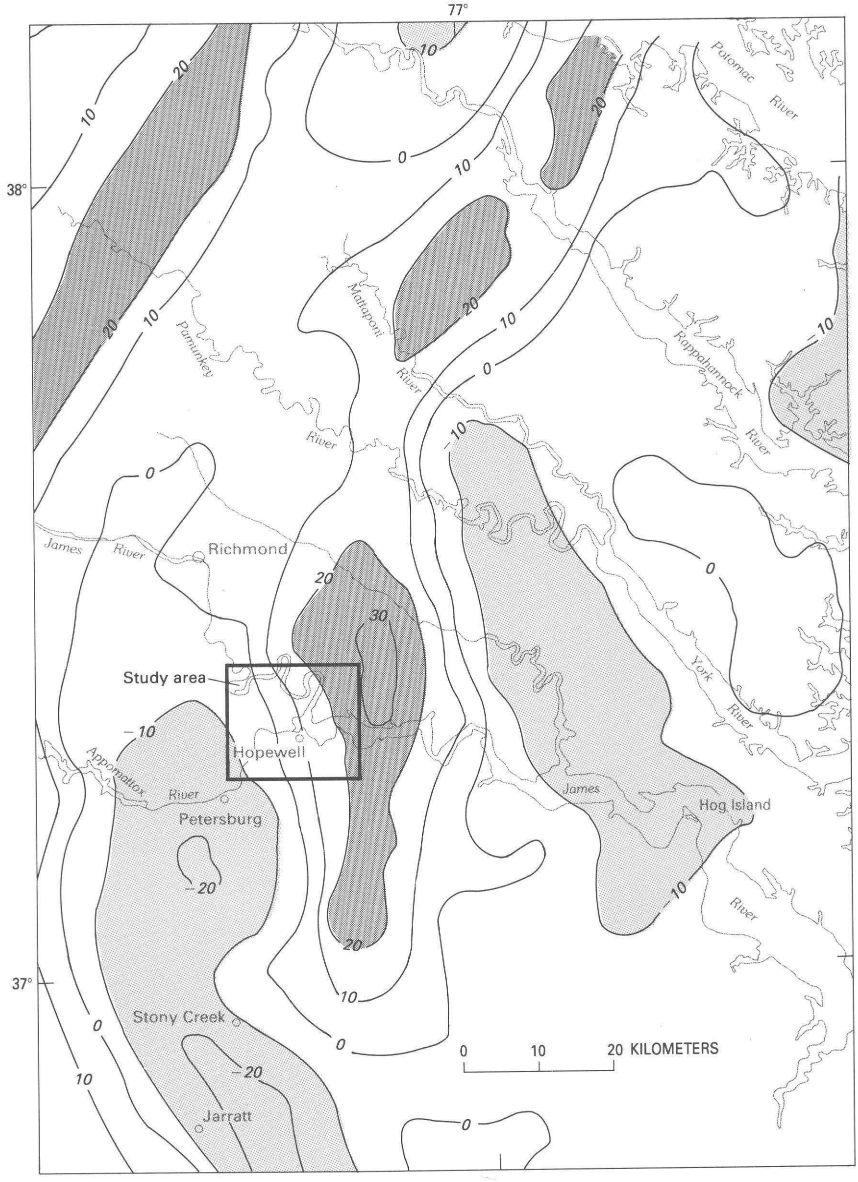

FIGURE 3.—Relation of major Bouguer gravity trends to study area. Gravity highs are dark-shaded, and gravity lows are light-shaded (modified from Johnson, 1977). Contour interval, 10 mGal.

assistance in identification of Tertiary mollusks; to Raymond A. Christopher (USGS) for palynologic work on my Cretaceous samples; to Thomas R. Worsley (Ohio University) for nannofossil identifications for several Paleocene and Eocene suites; and to W. Burleigh Harris (UNC-Wilmington) for glauconite age dating of several Paleocene samples.

DEFORMATION OF COASTAL PLAIN SEDIMENTS

PREVIOUS INVESTIGATIONS

Most of the early stratigraphic and structural studies of this updip part of the southeastern Virginia Coastal Plain were done by Darton (1891, 1911). He noted possible displacements in sediments of the Potomac Group (now of formation rank in Virginia) near Richmond and Petersburg. Stephenson (1928) wrote: "in addition to the general tilting (of the Coastal Plain units), there was broad differential warping along axes at right angles to the trend of the Coastal Plain, which has produced the lobelike overlapping of younger formations on older formations in the downwarped area."

Cederstrom (1945a, p. 53) expanded on Stephenson's observations and identified "a broad pre-Miocene, transverse, synclinal axis in Virginia, extending from the vicinity of Stoney Creek and Jarratt to the southeastern corner of the State, on the basis of the Miocene overlap which extends farther inland at these localities than it does in northern Virginia or in northern North Carolina." Cederstrom also thought that a basin, controlled by basement faulting, occupied the area immediately north of the present James River from Hampton Roads northwestward at least as far as Hog Island, Surry County (fig. 1).

Cederstrom (1945b) believed that post-Late Cretaceous channeling generally paralleling the present James River valley probably accompanied the faulting. He also suggested that excessive thicknesses of Eocene greensands had accumulated in the early Eocene or pre-Eocene basin north of the James. Cederstrom included as Eocene what are now known to be both Paleocene and Eocene units, and, therefore, his ideas of channeling, penecontemporaneous faulting, and excessive basin filling encompass Paleocene as well as Eocene deposition.

Cederstrom (1945a) also cited the earlier work of Clark and Miller (1912) in which they observed that at Point of Rocks on the Appomattox, Cretaceous strata rose to an altitude of about 25 m above sea level, and that about 1.6 km to the west (updip), Eocene strata were found nearly at sea level. Clark and Miller had not recognized faulting in this area; however, Cederstrom (p. 57) stated that "it is apparent that a part of the area west of Point of Rocks is either infolded or infaulted."

Other evidence of Coastal Plain deformation recorded during the last few decades includes a reverse fault of small throw exposed in unconsolidated sediments along the Fall Zone at Triangle, Va. (Cederstrom, 1939); a reverse fault in the Potomac Formation at Drewrys Bluff on the James River, and another along U.S. Route 1 near Quantico, Va. (Cederstrom, 1945a); basement gneiss faulted over Pleistocene terrace gravels in Washington, D.C. (Darton, 1951); and several locations of post-Cretaceous faulting in Virginia and North Carolina, particularly where faults of small displacement have cut "young" fluvial gravels (White, 1952).

In discussing the implications of the broad and gentle east-west folding and the steeper folding localized along the James River, Cederstrom (1945b, p. 91) stated that "it is likely that the post-Miocene folding is genetically related to the faults (or series of faults) which created the Eocene basin." Cederstrom thought that the compressional forces responsible for the reverse fault movements may have originated from the settling of large segments of the basement rock.

RECENTLY DISCOVERED COASTAL PLAIN FAULTS

The Brandywine fault zone in the subsurface of southern Maryland was the first true fault zone mapped in the Middle Atlantic Coastal Plain. This zone was discovered during subsurface exploration for gas storage areas, and, as currently understood (fig. 4), it includes two en echelon, east-dipping, high-angle reverse faults (Jacobeen, 1972). The throw on one of the faults exceeds 70 m; the throw on a second fault is about 30 m. The reverse faulting involves basement crystalline rocks. Maximum offset (70 m) is observed at least to the top of the Cretaceous Arundel Formation in Maryland. Jacobeen concluded that much of the fault movement occurred during the Cretaceous, but that movement continued sporadically into the Miocene. He also speculated that this fault system could represent a reversal of movement along an earlier Triassic fault system.

Mixon and Newell (1977, 1978) have documented Cretaceous and Tertiary deformation along the Fall Zone in northeastern Virginia (fig. 4). There, the Stafford fault system includes four en echelon, northeast-trending structures that extend for at least 56 km parallel to the Fall Zone. These faults are all northwest-dipping reverse faults; Piedmont crystalline rocks are faulted at high angles over much younger Coastal Plain strata. The major deformation occurred in Cretaceous through middle Tertiary time, but these authors indicate that some latest Tertiary or Quaternary movement may have occurred. Fault displacements range from 15 to 60 m.

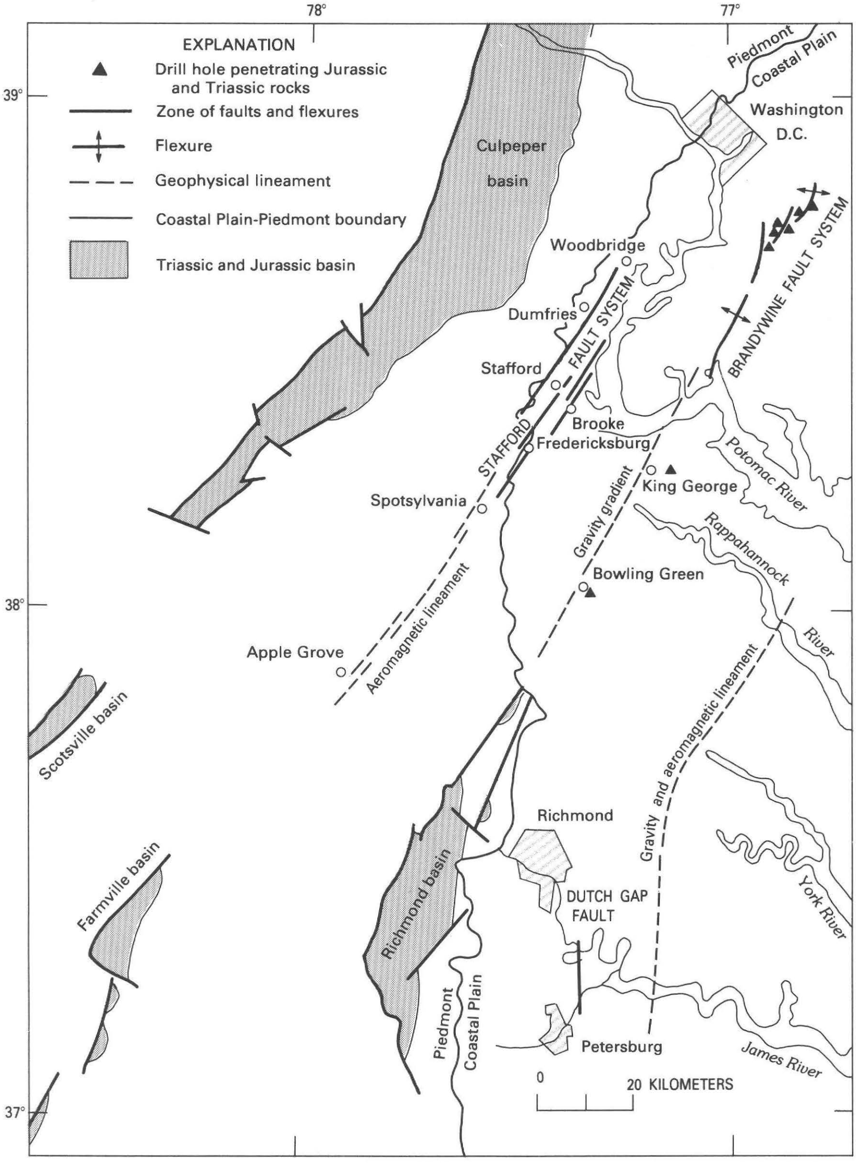

FIGURE 4.—Alinement of Stafford and Brandywine fault systems, Triassic and Jurassic basins, and geophysical lineaments (modified from Mixon and Newell, 1978).

Prowell and O'Connor (1978) delineated the Belair fault zone near Augusta, Ga., which includes a series of at least eight northeast-trending, en echelon reverse faults that cut the inner margin of the Coastal Plain in a zone at least 25 km long. Reinhardt and others

(1979) have discovered evidence for Cenozoic faulting near Warm Springs, Ga., where upper Paleocene (lower Sabinian) and younger sediments have been offset 3–10 m across several high-angle northeast- to northwest-trending reverse faults.

Collectively, these works show that high-angle reverse faulting along the inner Coastal Plain margin is apparently the rule, rather than the exception. Faults discovered at random during the last 30 years are now known to be part of a widespread fabric of reverse fault zones and are not merely curious anomalies.

PHYSIOGRAPHY

The study area includes much of the eastern part of Chesterfield County and the northern part of Prince George County adjacent to the James River (pl. 1). Most of this area consists of rolling uplands having low relief which are cut by a few narrow valleys that grade to the James River. The James is bounded by extensive flat terraces; older, high-level terraces are best preserved on flat interfluves. The terrace margins are extensively dissected. Each lower terrace is cut into an adjacent higher (older) terrace. The lower, more recent, James and Appomattox River terraces are less dissected and show surface morphologies that preserve a record of fluvial processes.

The present distribution of sediment types and surface features found in the lower terraces and along the present major drainages is the result of a complex fluvial- estuarine system. This system is within a series of linear valleys, roughly parallel to each other and all parallel to the regional slope. The deposits within the valleys are most evident along the James River, particularly in terraces II and III (pl. 1). Meander scars mark the ancient river's contact with the valley walls. On some terrace surfaces, point-bar remnants, cutoff meanders, and other features of a paleo-fluvial system can be recognized. These geomorphic features are weathered, indicating the relative antiquity of the fluvial-estuarine system.

The James and Appomattox Rivers, together with their tributaries, constitute the most recent fluvial-estuarine system. Active processes in the system now are channel flow, overbank flow and swamp and marsh development, point-bar deposition, and relatively rapid downcutting of major tributaries into the unconsolidated Tertiary sediments.

Swamp and marsh development dominates the sinuous channels of the north reach of the Appomattox River from Petersburg to Point of Rocks. Marshes are also prevalent along the James River, but not as long interchannel deposits like those on the Appomattox. Marshes along the James River are confined to the meander necks, most of which have been at least partly severed from the mainland by man-made cutoffs. Massive point bars in the meander necks have been mined for their sand and gravel deposits, and the ensuing effects of tides and storm wash have partly refilled the excavations with modern sediments.

Earlier geologic investigations interpreted the regional geomorphology. A number of terraces were observed by Clark and Miller (1912). They related each terrace to the deposition of sediments in a shallow-marine environment during successive transgressions by the sea. Clark and Miller considered all the sediments composing each terrace to be a single formation.

Modern concepts of terrace development have emphasized the recognition of facies changes within sediments composing a single terrace unit. The works of Moore (1956), Coch (1968), Oaks and others (1974), and Johnson (1969) and this study have shown that each terrace sequence changes upward from nearshore marine sediments through estuarine deposits, to sands and gravels dominated by fluvial characteristics.

Five terrace surfaces are recognized in the study area,and associated sediments may be correlative to the following formations: the Yorktown (Pliocene), Bacons Castle of Coch (1965) (Pliocene and (or) Pleistocene), Norfolk (Pleistocene), and Tabb of Johnson (1976) (Pleistocene). Additionally, Holocene alluvium and tidal-marsh sediments are present.

Repeated transgressive-regressive cycles produced the sequence of terrace surfaces shown in figure 5. Upon each successive emergence of the land following a transgression, the major rivers reoccupied those portions of their old valleys that had not been filled or cut away. Occasionally, filled valleys were recut, and smaller valleys were obliterated by these transgressive-regressive cycles. The result of renewed cutting into aggraded valley fill is readily demonstrated along the James River from Jones Neck Cutoff downstream to Bermuda Hundred. Along this reach the entire, 15–24 m of riverbank cliff exposes material that originated as aggrading fill deposited during several transgressive-regressive pulses from Miocene to Pleistocene time. The modern valley was subsequently carved into the older filled valley. Remnants of older James and Appomattox River channel and point-bar deposits are found on parts of terrace II. These sediments have been partly to completely removed by subsequent erosion and channel shifting of the modern rivers. Evidence also exists for constructive deltaic deposition from the higher part of terrace IV (IV B) to the lower surfaces of terrace IV A (pl. 1).

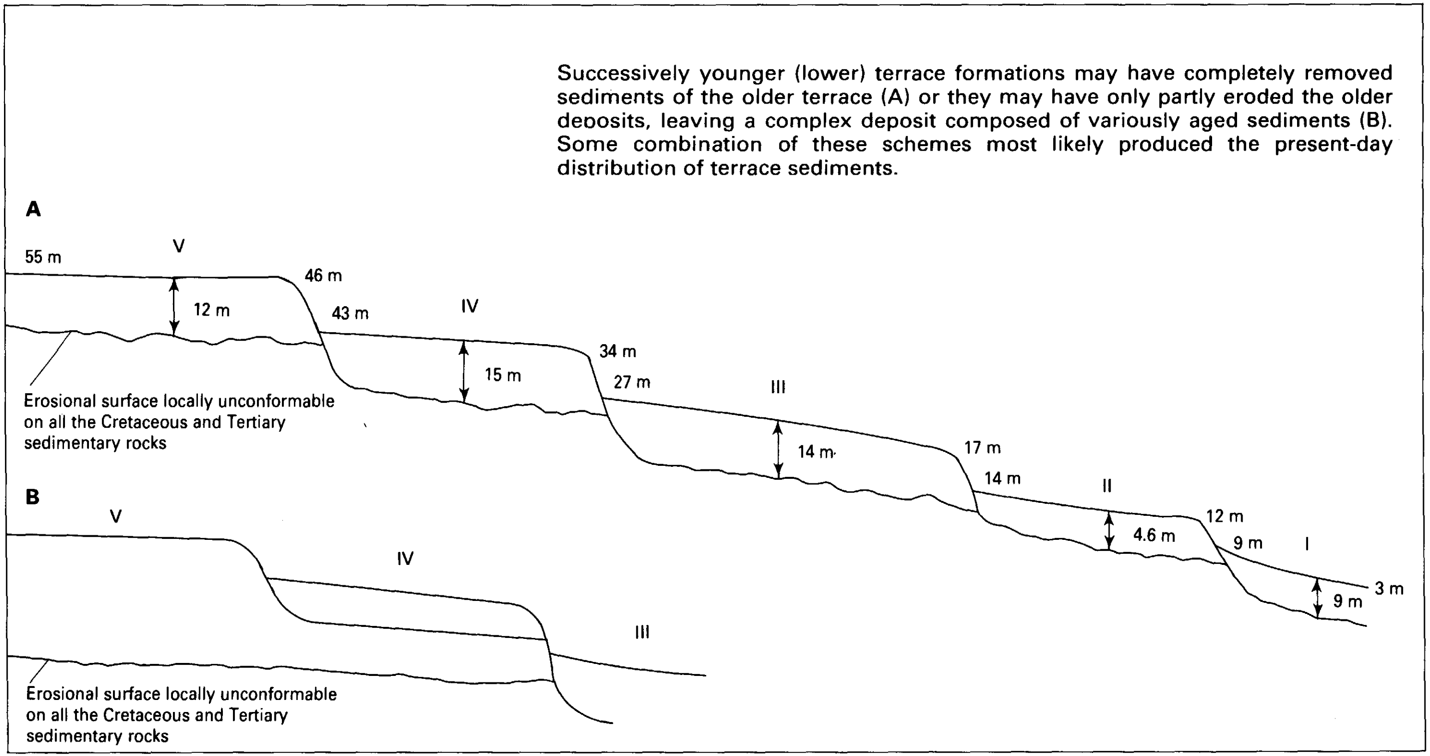

FIGURE 5.—Pliocene and Pleistocene terraces along the James and Appomattox Rivers in the study area. Altitudes are in meters above mean sea level (see pl. 1). Thickness of terrace deposits has been assumed from topographic expression.

The recutting process was established during repeated transgressive-regressive cycles. During transgression, the sea moved landward over a pre-existing erosion surface. Older sedimentary units were partly or completely destroyed and were reworked into younger deposits. Following regressions, these sediments were in turn reshaped by fluvial processes. In the study area, this pattern is present in each cycle. Each terrace has about the same thickness, with the possible exception of terrace II (fig. 5).

STRATIGRAPHY

A generalized stratigraphic column for the Lower Cretaceous through the Pleistocene section in the vicinity of Hopewell, Va., is presented in figure 6. Assignment of formation boundaries is based on lithology and supplemented by biostratigraphic zonation where possible.

The distribution of sediments in the Hopewell area is generally consistent with the regional framework established by Brown and others (1972) and by Reinhardt and others (1980a, 1980b). The entire Upper Cretaceous section and a part of the basal Paleocene are missing in the study area. The base of the Aquia Formation (Paleocene) is the most distinctive unconformity recognized in the Virginia Coastal Plain. Locally, this hiatus represents a timespan of about 45 m.y.

Lower Cretaceous sedimentary rocks, the Potomac Formation, are assignable to pollen zones II-A and II-B of Doyle and Robbins (1977) and Brenner (1963). These rocks are now known to extend southward to include the Hopewell area.

Marine sections of the Aquia (Paleocene) and Nanjemoy (Eocene) Formations crop out in the central and eastern parts of the study area. Sedimentary structures within both units, as well as within the remainder of the Tertiary marine section, indicate a rapid westward shallowing toward the present Fall Zone. The Marlboro Clay, which separates the Aquia and Nanjemoy greensands, appears genetically related to the Aquia Formation, rather than to the Nanjemoy Formation as previously accepted.

The Calvert Formation (Miocene) is absent south of the James River in the study area. Sediments of Miocene age locally include a sparsely fossiliferous facies of the "Virginia St. Marys Formation," (see Gibson, 1982) which is discussed in detail on p. 27–28. East of Bailey Creek (pl. 1), the "Virginia St. Marys" has been removed by uplift and erosion in some areas where the Yorktown Formation (Pliocene) rests unconformably on the Nanjemoy Formation (Eocene).

Terrace sediments range in age from Pliocene through Pleistocene.

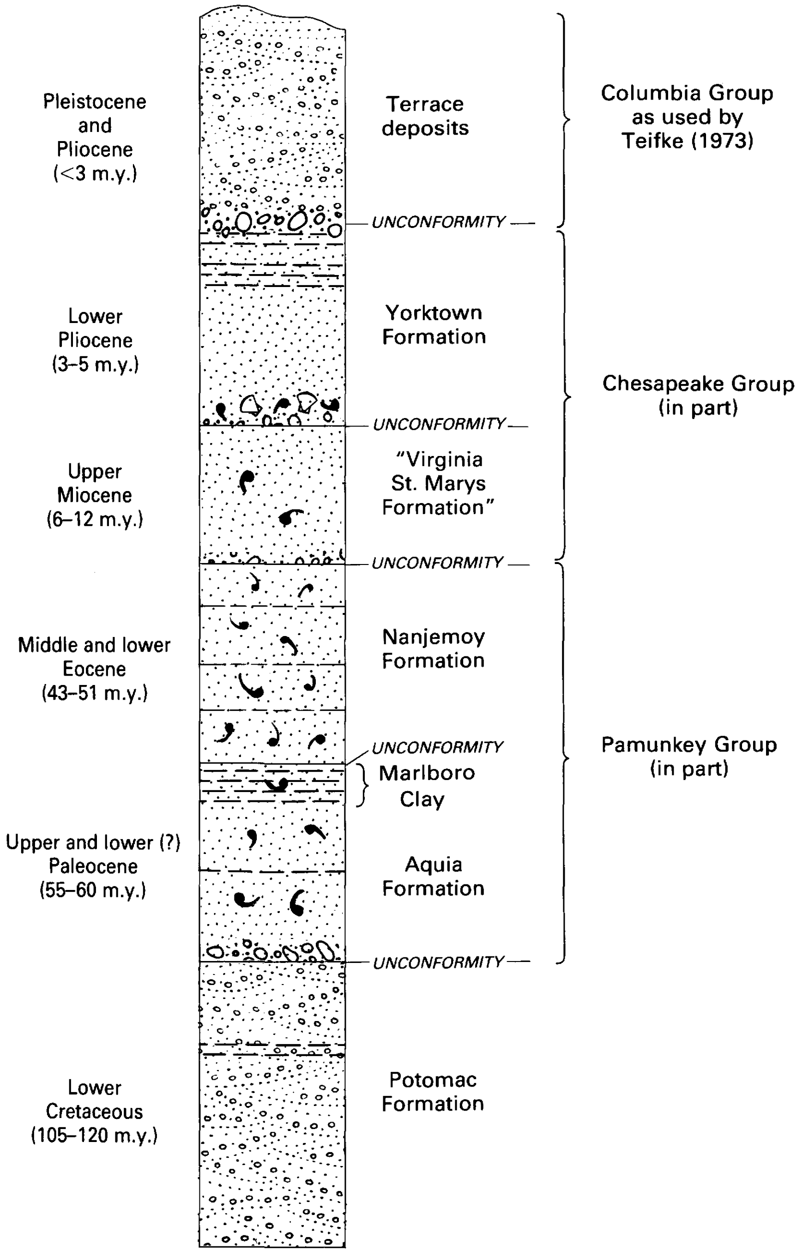

FIGURE 6.—Generalized stratigraphic column showing Cretaceous, Tertiary, and Quaternary units in the study area. Approximate depositional timespan is indicated within series.

CRETACEOUS SYSTEM—POTOMAC FORMATION

DESCRIPTION

The Potomac Formation is the basal unit of the Coastal Plain of Virginia, Maryland, Delaware, and southern New Jersey. Throughout the greater part of the Salisbury embayment, the Potomac nonconformably overlies a basement of Precambrian and Lower Paleozoic metamorphic and igneous rocks that are highly eroded and weathered to thick saprolite. The Potomac overlies Triassic and Jurassic rocks (of the Newark Group) near Doswell, Va. (Fontaine, 1896), and possibly in the subsurface of Caroline County, Va. (Cederstrom, 1945b). Several other possible occurrences of subsurface Triassic and Jurassic rocks have been noted underlying Charles, Prince George's, Wicomico, and Worcester Counties, Md. Sediments overlying the Potomac Formation vary widely in age. Overlying units include Upper Cretaceous sedimentary rocks of the Magothy and Severn Formations in northern Maryland and Paleocene, Eocene, Miocene, Pliocene, and Quaternary deposits in southern Maryland and Virginia.

The "Potomac Group," as originally defined by McGee (1885), occupied the interval between the Newark Group and the Cretaceous greensands of New Jersey and was separated from each by a hiatus. Darton (1891, 1893) and Ward (1895) retained the "Potomac Group." Clark and Bibbins (1897), introducing a terminology that has survived to the present in Maryland, divided the "Potomac Group" into four formations: the Patuxent, Arundel, Patapsco, and Raritan. These formations are not recognized in Virginia, where the entire Cretaceous section is referred to as the Potomac Formation.

In the James-Appomattox River region of Virginia, the Potomac Formation consists of alternating sequences of very light gray to white, medium to very coarse grained feldspathic sand, gravel, and silty to sandy clay. These sediments show lithologic variations over short distances, both laterally and vertically. The gravels are commonly very coarse, and the sands are often trough crossbedded and contain a considerable clayey-silt fraction. Individual sand-sized grains are mostly angular quartz, although feldspar may constitute as much as 40 percent or more of the sand grains in some outcrops.

Bedding was observed in virtually all fresh exposures of these sediments. Curved bedding planes defining lenticular sedimentation units were commonly found in gravels and crossbedded sands. Undulatory bedding is generally associated with finer grained deposits and may reflect sediment accumulation on irregular surfaces. However, the common occurrence of contorted and disrupted bedding suggests that penecontemporaneous slumping and compaction are responsible for some irregularities. The occurrence of large-scale inclined bedding in thick gravels and in interstratified coarse sands and gravels (fig. 7) is typical of sedimentation in braided river channel deposits (and in point and channel bars) (Glaser, 1969).

Clay clasts are quite common in the coarse clastic beds and may be rounded, angular, or flattened. They occur in virtually all of the gravel beds and in most of the sand units as scattered chips and are concentrated along bedding planes and the basal parts of beds. The clasts usually contain no internal structure, although some exhibit secondary Liesegang banding. Uncommonly, smaller clay balls are armored with pebbles.

Scoured and filled troughs are prevalent in the sands, and the filled channels commonly contain coarse-grained to pebbly sand, typically having concentrations of pebbles, cobbles, or clay clasts at the base. Figure 8 shows an excellent example of this type of channel fill, as exposed near Point of Rocks.

Lignitized coniferous wood and a well-preserved microflora are abundant in the gray to black clays and clayey silts of the Potomac Formation. Fragments of lignite and petrified wood pseudomorphs range in size from splinters to small logs. The wood is replaced by hematite, limonite, pyrite, marcasite, or quartz. Cellular structure is commonly preserved.

Liesegang banding is a common secondary structure in the Potomac sediments, both in the sands and the clays. Patterns of parallel, closely spaced bands of yellow, brown, or purple limonite-cemented or -coated sediment may be mistaken in the field for crossbedding in the absence of well-defined textural stratification.

Potomac gravels are composed mostly of subrounded pebbles and cobbles of vein quartz, quartzite, or quartz sandstone. A small percentage of other rocks, such as chert, thoroughly weathered pebbles of quartzo-feldspathic, gneissic, or granitic rocks, and several metavolcanic and low-grade metamorphic rock types are also found. These gravel deposits are typically interbedded with arkosic sands and at some localities contain boulders nearly 0.5 m in diameter, indicating transport and abrasion over relatively short distances. The nonresistant boulders have been weathered to saprolite.

Indurated ledges produced by clay cementation in the arkoses and subarkoses are found on well-drained slopes along the major rivers. These rocks crop out at Point of Rocks on the Appomattox River, along the south bank of the abandoned James River channel around Farrar Island, and near Halls Island on the east bank of the Appomattox River (pl. 1).

The Potomac Formation thickens southeastward across the study area from approximately 30 m along the western margin to nearly

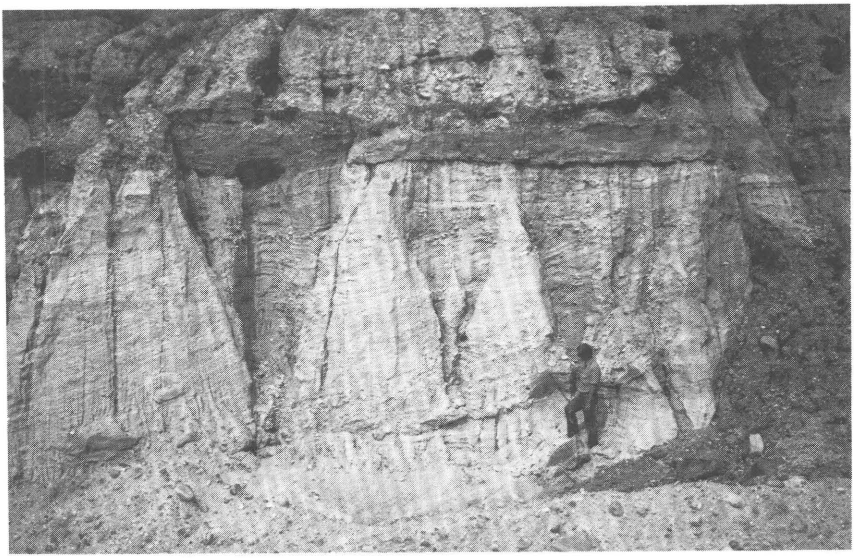

FIGURE 7.—Typical outcrop of fluvial crossbedded arkosic sands of the Potomac Formation. Dark layer near top of picture is a silty clay lens. Contact with overlying Pleistocene is 2 m above dark horizon.

107 m at the eastern edge. A major disruption in the altitude of the upper contact with the overlying Aquia Formation occurs along a line generally paralleling the north-trending reach of the Appomattox River, as shown by the structure contours (fig. 9). The upper contact dips beneath the ground surface in the vicinity of the crossing of the Appomattox River by Virginia Route 10 at Hopewell.

ENVIRONMENT OF DEPOSITION

Depositional environments within the Potomac Formation have been studied by a number of workers including Fontaine (1896), Clark and Bibbins (1897), Berry (1906, 1911), Hansen (1968), Glaser (1969), and Reinhardt and others (1980a). Clark and Bibbins (1897) concluded that the coarse basal parts of the unit indicated rapid deposition in shallow water. They envisioned the existence of an extensive sound, embayment, or estuarine environment, or combinations of these environments, along the mid-Atlantic coast. Glaser (1969) demonstrated that the Potomac sediments were deposited in a complex fluvial and deltaic environment. The petrographic and palynologic study of Reinhardt and others (1980a) suggests the migration of major fluvial-deltaic lobes progressively northward in Aptian through Cenomanian time.

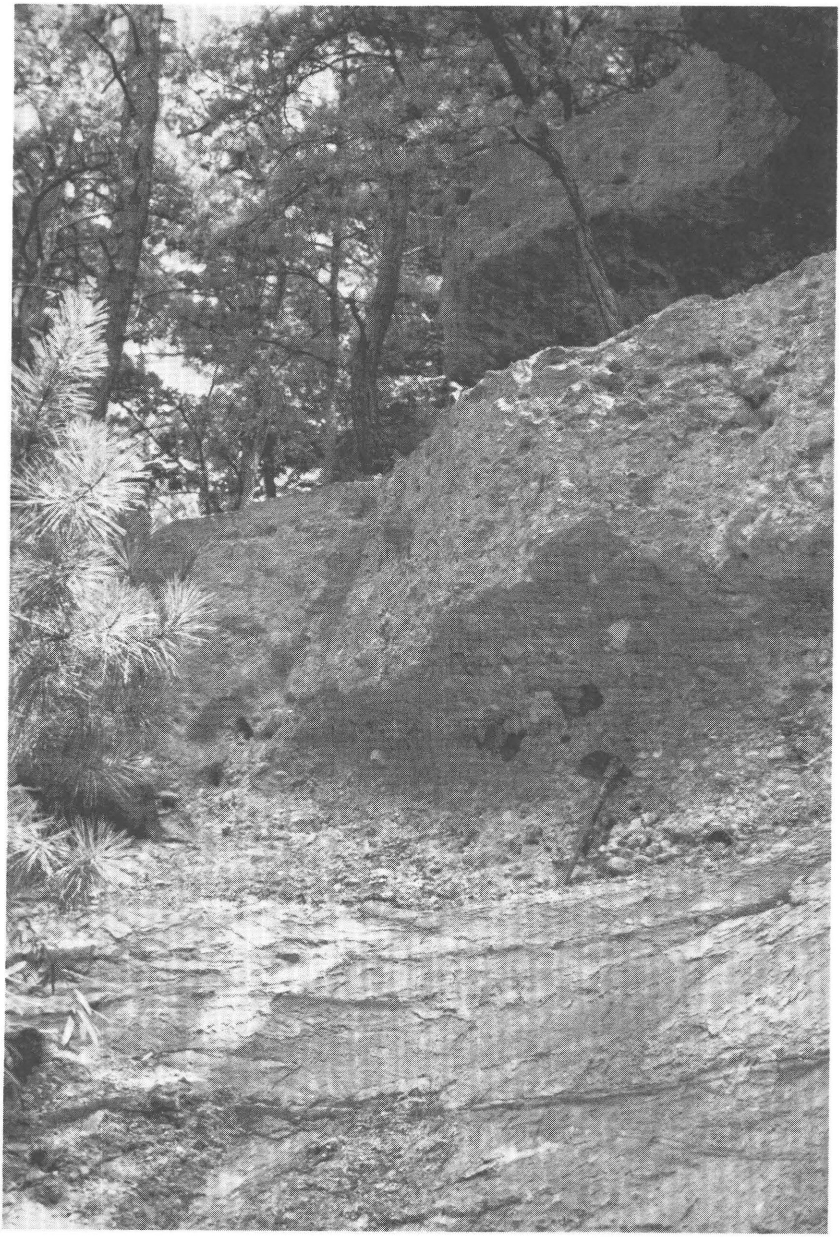

FIGURE 8.—Outcrop of indurated Cretaceous sedimentary rocks of the Potomac Formation at Point of Rocks. Note coarse channel fill near shovel.

A coarse biomodal sorting of the sediments, abundant plant fragments, scour-and-fill structures, clay-clast conglomerates, and len-

FIGURE 9.—Structure contours showing the base of the Aquia Formation. Datum is sea level. Contour interval, 10 ft. Dots represent data points.

ticular bedding all compare with the modern alluvial valley-fill of the Mississippi River, as described by Fisk (1944). The general lack of silt-clay strata in the lower part of the Potomac Formation may result from the dominance of bedload deposition and limited flood-plain sedimentation. The large-scale inclined bedding, particularly in the gravels and coarse pebbly sands, is similar to the bedding in the channel bars of braided rivers described by Doeglas (1962). Intraformational clay clasts in Potomac sands and gravels indicate rapid channel-shifts and erosion of cohesive clay banks. Perhaps rapid channel-shifting accounted for the paucity of overbank fine-grained sediment. Fining-upward point-bar and channel-bar sequences are typically truncated, further indicating rapidly shifting channels.

AGE

Analyses of pollen samples from carbonaceous clayey silts within the Potomac Formation in the study area have yielded Early Cretaceous ages equivalent to pollen zone I (Barremian to Aptian) and zone II–B (lower to middle Albian), as defined by Doyle and Robbins (1977) and Brenner (1963) (R.A. Christopher, USGS, Reston, Va., written commun., 1979). Most of the samples contained a moderately abundant and diverse terrestrially derived microflora. No dinoflagellate cysts or acritarchs were observed, indicating a lack of marine influence. One assemblage was dominated by *Classopollis torosus*, which, with the presence of monocolpate angiosperm pollen and the absence of tricolpate and tricolporate angiosperm pollen, is the primary basis for assignment to zone I (Barremian to Aptian). The tricolpate angiosperm pollen first appeared at the very top of zone I, and they dominate this and younger assemblages. The repeated absence of these species in the samples, coupled with the presence of several other guide fossils such as *Kuylisporites lunaris* and *Equisetosporites virginiaensis*, provided Christopher sufficient data for assignment to zone I.

One sample from the Sadler Materials quarry contained a low frequency of tricolpate angiosperm pollen species, including *Tricolpites albiensis, T. crassimurus, "Retitricolpites" vermimurus*, and *Tricolpopollenites parvulus*. All of these species first occur in pollen subzone II–A, and all extend into subzone II–B (lower Albian).

A sample from the Lone Star quarry yielded tricolpate grains having wider variety and greater frequency than those of the Sadler Materials quarry sample, and one species not previously recorded from below subzone II–B (*Ajatipollis sp. A*). Tricolpate grains also included *Tricolpites micromunus, T. albiensis, T. sagax, T. crassimurus, "Retitricolpites" vermimurus*, and *"R." magnificus* (?). Based on the presence of *Ajatipollis sp. A* and the higher relative frequency and greater diversity of tricolpates, Christopher placed this sample in the basal part of subzone II–B (lower to middle Albian).

PALEOCENE SERIES—AQUIA FORMATION

DESCRIPTION

The Aquia Formation rests unconformably upon the irregularly eroded surface of the Potomac Formation sediments. The Aquia is unconformably overlain by the Nanjemoy Formation (Eocene). Locally, the Aquia Formation is overlain unconformably by unconsolidated Pleistocene deposits where the Nanjemoy and (or) younger Tertiary sediments have been removed by erosion.

The Aquia Formation was named from Aquia Creek, a tributary of the Potomac River in Stafford County, Va. (Clark, 1895, 1896). The best exposures of this unit occur along lower Aquia Creek and along the south bank of the Potomac River in Stafford and King George Counties, Va.

The Aquia Formation consists of massive, greenish-gray to greenish-black, fine to very fine, well-sorted sand. It is glauconitic and typically micaceous. Pods of glauconite-rich sand occur as concentrations in burrows. Molds of pelecypods and gastropods occur abundantly in some beds, but shell material is commonly poorly preserved, except for some calcitic forms. The unit weathers to a light-greenish-gray to reddish-brown. A representative section is exposed on the south bank of the James River, just east of Bailey Creek (pl. 1). A characteristic basal gravel in the Aquia consists of a bed containing rounded quartz pebbles and glauconitic sand from 0.5 to 3 m thick. The thickest section of the gravel occurs in the Sadler Materials borrow pits on the east bank of the Appomattox River. Typically along the James River, this basal gravel is 0.6–1.0 m thick. The upper contact of the Aquia is marked by a gradual increase in the silt and clay fraction, grading to the Marlboro Clay. This contact dips beneath the ground surface in the vicinity of Jordan Point. Elsewhere downdip, indurated shell and limestone lenses occur within the unit in the subsurface. In outcrop, the Aquia Formation is about 6 m thick on the James River south of Farrar Island. Along Ashton Creek it is 9–11 m thick. Thickness increases eastward from the representative section at Bailey Creek where at least 9 m is exposed.

The Aquia Formation is the lowermost of three units included in the Pamunkey Group (Paleocene and Eocene), the uppermost unit being the Nanjemoy Formation. These two greensands are separated locally by a middle unit of thin, massive, gray to red clay, known as the Marlboro Clay.

The Marlboro Clay is an excellent marker bed in the study area. A representative section exists above the Aquia Formation just east of the mouth of Bailey Creek (pl. 1). At Bailey Creek, the clay is 3.4 m thick and varies from gray to pink. The lower contact is gradational from the glauconitic sand of the Aquia, to clay containing thin sand laminae, to the pure clay of the Marlboro over a 1-m interval. The upper contact is marked by numerous burrows filled with glauconitic sand and quartz and phosphate pebbles of the overlying Nanjemoy Formation. The relationships at the lower and upper contacts of the Marlboro Clay with the Aquia and Nanjemoy Formations respectively are observable throughout the study area. Similar occurrences are noted in northern Virginia (R. B. Mixon, USGS, Reston, Va., oral commun., 1978) and in the Oak Grove core (Reinhardt and others, 1980b). These observations indicate that the Marlboro Clay is genetically related to the underlying Aquia Formation and, more realistically, that it should be treated as a separate unit rather than be included with the Nanjemoy Formation, as had been previously accepted (Darton, 1948). Glaser (1971) and Reinhardt and others (1980b) recommended that the Marlboro be defined as a separate unit because of its lithologic continuity and mappability over a considerable area of southern Maryland and Virginia.

ENVIRONMENT OF DEPOSITION

The Aquia Formation has yielded numerous and diverse marine fossils including invertebrates, fishes, and reptiles (Clark and Miller, 1912); molluscan assemblages predominate. At some localities glauconite may represent as much as 60 percent of the sand-sized fraction of the Aquia. Teifke (1973) stated that the shape of glauconite grains in the Aquia suggests relatively slow accumulation. Clark and Miller (1912) believed that most of the Aquia was deposited in quiet and probably relatively deep water. Gibson and others (1980) found a very low diversity of only 16 foraminifera species, indicative of a shallow-marine environment, in the part of the Oak Grove core that is correlative to the Aquia in the Hopewell area. However, the grain size, sorting, and bedforms of most of the Aquia in the Oak Grove core (Reinhardt and others, 1980b) tend to support Clark and Miller's conclusions.

Gastropod and pelecypod molds and a high percentage of glauconite characterize the Aquia Formation at Hopewell. Nearshore deposition along the western part of the study area is indicated by a 3.0- to 3.7-m-thick layer of basal gravel in the vicinity of the Appomattox River and by an increase in quartz-pebble and cobble size within the greensands westward. The thick basal gravel along the Appomattox may represent the sediments of a paleo-river flowing into the shallow Aquia sea.

Nogan (1964) and Gibson and others (1980) interpreted foraminiferal data to indicate brackish water to less than normally saline water conditions at the time of deposition of the Marlboro; low dinoflagellate diversity and the abundance of two specific forms suggest an estuarine environment for the Marlboro. The presence of freshwater algae, reported by Gibson and others (1980), lends additional support for a brackish-water environment of deposition for the Marlboro Clay. These authors further suggest that the presence of a large number of fern spores in Marlboro samples indicates moist climatic conditions during deposition.

Reinhardt and others (1980b) observed that the Marlboro represents a considerable divergence in texture and mineralogy from the overlying and underlying greensands. They noted that key differences are abundant stable heavy minerals in the Marlboro, a high kaolinite content compared to the illite-and-smectite compositions characterizing the greensands, and the occurrence of reworked Paleozoic and Late Cretaceous palynomorphs in the Marlboro. They stated that these features suggest a strong extrabasinal influence. High rainfall could have produced increased runoff from low-lying and deeply weathered Piedmont and inner Coastal Plain terrain immediately to the west. This interpretation is compatible with Gibson and others' (1980) conception of a moist climate. Such an erosional event could have been responsible for a series of mudflows that blanketed the area. Deposition would have been rapid, especially in comparison to that of the greensands, and would have preserved the color and mineralogy of much of the pink Marlboro Clay (Reinhardt, USGS, Reston, Va., oral commun., 1978).

AGE

Within the coarser sands of the Aquia Formation are fragments of bone, shark and ray teeth, poorly preserved internal molds of gastropods (including *Turritella mortoni*) and pelecypods, and pelecypod shell fragments. Worm tubes and echinoderm spines were also noted in places. L. W. Ward (USGS, Reston, Va., written commun., 1978) placed the Bailey Creek Aquia section in the upper Paleocene (Paspotansa Member of the Aquia Formation) on the basis of the occurrences of *Ostrea sinuosa* and *Turritella mortoni.* Calcareous nannofossils contained within the sediments were examined by T. R. Worsley (written commun., 1979). He found a low-diversity but well-preserved assemblage of coccoliths indicating placement in zone NP 9 (Berggren, 1972) (uppermost Paleocene). The results of his findings are shown in table 1.

Sporomorph assemblages are found throughout the Marlboro Clay, and they provide the basis for dating the unit by correlation with assemblages from the Gulf Coast and southern Atlantic Coastal Plain (Frederiksen, 1979). The data suggest that the age of the uppermost part of the Marlboro is either latest Paleocene or earliest Eocene, perhaps representing slightly younger rocks than those previously studied in the southeastern United States (Gibson and others, 1980).

TABLE 1.—*Fossil listing for identified Aquia (Paleocene) species*
[Identification of nannoplankton by T. R. Worsley]

Macrofossils
Turritella mortoni Conrad
Crassatellites alaeformis (Conrad)
Calcareous nannoplankton
Discoaster multiradiatus
Zygodiscus sigmoides
Ellipsolithus distichus
Fasciculithus tympaniformis

EOCENE SERIES—NANJEMOY FORMATION

DESCRIPTION

The Nanjemoy Formation unconformably overlies the Marlboro Clay and is unconformably overlain by the Miocene "Virginia St. Marys Formation" in the western part of the study area (west of long 77°16′) and by the Pliocene Yorktown Formation east of this line. The Nanjemoy was first described by Clark and Martin (1901) along Nanjemoy Creek, a stream flowing into the Potomac River from southern Maryland. The Nanjemoy is the uppermost unit of the Pamunkey Group and consists of massive, olive-black to greenish-black, fine to very fine, moderately well-sorted, micaceous glauconitic sand. Zones of predominantly clayey silt tend to be lighter in color and contain less glauconite than the sandier zones. Glauconite-rich sands are concentrated in burrows. The unit weathers to a light-greenish-gray to reddish-brown.

Molds of pelecypods are abundant in most of the section; however, very few are preserved well enough to distinguish species. The better preserved molds are concentrated in small lenses, which commonly contain shark teeth. A representative section is found 0.8 km east of Bailey Creek, along the south side of the James River, in a gully leading down from the end of Virginia Route 644 to the river. East of this representative section, and particularly in the subsurface, the upper limit of the Nanjemoy is marked by a calcite-cemented layer 0.3–0.6 m thick. This layer contains abundant *Ostrea sellaeformis* and other shells. Locally, this limestone layer contains small-scale solution cavities. The Nanjemoy Formation thickens eastward from the vicinity of Bailey Creek, where it is approximately 14 m thick.

ENVIRONMENT OF DEPOSITION

Both the Aquia and Nanjemoy greensands represent transgressive events of some similarity in the latest Paleocene and early and middle Eocene respectively (Reinhardt and others, 1980b). Fossils are generally better preserved in the Nanjemoy than in the Aquia Formation in the study area. As with the Aquia, pelecypods and gastropods are dominant, but glauconite generally is not as abundant in the Nanjemoy as in the Aquia. Teifke (1973) found that Aquia glauconite was predominantly formed in place, whereas glauconite in the basal Nanjemoy was reworked. He noted that glauconite in the Nanjemoy showed evidence of considerable abrasion as well as slight to intense chemical decomposition, indicating either a reworking of Aquia glauconite or genesis and deposition in a high-energy environment. Nanjemoy glauconite was also commonly found to be more lustrous and coarser than the accompanying quartz grains. Gibson and others (1980) have concluded, on the basis of changes in foraminiferal faunas in the Oak Grove core, that the basal Nanjemoy greensands represent the beginning of marine transgression with water depth increasing upward in the section. They conclude further that faunas in the upper part of the Nanjemoy indicate a gradual shallowing, representing the termination of the Nanjemoy transgression.

The presence of glauconite and of a diverse microfossil assemblage, and the generally mottled (bioturbated?) appearance of these sediments, suggest a relatively slow rate of deposition. The development of diverse macrofaunal assemblages, the scattered whole (and occasionally imbricated) shell material, and the concentration of mica flakes and abraded shell debris along bedding planes support an interpretation of weak to moderate current activity within a shallow marine realm.

AGE

Bone fragments, shark and ray teeth, internal molds of gastropods and pelecypods, worm tubes, and pelecypod shell fragments occur within the Nanjemoy greensands. The better specimens are concentrated in lenses. Among the identified macrofossils are *Cubitostrea sellaeformis* (a middle Eocene guide fossil), *Venericardia potapacoen-*

sis, Meretrix subimpressa, Corbula subengonata, and *Nuculana improcera.* Worsley (oral commun.) has identified calcareous nannofossils including *Discoaster lodoensis* and *Chiasmolithus solitus.* The presence of these species and the marked absence of several other indicative forms place the Nanjemoy Formation in the early-to-middle Eocene nannofossil zone NP-13 (Berggren, 1972).

Harris (oral commun.) determined a rubidium-strontium age for seven glauconitic concentrates collected from a single Nanjemoy outcrop. The average modal age for these samples is in excellent agreement with recent European glauconite ages, suggesting that the top of the NP-13 nannofossil zone (lower-middle Eocene boundary) is at 44 m.y. However, Harris apparently did not consider that Nanjemoy glauconites are reworked; thus the age of the glauconites may not represent the age of the formation. The fossils identified in the Nanjemoy Formation are listed in table 2.

Biostratigraphic data from Gibson and others (1980) indicate that no large unconformities are present within the Pamunkey Group; however, several minor unconformities might exist. If they do exist, they are certainly not of the magnitude of the unconformity between the Early Cretaceous Potomac Formation and the late Paleocene Aquia Formation along the James and Appomattox Rivers.

TABLE 2.—*Fossil listing for identified Nanjemoy (Eocene) species*
[Identification of nannoplankton by T. R. Worsley]

Macrofossils
Cubitostrea sellaeformis Conrad
Venericardia potapacoensis Clark and Martin
Meretrix ovata Conrad
Meretrix subimpressa Conrad
Corbula subengonata Dall
Nuculana improcera (Conrad)
Calcareous nannoplankton
Discoaster lodoensis
Chiasmolithus solitus
Discoaster barbadijensis
Zygolithus dubius

MIOCENE SERIES—"VIRGINIA ST. MARYS FORMATION"

DESCRIPTION

The Miocene series is represented locally by a sparsely fossiliferous, fine-grained marine facies of the "Virginia St. Marys Formation" (see Gibson, 1982). The Calvert Formation (Shattuck, 1906) of Miocene age has been removed by erosion in the study area south of the James River (Blackwelder and Ward, 1976). Elsewhere in the Virginia Coastal Plain, the Calvert extends as far inland as Richmond and Washington, D.C.

In the updip areas west of Bailey Creek, discontinuous patches of fine-grained Miocene marine sand unconformably overlie the Eocene Nanjemoy Formation. The Pliocene Yorktown Formation unconformably overlies the marine sand. The Miocene unit was largely removed by late Pliocene to recent erosion over much of the study area.

"St. Marys Formation" is used properly as a stratigraphic term in Maryland, where it was established by Shattuck (1902) from the exposures in St. Marys County. Clark and Miller (1912) extended the formation into Virginia, and Mansfield (1943) subdivided the St. Marys Formation in Virginia into three faunal zones. Only zone 2 of Mansfield (*Crassatellites meridonalis* zone), which is younger than the St. Marys Formation in Maryland, crops out in southeastern Virginia. Beds of this age in Virginia have since been referred to as the Claremont Manor (lower unit) and Cobham Bay (upper unit) members of the Eastover Formation by Blackwelder and Ward (1976) and Ward and Blackwelder (1980). The author's tentative interpretation is that the unit exposed in the present study area is a Cobham Bay equivalent,and it is mapped as the "Virginia St. Marys Formation." The "Virginia St. Marys Formation" consists of light-greenish-gray to greenish-gray, fine to very fine, well-sorted sands that predominate in sections east of Bailey Creek. Updip from Bailey Creek, these sands are interbedded with layers of blocky clay in a suite of repeated fining-upward sequences. The sands often contain scattered small (3 mm) rounded quartz pebbles and shell ghosts of *Turritella*, *Chesapecten*, and small clams (probably *Spisula rappahannockensis*). These sands weather grayish- to yellowish-orange. Where exposed, the upper contact is marked by a lag deposit of small rounded quartz pebbles; molds of various pecten species and other mollusks occur. The shell-rich lag deposit is the base of the massive, blocky, clayey-silt facies of the overlying Yorktown Formation. The lower contact is marked by scattered, rounded, quartz and phosphate pebbles immediately overlying the glauconitic sands at the top of the Nanjemoy Formation. A representative section of the "Virginia St. Marys Formation" approximately 9 m thick is located behind the Harbor East trailer court on the south bank of the old James River channel around Farrar Island. The unit is approximately 6 m thick in a borrow pit near the intersection of Virginia Routes 646 and 156, about 0.6 km southeast of the confluence of Manchester Run and Bailey Creek. This formation was not found anywhere east of long 77° 16′ in the study area.

ENVIRONMENT OF DEPOSITION

In the eastern part of the study area, the "Virginia St. Marys Formation" was completely eroded by the trangressing sea into which the Yorktown Formation was later deposited. Miocene fossil remains, including the thick cardinal areas of *Isognomon*, abraded *Turritella plebeia* (?), *Chesapecten middlesexensis*, and others, indicate a marine to nearshore-marine environment. The suite of interbedded sands and blocky clays occurring in repeated fining-upward sequences in the western part of the study area seems to indicate shallowing to the west and more offshore conditions to the east.

AGE

The absence of identifiable, in-place fossils leaves room for speculation. Stratigraphic position and late Miocene shell remains found in the basal zone-I Yorktown sediments allow a tentative biostratigraphic correlation of this unit with the upper Miocene Cobham Bay Member of the Eastover Formation as defined by Ward and Blackwelder (1975, 1980) and L. W. Ward (USGS, Reston, Va., oral commun., 1978). A complete fossil list for this unit is included in table 3.

PLIOCENE SERIES—YORKTOWN FORMATION

DESCRIPTION

In the western part of the study area, the Yorktown Formation unconformably overlies the upper Miocene "Virginia St. Marys Formation." East of long 77°16′, the transgressing Yorktown sea completely eroded the "Virginia St. Marys Formation," and the lower part of the Yorktown lies unconformably on the greensands of the Eocene Nan-

TABLE 3.—*Fossil listing for identified Virginia St. Marys (Miocene) mollusk species*

[Occurrence of species is indicated by "x". Tsm, "Virginia St. Marys Formation," equivalent to Cobham Bay and Claremont Manor Members of Eastover Formation of Ward and Blackwelder (1980). Ty, Yorktown Formation, zones I and II of Mansfield (1943)]

	Tsm	Ty zone I	Ty zone II
Arca centenaria Say	--	--	x
Astarte undulata Say	--	--	x
Chama congregata Conrad	--	--	x
Chesapecten jeffersonius (Say)	--	x	--
madisonius (Say)	--	--	x
middlesexensis (Mansfield)	x	--	--
septenarius (Say)	--	--	x
Crepidula sp.	--	--	x
Ecphora quadricostata (Say)	--	--	x
Glycymeris subovata (Say)	x	--	--
Isognomon sp.	x	--	--
Ostrea disparilis Conrad	--	x	--
Phacoides anodonta (Say)	--	x	--
Placopecten clintonius (Say)	--	x	--
Plicatula marginata (Say)	--	x	--
Pseudochama corticosa (Conrad)	--	--	x
Septastrea marylandica	--	--	x
Teredo calamus Lea	x	--	--
Venericardia granulata Say	--	x	--

jemoy Formation (fig. 10). There the lowermost Yorktown sediments contain a mixed assemblage of late Miocene to early Pliocene fossils.

The Yorktown Formation was named by Clark and Miller (1906) from the exposures of shelly sands and clays along the York River in the vicinity of Yorktown, Va. Clark and Miller (1912) extended the formation into North Carolina. Mansfield (1943) divided the Virginia Miocene units into four faunal zones. Stephenson and MacNeil (1954) designated unfossiliferous sands and gravels in Maryland as nearshore-marine equivalents of the marine Yorktown in Virginia. Ward and Blackwelder (1980) divided the Yorktown into four members. Gravels capping the uplands in the Fredericksburg area have been interpreted as a fluvial-deltaic facies of the Yorktown Formation (Newell, 1978).

Four major lithologies occur within the Yorktown in the study area. A representative section is exposed in a steep stream bank on the east side of Virginia Route 10, 0.4 km southeast of Chappell Creek. A basal lag of rounded phosphate and quartz pebbles and cobbles, shark teeth,

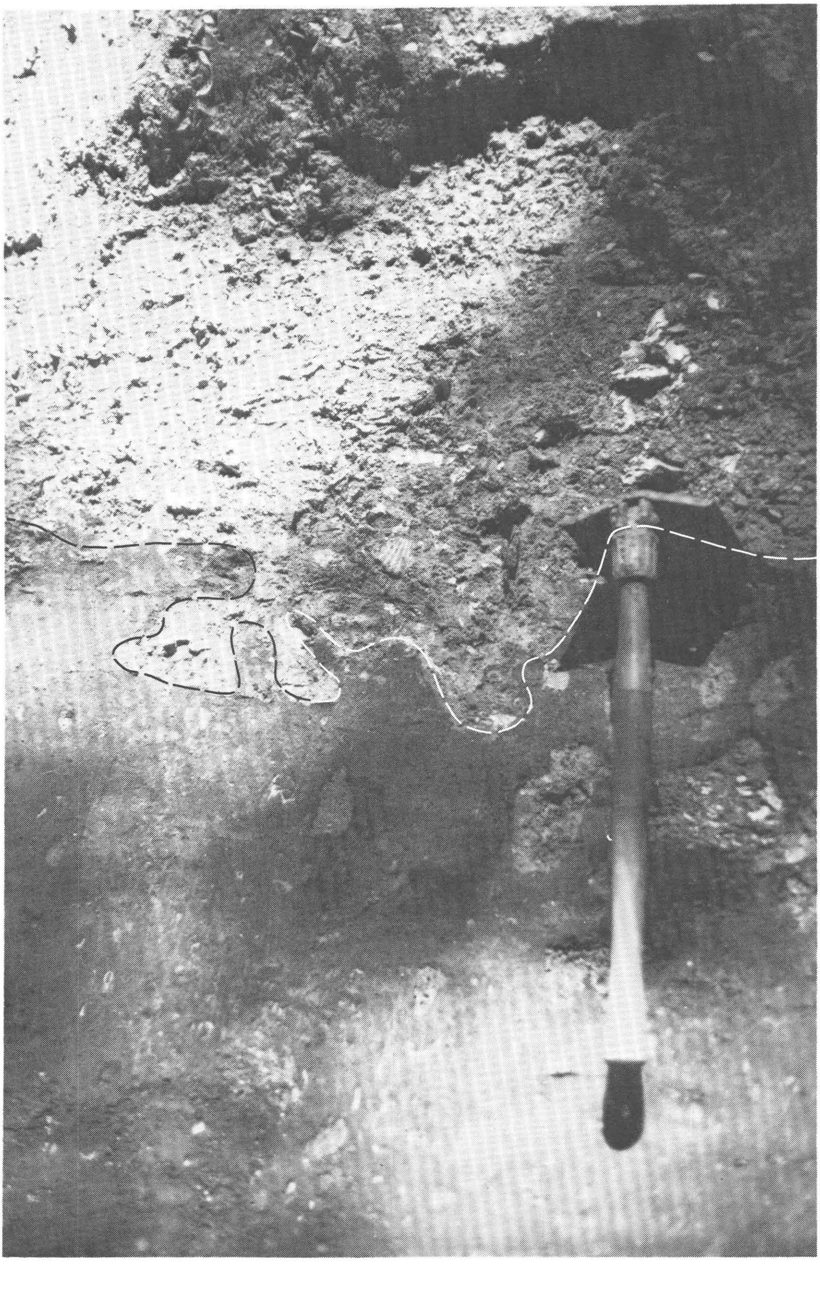

FIGURE 10.—Typical contact between darker greensands of the Nanjemoy Formation (Eocene) and overlying fossiliferous portion of the Yorktown Formation (Pliocene). Contact is highlighted by dashed line. The Miocene unit or units have been removed by erosion in a major part of the study area. Shovel shows scale.

vertebrate remains, corals, and shell debris marks the contact with the Nanjemoy. Relief on the contact is as much as 0.6–0.9 m.

The basal Yorktown is composed of a dark-greenish-gray, very fossiliferous, poorly sorted, very fine to medium sand constituting a shell hash. The macrofossil assemblage is predominantly molluscan. This basal unit is overlain by a light-greenish-gray bioclastic sand, which is very fine to fine, well sorted, and somewhat glauconitic. The bioclastic fraction consists of sand-size shell fragments, larger shell remains, and echinoderm or sponge spicules. This sand grades upward into a sequence of bluish- to greenish-gray clayey silts commonly containing gastropod and mollusk molds and (or) gray to reddish-orange, laminated, sand-clay layers and massive blocky clayey silts. In the western part of the study area, this fine-grained sequence is partly or completely missing, and the uppermost part of the Yorktown is represented by interbedded well-sorted sands having noded, clay-lined *Ophiomorpha* burrows and poorly sorted crossbedded sands containing pebble stringers. The total thickness at the representative section is approximately 18 m. The Yorktown Formation is missing over much of the central part of the study area, between Point of Rocks and Bailey Creek. For the most part, the areas west of Point of Rocks and east of Bailey Creek are underlain by a sequence of late Pliocene and Pleistocene terraces that unconformably overlie the Yorktown sediments.

ENVIRONMENT OF DEPOSITION

As noted in the lithologic description of the Yorktown, at least four facies are distinguishable. The very fossiliferous basal part, which crops out only to the east of Bailey Creek, represents a transgressing, high-energy, nearshore zone in which underlying sediments were eroded and redeposited on the basal beds of the Yorktown Formation. In the study area, this facies is about 1.5 m thick. Conformably above the basal facies is a well-sorted bioclastic sand. As shown by the preservation of echinoderm spines and some larger shell remains, this facies probably developed below the wave base. The two sediment types that overlie the bioclastic facies, clayey silt containing abundant mollusk molds and laminated sand-clay layers and blocky clayey silts, were deposited in a much lower energy environment than the underlying sands and bioclastic sands. The sand-clay layers and clayey silts probably are the result of back-bay or protected-bay deposition. The uppermost facies of *Ophiomorpha*-burrowed sands and crossbedded sands represent alternating estuarine and fluvial parts of a regressive phase of the Yorktown Formation. When viewed as a whole, the suite of Yorktown sediments reflects a transgressive-regressive series of environments ranging from the offshore shell accumulations to the estuarine and even fluvial beds near the top of the section.

AGE

Abundant macrofossils exist in outcrops of the Yorktown east of Bailey Creek (see table 3). *Placopecten clintonius, Chesapecten septenarius, Astarte undulata*, and other mollusks indicate an early Pliocene age (zone II of Mansfield, 1943) for part of this formation. In the lower transgressive part of the formation, reworked middle to late Miocene guide fossils have been retained in a basal lag and mixed with the younger transgressing sediments.

PLIOCENE AND PLEISTOCENE TERRACE SEQUENCES

At least five terrace surfaces are recognized in the study area. These surfaces border the major drainages of the James and Appomattox Rivers. The terrace surfaces range in altitude from 3 to 55 m. Four scarps, which identify the surfaces, are also recognized. Terrace materials beneath the surfaces unconformably overlie all of the Cretaceous and Tertiary units found in the area (fig. 11). These sediments constitute the youngest rocks at any given locality.

The terrace surfaces have been numbered from I to V (lowest to highest in altitude) for purposes of this report. These surfaces rise between scarps and increase in altitude westward toward the Fall Zone.

The terrace materials underlying these surfaces are primarily combinations of sandy clays, laminated clayey silts and sands, crossbedded sands, and pebble to cobble gravels, which are all typically highly oxidized to various hues of yellow and orange. These deposits are thought to represent nearshore, fluvial-estuarine depositional systems associated with the various sea-level changes that occurred during the Pliocene and Pleistocene Epochs. Some of the terrace IV sediments may represent the regressive phase of the Pliocene Yorktown Formation.

The highest terrace in the study area is terrace V. Its surface altitude ranges from 43 to 55 m (fig. 5). Slightly higher surfaces west of the study area may be remnants of this surface. The sediments underlying the terrace V surface are at least 12 m thick. They are characterized by abundant trough crossbeds, cut-and-fill structures, repeated fining-upward sequences, and truncated sequences, indicating fluvial deposition.

FIGURE 11.—Low-level (3-m altitude) Pleistocene gravels overlying kaolinitic sands of the Lower Cretaceous Potomac Formation at Jones Neck on the James River. Shovel shows scale.

The terrace-V surface encompasses the area upon which Fort Lee (south of the study area) has been built. A small part of this terrace extends northward from the south edge of the map area near long 77°14′ (pl. 1). The western part of "peninsular" Chesterfield County, roughly between the old James River channel south of Farrar Island and the

Appomattox River at Ashton Creek (pl. 1) is also covered by the terrace V surface. The material underlying this surface was called marine sand and gravel by Shaler (1890). It was also referred to by Darton (1891) as the fluvial "Lafayette Formation." Wentworth (1930) revived Clark and Miller's (1906) terminology, designating the terrace plain as the "Sunderland terrace" and the underlying materials as the Sunderland Formation. Moore (1956) returned to Rogers' (1884) earlier concepts of terrace formation in designating these deposits as the fluvial part of the fluvial-marine "Kilby Formation." More recently, Oaks and others (1974) abandoned all previous terminology, believing that the terrace and the underlying materials were not necessarily related. As a result, they named the surface the Prince George upland and the sediment underlying this surface the fluvial Bacons Castle Formation of Coch (1965).

The second-highest terrace surface (terrace IV) ranges in altitude from 27 to 43 m. Terrace IV is cut into the higher and older terrace V. This surface can be subdivided into two benches (IVa and IVb) along the east bank of the Appomattox River. Sediments underlying the surface are approximately 15 m thick and show fluvial characteristics similar to terrace V materials (fig. 12). Unlike terrace V sediments, terrace IV sediments are commonly quite feldspathic. The terrace materials are best exposed in several borrow pits along the old James River channel around the south margin of Farrar Island.

Terrace IV sediments underlie the terrain along the Norfolk and Western Railway from Kenwood subdivision to Petersburg. The headwaters of Bailey Creek cut the terrace south of Hopewell. Although the sediments underlying this plain commonly reflect a fluvial depositional environment, at several localities these deposits have marine, or at least estuarine, affinities. Generally, these deposits can be mapped as a fluvial part (regressive phase) of the Pliocene Yorktown Formation. Various earlier names for terrace IV sediments include the Columbia Group of Darton (1891), the marine part of the "Kilby Formation" of Moore (1956), the "Wicomico terrace sediments" of Clark and Miller (1906) and Wentworth (1930), and the Isle of Wight Plain underlain by the lagoonal Windsor Formation of Coch (1968; and Oaks and others, 1974).

Terrace III has surface altitudes ranging from 14 to 27 m. Sediments underlying this surface are approximately 14 m thick and are characterized mostly by fluvial sedimentary structures. The terrace extends from the Appomattox River Bridge to near Cabin Creek in Hopewell and is dissected by Johnson Creek in Chesterfield County between the James and Appomattox Rivers.

Terrace II exists as an arcuate middle land between the lower terrace of Bermuda Hundred and terrace III near the mouth of Shand Creek

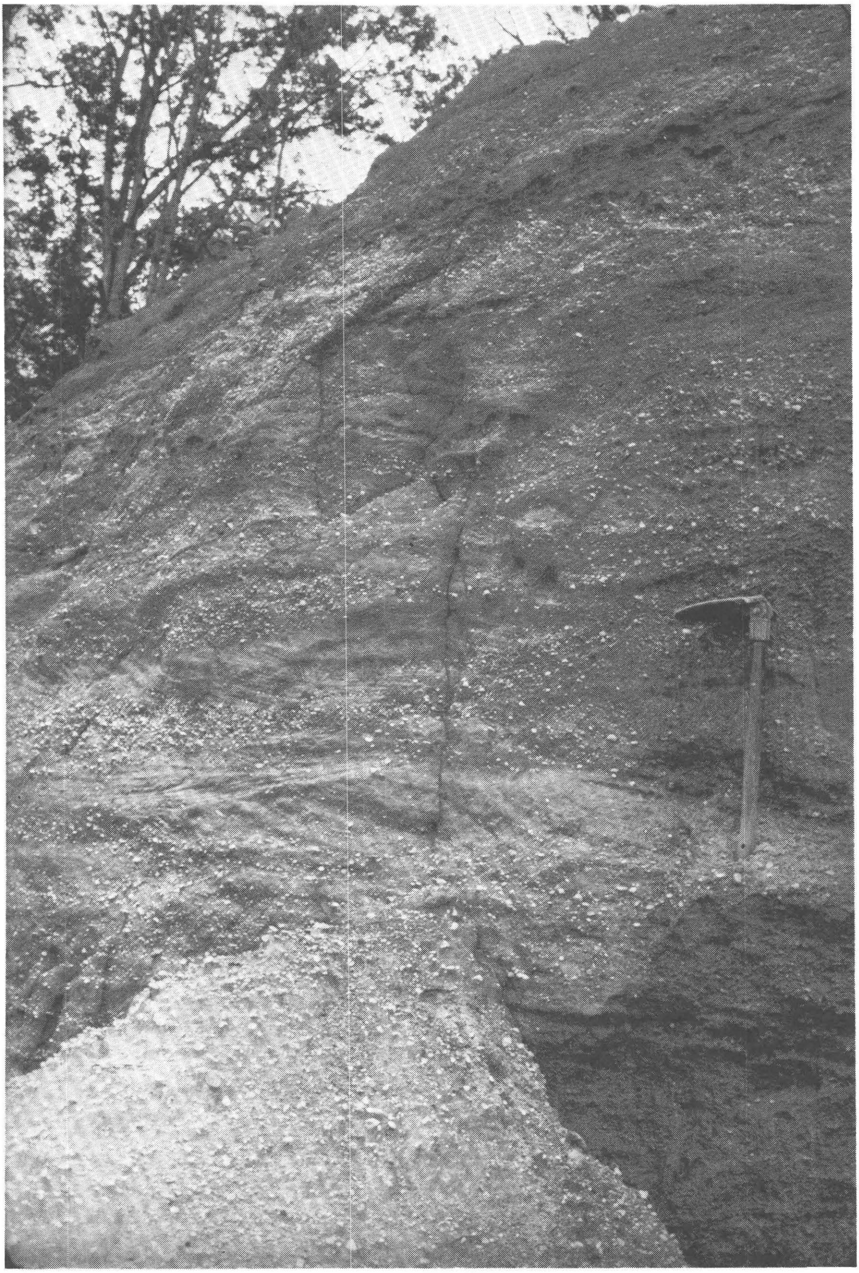

FIGURE 12.—Typical outcrop of sediments underlying the surface of terrace IV. Note trough crossbedding and gravel stringers. Shovel shows scale.

(pl. 1). The terrace II surface ranges in altitude from 9 to 14 m. Several smaller patches of terrace II occur near the mouth of Johnson Creek. The most extensive occurrences of terrace II are just above water level from Bailey Creek to City Point in Hopewell, and along the west bank of the Appomattox River south of Point of Rocks. The sediments underlying this surface have exclusively fluvial characteristics and occur in older dissected channel and point-bar deposits. The deposits define early courses of the James and Appomattox Rivers.

The lowest terrace (terrace I) ranges in surface altitude from 3 to 9 m. Terrace I generally abuts Holocene alluvial fill or a cut bank along the James and Appomattox Rivers. Terrace I sediments completely underlie Jordan Point on the James and Bermuda Hundred near the Turkey Island Cutoff, compose a major part of Curles Neck, and occupy both banks of the Appomattox south of Point of Rocks. These materials, like those underlying terrace II, are exclusively fluvial.

HOLOCENE ALLUVIAL SEQUENCE

Holocene alluvial fill, composed of clays, sands, and gravels, constitutes the flood plains of minor streams and formed as extensive point-bar and channel-bar deposits of the James and Appomattox Rivers. Organic-rich silty clays and sands formed in swamps and tidal marshes border the fluvial-bar deposits and tidal tributaries to these rivers. Spoil from dredged shipping channels, sanitary landfills, and manmade lands are locally important contributors to these sediments.

Holocene sediments range in thickness from less than 0.3 m onshore to 12 m in some manmade lands. An unknown thickness of Holocene sediments floors the James and Appomattox Rivers. Swamp and marsh deposits are typically less than 3 m thick.

STRUCTURAL GEOLOGY

STRUCTURE CONTOURS

Structure maps have been constructed on the Cretaceous-Paleocene, the Paleocene-Eocene, and the late Eocene unconformities. Control for contours is from outcrops, 26 power-auger holes, and 8 lithologically and petrographically logged water wells recorded by Teifke (1973). The contour map of the Cretaceous-Paleocene horizon is shown in figure 9. The westernmost linear zone of steep (nearly vertical) dips generally parallels the north-south reach of the Appomattox River. There, the steep gradient of the Cretaceous-Paleocene unconformity indicates a downstep of about 20 m. Across the steep gradient, the contact drops from an altitude of nearly 26 m on the east to about 6 m on the west (fig. 9). Because the contoured horizon represents an erosional unconformity (the eroded surface of the Potomac Formation prior to deposition of the Aquia Formation), the contouring reflects local relief on that unconformity. However, nowhere in outcrop does erosional relief on the Potomac-Aquia contact exceed 3 m; in fact, erosional relief commonly is less than 0.6 m. Considering that this contact where paralleling the Appomattox River has more relief, approximately 20 m (fig. 9), it is inferred that this relief actually represents the trend and offset of a fault zone, here named the Dutch Gap fault zone.

A second area of steeper gradients is shown between City Point and Bailey Creek (fig. 9). It parallels the steeper gradient area on the Dutch Gap fault zone. Perhaps the City Point-Bailey Creek zone marks the eastern boundary of an uplifted fault block, of which the Dutch Gap fault is the western boundary. The flattened area just to the east of this zone may define a graben-like structure (see cross section A–A′ on plate 2 for a graphic depiction of this interpretation). Local uplift is suggested east of Bailey Creek, because the Miocene sediments there were eroded by the transgressing Pliocene sea. This positive feature was named the Hopewell High by Ward and Blackwelder (1980).

POWER-AUGER DRILLING AND OUTCROP CONTROL

Numerous auger holes were drilled to better define the steeper structures paralleling the Appomattox River, indicated on the structure contour map. The auger data were used in conjunction with nearby outcrop control to produce a set of geologic cross sections. Three of these sections, A–A′, B–B′, and C–C′, are perpendicular to the structure-contour lines (pl. 1 and fig. 9). These sections show a single, high-angle reverse fault. Another cross section, D–D′, on the south bank of the old James River channel south of Farrar Island (pl. 1), shows that the Dutch Gap fault zone is more complex in that area. Four auger holes, 16, 26, 25, and 15, are used to correlate subsurface deposits with an extensive outcrop (H–17). As seen on section D–D′ (pl. 2), the outcrop contains exposures of Cretaceous, Paleocene, Eocene, Miocene, and Quaternary sediments. Auger hole 16 yielded only Cretaceous, Paleocene, and Quaternary samples. At this hole, the Paleocene greensands are nearly 2.5 times as thick as in the outcrop only 61 m to the west. This can be explained by an upwarping of the Cretaceous and younger sediments on the downdropped block across the fault zone (see cross section A–A′, pl. 2) accompanied by the stacking of thin slices of sediment by splays conjugate to the main fault. On section D–D′, the location of faults, dip angles, and the basal contact of the terrace sediments over the faults has been inferred based on the trenched part of this section (see enlargement, section D–D′, pl. 2).

Cross section B–B′ (pl. 2) crosses the steep gradient west of Point of Rocks. Several deeply entrenched streams flowing southward into Ashton Creek have created good outcrops. Units as young as Yorktown (Pliocene) are mapped on the downdropped block (west side), whereas only Cretaceous and Quaternary sediments occur on the upthrown block. A trenched exposure (trench I) of the fault zone was made along the line of this section on a low terrace bordering the north bank of Ashton Creek.

Section C–C′ is based in part on a line of auger holes drilled by C. G. Haag (Sadler Materials, Inc., written commun., 1978). The section crosses the steep gradient from the downdropped block on a low terrace bordering the Appomattox River to the highlands formed by the uplifted block, along which the Norfolk and Western Railway is located.

On strike with the trend of the contour lines, several smaller-scale reverse faults in the Cretaceous sedimentary rocks (probably conjugate to the main reverse faulting) can be viewed along both the James and Appomattox Rivers. The more accessible of these outcrops are found on the south bank of the James at Dutch Gap (fig. 13); along the west bank of the Appomattox directly north of Cobbs Island (fig. 14); and along the east bank of the Appomattox near the Federal Reformatory's sewage disposal plant.

TRENCHED FAULT EXPOSURES

A trenched exposure (trench I) across a part of the fault zone was made on a low terrace bordering the north bank of Ashton Creek. The purpose of the trench was to examine the style of fault movement and to determine whether or not the fault had offset the Quaternary terrace gravels. The trenched exposure was 15 m long and 10 m deep. As shown on plate 2 and in figures 15 and 16, the Dutch Gap fault zone includes splays of high-angle reverse faults that do not offset the Quaternary cover. The interpretation of cross section A–A′ (pl. 2) concurs with the fault relations observed in trench I. Upwarping of the Cretaceous–Paleocene contact, which is essentially flat for nearly 2.4 km west of the trench (cross section B–B′ on pl. 2), results in that contact rising 3.4 m over a ground distance of 9 m as the contact approaches the fault zone from the west. This evidence has been incorporated into the construction of section D–D′ (pl. 2).

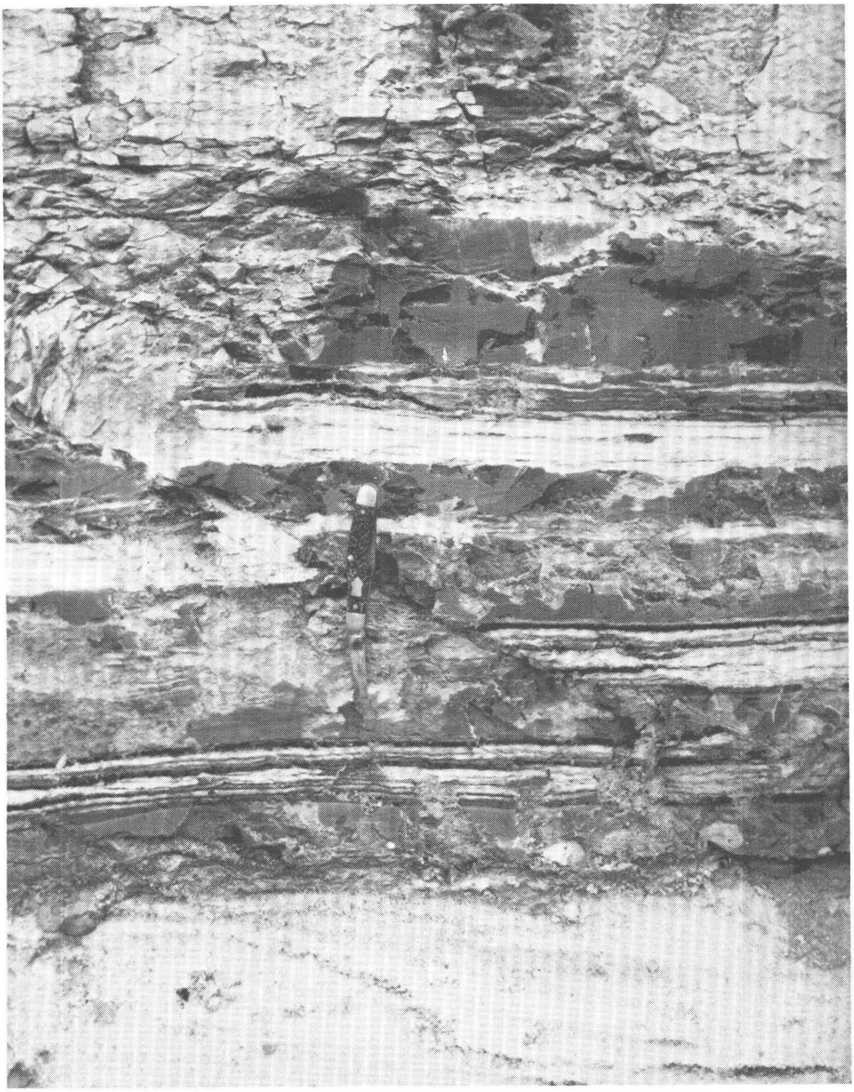

FIGURE 13.—Small-scale reverse fault in sedimentary rocks of the Potomac Formation at Dutch Gap on the James River. 15-cm knife shows scale.

A second trenched exposure (trench II) was excavated between auger holes 25 and 26 (pl. 2). As shown in the enlargement of section D-D′, the Cretaceous-Paleocene contact is offset by multiple small splays sandwiching thin lenses of the Aquia basal gravel between intervals of Aquia greensand. These splays could not be traced for any distance into the Aquia sediments. Extreme caving of the trench walls and the locally considerable depth of the Cretaceous-Paleocene contact precluded any further examination by trenching of the nature of faulting in this area.

Two units overlie the Aquia Formation in trench II. Both units have nearly planar lower contacts and show no evidence of displacement. The upper unit contains a variety of fluvial deposits and is correlated with Pleistocene terrace IV. The unit immediately above the Aquia Formation consists of a series of poorly sorted sands containing many small clay balls, thin clay lenses, and multiple fining-upward sequences and truncated sequences. This unit has been tentatively correlated with the Pliocene and (or) Pleistocene Bacons Castle Formation of Coch (1965). The vertical sequence of these two upper Pliocene to Pleistocene fluvial deposits may be explained by scheme "B" in figure 5, where the younger terrace IV sediments were deposited over a partly eroded segment of Coch's older Bacons Castle unit.

FAULTING DURING TERTIARY DEPOSITION

As seen in cross-section A–A′ (pl. 2), the Cretaceous–Paleocene contact is displaced on the Dutch Gap fault zone. Although much of the area was beveled prior to terrace deposition, enough outcrop evidence exists to indicate that faulting has continued at least through early Pliocene time.

The Nanjemoy–Yorktown (Eocene–Pliocene) contact in the vicinity of Bailey Creek occurs at an altitude of about 21 m. Regional mapping to the east shows that this contact has a dip of approximately 2 m/km to the southeast. The dip of the Potomac–Aquia (Cretaceous–Paleocene) contact in this area is about 1.7 m/km. By projecting the Nanjemoy–Yorktown contact updip to the vicinity of the Dutch Gap fault zone (about 13 km), one may infer that the lowermost Yorktown sediments there should occur at nearly 49 m altitude. However, the lowermost Yorktown sediments are actually at about 27 m altitude just west of the Dutch Gap fault zone along Ashton Creek; the base of the Yorktown Formation is 22 m below its expected altitude. Although the regional dip may flatten closer to the paleo-shoreline (westward), such flattening cannot account for all of the 22 m, whereas faulting could.

In like manner, the "Virginia St. Marys"–Yorktown (Miocene–Pliocene) contact is anomalously low across the Dutch Gap fault zone. Just south of Hopewell, along Bailey Creek, this contact occurs at an altitude of about 27 m. A projection of this contact updip (about 10.5 km, at 2 m/km) to the fault zone gives an altitude of about 48 m. Instead, the altitude found about 0.8 km west of the fault was about 26 m. Again, the difference was approximately 22 m.

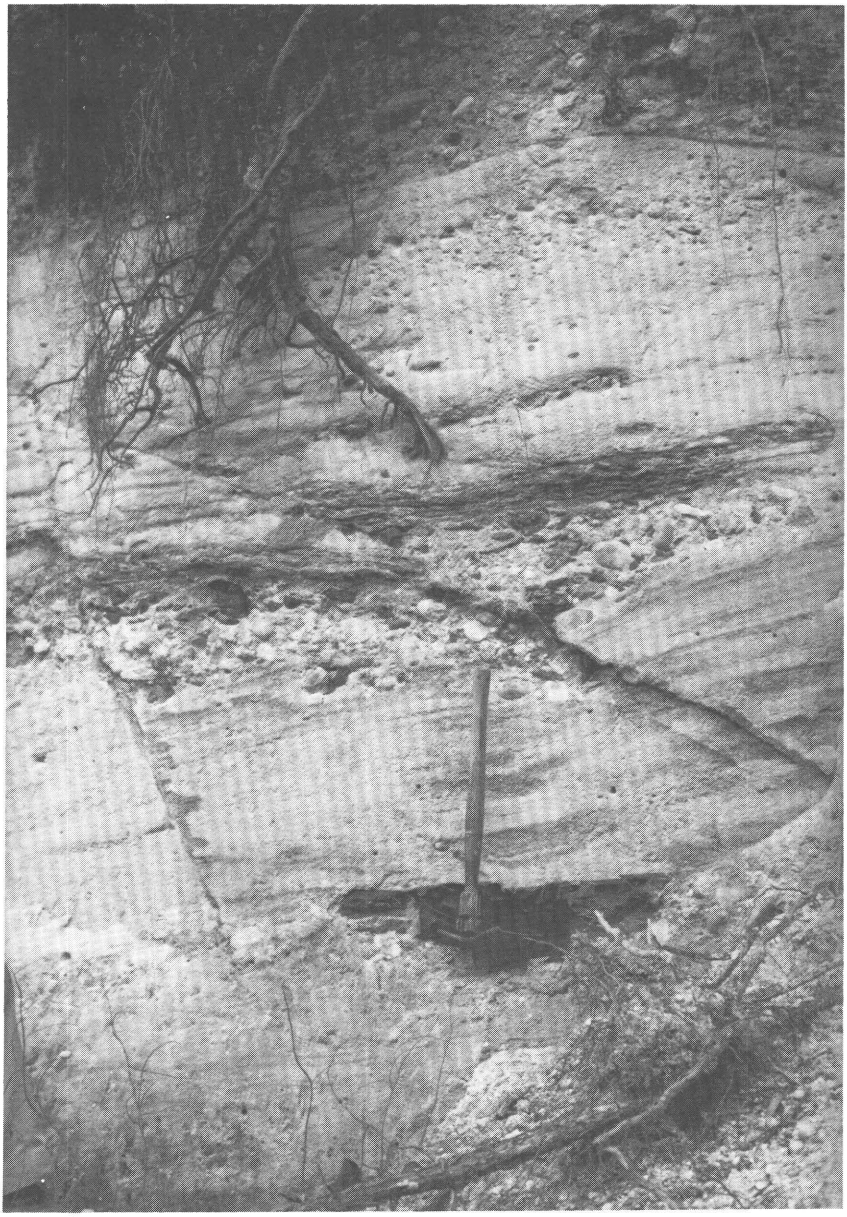

FIGURE 14.—Reverse fault in arkosic sands of the Potomac Formation along west bank of the Appomattox River. Shovel shows scale.

The well-documented offset on the Potomac–Aquia (Cretaceous–Paleocene) contact at the Dutch Gap fault zone is about 20 m (a rate of nearly 0.2 m/m.y. for the duration of Cretaceous and Paleocene time).

FIGURE 15.—View inside exposure at trench I, near the Appomattox River. Geologist's hand points to unconformity between Cretaceous sedimentary rocks and overlying Pleistocene sand ("X" in trench I diagram, pl. 2).

The postulated offset on the lowermost Pliocene sediments, caused by continued faulting, is less than 20 m, possibly 4.6–6.0 m; therefore the rate during the early Pliocene may have been as much as 1.2 m/m.y. These values suggest that the rate of fault movement in the Dutch Gap fault zone increased after Paleocene time.

COMPARISON WITH STAFFORD AND BRANDYWINE FAULT SYSTEMS

The Dutch Gap fault zone is part of a system of en echelon faults similar to the Stafford and Brandywine fault systems. The faulting near Bailey Creek paralleling the Dutch Gap fault zone has already been discussed. It is possible that the north-south reach of the James River from Richmond to Drewrys Bluff is fault controlled; if so, this structure too would parallel the Dutch Gap trend.

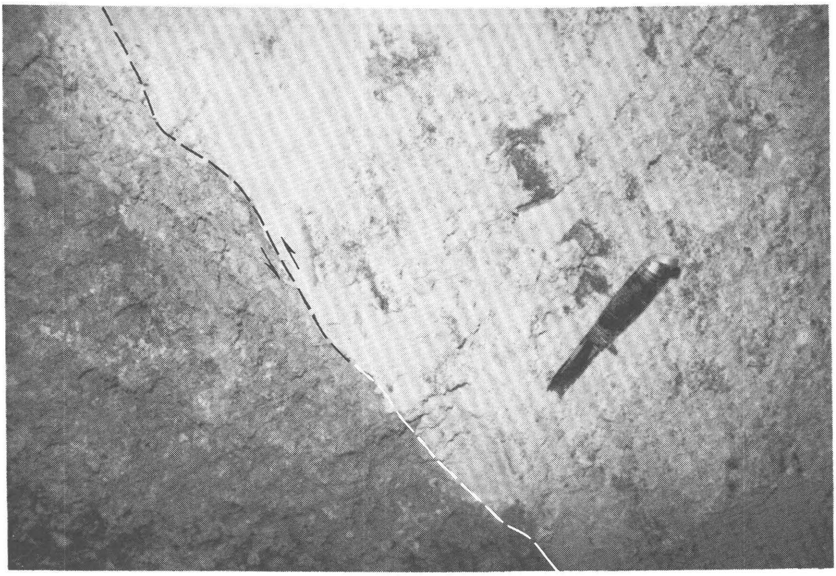

FIGURE 16.—Closeup view of fault exposed in trench I, showing kaolinitic Cretaceous sand (white, on right) juxtaposing much coarser greenish Cretaceous sand. Dashed line highlights fault; arrows indicate direction of relative movement on either side. 10-in. knife shows scale. Location of fault-view is indicated by "Y" in trench I diagram on plate 2.

The three known fault systems, Stafford, Brandywine, and Dutch Gap (fig. 4), consist of high-angle, en echelon reverse faults. The Stafford and Brandywine fault zones are known to have basement offsets; the amount of crystalline basement displacement on the Dutch Gap fault has not been determined, but must be 20 m or more. The Brandywine and Dutch Gap fault zones display up-to-the-coast (east) displacements whereas the Stafford faults are up-to-the-Piedmont (west). All of these fault zones follow known subsurface geophysical lineaments. The three zones of faulting parallel major drainage deflections in the Potomac, James, and Appomattox Rivers and are roughly parallel to the trend of the Fall Zone in their respective regions. These systems may parallel earlier Triassic fault system trends. Jacobeen (1972) and Mixon and Newell (1977) noted that subsurface geophysical lineaments seem to link parts of known Triassic trends with some of these faults (fig. 4). Triassic rocks are known from a water well near Bowling Green, Va. (Hubbard and others, 1978), along the gravity gradient coincident with the trend of the Brandywine faults. Geophysical evidence also suggests buried Triassic sediments in the vicinity of King George. Buried Triassic rocks have been reported from water wells just west of the Dutch Gap fault zone in Chesterfield County, but these reports are, as of yet, unconfirmed.

SUMMARY

Mapping has defined a north-trending zone of reverse faults (the Dutch Gap fault zone) extending at least 13 km from the southern boundary of the Hopewell 7-1/2-min quadrangle northward to the James River. The fault zone parallels the northward reach of the Appomattox River from Petersburg to Point of Rocks. As much as 20 m of vertical displacement has been recognized on the contact between the Cretaceous Potomac Formation and the Paleocene Aquia Formation. The younger Tertiary units appear to have somewhat smaller displacements than those on the Paleocene sediments. The offset on the crystalline bedrock-Potomac Formation unconformity is not yet known but must be 20 m or more, because this contact does not crop out in the vicinity of the fault zone and drill-hole data have not yet been acquired. Increasing amounts of displacement with depth represent the aggregate of many small fault movements that continued through the Tertiary.

One of the faults in the Dutch Gap fault zone has been truncated by erosion on a low (3-m altitude) Pleistocene terrace, as exposed in trench I. A second fault (exposed in trench II) has been truncated by erosion on a Pleistocene terrace 35 m above sea level and is overlain by a unit tentatively correlated with the Pliocene and (or) Pleistocene Bacons Castle Formation of Coch (1965). The absence of Pleistocene or Pliocene-Pleistocene displacement in these excavated exposures places an upper age limit for movement along these two faults; however, the age of movement may be different for other en echelon faults in this zone.

The entire Upper Cretaceous section and a part of the basal Paleocene are missing in the map area. Locally, this hiatus represents about 45 m.y. Lower Cretaceous sedimentary rocks assignable to pollen zones II–A and II–B (lower Albian and lower to middle Albian) as designated by Brenner (1963) and Doyle and Robbins (1977) crop out in the Hopewell area. Progressively younger Cretaceous sediments crop out northward along the inner Coastal Plain outcrop belt. This distribution is the basis for the rolling depocenter concept presented by Reinhardt and others (1980a), in which the areal extent of each successively younger center of deposition during Cretaceous time appears to be displaced northward into the Salisbury embayment.

The Marlboro Clay, which separates marine sections of the Aquia and Nanjemoy Formations, appears genetically related to the Aquia Formation, rather than to the Nanjemoy Formation as previously accepted.

The Calvert Formation is absent south of the James River in the study area. Sediments of Miocene age locally include a sparsely fossiliferous facies of the "Virginia St. Marys Formation." East of Bailey Creek, the Miocene sediments have been removed by erosion following uplift, and the Pliocene Yorktown Formation rests unconformably on the Eocene Nanjemoy Formation.

Several other faults or fault zones may exist paralleling the Dutch Gap trend. One such zone possibly controls the southward reach of the James River from Richmond to Drewrys Bluff. Deposition in the vicinity of Bailey Creek has also probably been structurally controlled. The Tertiary section thickens dramatically north of the James River. Cederstrom (1945b) speculated that a fault controlled that course of the James River, downdropping the block to the north. Such a fault would trend nearly perpendicular to the Dutch Gap trend.

The Pliocene-Pleistocene terrace stratigraphy has been only generally examined in this report. Correlation of the James River terraces with the marine Pleistocene stratigraphy of the Chesapeake Bay region will provide an upper time limit for movement along the Dutch Gap fault zone.

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