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Geologic Map of New Jersey: Central Sheet

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INTRODUCTION

The central bedrock sheet (scale 1:100,000) covers an area of approximately 2,300 square mi in central New Jersey. Parts of two large sedimentary basins crop out within the borders of this geologic map. The early Mesozoic Newark basin is exposed in the north, and a Cretaceous to Miocene basin is present in the south. A thin salient of Proterozoic and lower Paleozoic rocks separates the two basins in the vicinity of Trenton. Thus, rocks exposed in the central bedrock sheet range in age from Middle Proterozoic to Miocene. Younger sediments are widespread within the map area, but these are shown on a separate surficial geologic map.

Maps showing the generalized regional distribution of early Mesozoic basins and Coastal Plain basins and arches are illustrated in figure 1. The Mesozoic and Cenozoic basins contain part of the physical record of continental rifting and subsequent continental-margin development for the U.S. Atlantic margin. Rocks of the early Mesozoic Newark basin record the early rifting history of faulting, sedimentation, and magmatism. The sedimentary rocks in this basin were deposited wholly in non-marine, largely alluvial and lacustrine, environments. The rocks in the Cretaceous to Miocene basin represent a markedly different style of sedimentation. This basin largely developed due to the progressive overlap of a cooling and contracting crystalline craton by deposits formed in deltaic to marine environments. The filling of this basin (in a broad sense, the Atlantic Ocean) produced a broad continental terrace, most of which is now submerged. An emerged part of this terrace, the New Jersey Coastal Plain, is shown on the geologic map.

One notable difference between the early Mesozoic Newark basin and the Cretaceous to Miocene basin is that rocks of the Newark basin are consolidated, whereas rocks of the Coastal Plain (Cretaceous to Miocene basin) are, for the most part, unconsolidated. This physical property makes the Coastal Plain sediments particularly suitable as a ground-water source.

The bedrock geologic map is accompanied by two plates that show a Newark basin and Piedmont cross section and Coastal Plain gamma-log profiles (Plates 2 and 3). Lastly, the map was compiled using 7.5-minute geologic quadrangle maps and other maps and publications falling within the central sheet. Many of these maps are referred to in the unit descriptions.

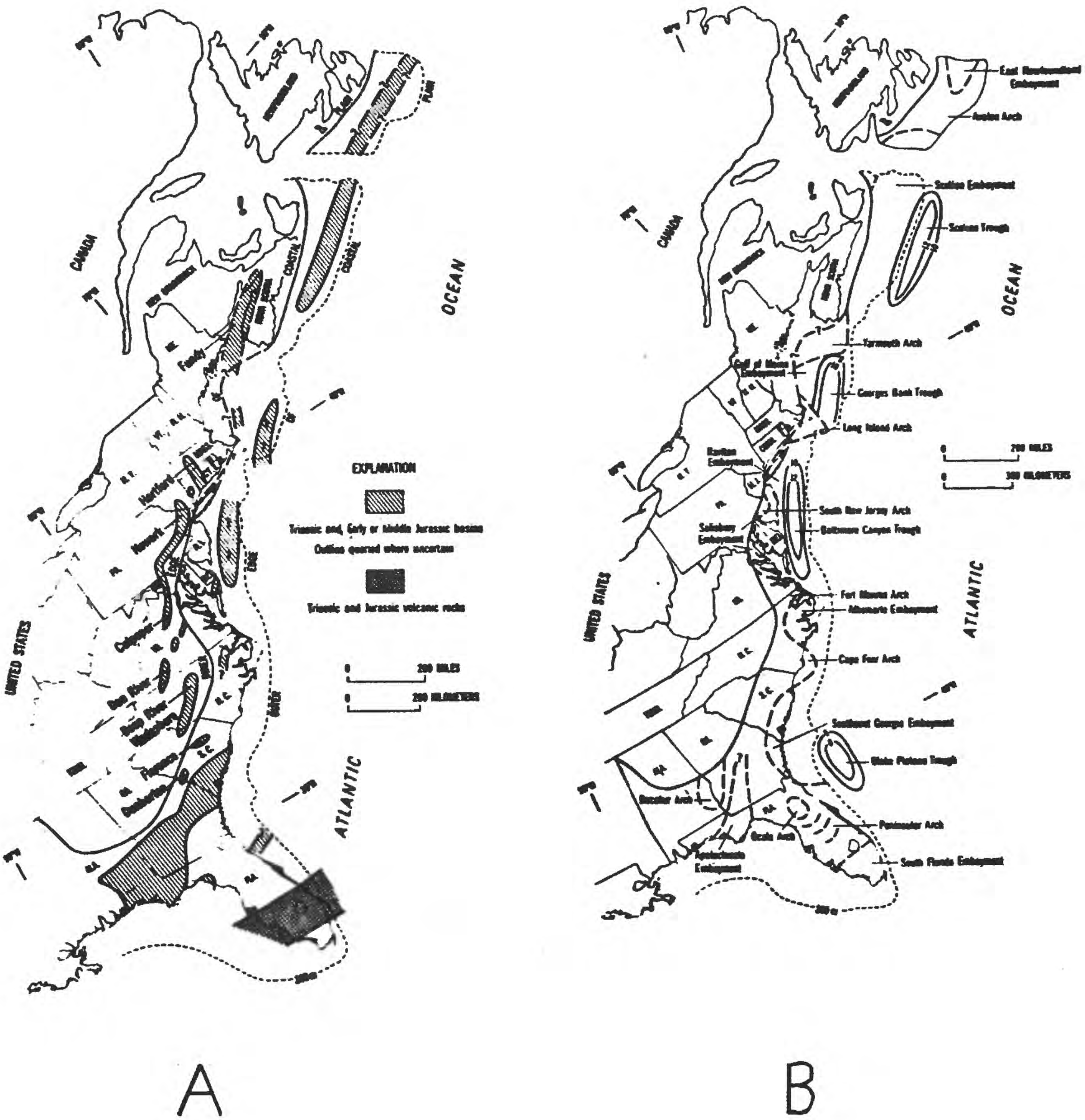

Figure 1. A - Generalized map showing distribution of Triassic and Jurassic rift basins along North Atlantic margin of North America (from Owens, 1983). B - Generalized map showing distribution of Coastal Plain basins and highs (arches) along North Atlantic margin of North America (from Owens, 1983).

STRATIGRAPHIC NOMENCLATURE

The new State map shows significant changes in the Coastal Plain from the old State map of Lewis and Kümmel (1910-1912, revised 1950). In the new map, several new and revised units have been outlined. The Raritan and Magothy Formations, shown as a single unit on the old map, have been subdivided into three formations; the Potomac, Raritan, and Magothy Formations. The Raritan and Magothy also reflect the changes suggested by Wolfe and Pakiser (1971) in which the Magothy was greatly expanded at the expense of the Raritan. The Cheesequake Formation is new. The Wenonah and Mount Laurel Formations, which were lumped as a single unit on the old map, have been mapped separately. In the Upper Cretaceous, the Red Bank Formation has been mapped separately from the Tinton Formation; the Red Bank has been mapped as two members, the Sandy Hook and Shrewsbury. In the upper Tertiary, the Shiloh Marl is raised to formation rank and one new unit is shown, the Wildwood Formation.

Many reports use group names for the lowest Tertiary beds (Rancocas) and uppermost Cretaceous (Matawan and Monmouth). The groups were the original names of formations of the uppermost Cretaceous and lowest Tertiary in this region which were subsequently subdivided into a number of formations. This group nomenclature has been utilized by some into recent times (Olsson and others, 1988). Once it was recognized that the outcropping formations were cyclic and that the formations within the cycles were nearly the same age (Owens and Sohl, 1969), the group concept was no longer used by the USGS. The Monmouth Group illustrates the uselessness of this group versus using the cycles. The Monmouth Group consists of the Mount Laurel, Navesink and Red Bank Formations. In the cyclic concept the Marshalltown, Wenonah and Mount Laurel Formations are a single cycle in which all the units are nearly the same age (late Campanian) and the contacts between units gradational. The Navesink, which overlies the Mount Laurel, belongs to the Navesink-Red Bank cycle (middle to upper Maastrichtian). In addition the Mount Laurel-Navesink contact is a major unconformity in this region. Similar problems exist in the Matawan and Rancocas Groups. For these reasons the group status for these units was not used.

Each of the formations have been assigned an epoch and standard age. For the Cretaceous, the correlations of Perch-Nielsen (1985) were followed. For the Cenozoic, the time scale of Berggren and others (1985) was used.

In most cases the mapped units have been called formations rather than a textural designation as was used on the old State map. The reason for this was in almost all cases a single lithology is not representative of any formation regionally.

ACKNOWLEDGEMENTS

Many people and organizations supplied help or data to create the central bedrock map. This map is produced under the COGEOMAP program, a cooperative between the United States Geological Survey (USGS) and the New Jersey Geological Survey. The USGS Geologic Division, Branch of Eastern Regional Geology (J.P. Owen's, Project Chief), and the Paleontology and Stratigraphy Branch (N.F. Sohl, Project Chief), provided the bulk of the

geologic information. L.M. Bybell and G.W. Andrews provided age information of subsurface units. Members of the USGS Water Resources Division in Trenton, N.J. also provided a large amount of support to the project, notably Otto Zapezca. This group supplied support in the drilling of some of the coreholes and provided most of the geophysical logs. An integral part of the map was to produce detailed subsurface framework. Most of the drilling was done by the personnel from the Branch of Eastern Regional Geology primarily Donald Queen and Eugene Cobbs.

The text for the various plates were reviewed thoroughly and intensively by Gregory Gohn of the USGS and Richard Dalton of the New Jersey Geological Survey. These outstanding reviewers improved the style and to a degree the substance of these texts.

DESCRIPTION OF MAP UNITS (Plate 1)

Coastal Plain Sediments

Tch

Cohansey Formation (middle Miocene, Serravallian)--Sand, loose, white to yellow in most outcrops, locally gravelly and less commonly clayey. Locally stained red or orange brown by iron oxides. In a few areas, the sands have been cemented into large blocks of ironstone.

This formation is the major surface unit in the central New Jersey Coastal Plain. The maximum thickness in the map area is about 200 ft. The Cohansey has been extensively eroded and stripped from large areas of the New Jersey Coastal Plain, particularly in the north; detached Cohansey outliers are common. In spite of its widespread nature, the Cohansey is poorly exposed because of its loose sandy composition, which causes it to slump easily. Fortunately, because of this same sandy nature, the Cohansey has been widely mined, and man-made exposures are common in many areas. In general, the Cohansey sands are crossbedded, although the style of crossbedding varies significantly depending upon the environment of deposition. Most of the crossbedding is trough type, especially in the non-marine channel fill deposits (Owens and Sohl, 1969, fig. 14A and C), and the scale of the crossbeds varies from small to large. In some areas, planar bedding is well developed in sections having abundant marine burrows (generally clay-lined Ophiomorpha nodosa). Such marine-influenced beds (largely foreshore deposits) occur west of Asbury Park (Asbury Park quadrangle), near Adelphia (Adelphia quadrangle), north of the Lakehurst Naval Air Station (Lakehurst quadrangle), and at Juliustown (Columbus quadrangle) (Owens and Sohl, 1969, fig. 14D). Rarely, as near West Berlin (Clementon quadrangle), shell ghosts have been observed (Newell and others, 1988).

Sands in the Cohansey typically are medium grained although the range is from fine to very coarse grained. The bulk of the sand is poorly to well sorted. Gravel beds are present in updip areas such as near New Egypt in the Atlantic Highlands and in the highlands near Bennegat in the southeastern corner of the map area. Most of the gravel is 0.5 to 1.0 in in diameter, but pieces to about 4 in in length are present. Most of the gravel is quartz with small amounts of black chert and quartzite. Sands in the Cohansey generally consist of quartz and siliceous rock fragments. Locally, some beds are micaceous, and in the Lakehurst area some of the beds have high concentrations of "black" sand (pseudorutile) which were once extensively mined.

Pseudorutile is the major opaque heavy mineral in the Cohansey throughout its outcrop. The other important non-opaque heavy minerals are zircon, tourmaline, and rutile. Staurolite and sillimanite are the major accessory non-opaque minerals. Leucoxene and, to a lesser degree ilmenite, are common opaque minerals. A large number of other minerals are present in trace amounts.

Clays in the Cohansey consist principally of kaolinite and illite and commonly occur as discrete, thin, discontinuous beds. These beds are dark gray where they are unweathered; where weathered, they are white or red. Locally, as near Lakehurst, thick clays have been uncovered during the mining of ilmenite. The clay at Lakehurst is informally called the Legler lignite (Rachele, 1976), and is dark gray and very lignitic.

The Cohansey Formation lies unconformably on the underlying Wildwood Formation, Shiloh Marl and Kirkwood Formation in outcrop. The Cohansey commonly is found in channels cut down into the underlying formations. The basal contact with underlying formations, therefore, is highly irregular. Where the Kirkwood consists of sandy light-colored sediments, the contact is drawn below the crossbedded Cohansey sediments. Where the Cohansey rests on the dark silty beds of the underlying formation, the contact is drawn between light-colored Cohansey sediments and the underlying dark sediments.

The age of the Cohansey is controversial largely because no calcareous micro- or macrofauna have been found in this formation. The best indication of its age comes from pollen and spores obtained from the dark carbonaceous clays. Rachele (1976) analyzed the microflora from the Legler site and noted that the Cohansey had a rich and varied assemblage. Included in the assemblage were several genera labelled "exotics", which no longer occur in the northeastern United States: <u>Englehardtia</u>, <u>Pterocarya</u>, <u>Podocarpus</u>, and <u>Cyathea</u>. Greller and Rachele (1984) estimated that the age of the microflora is middle Miocene. Ager (<u>in</u> Owens and others, 1988) analyzed the Cohansey from a corehole in the southern New Jersey Coastal Plain and agreed with the middle Miocene age assigned by Greller and Rachele. The Cohansey, therefore, is probably Serravallian (middle Miocene).

Tw

Wildwood Formation (middle and lower Miocene, Langhian and Burdigalian)--New formation named for a well near the Cape May Peninsula in southernmost New Jersey. This type locality is more fully described in the southern bedrock map. Dark-gray to olive-gray, massive to very thick-bedded clay to very fine sand, micaceous, woody, locally very diatomaceous, especially in the basal beds. Underlies a small area in the southeastern corner of the map where the Cohansey Formation has been eroded away. Capped by thin to thick beds of Quaternary alluvium, and therefore a subcrop formation. Contact with the underlying Shiloh

Marl is sharp and unconformable. The formation is as much as 120 ft thick in this map area.

Mineralogy was only analyzed for its clay type. The clay mineralogy is largely equal amounts of illite/smectite, illite, and kaolinite.

The age of the Wildwood in the map area was determined from diatoms. The diatoms present fall within the Delphineis ovata Range Zone or East Coast Diatom Zone (ECDZ) #2 (Andrews, 1987). Besides D. ovata, other marker species include Sceptroneis caduceus, S. granidis, Cosinodiscus lewisanus and Rhaphoneis margaritata. The age of this zone is late Burdigalian and early Langhian (early and middle Miocene).

Tkw

Kirkwood Formation (lower Miocene, Burdigalian to Aquitanian)--Sand and clay; sand, mostly in upper part of the formation, typically light yellow to white, extensively stained by iron oxides, especially in near-surface beds. Massive to thick bedded in the updip western outcrop belt. Locally, crossbedded near Lakewood in the updip northern outcrop. Dark-gray, massive to thin-bedded clay or clay-silt in the lower part of the formation. This lower part is only exposed where the Coastal Plain has been deeply entrenched and back-stripped. Underlies a broad irregular area in the north where the overlying Cohansey Formation has been extensively stripped away. Outcrop more contiguous as a belt in the western area but is still highly eroded. Kirkwood outliers are common in this area. Unit is as much as 100 ft thick in the north, about 70 ft thick in the west-central area, and over 200 ft thick in the southeastern corner of the map.

Exposures of the Kirkwood, particularly the upper sand facies, like those of the overlying Cohansey, are poor because of their sandy nature. Knowledge about the composition of this unit in the outcrop belt is restricted to information from pits and road cuts.

The Kirkwood unconformably overlaps several formations. Commonly, the basal Kirkwood has a reworked zone from 1 to 4 ft thick that contains fine to very coarse sand and locally fine gravel; it is often very glauconitic and less commonly has woody fragments. This reworked zone is present throughout the Kirkwood.

In outcrop, the Kirkwood consists of a lower, dark-colored, clayey and micaceous, fine-grained sand (transgressive) and an upper, light-colored, massive or thick-bedded to crossbedded sand (regressive).

The lower, dark clayey unit, called the Asbury Park Member, is exposed in the north in pits north of Farmingdale (Farmingdale quadrangle), in a few cuts along the Manasquan River north of Farmingdale, and along the Shark River northeast of Farmingdale. The best exposures show that the basal Kirkwood is a thin-bedded sequence of dark-gray clay and light-colored, massive to locally crossbedded, fine sand. The clay-silt beds are very woody, both finely dispersed or coarse and micaceous. Flattened lignitized twigs and other plant debris are common in these beds. Locally, the clay beds have irregularly-shaped sand pockets, which may represent some type of burrow. These beds were previously called the Asbury Clay by Kümmel and Knapp (1904). These basal beds are also widely exposed in the Mount Holly and Pemberton quadrangles in the west-central outcrop belt. There, poor exposures make it difficult to determine the bedding. Lithologically, however, they are very dark-gray, very micaceous, very fine- to fine-grained quartz sand. Lignitic material is very abundant. These dark beds weather readily to a light-yellow, micaceous, massive sand, the most common lithology in the Kirkwood of the western belt.

The beds in the upper part of the Kirkwood are white, yellow, or iron-oxide stained and crossbedded to thick bedded. The thick-bedded units commonly consist of interbeds of fine micaceous sand and coarse to fine gravelly sand in the western outcrop belt. Some of these beds are intensely burrowed. The crossbedded units are most common in the Lakewood quadrangle. These beds commonly display trough crossbeds and have high concentrations of ilmenite. A few burrows were observed in the crossbedded sands in the Lakewood quadrangle. In general, the upper bedded sands of the Kirkwood are a maximum of 50 ft thick.

The sand fraction of the light-colored sand facies is principally quartz and muscovite. The opaque heavy minerals are mainly pseudorutile with smaller amounts of leucoxene and ilmenite. The non-opaque fraction contains mainly zircon, tourmaline, rutile, sillimanite, staurolite, garnet, and locally chloritoid. Except for the presence of chloritoid, these light colored beds probably are weathered horizons and resemble the heavy mineral assemblage in the Cohansey Formation.

The heavy mineral assemblages in the dark clayey units are similar to those in the light-colored Kirkwood sand. The light-mineral fraction of the dark-colored clays has significantly more feldspar (10-15 percent) and rock fragments (10-15 percent) than in the light-colored sands. It is probable that the feldspars were leached from the upper sand beds during post-depositional weathering.

The clays in the dark-colored beds are mainly kaolinite and illite with small amounts of illite/smectite (I/S). I/S is absent in the weathered light-colored sand beds.

The age of the outcropping Kirkwood is early Miocene based upon the presence of the diatom Actinoptychus heliopelta found near Oak Glen (Farmingdale quadrangle) (Goldstein, 1974). This diatom would place the outcropping Kirkwood in the lower part of the E.C.D.Z. #1 of Andrews (1987). The age of this zone is early Miocene (Burdigalian) (Andrews, 1988). Sugarman and others (1993) report strontium isotope ages of 22.6-20.8 Ma for this unit therefore extending the age of the lower part of the unit to Aquitanian.

Tsr

Shark River Formation (middle and upper Eocene, Priabonian through Lutetian)--Glauconite sand, somewhat silty and clayey, light brown to medium gray. Sand is medium to coarse grained, locally indurated at top and noncalcareous throughout. Mollusk impressions (mainly Venericardia perantiqua) were observed in the Farmingdale quadrangle. The Shark River is exposed only at a few localities near Farmingdale along the Manasquan and Shark Rivers where most outcrops are small, less than 10 ft in height and in several tributaries to Deal Lake in the

Asbury Park quadrangle (Sugarman and Owens, 1994). The contact with the overlying Kirkwood Formation, where exposed, is sharp and disconformable. No exposures of the contact with the underlying Manasquan Formation were observed. To better establish the stratigraphic relationships, thickness, and lithic character of the Shark River, a hole was cored at Allaire State Park about 4 mi south of Farmingdale. The Shark River in the corehole is about 70 ft thick and consists of two fining-upward sections: a glauconite sand is present at the base and a clay or silt is present at the top of each cycle. The Shark River in this hole has an overall green color and an abundant microfauna. The clays in the Shark River are mainly illite/smectite (I/S) with smaller amounts of illite and kaolinite. Locally, small amounts of clinoptilolite and less commonly cristobalite are present. Because of the fine-grained nature of this unit, sand-sized heavy and light minerals were not studied.

No calcareous nannofossils remain in the few outcrop localities of the Shark River. However, calcareous nannofossils are abundant in subsurface Shark River sections and indicate assignment to Zones NP 14 through 18 (Martini, 1971) (the entire middle Eocene and the early part of the late Eocene). Because of erosion, the entire sequence of Zones NP 14 through 18 is never found in any one individual corehole in the part of New Jersey covered by this map. Elsewhere in New Jersey, as in the ACGS #4 corehole near Mays Landing, all five calcareous nannofossil zones are represented.

Tmq

Manasquan Formation (lower Eocene)--Consists of several lithologies. Where seen in the northern New Jersey Coastal Plain, this unit consists of a lower, clayey, quartz-glauconitic sand, which is exposed intermittently along the Manasquan River near Farmingdale, and an upper, fine quartz sand or silt, exposed along Hog Swamp Brook west of Deal, N.J. (Asbury Park quadrangle). Enright (1969) gave member names to each of these facies (Farmingdale Member for the quartz-glauconite sand and Deal Member for the fine sand to silt). These members are not used in this map because they cannot be followed for any distance in the subsurface, nor are they continuous throughout the outcrop belt.

The formation is best exposed along the western outcrop belt from the Fort Dix Reservation (New Egypt quadrangle) on the northeast to Medford Lakes quadrangle on the southwest. There, the lower part of the formation consists of 15 ft of massive, dark-grayish-green, medium to coarse-grained glauconite-quartz sand. Glauconite in general increases upward in this section, and the lower 2 to 3 ft commonly contains calcareous debris and phosphatized internal fossil molds that are reworked from the underlying Vincentown Formation. The upper, thicker part of the formation is approximately 25 ft thick and consists primarily of a blue-green to pale-gray, very clayey, quartz-glauconite sand (about 20 percent). Locally, the glauconite content of this bed is variable, and the unit becomes almost a pure blue-green clay-silt at a few places, especially near Pemberton, N.J.

The light-mineral fraction consists of quartz and lesser amounts of potassium feldspar. The feldspar content is much lower than in the overlying Kirkwood

Formation. In the opaque fraction, ilmenite is the major mineral, and pseudorutile and leucoxene are minor constituents. The non-opaque heavy mineral suites in the Manasquan samples are immature assemblages, containing local concentrations of the more labile constituents hornblende, epidote, and garnet. In addition, the metamorphic minerals staurolite, sillimanite, and kyanite are also present in significant concentrations. The clay minerals are a mixture of all the major types: kaolinite, illite/smecitite, and illite.

Except for casts and molds of mollusks (especially Venericardia perantiqua), the Manasquan in outcrop is unfossiliferous. The age of formation was determined in the unweathered subsurface beds.

Tvt

Vincentown Formation (upper Paleocene)--Sand, typically very glauconitic and clayey in basal part, grading upward to less glauconitic and more fossiliferous sand above. Although the Vincentown is a widespread unit in the northern New Jersey Coastal Plain where it is extensively dissected, it is exposed in the western outcrop belt only where the overlying formations have been stripped away. The best exposures occur in the Pemberton, New Egypt, and Mount Holly quadrangles.

The Vincentown Formation is thickest in the northern Coastal Plain where it is over 135 ft thick. There, the unit is generally a shelly sand where unweathered and largely a massive quartz sand where weathered. Because of its unconsolidated nature, most of the unit consists of weathered beds, and there are few exposures of this unit except in dug pits. The unweathered Vincentown sand is exposed intermittently along the Manasquan River near Farmingdale. Several holes were also cored into this unit in the vicinity of Farmingdale where the calcareous nature of unweathered Vincentown samples was observed throughout. In addition, the formation is more clayey and the sand finer grained toward the base in the subsurface. The contact with underlying Hornerstown Formation is disconformable. Locally, there are shell beds (bioherms) up to 5 ft thick along this boundary. The shells in the bioherms are typically of a restricted fauna and contain the brachiopod Oleneothyris harlani (Morton) in the lower beds, and the oyster Pycnodonte dissimilaris is found in higher beds. The upper beds of the Vincentown, especially along the western outcrop belt, consist primarily of dark-gray to green-gray, massive, silty, glauconite sand typically containing a few percent of quartz. This unit is as much as 40 ft thick. Where weathered, as in most outcrops, the glauconite sand is light colored. Locally, along the western belt, there is calcarenite or coquina characterized by an abundance of bryozoans. These fossiliferous beds are about 20 to 25 ft thick and are particularly well exposed along Shingle Run in the New Egypt quadrangle and in the streams which cross the Vincentown outcrop belt in the Pemberton quadrangle.
The Vincentown is well exposed in the New Egypt, Pemberton, and Mount Holly quadrangles. The basal contact and the Oleneothyris bioherms are exposed at a number of localities along Crosswicks and Lahaway Creeks and their tributaries.

The mineralogy of the Vincentown sediments resembles that of the overlying Manasquan Formation, both in the sand and clay fractions.

Calcareous nannofossils, which are present in some Vincentown outcrops, are from Zones NP 5 (the Oleneothyris beds) and NP 9 (both zones are late Paleocene in age). Vincentown sediments are much more fossiliferous in the subsurface and contain Zones NP 5 through NP 9 inclusive (the entire late Paleocene). The Vincentown corresponds in age with the Aquia Formation of Virginia and Maryland. There have been numerous studies of the foraminifera of the Vincentown, particularly from the calcareous beds in the western outcrop belt. These studies indicate that the Vincentown includes the planktic foraminifera zones P3b through P6a (Olsson and others, 1988). A K/Ar age of 56.4±18 Ma was determined for the basal beds near New Egypt (Owens and Sohl, 1973).

Tht

Hornerstown Formation (lower Paleocene, Danian)--Glauconite sand, massive, extensively bioturbated, locally clayey, dark gray to dusky green, fine to medium-grained, locally has a few percent quartz in base. The glauconite grains in the Hornerstown are typically dark green and have botryoidal shapes. Hornerstown outcrops occur in a thin belt throughout most of the western outcrop area, and the formation is extensively dissected in the northern New Jersey Coastal Plain where it occurs in several outliers detached from the main outcrop belt. The Hornerstown weathers readily to iron oxide because of its high glauconite content. It unconformably overlies several formations throughout its outcrop belt, including the Tinton Formation in the extreme north, the Red Bank Formation in the northwest and west-central areas, and the Navesink Formation in the west-central and southern part of the map area. Some have argued that the basal contact is transitional, but an unconformity can be demonstrated at many localities throughout its outcrop belt and in the subsurface.

The Hornerstown is unconformably overlain by the Vincentown Formation throughout its entire outcrop belt and was extensively dissected and thinned during the Vincentown transgression. The Hornerstown ranges from about 5 to 20 ft in thickness.

The Hornerstown in most areas is nearly a pure glauconite greensand and it was once extensively mined for this mineral. In many areas, where slightly weathered, the formation has an overall green color and the clay minerals are almost pure glauconite. Where the matrix is dark gray (less weathered), the clay minerals are a mixture of illite/smectite, kaolinite, and illite. Because this unit contains so little sand-size clastic material, there is little reliable information regarding the sand mineralogy.

The Hornerstown has no calcareous fossils in outcrop. Some authors have assigned a Cretaceous age to the unit based in part on a vertebrate fauna found at the base at Sewell, N.J. (Woodbury quadrangle) (Koch and Olsson, 1977) However, in the core at Allaire State Park, Hornerstown samples contain calcareous nannofossil zones NP 2, NP 3, and NP 4 (Paleocene). This is the only locality in New Jersey that contains Zone NP 2; elsewhere, the Hornerstown is confined to Zones NP 3 and NP 4. Zone NP 1 (lowermost Paleocene) was never observed, and it is assumed that the Cretaceous-Tertiary boundary in New Jersey is unconformable.

Kt

Tinton Formation (Upper Cretaceous, upper Maastrichtian)--Sand, quartz and glauconite in varying proportions; very clayey and locally indurated by siderite into hard, massive ledges. Dark gray to dark yellow where unweathered; where weathered, siderite changes to orange brown because of iron oxides, and the formation is extensively stained or cemented in exotic patterns (Owens and Sohl, 1969, fig. 11D). The Tinton crops out only in the northern Coastal Plain from Sandy Hook to the northernmost part of the Roosevelt quadrangle. It unconformably overlies the Red Bank Formation at a number of localities in the high hills of the northern Coastal Plain, most notably near Perrineville in the Roosevelt quadrangle and near Morganville in the Keyport quadrangle. In these updip area, the Tinton typically has fine gravel (up to 0.376 in maximum diameter) or large shell concentrations along its basal contact. This basal bed typically is a massive, glauconitic (10-35%), fine to medium quartz sand with scattered granules to fine gravel. The massive character of the bed is the result of extensive bioturbation. Burrows filled with glauconite sand of the Tinton project downward into the quartz sands of the underlying Red Bank Formation.

Downdip and at lower elevations, the Tinton is less weathered, much darker colored, and more glauconitic. There the unit is typically indurated to a hard mass. The type locality on Pine Brook at Tinton Falls (Long Branch quadrangle) lies within this downdip area. At the falls, 20 to 25 ft of the Tinton is exposed that has a higher glauconite content than the updip area. The glauconite at the Tinton Falls is light green to pale yellow rather than the deep green seen elsewhere. Many of the grains have a smooth polished surface that is almost lustrous. Thin sections of the Tinton reveal that many of these grains are oolitic (Owens and Sohl, 1973). X-ray analyses show these grains to be mixed clay minerals, not pure glauconite. K/Ar determinations indicate an age that is considerably older than indicated by fossils in the Tinton.

The Tinton Formation at Tinton Falls has scattered calcitic fossils, but aragonitic shells are represented only by molds. Richards (1958) recorded 30 species of mollusks from the Tinton in this area. Of special importance are _Sphenodiscus_ _lobatus_, _Cucullaea_ (_Idonearca_) _littlei_ and _Scabotrigonia_ _cerulia_. In New Jersey, _Scabotrigonia_ _cerulia_ is restricted to the Tinton. All three species are common to the upper Maastrichtian _Haustator_ _bilira_ Zone of Sohl (_in_ Owens and others, 1977). No calcareous nannofossils or planktic foraminifera were obtained, and the Tinton's exact placement in the upper Maastrichtian is unknown. Strontium isotopic analysis on calcareous shells from the Tinton yielded ages of 66.2 to 65.6 Ma or an upper Maastrichtian age (Sugarman and others, 1995).

Red Bank Formation (Upper Cretaceous, upper and middle Maastrichtian)--This formation consists of two thick lithofacies and one thin lithofacies. In the northernmost outcrop belt, Olsson (1963) named the lower thick facies the Sandy Hook Member (Krbsh on map) and the upper major facies the Shrewsbury Member

(Krbs). These lithofacies thin and change toward the southwest where they merge with an unnamed thin, dark-gray, very micaceous, quartz-glauconite sand. The Red Bank, like the overlying Tinton, crops out only in the northern Coastal Plain from Sandy Hook to near New Egypt. The Red Bank outcrop belt is widest in the north and thins southwestward. Because of the scale of the map, only the thicker Sandy Hook (Krbsh) and Shrewsbury (Krbs) Members are shown. The unnamed (and not separately mapped) glauconite member of the Red Bank was mapped in detail in the Roosevelt, Allentown, and New Egypt quadrangles (Owens and Sohl, 1969, fig. 11C). The significant facies change between the Sandy Hook Member and this unit were followed in detail through this region. Olsson (1963) and Koch and Olsson (1977) considered the glauconite facies to be equivalent to both the Red Bank and the Tinton. The constraints imposed by the mapping, however, show that this relationship cannot be correct, at least not in outcrop. The glauconite member of the Red Bank is unfossiliferous for the most part. Koch and Olsson (1977) reported a dinoflagellate assemblage, presumably from the glauconite member of the New Egypt area, which would indicate a late Maastrichtian age. In our interpretation, based on stratigraphic position, their dinoflagellate assemblage would be equivalent only to the planktic assemblage found in the lower part of the Red Bank at Poricy Brook.

Mineralogically, the Sandy Hook Member and the unnamed glauconite member near New Egypt have similar sand and clay mineral compositions. The distribution of the unnamed very micaceous, glauconite member can be seen on the detailed maps of the Roosevelt (Minard, 1964), Allentown (Owens and Minard, 1966), and New Egypt (Minard and Owens, 1962) quadrangles.

The Red Bank Formation is of late middle and late Maastrichtian age primarily based on the presence of the ammonite Sphenodiscus lobatus and the planktic foraminifera in the lower part of the Red Bank studied by Smith (in Owens and others, 1977) from the Poricy Brook locality. The concurrence of Rugoglobigerina scotti and Globotruncana contusa place this member well above the base of the Gansserina gansseri subzone in the upper Maastrichtian. Sugarman and others (1995) assigned an upper Maastrichtian CC26 zone to the unit. Wolfe (1976) studied the pollen in the basal Red Bank and assigned it to the CA6/Ma-1 zone (Maastrichtian). Sr-isotope age estimates for the Red Bank average 65.8 Ma, which are nearly identical with the Tinton Formation (Sugarman and others, 1995).

Krbs

Shrewsbury Member--Sand, light yellow to red or dark brown; mostly massive (although small-scale cross bedding is present locally); fine to coarse quartz, slightly glauconitic; sparse quartz granules are scattered throughout the sands, somewhat clayey and micaceous. The Shrewsbury is extensively burrowed but is otherwise unfossiliferous. The burrows, which are in part responsible for its massive appearance, are small in length and diameter. Locally, small "Callianassa"-type burrows are present but are uncommon. The sand fraction of the Shrewsbury consists primarily of quartz with moderate amounts of feldspar, and at the base, a small amount of glauconite. The opaque heavy minerals are dominated by ilmenite with small amounts of pseudorutile and leucoxene. The major non-opaque minerals are epidote, staurolite, and zircon. The maximum thickness of the Shrewsbury Member is somewhat over 100 ft in the highlands near Matawan, N.J. (Keyport quadrangle). The Shrewsbury thins southwestward to near Arneytown (New Egypt quadrangle) where it pinches out or has been eroded away during or before the deposition of the Hornerstown Formation. Contact with underlying Sandy Hook Member is gradational.

Krbsh

Sandy Hook Member--The Shrewsbury Member of the Red Bank Formation is gradational into the Sandy Hook Member. The transition occurs within several feet and is characterized by an increase in clay, quartz, silt, mica, and fine pieces of wood in the Sandy Hook Member. Locally, the Sandy Hook is a massive, dark-gray, very micaceous and fossiliferous, clayey fine sand, which is well exposed at Poricy Brook in the Long Branch quadrangle. The Sandy Hook is much thinner than the overlying Shrewsbury Member and is a maximum of 30 ft thick. In general, the sand in the Sandy Hook consists of quartz with feldspar and mica occurring as significant accessory minerals. The micas include muscovite, cholorite, and biotite. The opaque heavy minerals are mainly ilmenite with lesser amounts of pseudorutile and leucoxene. The non-opaque heavy mineral suite is characterized by epidote, garnet, and staurolite. Fine-grained pyrite is abundant in all the processed samples. The clay minerals in the Sandy Hook Member are about equal amounts of kaolinite, illite, and illite/smectite.

Kns

Navesink Formation (Upper Cretaceous, Maastrichtian)--Glauconite sand, dark gray, clayey and silty, locally shelly, especially in northern New Jersey Coastal Plain, locally has a light-yellow, pebbly, fine to coarse glauconite quartz sand at the base. Crops out in a narrow belt throughout the entire map area. Because of its clayey nature, the formation is exposed in many valleys which cut across its outcrop belt. The unit is massive and extensively bioturbated (Owens and Sohl, 1969, fig. 10D). Where weathered, the dark-gray clay-silt matrix changes color to a pale brown. It is in these weathered beds that the extensive bioturbation is evident. The Navesink commonly has large calcareous shells that are concentrated as shell beds at some localities, while at other localities only individual shells are present. Shells are also common in the basal quartz sand, particularly Exogyra costata the belemnite Belemnitella americana. The upper contact with the Sandy Hook Member and unnamed glauconite member of the Red Bank Formation is gradational over several feet. The basal unit of the Navesink is a massive, pebbly, fine- to coarse-grained, somewhat glauconitic quartz sand, which is as much as 7 ft thick. A photograph of this basal Navesink bed is shown in Owens and Sohl

(1969, fig. 10A). This basal quartz sand is lithologically similar to the underlying Mount Laurel Formation, but was formed by the reworking of the Mount Laurel during emplacement of the Navesink (transgression). This interpretation was first proposed by Owens and others (1977).

Petrologically, the Navesink is dominantly a glauconite sand except locally at its base where quartz is abundant. Locally, the Navesink has small amounts of sand-sized mica. As is typical in many of the more glauconitic sands, the Navesink has few heavy minerals. Where heavy minerals were obtained, the non-opaque, heavy mineral assemblages are similar to those in the overlying Sandy Hook Member of the Red Bank Formation. The clay mineralogy in the Navesink and basal Red Bank is also similar.

The Navesink and Red Bank deposits represent a transgressive (Navesink)-regressive (Red Bank) cycle of sedimentation (Owens and Sohl, 1969). The cycle is asymmetric and unconformity-bounded at top and bottom. Within the cycle, the formational contacts are gradational.

The age of the Navesink was determined from both the macrofauna and microfauna. The planktic foraminifera from the lower part of the Navesink, including the lower half of the glauconite sand facies, are indicative of the Rugotruncana subcircumnodifera subzone of early Maastrichtian age (Smith, in Owens and others, 1977). The upper part of the Navesink contains Exogyra costata, Sphenodiscus lobatus and Pycnodonte vesicularis. These indicate a middle to late Maastrichtian age. Planktic foraminifera from the upper part of the Navesink represent the Gansserina gannsseri subzone of middle Maastrichtian age (Smith, in Owens and others, 1977). The pollen in the Navesink and basal Red Bank are similar; the Navesink microflora is a CA6/MA-1 assemblage in Wolfe's (1976) classification. The Navesink, therefore, ranges from early to late Maastrichtian. Sugarman and others (1995) assigned a middle Maastrichtian zone CC 25 to the Navesink.

Kml

Mount Laurel Formation (Upper Cretaceous, upper Campanian)--Sand, glauconite quartz, loose, interbedded with thin clay beds (Owens and Sohl, 1969, fig. 10A), especially in the northern N.J. Coastal Plain; more massive in the west-central outcrop belt. Typically medium gray weathering to white or light yellow and locally stained to orange brown by iron oxides. Sand, mostly medium grained, although there is a tendency for an increase in grain size from the base toward the top. Small pebbles are commonly scattered throughout, especially in the west-central area. Locally, has small, rounded siderite concretions in the interbedded clay-sand sequence of the formation. Fossils, typically the oyster Agerostrea falcata are found in the middle and lower part of the massive facies. Exogyra cancellata and Belemnitella americana are common in upper beds in the west-central area (New Egypt quadrangle).

The Mount Laurel occurs in a continuous belt that is narrowest in the north and widest in the southwestern part of the map area. The Mount Laurel varies in thickness in the northern Coastal Plain but maintains a 30-ft thickness from the

Roosevelt quadrangle to the Runnemeade quadrangle in the west. The thickness variation in the north is due in part to the extensive interfingering of this formation with the underlying Wenonah Formation. Weller (1907) and Kümmel (1940) assigned only about 5 ft of section to the Mount Laurel in the north. Actually, these beds have been assigned to the overlying Navesink in our map. The interbedded sequence, which is the major facies in the north, ranges up to about 15 feet in thickness. These interbeds have well developed large burrows (Martino and Curran, 1990), mainly Ophiomorpha nodosa, but less commonly Rosselia socialis.

Gradation of the Mount Laurel into the underlying Wenonah, especially in the west-central area, is accompanied by an increase in clay, silt, and mica. This transition takes place over about a 5-ft interval. Here, the Mount Laurel is mainly massive (Owens and Sohl, 1969, fig. 10B).

Petrologically, the Mount Laurel sand is quartz with varying amounts of glauconite and feldspar. Micas (muscovite and biotite) are common near the base. The non-opaque heavy minerals are ilmenite, pseudorutile, and leucoxene. The non-opaque heavy mineral fraction is characterized by hornblende, epidote, and garnet. A large number of other heavy minerals are accessories. The clay mineral assemblage contains all the major clay groups: illite/smectite, kaolinite, and illite.

The Mount Laurel Formation is of late Campanian age based on the assignment of zone CC 22b to the formation by Sugarman and others (1995).

Kw

Wenonah Formation (Upper Cretaceous, upper Campanian)--Sand, fine grained, silty and clayey, very micaceous, with local high concentrations of sand-sized lignitized wood. Dark gray where unweathered, light brown to white where weathered. Massive to thick bedded, extensively bioturbated (Owens and Sohl, 1969, figs. 9A-B). Locally, has large Ophiomorpha nodosa as at Irish Hill in the Runnemeade quadrangle. Crops out in a narrow belt in northern Coastal Plain and a broad belt in southwestern part of the outcrop belt. Isolated Wenonah outliers are detached from the main belt. Ranges in thickness from about 30 ft in northern Coastal Plain to about 70 ft in the southwestern corner of the map.

The Wenonah is gradational into the underlying Marshalltown Formation. The transition zone of several feet is marked by a decrease in mica and an increase in glauconite sand.

Sand minerals are mainly quartz and mica. Small amounts of feldspar (5-10 percent) are present. Finely crystalline pyrite is a common mineral in most samples. The other opaque heavy minerals are leucoxene and ilmenite. The non-opaque heavy minerals include epidote, garnet, zircon, tourmaline, and rutile. The clay minerals are usually illite and kaolinite, although lesser amounts of chlorite and illite/smectite are also present.

Fossil casts are common throughout most of the Wenonah. Weller (1907) reported the presence of Flemingostrea subpatulata in the Wenonah at Hop Brook in the Marlboro quadrangle. This fossil is an indicator of a late Campanian age. Wolfe (1976) placed the Wenonah microflora in his CA5A assemblage, which he considered to be late Campanian in age. Kennedy and Cobban (1994) examined a collection of ammonites which included Menuites portlock, Placenticeras placenta, P. minor n. sp., Nostoceras (Nostoceras) puzosiforme n. sp., Nostoceras (Nostoceras) aff., N. colubriformus, Didymoceras n. sp., Parasolenocaras sp., Baculites cf., B. scott and Trochyscaphires pulcherrimus. The presence of M. portlocki and T. pulcherrimus is an indicator of upper but not uppermost Campanian.

Kmt

Marshalltown Formation (Upper Cretaceous, upper Campanian)--Sand, quartz and glauconite, fine to medium grained, dark gray, very silty, weathering to light brown or pale red, massive and extensively bioturbated (Owens and Sohl, 1969, fig. 8C). Very glauconitic in basal few feet; glauconite decreases in concentration upward. Locally, very micaceous with sparse carbonized woody fragments. Fine-grained pyrite common throughout formation. Crops out in a narrow belt throughout the map area. Like the overlying Wenonah Formation, the Marshalltown also occurs in isolated outliers detached from the main outcrop. The formation ranges in thickness from 5 to 10 ft. Best exposed along Crosswicks Creek in the Allentown quadrangle. There, the unconformable contact with the underlying Englishtown Formation is exposed at several localities. The basal few inches of the Marshalltown contains siderite concentrations, clay balls, and woody fragments reworked from the underlying Englishtown. Numerous burrows, locally filled with glauconite, project downward into the Englishtown for about 3 ft giving a spotted appearance to the upper part of the Englishtown (similar to that shown in figure 9, Owens and others, 1970). The lower part of the Marshalltown is typically massive, dark-gray, highly bioturbated, silty, quartz-glauconite sand. At a few places there is a thin, fine, pebbly zone in the middle of the formation. Large fossil impressions are common in this pebbly zone. In the upper part of the formation, quartz increases to about 40 percent. The Marshalltown has small to moderate percentages of mica (mostly green chlorite) and small amounts of wood.

The sand and clay petrology of the Marshalltown is similar to that of the overlying Wenonah and a similar source area for the two formations is indicated. Within the map area, only a few long-ranging megafossils occur near Fellowship (Moorestown quadrangle) and Timber Creek (Camden quadrangle) (Richards, 1967). To the south in the type area of the Marshalltown, Weller (1907) reported diverse molluscan assemblages, but these serve only to indicate a Campanian age. More important is Olsson's (1964) report of the late Campanian foraminifera Globotruncana calcarata Cushman from the upper part of the formation. No G. calcarata were found during our investigations. Wolfe (1976) assigned the pollen assemblage of the Marshalltown to his zone CA5A which he considered to be Campanian.

The Marshalltown is the basal transgressive unit of a cycle of sedimentation that includes the regressive deposits of the overlying Wenonah and Mount Laurel Formations. In this respect, the cycle resembles the overlying Red Bank Formation to Navesink Formation cycle in its asymmetry. The Marshalltown has been assigned zones CC 20/21 in outcrop at Auburn, NJ.

Ket

Englishtown Formation (Upper Cretaceous, lower Campanian)--Sand, mostly loose, fine to coarse grained, fine pebbly, locally interbedded with thin to thick beds of dark clay (Owens and Sohl, 1969, fig. 8B). Abundant carbonaceous matter, with large lignitized logs locally, especially in clay strata. Sands are extensively trough crossbedded and planar beds are common (Owens and Sohl, 1969, fig. 8A), particularly west of Mount Holly in the Mount Holly quadrangle. In a few areas in the western outcrop belt, trace fossils are common, typically the burrow Ophiomorpha nodosa. Commonly pyritic, especially in the carbonaceous-rich beds. Pyrite occurs as finely disseminated grains or less commonly as pyritic masses up to 2 ft in diameter. At the base there commonly is a massive sand containing small-to-large, soft, light-gray siderite concretions. Underlies a broad belt throughout the map area. Ranges in thickness from about 140 ft in the north to 90 ft in the western outcrop belt. However, because of its loose unconsolidated nature, the formation is unusually poorly exposed; good exposures do occur along Crosswicks Creek near Walnford in the Allentown quadrangle. Other ephemeral exposures were observed in pits. The basal contact with the underlying Woodbury Formation is transitional over several feet and was drawn where quartz sand becomes a major constituent (in the Englishtown). Quartz is the major sand mineral, but feldspar, in concentrations up to 10 percent of the sand fraction, also is present. Locally, the unit is sparsely to moderately micaceous (muscovite) in the sands and very micaceous in the clay strata. Opaque heavy mineral assemblages are dominated by ilmenite and leucoxene; pseudorutile is present in small amounts. The non-opaque fractions have many species, including the most resistant minerals (zircon, tourmaline, rutile) and metamorphic minerals (sillimanite, kyanite, staurolite, garnet, epidote, hornblende, and chloritoid). Clay mineral suites from the clayey strata include all the major clay minerals in about equal proportions.

The age of the Englishtown in outcrop within the map area could not be determined directly. Macrofossil casts were collected from the siderite concretions in the base of the Englishtown in the Allentown quadrangle. Both gastropods and pelecypods were present, but the assemblage was dominated by the pelecypod Cymella bella. That species, however, is long ranging and is not useful in establishing the age of the Englishtown. These fossils do indicate a marine origin for at least the lower part of the Englishtown. Its age is inferred from the stratigraphic position and its pollen content. Wolfe (1976) examined the pollen in the Englishtown and concluded it was distinct and older than the pollen assemblage in the overlying Marshalltown. Wolfe designated this microflora as zone CA-4 and assigned it to the lower Campanian.

Kwb

Woodbury Formation (Upper Cretaceous, lower Campanian)--Clay-silt, dark gray when unweathered or shades of brown and orange pink where weathered. Iron oxides fill fractures or occur in layers in the most weathered beds. Massive (Owens and Sohl, 1969, fig. 7D), except at base where thin quartz sand layers are common. Locally, near top, thin stringers of pale, greenish-brown, smooth-surface glauconite occur. Conspicuously micaceous throughout and also contains significant concentrations of finely dispersed pyrite and carbonaceous matter. Small pieces of carbonized wood up to 6 in in length are also common. Small siderite concretions are abundant in the Woodbury in the northern part of the outcrop belt. Underlies a broad belt through the map area; belt tends to thin in the highlands in the north and widens to the southeast. Unit pinches out or changes facies, however, in the southwestern corner of the map. Overall, the Woodbury maintains a thickness of 50 ft throughout most of its outcrop belt. Because of its resistant clayey nature, the Woodbury is well exposed in most of the streams which cross its outcrop belt.

The petrology of the sand and clay minerals in the Woodbury are similar to those in the overlying Englishtown Formation. Fossil imprints are common throughout. An extensive Woodbury macrofauna was described by Weller (1907) throughout its outcrop belt with most of the described faunas occurring in the siderite concretions in the north. Included in his descriptions is a fauna from a tributary to the Cooper River paralleling Maple Avenue in the Camden quadrangle. This assemblage is unusual in that it is the only existing outcrop of the Woodbury where calcareous and aragonitic shells are still intact.

Approximately 15 ft of the Woodbury is exposed for some distance along this creek and consists of a massive, clayey silt that has a small concentration of glauconite sand. The clay-silt is very micaceous and has scattered chlorite, muscovite, and biotite. Small to large (up to 12 in) pieces of carbonized wood are scattered throughout the silt. Most of the fossils are small, fragmented, and are concentrated in small pockets, but larger intact calcareous fossils are scattered throughout the Woodbury. Weller (1907) recorded about 57 species from this locality. In addition, this was the same locality from which the dinosaur <u>Hadrosaurus</u> <u>foulkii</u> was collected. Pollen collected from the Woodbury was assigned to pollen assemblage CA3 by Wolfe (1976). All the biostratigraphic data suggest that the Woodbury is early Campanian in age.

Kmv

Merchantville Formation (Upper Cretaceous, lower Campanian)--Glauconite sand, very clayey and silty, locally has high quartz sand content. Very micaceous at base. Beds of dark-gray concretions are common in northern outcrops. Dark gray to gray green where unweathered, weathers to pale yellowish brown. Locally, has extensive iron incrustations in near-surface weathered beds. Massive to thick bedded (Owens and Sohl, 1969, fig. 7B-C). Fossil molds are common with most being phosphatic. In the south, fossils typically occur in siderite concretions. No calcareous fossils have been found in outcrop in this unit.

The Merchantville occurs as a continuous narrow to wide belt throughout the map area. The unit is thinnest in the north, about 20 ft thick, and is thickest in the Trenton area in the west-central areas where it reaches about 70 ft in thickness. The formation maintains about the same thickness in the Camden region, but it is best exposed in the Trenton East quadrangle, mainly in the tributaries on the west side of Black Creek and south of Bordentown where the entire thickness of the formation can be seen in gullies.

The Merchantville is gradational into the overlying Woodbury Formation. The contact is drawn where glauconite is no longer a major sand constituent. The basal contact with the underlying Magothy or Cheesequake Formations is sharp and disconformable. Commonly, a reworked zone about one to three feet thick is present at the base of the Merchantville. This bed contains reworked lignitized wood, siderite concretions up to 5 in in diameter, scattered pebbles and coarse quartz sand and is exclusively burrowed. The burrows commonly project downward into the underlying formations.

The sand fraction of the Merchantville is mainly quartz and glauconite. Feldspars and micas are also present in significant amounts. The opaque heavy minerals are dominated by ilmenite, and lesser amounts of leuxocene and pseudorutile. The non-opaque heavy mineral fraction is characterized by epidote, garnet, and staurolite. A large number of other minerals are also present, especially chloritoid. In general, the Merchantville heavy mineral assemblage would be considered a full suite of non-opaque minerals.

The Merchantville lacks calcareous microfossils in outcrop, but does contain an abundance of macrofossils preserved as internal and external molds. Of special importance is the presence of the ammonites Scaphites hippocrepis and Delawarella delawarensis. In addition to the localities listed by Weller (1907), these species have been found during this survey in the Oschwald pit in the Keyport quadrangle in the north and at Maple Shade near the type locality in the south. The Scaphites is of the type III variety of Cobban (1969) and is indicative of the lower, but not the very lowest, Campanian. More recently, Kennedy and Cobban (1993) detailed the ammonite fauna collected by a variety of people. They expanded on Cobban (1969) analyses. The ammonite assemblage includes Pachydiscus (Pachydiscus) sp., Pseudoacholenbachia cf.,P. chispaensis, Placenticeras placenta, Texanites (Texanites) sp., Menalrtes (Delawarella) delawarensis, M. vanuxemi, Menabites (Bererella) sp., Submortoniceras punctatum, S. uddeni, Cryptotexanites paedomorthicus sp., Glyptoyoceras sp., Chesapeaketta nodatraum, Baculites haresi, and Scaphites (Scaphites) hippocrepis III. They concluded that the Merchantville is upper lower Campanian. Wolfe (1976) indicated that the Merchantville microflora was distinct from overlying and underlying units and designated it zone CA2; he assigned an early Campanian age to this unit. The Merchantville is the basal bed of a lower Campanian transgressive-regressive cycle that includes the overlying Woodbury and Englishtown Formations.

The Merchantville faunas were analyzed by Sohl (in Owens and others, 1977) and he concluded that the northern faunas represented deposition on the lower shoreface or in the transition to the inner shelf, whereas the southern fauna was a deeper water assemblage, probably inner shelf.

Kcq

Cheesequake Formation (Upper Cretaceous, lower Campanian and upper Santonian)--Intercalated thin to laminated, dark-gray, weathering to light tan, micaceous clay or clayey silt (Owens and Sohl, 1969, fig. 7A) with abundant woody fragments and light fine-grained micaceous sand, most commonly horizontally bedded with rare small scale crossbeds; common small cylindrical burrows in the updip area. Abundant small (~2 inches) rounded pale-gray siderite concretions occur in thin discontinuous beds. Interfingers rapidly within a short distance with massive, extensively bioturbated, dark-gray, very micaceous, somewhat clayey and woody clay-silt. The clay-silt at the base of the formation has extensive cylindrical burrows filled with fine-grained, light- to medium-green botryoidal glauconite. Siderite concentrations, some as much as 5 in, are present in this downdip facies. Additionally, the silt-sand layers are also extensively burrowed locally obliterating the bedding.

Overlies Magothy Formation with a sharp contact with reworked siderite concretions and some glauconite and coarse-grained quartz sand occurring along the boundary. Exposed only in the South Amboy and Keyport quadrangles. Here, the unit is about 45 ft thick. The light sand minerals are primarily quartz with lesser amounts of rock fragments and feldspar. The opaque heavy minerals are mostly ilmenite with smaller amounts of pseudorutile and leucoxene. The non-opaque heavy minerals include zircon, tourmaline, staurolite and chloritoid. The clay minerals are a mixture of illite/smectite, illite and kaolinite.

The age of the Cheesequake in outcrop was determined from its pollen (Litwin and others, 1993). The pollen assemblages lie somewhere between the Merchantville Formation microflora (zone CA2 of Wolfe, 1976 classification - lower Campanian) and the uppermost Magothy microflora (?Pseudoplicapollis cuncata-Semiculopollis verrucosa zone of Christopher, 1979, upper Santonian). It is probable that the Cheesequake Formation contains the Santonian-Campanian boundary. This unit was not recognized by Petters (1976) when he concluded that the Magothy and Merchantville interfingered in the subsurface and the Merchantville was in part Santonian.

Kmg Magothy Formation (Upper Cretaceous, Santonian)--Sand, loose, light colored, interbedded with thin-to-thick, dark-gray, very lignitic clays or silts. Less commonly has beds of gravel. Formation characterized locally by rapid vertical and lateral facies changes. On the old State map (Lewis and Kümmel, 1910-1912, revised 1950) the Magothy was considered to consist of only one lithology, presented by the Cliffwood beds at Cliffwood Beach. Subsequently, pollen studies of this restricted formation and the members of the underlying Raritan Formation showed that most of these members were the same age as the Magothy. The Magothy was redefined and considerably expanded (Wolfe and Pakiser, 1971).

The Magothy is best exposed and thickest (about 270 ft) in the northern Coastal Plain near Raritan Bay. The Magothy outcrop belt is widest in the north and narrows to the southwest where the formation is about 90 ft thick. In spite of its substantial thickness in the southwest, the formation is poorly exposed largely because of its loose sandy nature and widespread cover by younger sediments.

Kümmel and Knapp (1904) recognized that the Magothy (as used here) contained a large number of lithologies. At the time of their study, the Magothy was extensively mined for its clay and sand in the northern Coastal Plain, and they had many exposures to examine. As a result, their subdivisions had economic designations (for example, Amboy stoneware clay). Barksdale and others (1943) later gave formal geographic names to these subdivisions, which will be discussed individually.

a. Cliffwood beds--The Cliffwood beds are typically very sandy, horizontally bedded to crossbedded (mainly small-scale trough crossbeds) (Owens and Sohl, 1969, fig. 6C). Thin layers of dark, finely comminuted, carbonaceous matter are interbedded with the sands. The carbonaceous units are conspicuously micaceous; the sands are less so. The sands are typically fine to medium grained and are locally burrowed. Several types of burrows occur including the small-diameter Ophiomorpha nodosa and some that are not clay lined. Slabs of dark reddish-brown siderite were common at the base of the bluff before this outcrop was cemented over. Some of these slabs had many fossil molds, typically a large number of pelecypods. Lower in the section, between high and low tide level, there is a pale-gray clay-silt about 5 ft thick with many small reddish-brown siderite concretions. These concretions have many fossils which were described in detail by Weller (1904). The Cliffwood beds are about 25 ft thick in outcrop.

Equivalents of the Cliffwood beds are exposed near the Delaware River between Trenton and Florence (Owens and Sohl, 1969, fig. 6D). These beds are mainly sand, as are those at Cliffwood Beach, but they tend to have more crossbedding than the typical Cliffwood strata and no burrows or marine fossils. In addition, beds of quartz gravel are present in the Cliffwood near Riverside.

b. Morgan beds--The Morgan beds occur only in the northern Coastal Plain. They consist of horizontally interbedded, thin, dark clays and light-colored, fine-grained, micaceous sands (Owens and Sohl, 1969, fig. 6B). Clay is locally more abundant in the Morgan than in the Cliffwood beds. The sands range from massive to locally crossbedded and locally have finely comminuted organic matter. This unit is only exposed in the South Amboy quadrangle where it is as much as 40 ft thick. It grades downward into underlying clay.

c. Amboy Stoneware Clay Member--This member crops out only in the South Amboy quadrangle and is mainly dark-gray (weathering to white) interbedded clay (major) and silt to fine-grained quartz sand (Owens and Sohl, 1969, fig. 6A). The clays have abundant, finely comminuted, carbonaceous matter and fine mica flakes. Small cylindrical burrows are common throughout this unit. Locally, the clays are interbedded with sands and contain large pieces of lignitized logs, which are bored (Teredolites). Large slabs of pyrite-cemented sand are associated with the woody beds. Amber is also common in some of the wood. This unit is approximately 25 ft thick, but tends to pinch out along strike.

The Amboy Stoneware appears to lie disconformably on the underlying sand.

d. Old Bridge Sand Member--The Old Bridge Sand Member is dominantly a light-colored, loose sand, extensively crossbedded (Owens and Sohl, 1969, fig. 5C) and locally interbedded with dark-gray laminae; the clays are highly carbonaceous, woody, in discontinuous beds especially near the base of the unit. The scale of crossbedding on the sands varies from small to large. Locally, small burrows are present in some of the sands. These sands range up to 40 ft in thickness, and they rest disconformably on the underlying unit.

e. South Amboy Fire Clay Member--The South Amboy Fire Clay Member is the basal member of the Magothy Formation. In some respects, this unit resembles the Amboy Stoneware Clay Member, particularly in its lensing character. This unit is best exposed in pits east of Parlin in the South Amboy quadrangle and locally in the Delaware River valley at the base of the bluffs at Florence (Bristol quadrangle). The South Amboy typically is a dark, massive to finely laminated clay. The clay is locally oxidized to white or red. The South Amboy Fire Clay Member commonly occurs in large channels and has local concentrations of large, pyrite-encrusted, lignitized logs. Some of the clay is slumped, suggesting some possible post-depositional undercutting during channel migration. The clay is interbedded with fine- to medium-grained, crossbedded sands. The basal contact with the underlying Raritan is well exposed in the Sayre and Fisher Pit in Sayreville where the contact is physically marked by a deeply weathered gravel zone.

Picking the lower contact of the Magothy in the Delaware River valley is difficult because the lower part of the Magothy is lithically similar to the underlying Potomac Formation. The contact was selected in this area at the base the lowest black clay in the Magothy.

Quartz is the most abundant sand mineral in the Magothy. Muscovite, and to a lesser degree feldspar, are accessory minerals. Feldspars are more abundant in the west-central belt. In the opaque fraction, ilmenite and leucoxene are the major constituents. The non-opaque assemblages are highly variable at outcrop and regional scales. In general, the assemblages are characterized by high concentrations of the most weathering-resistant minerals, zircon, tourmaline, and rutile. The metamorphic minerals staurolite, sillimanite, and kyanite are common constituents in most assemblages. Epidote and garnet are common constituents in a few samples. In the northernmost outcrop area, chloritoid is abundant locally in the middle and upper parts of the Magothy Formation. The clay minerals in the Magothy are mainly kaolinite and illite. Illite/smectite is only present locally in a few samples.

The age of the Magothy is difficult to determine from calcareous macro- and micro-fossils because of their usual absence in the outcrops. The best faunas were obtained from siderite concretions and slabs in and near Cliffwood Beach, and therefore, are only from the top of the formation. These faunas were discussed in detail by Weller (1904, 1907) and supplemented by Sohl (Owens and others, 1977). Of specific note in the Cliffwood Beach fauna is the presence of Ostrea cretacea, which suggests that the upper part of the Magothy is late Santonian in age. Wolfe and Pakiser (1971) and Christopher (1979, 1982) discussed the microfloral assemblage in the Magothy. Christopher subdivided the Magothy into three zones: Complexipollis exiqua-Santalacites minor (the oldest) ?Pseudoplicapolles longiannulata-Plicapollis incisa (middle), and ?Pseudoplicapollis cuneata-Semioculopollis verrucosa (youngest). The oldest zone was originally considered to be as old as Turonian by Christopher, but subsequently (Christopher, 1982) he considered it to be post-Coniacian. The middle and upper zones are also most probably Santonian. In his study Christopher (1979) followed the nomenclature for the subdivisions elaborated upon earlier. The Cliffwood and Morgan beds, and presumably the upper thin-bedded sequence, would include the youngest pollen zone; the Amboy Stoneware Clay Member and perhaps the uppermost part of the Old Bridge Sand Member, the middle zone; and the lower part of the Old Bridge Sand Member and South Amboy Fire Clay Member, the oldest zone. In summary, the Magothy is considered to be of Santonian age.

Kr

Raritan Formation (Upper Cretaceous, upper Cenomanian)--The Raritan Formation consists of four units as outlined by Barksdale and others (1943): Sayreville Sand Member, Woodbridge Clay Member, Farrington Sand Member, and the informal Raritan fire clay (oldest). Of these, the Sayreville Sand Member and Raritan fire clay are too small to be mapped at the scale of our map. The Raritan Formation, as shown on the surface map, therefore, consists of a thick, upper clayey silt (Woodbridge Clay Member) and a lower sand (Farrington Sand Member)

a. Woodbridge Clay Member--Silt, very clayey, dark gray weathered to red brown or white, locally interbedded with light-gray, very clayey, fine- to very fine-grained sand (Owens and Sohl, 1969, fig. 5A). Very micaceous (muscovite, chlorite, and biotite) in both silty and sandy beds. Very woody, mostly fine pieces in layers and coated with pyrite. Locally, tree stumps in growth position have been found near the base of the unit. In addition, transported individual logs several feet in length are present. Siderite in discontinuous beds and in flattened slab concretions up to about 2 ft in maximum diameter are common in the Woodbridge. Fossil casts, mainly of marine molluscs, are also common particularly in slabs near the top of the formation. Locally, well-developed Ophiomorphia nodosa filled with iron oxides have weathered out from the clay-silt.

The Woodbridge is approximately 70 ft thick in the vicinity of Sayreville (South Amboy quadrangle), where the South River has stripped away the overlying Magothy Formation. It crops out in many places in the Perth Amboy and New Brunswick quadrangles to the north, but not in the quadrangles to the south or southwest. The Woodbridge does not crop out in the Delaware River valley southwest of Trenton.

Woodbridge sands are primarily quartz and mica; feldspar is present in very small amounts. The opaque heavy minerals are primarily ilmenite and leucoxene. The non-opaque fraction is dominated by zircon, tourmaline, and rutile; chloritoid and andalusite are common accessories.

The clay minerals in the Woodbridge are dominantly a kaolinite-illite assemblage. Mixed-layer clays (illite/smectite) are present only in minor amounts.

The late Cenomanian ammonites Metoicoceras bergguisti and Metengonoceras sp. have been described from the upper part of the Woodbridge in outcrop (Cobban and Kennedy, 1990). Pollen from the unit belongs to the Complexipollis-Atlantopollis Assemblage Zone, which is latest Cenomanian and early Turonian in age (Christopher, 1979, 1982).

b. Farrington Sand Member--Sand, white, crossbedded, fine to medium, very micaceous; interbedded with thin to thick, dark, silt beds. No burrows were observed in the unit. This unit is exposed only in pits dug below the overlying Woodbridge Clay Member; typically, it is about 30 to 35 ft thick. This member is best exposed in the Sand Hills just north of the map boundary in the Perth Amboy quadrangle. The light sand minerals in this unit are quartz and rock fragments. The opaque and non-opaque heavy minerals are similar to those in the Woodbridge Clay Member. Pollen in the Farrington is also similar to the pollen in the Woodbridge.

KpIII Potomac Formation, unit III (Upper Cretaceous, lower Cenomanian)--Sand, fine to coarse, light colored, loose, crossbedded, somewhat gravelly interbedded with clays, white or variegated red and yellow, massive. Beds of dark gray woody clays occur rarely.

The Potomac Formation crops out only in the Delaware River valley where the river and its tributaries have eroded away the overlying formations. The Potomac has been mapped in a broad belt parallel to the inner edge of the Coastal Plain. In spite of this width, the Potomac is very poorly exposed because of a widespread cover of surficial sediments and therefore is largely a subcrop unit. The best exposures occur where the surficial material has been mined away in Pennsylvania near Morristown and in the Camden area of New Jersey.

Contact with the overlying Magothy Formation is difficult to pick where the basal Magothy also contains variegated clays. In general, the basal Magothy has more dark-colored clays, and the contact was drawn using this criterion. The basal contact of the Potomac with the underlying crystalline rock is not exposed in New Jersey.

Sand bodies in the Potomac occur in large channels. The scale of crossbedding ranges from small to very large (Owens and Sohl, 1969, fig. 5D). Rip-up clay clasts are abundant in some of the sand beds. Fine quartz gravel is present in some of the coarser beds. The sands are mostly quartz and rock fragments. Small amounts of sand-size mica are also present. Heavy minerals are sparse in these sands. The opaque fraction consists typically of pseudorutile and leucoxene; fresh ilmenite is only present in small amounts. In the non-opaque fraction, the most resistant minerals zircon, tourmaline, and rutile dominate. Small amounts of epidote, staurolite, and sillimanite are accessories.

The clay units in the Potomac are more obviously bedded than the sands. Locally, however, massive clay plugs within channels are present. The clay minerals in both dark-gray and light-colored variegated beds are mostly kaolinite and illite.

Biostratigraphically, the Potomac has been separated elsewhere into three pollen zones, zones I, II, and III of Doyle (1969). Samples collected from the Potomac Formation in the Camden area and along the river nearby contain pollen assemblages of early Cenomanian age (zone III) (L. Sirkin, written commun., 1988).

Rocks of the Newark Basin

Intrusive rocks

Jd

Diabase (Jurassic)--Concordant to discordant, predominantly sheet-like intrusions of medium- to fine-grained diabase, and dikes of fine-grained diabase; dark greenish gray to black; subophitic texture. Dense, hard, sparsely fractured rock composed mostly of plagioclase (An_{50-70}), clinopyroxene (mostly augite) and magnetite-ilmenite. Orthopyroxene (En_{75-80}) is locally abundant in the lower part of the sheets. Accessory minerals include apatite, quartz, alkali feldspar, hornblende, sphene, and zircon. Olivine rarely occurs. Diabase bodies in the map area are derived primarily from high-titanium, quartz-tholeiite magma. Sedimentary rocks within about 1000 ft above and 650 ft below major diabase sheets are thermally metamorphosed; red mudstone is typically altered to indurated, bluish-gray hornfels, commonly with clots or crystals of tourmaline or cordierite; gray argillitic siltstone is typically altered to brittle, black, very fine-grained hornfels. Principal sill-like intrusions are 1200 to 1300 ft thick. Dikes range in thickness from 10 to 30 ft and are commonly many miles long.

Sedimentary and bedded volcanic rocks of the Newark Supergroup

Brunswick Group

Jp

Preakness Basalt (Lower Jurassic)--This small body of very coarse-crystalline basalt occurs in the Sand Brook syncline. It is correlated with the Preakness Basalt of the Second Watchung Mountain on the basis of chemical composition and stratigraphic position. Very dark-greenish-gray to black basalt. Texture is subophitic; plagioclase and augite crystals are nearly equal in size; no fine-grained groundmass. Plagioclase is subhedral, mostly 0.008 to 0.012 in. long, with a few crystals up to 0.08 in. long; composition is $An_{55\text{-}60}$. Clinopyroxene and orthopyroxene grains are equant, mostly anhedral, 0.012 in. average diameter. Iron-titanium oxides are mostly interstitial, 0.08 to 0.02 in. diameter. Thickness of unit is unknown in map area.

Jf

Feltville Formation (Lower Jurassic)--Mostly fine-grained feldspathic sandstone, coarse siltstone, and silty mudstone; brownish red to light grayish red. Fine-grained sandstone is moderately well sorted commonly cross laminated, and contains 15 percent or more feldspar; interbedded with mudstone, indistinctly laminated, bioturbated and calcareous in places. A thin bed (0 to 7 ft thick) of black microlaminated carbonaceous limestone and gray calcareous mudstone occurs near the base; it contains fish and plant fossils, and thermally mature hydrocarbons. Thickness of unit in the Sand Brook syncline is about 510 ft.

Jo

Orange Mountain Basalt (Lower Jurassic)--Dark-greenish-gray, fine-grained to aphanitic basalt composed mostly of calcic plagioclase and augite; crystals smaller than 0.04 in. Consists of three major tholeiitic lava-flow sequences, each about 250 ft thick. Lowest flow is generally massive with widely spaced curvilinear joints; middle flow is massive or has columnar joints; lower part of uppermost flow has pillow structures and upper part has pahoehoe flow structures. Thickness in map area is about 525 ft.

J₮p

Passaic Formation (Lower Jurassic and Upper Triassic)--Predominantly red beds consisting of argillaceous siltstone, silty mudstone, argillaceous very fine-grained sandstone, and shale; mostly reddish brown to brownish purple, and grayish red. Upper Triassic gray lake deposits (₮pg) consisting of gray to black silty mudstone, gray and greenish- to purplish-gray argillaceous siltstone, black shale, and medium- to dark-gray argillaceous fine-grained sandstone are abundant in the lower half of the Passaic Formation and less common and thinner in the upper half.

Red beds occur typically in 10- to 25-ft thick, cyclic playa-lake-mudflat sequences and fining-upward fluvial sequences. Lamination is commonly indistinct due to burrowing, desiccation, and paleosol formation. Where layering is preserved, common bedforms are wavy parallel lamination and trough and climbing-ripple cross lamination. Calcite- or dolomite-filled vugs and flattened cavities, mostly 0.02 to 0.08 in. across, are common, especially in the lower half. Sand-filled burrows 0.08 to 0.2 in. in diameter are common in the upper two-thirds of the unit. Desiccation cracks, breccias, and curled silt laminae are abundant in the lower half, less common in the upper half. Lake cycles, mostly 7 to 17 ft thick, typically consist of a basal argillaceous siltstone (usually greenish gray), a medial lake-bottom fissile mudstone or siltstone (dark gray to black; commonly pyritic, carbonaceous, fossiliferous, and in places calcareous), and an upper thick-bedded argillaceous siltstone (gray to reddish and purplish gray; typically with desiccation cracks and breccias, burrows, and mineralized vugs). Gray lake beds commonly occur in groups of two to five cycles; they also occur singly in some parts of the formation. Several lake-bed sequences consisting of one or two thick groups of drab-colored beds as much as 100 ft thick or more can be traced over tens of miles. Some thin gray units are depicted with slightly exaggerated thickness. Other thin or sparsely exposed gray beds have been omitted from the map. Many gray-bed sequences shown on the map can be locally correlated within fault blocks; some can be correlated across major faults or intrusive rock units. Thickness of the formation between Sourland Mountain and Sand Brook syncline is about 1100 ft.

TRl

Lockatong Formation (Upper Triassic)--Predominantly cyclic lacustrine sequences consisting of silty argillite (commonly dolomitic or analcime-bearing), laminated mudstone, silty to calcareous, argillaceous very fine-grained sandstone and siltstone (commonly pyritic), and minor silty limestone; mostly light to dark gray, greenish gray, and black. Grayish-red, grayish-purple, and dark-brownish-red sequences (TRlr) occur in some places, especially in upper half. Two types of cycles are recognized: fresh-water-lake (detrital) and alkaline-lake (chemical) cycles. Fresh-water-lake cycles average 17 ft thick. They consist of basal (transgressive fluvial to lake-margin deposits) argillaceous, very fine-grained sandstones to coarse siltstones with indistinct lamination, planar or cross-lamination, or disrupted to convolute bedding; desiccation cracks, root casts, soil-ped casts, and tubes are common. Medial (lake-bottom) deposits are laminated siltstones, silty mudstones, or silty limestones, dark gray to black, commonly with calcite laminae and grains and lenses, or streaks of pyrite; fossils are common, including fish scales and articulated fish, conchostracans, plants, spores, and pollen. Upper (regressive lake margin, playa lake, and mudflat) deposits are light- to dark-gray silty mudstones to argillitic siltstones or very fine-grained sandstones, mostly thick bedded to massive, commonly contains desiccation cracks, breccias, faint wavy laminations, burrows, euhedral pyrite grains, and dolomite or calcite specks. Alkaline-lake cycles are similar to fresh-water-lake cycles, but are thinner (averaging 10 ft), have fewer fossils (mainly conchostracans), and commonly have red beds, extensive desiccation features, and abundant analcime and dolomite specks in the upper parts of cycles. Thickness near Byram, N.J., is about 3500 ft. The formation thins to the southeast and northeast; thickness near Princeton is less than 2300 ft

Ꞧs

Stockton Formation (Upper Triassic)--Predominantly medium- to coarse-grained arkosic sandstone (light gray, light grayish brown, or yellowish to pinkish gray) and medium- to fine-grained arkosic sandstone (violet gray to reddish brown); with less common silty mudstone, argillaceous siltstone, and shale (reddish to purplish brown). Some coarse-grained sandstones in the lower part contain thick beds of conglomerate (Ꞧsc), which have been mapped in the vicinity of Stockton, N.J. Sandstone was deposited in high-gradient stream channels and are mostly planar bedded with scoured bases containing pebble lags and mudstone rip-ups. Upper parts of channel beds are commonly burrowed. Large-scale trough crossbeds occur in some very coarse-grained sandstone beds; smaller-scale trough and climbing-ripple cross lamination occur in the upper parts of channel sequences and in finer grained sandstone beds. Floodplain mudstones are typically irregularly thin bedded and extensively burrowed. Floodplain beds are thicker and more numerous in the central Newark basin, near the Delaware River. Thickness of the unit (including Ꞧsc) near Stockton, N.J. is about 4000 ft.

Piedmont Rocks

Rocks of the Trenton prong

Ꞓc

Chickies Quartzite (Lower Cambrian)--Upper part is interbedded medium-grained, crossbedded, medium-bedded, vitreous quartzite and medium- to thin-bedded, light-gray muscovite-quartz schist that locally contains tourmaline. Lower part contains scattered bodies of quartz-pebble conglomerate and much less quartz-muscovite schist that contains lenses of pure quartzite. Unit unconformably overlies the Middle Proterozoic rocks.

Zv

Metabasalt (Late Proterozoic)--Sequence of conformably layered volcanic rocks consisting of fine-grained to aphanitic, greenish-gray, retrogressively metamorphosed greenstone and greenschist. The greenschist contains clots and lenses of blue quartz and abundant sulfide. Unit does not crop out and is known only from subsurface borings and artificial exposures. Interpreted to be Late Proterozoic by Volkert and Drake (1993) on basis of geochemical similarity to Late Proterozoic diabase dikes in New Jersey Highlands.

Ygb

Gabbro (Middle Proterozoic)--Medium- to coarse-crystalline, medium- to dark-gray foliated rock composed principally of plagioclase (An_{35}) and clinopyroxene. Contains minor amounts of garnet, biotite, and sulfide. Chemically, the rock appears to be more siliceous than typical gabbros.

Yg

Gneiss, granofels, and migmatite (Middle Proterozoic)--Gneisses and granofels ranging in composition from felsic to intermediate to mafic; intermediate compositions are most common. Contains a wide variety of rock types including graphitic schist and marble. Many rocks are injected by a granitoid that has blue quartz and augen of potassic feldspar, and are, thereby, arteritic migmatites. One body of gneiss contains a 3 by 1.5 ft phacoid of gabbro that could be interpreted to be an olistolith. Unit probably represents a sequence of metasedimentary and metavolcanic rocks that have been heavily injected and migmatized by felsic magma.

Ya

Amphibolite (Middle Proterozoic)--Medium-grained, very dark-gray to black, foliated rocks consisting of hornblende and andesine. Some exposures are cut by bodies of white plagioclase pegmatite.

Obducted rocks

CZw

Wissahickon Formation (lower Paleozoic and Late Proterozoic)--Fine- to medium-grained biotite-quartz -plagioclase schist and gneiss that contains thin amphibolite layers. In many exposures the schist and gneiss occur in alternating layers suggesting a turbidite sequence of shale and graywacke. The rocks are at high metamorphic grade, and in places the more pelitic parts have partly melted forming veinitic migmatites. Some exposures show evidence of polymetamorphism as micaceous minerals occur both within the schistosity and as static porphyroblasts.

Explanation for Subsurface Framework (Plates 2 and 3)

INTRODUCTION

A subsurface lithostratigraphic framework was constructed for the Coastal Plain deposits of the central bedrock map using gamma logs as the main correlation tool (Plates 2 and 3). The log correlations were augmented by lithologic and fossil data from samples in several cored or partially cored drill holes. Biostratigraphic analyses of several faunal and floral groups were conducted to aid in dating many of the units into the subsurface. Also, a cross section of the Mesozoic basin and Piedmont rocks is included (Plate 2).

Gamma-log profiles were constructed for the Coastal Plain roughly parallel to the strike of outcropping formations and roughly following their dip (fig. 2). It has long been known that the strikes of these various formations differ, and by analogy, so do the dips. Therefore, the sections are neither true strike nor dip sections.

An additional problem, and in one sense a plus, is that large volumes of inner Coastal Plain sediments have been stripped during periods of erosion. In some cases, updip and downdip facies relations within a single unit are exposed as a result, and in other cases some units that are found mostly in the subsurface have been exhumed (such as the Shark River and Manasquan Formations).

GAMMA-LOG PROFILES

Most of the units shown on the gamma-log profiles are of marine origin. These units are distinctly unconformity bounded. Their basal unconformities are commonly marked by a distinct gamma-ray spike that represents a basal phosphatic or glauconitic lag deposit. Some of these subsurface units represent a complete transgressive-regressive cycle of sedimentation. As defined in outcrop (Owens and Sohl, 1969), these cycles are asymmetric in nature and are characterized by a glauconite sand at the base (transgressive bed), a clay-silt or clayey fine sand in the middle (regressive) and a well sorted quartz sand at the top (regressive). Each cycle repeats the same pattern so that the typical marine cycle is unconformable at both its base and top.

In those formations consisting of marginal-marine or non-marine sediments, gamma correlations are of less value for correlation. In such units, core recovery is a necessity. In actual practice, this situation occurs at the bottom of the Coastal Plain section (Potomac, Raritan, and Magothy Formations) and at the top (parts of the redefined Kirkwood and Cohansey Formations).

Correlations from the outcrop into the subsurface are commonly accompanied by facies changes, which vary from formation to formation. In some instances, the changes in lithology are rapid, for example, the Kc_4 cycle in which sand and silt facies of the Red Bank Formation change to a glauconite facies of the Navesink Formation within a few miles downdip.

In general, the gamma-log patterns vary from formation to formation and within

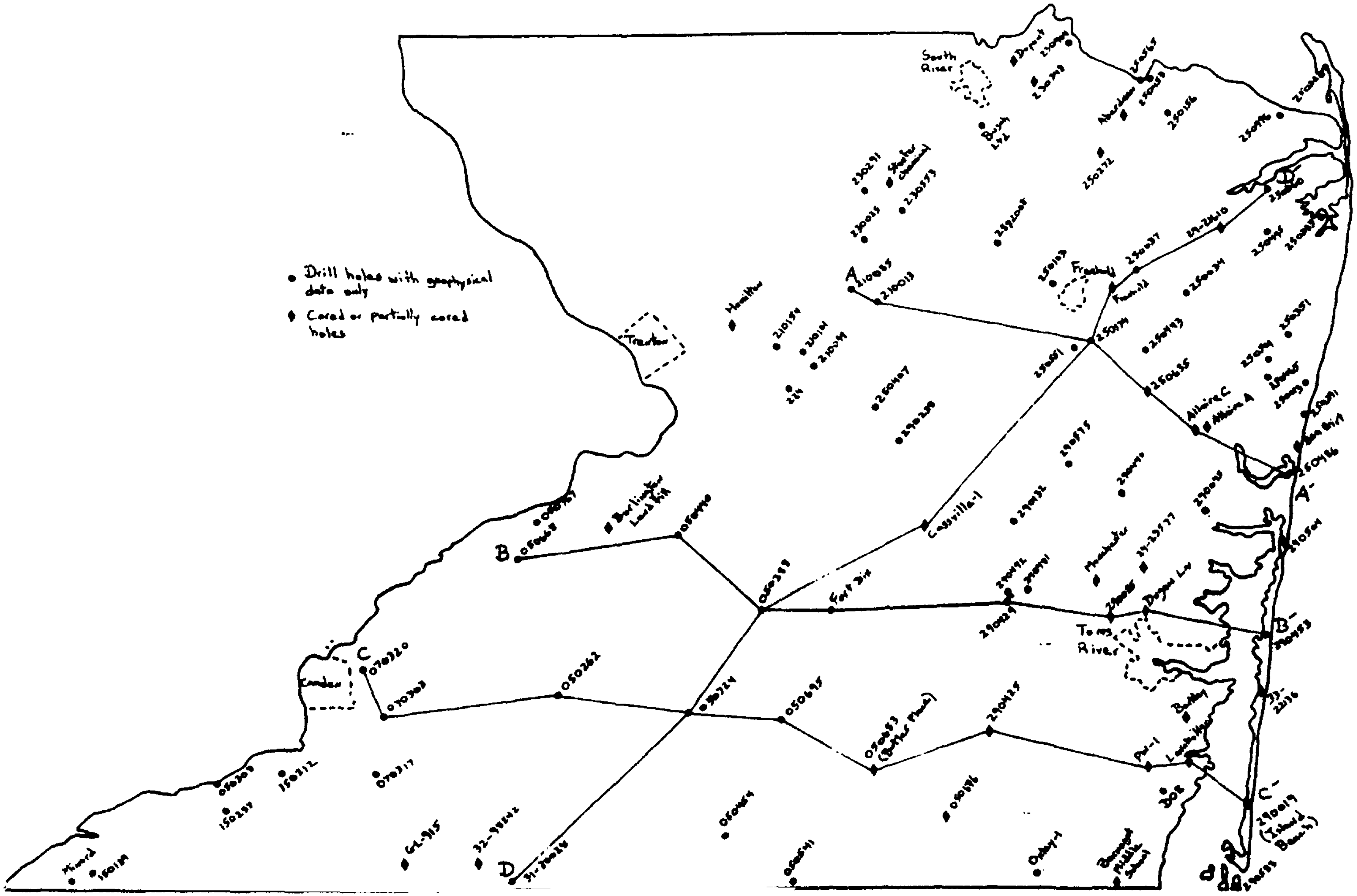

Figure 2. Map showing location of drill holes in the central sheet, New Jersey and lines of gamma-log profiles shown on Plates 2 and 3.

formations locally from site to site. With some formations, the change in gamma response is abrupt from non-clayey facies to more sandy facies and in others the transition from clay to sand is gradual. Predictably, lateral facies changes within formations also produce lateral changes in gamma-log response.

Figure 3 shows the gamma-ray signatures found most commonly with the different Coastal Plain units in the subsurface of New Jersey. A particularly fine gamma log (log I) from near Toms River, N.J. shows many of the geophysical signatures found through much of the subsurface of the New Jersey Coastal Plain. A second log (log III) from Barnegat Middle School shows the upper Tertiary beds in the regions which were not sampled at the chemical locality. A third log (log II) from the Freehold, New Jersey corehole is shown to illustrate features not shown in the above logs. Each of the characteristic gamma signatures is given a type letter which is cited with each of the formation descriptions.

1) Type A gamma signature associated with fluvial deposits (Toms River and Freehold logs)

The Potomac Formation is an example of a very thick pile of fluvially dominated sediments deposited in part in upper to middle delta plain. These deposits consist of abruptly lensing sands or gravelly sands and clays. Figure 3 is a typical log in this unit. This pattern consists of close to widely spaced gamma spikes deflected to the left representing thin to thick sand bodies interspersed with thin to thick spikes deflected to the right which are the clayey sediments. No consistent patterns were found between holes, which is a reflection of the abrupt facies changes within this type of environment.

2) Type B gamma signature associated with continental shelf deposits (Toms River, Freehold and Barnegat Middle School logs)

In contrast to the fluvial deposits, facies changes within the continental shelf marine deposits are gradual. Most commonly the gamma patterns in this type unit are a thick clayey unit in the base (pattern deflected to the right) and a gradual increase in sand upward through the section producing a gradual deflection to the left. Basically this represents a cycle of sedimentation or a sequence; e.g. a transgression followed by a regression. In the New Jersey marine cycles the transgressive beds are typically middle to outer shelf deposits. The middle shelf deposits are dark gray carbonaceous silts or clays and the middle to outer shelf deposits are dark colored glauconite-rich clayey sands. Both these lithologies have similar geophysical signatures and thus cannot be separated using this method. Therefore, correlations with the outcropping glauconite sands or the carbonaceous silts were not feasible and therefore they were lumped into a single unit. The upper sands most commonly are inner shelf deposits but not the innermost. The innermost marine deposits such as barrier and back barrier deposits found elsewhere in the Coastal Plain are absent in most of the cyclic deposits, most notably those of Late Cretaceous age. These very near-shore deposits are assumed to have been removed by post-depositional erosion. The near-shore sands are gradational with the underlying carbonaceous silts. For this reason, the subsurface cycles are mapped as a single formation (table 1). Subsurface cycles are given a numerical designation, shown in table 1. Correlating the individual cycles in the subsurface was relatively easy and formed a major technique used to construct the cross sections.

3) Type C gamma signature associated with superposed deep water sequences

Some of the lower and middle Paleogene formations are the deepest water marine

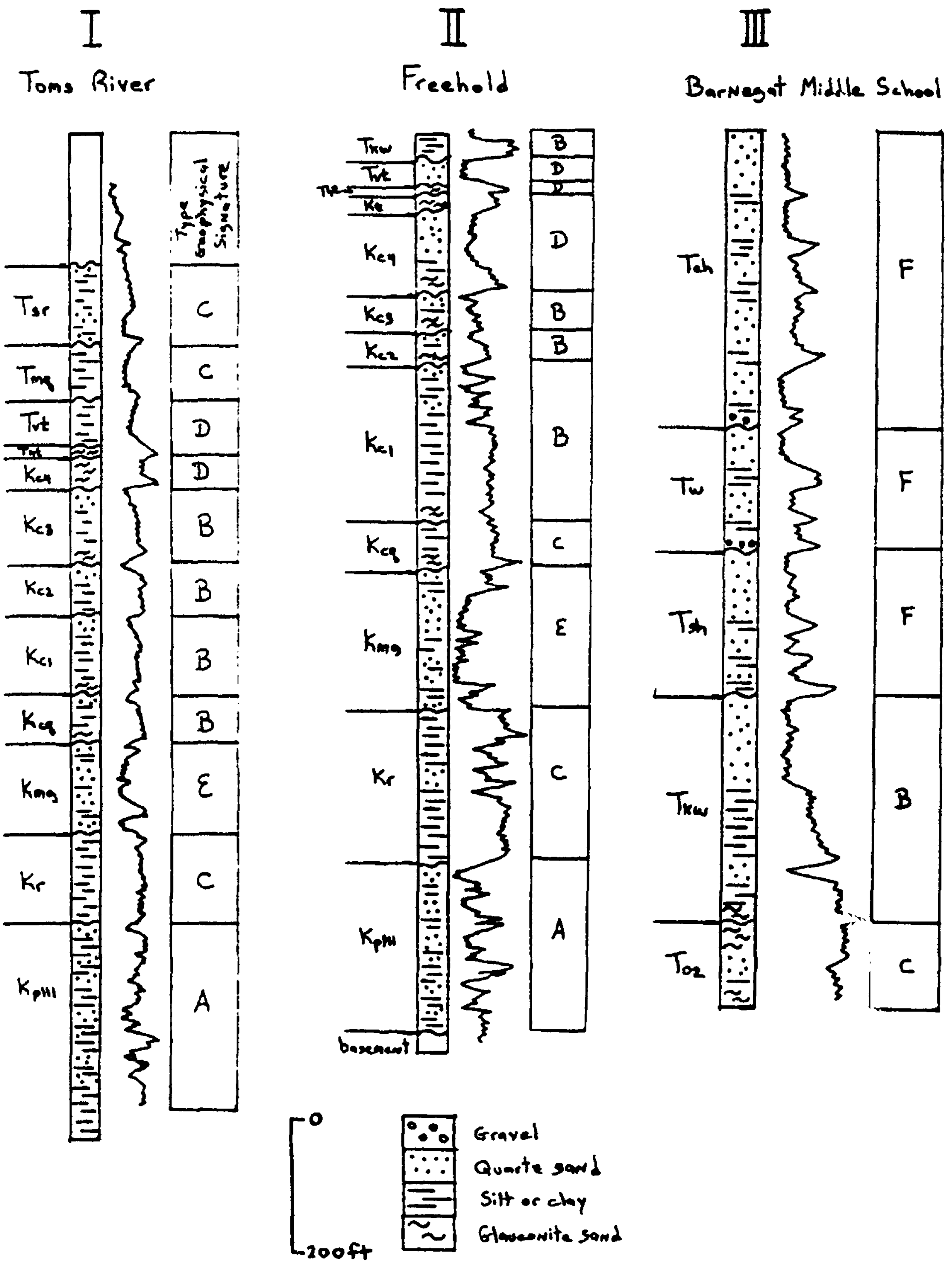

Figure 3. Diagram showing the relationship between lithology and associated geophysical signature in three partially or fully cored drill holes. Geophysical logs are a major correlation tool in the subsurface of the Coastal Plain and a wide variety of gamma logs are found. The geophysical signature or signatures have been assigned a letter designation that is discussed as most typical for each formation in the unit descriptions. Unit symbols are the same as map symbols.

Table 1. Surface to subsurface correlations for Coastal Plain units on the central sheet.

Surface	Subsurface
Cohansey Formation	Cohansey Formation
Wildwood Formation*	Wildwood Formation*
[absent]	Shiloh Marl**
Kirkwood Formation**	Kirkwood Formation**
[absent]	To_2 cycle
[absent]	To_1 cycle
[absent]	Te cycle
Shark River Formation	Shark River Formation
Manasquan Formation	Manasquan Formation
Vincentown Formation	Vincentown Formation
Hornerstown Formation	Hornerstown Formation
Tinton Formation	Tinton Formation
Red Bank Formation	Kc_4 cycle
Navesink Formation	
Mount Laurel Formation	
Wenonah Formation	Kc_3 cycle
Marshalltown Formation	
[absent]	Kc_2 cycle
Englishtown Formation	
Woodbury Formation	Kc_1 cycle
Merchantville Formation	
Cheesequake Formation*	Cheesequake Formation*
Magothy Formation	Magothy Formation
Raritan Formation	Raritan Formation
Potomac Formation, unit III	Potomac Formation, unit III
[absent]	Potomac Formation, unit II
[absent]	Potomac Formation, unit I

* New name
** Revised name

deposits preserved in the Coastal Plain. These include the Manasquan, Shark River and Vincentown Formations. These units are typically very fine-grained with varying amounts of fine-grained clasts and fine- to medium-grained glauconite sand. Gamma logs in these units typically have a flat field throughout as commonly found with clayey units. What is interesting in the Tertiary as compared with the Cretaceous units is the presence of a pronounced gamma spike below or at the base of the lower Tertiary units. This phenomenon often is used to separate units of similar lithology in the subsurface.

4) Type D gamma signature associated with marine deposits which undergo abrupt facies changes downdip

Facies changes are common in nearly all the Coastal Plain formations. As described above, abrupt facies changes are commonplace in the non-marine environment. Conversely facies changes in the Cretaceous shelf deposits are typically gradual. In some of the marine units, however, notably with the Vincentown and the Red Bank-Navesink cycle, the updip to downdip facies changes are abrupt. Figure 4 shows three logs within the Red Bank-Navesink cycle arranged in an up dip-downdip direction. The distance between the holes is about 11 miles. Basically the change of facies in this case is from the full cycle described in the continental shelf type in the updip to only a glauconite sand or the lithology of the basal facies in a fully developed cycle. One interpretation of the change within this cycle is that the upper most clastic facies were stripped post-depositionally. Another interpretation could be non-deposition of the coarser clastic facies. Fossil data support the latter interpretation as the downdip glauconite sand is the age equivalent of the entire cycle as determined from its fossil content. Therefore the lithic association shown in the three logs is the result of a change in facies from the shallower water middle and upper part of the updip cycles to the deeper water facies in the downdip beds.

5) Type E gamma logs not fitting any of the above examples (Toms River and Freehold logs)

The Magothy Formation has a gamma log typical of those found with the most sandy facies (fig. 3). The unusual gamma signature of this unit is due to the presence of thin to thick clayey beds interstratified and the persistence of the sand throughout most of the Coastal Plain. No other sandy Coastal Plain unit maintains its sandy character so far into the deep subsurface. In outcrop the Magothy is largely delta front facies or essentially a marginal marine-non-marine deposit. The few samples collected from this unit in the deep subsurface suggests a similar depositional origin. It would appear that the Magothy represents an environment which would produce a sheet of sand over a large area in a marginal marine system (e.g., mixed marine and non-marine). In the case of the Magothy the sheet sand would have been produced in a slowly regressing delta system with the distal end being continually reworked producing a dominantly sandy facies. This geologic environment produced the broad sheet sand associated with this unit.

6) Type F gamma signature associated with an interstratified marginal marine (Barnegat Middle School log)

This type of gamma log is commonly found in the upper Tertiary units which are on average the most sandy formations in the central bedrock map. This type of gamma log with relatively thick woody clay strata about 10 to 20 ft thick (increasing radioactivity or deflected to right) interstratified with thicker sand beds (decreased radioactivity or deflected to left) is

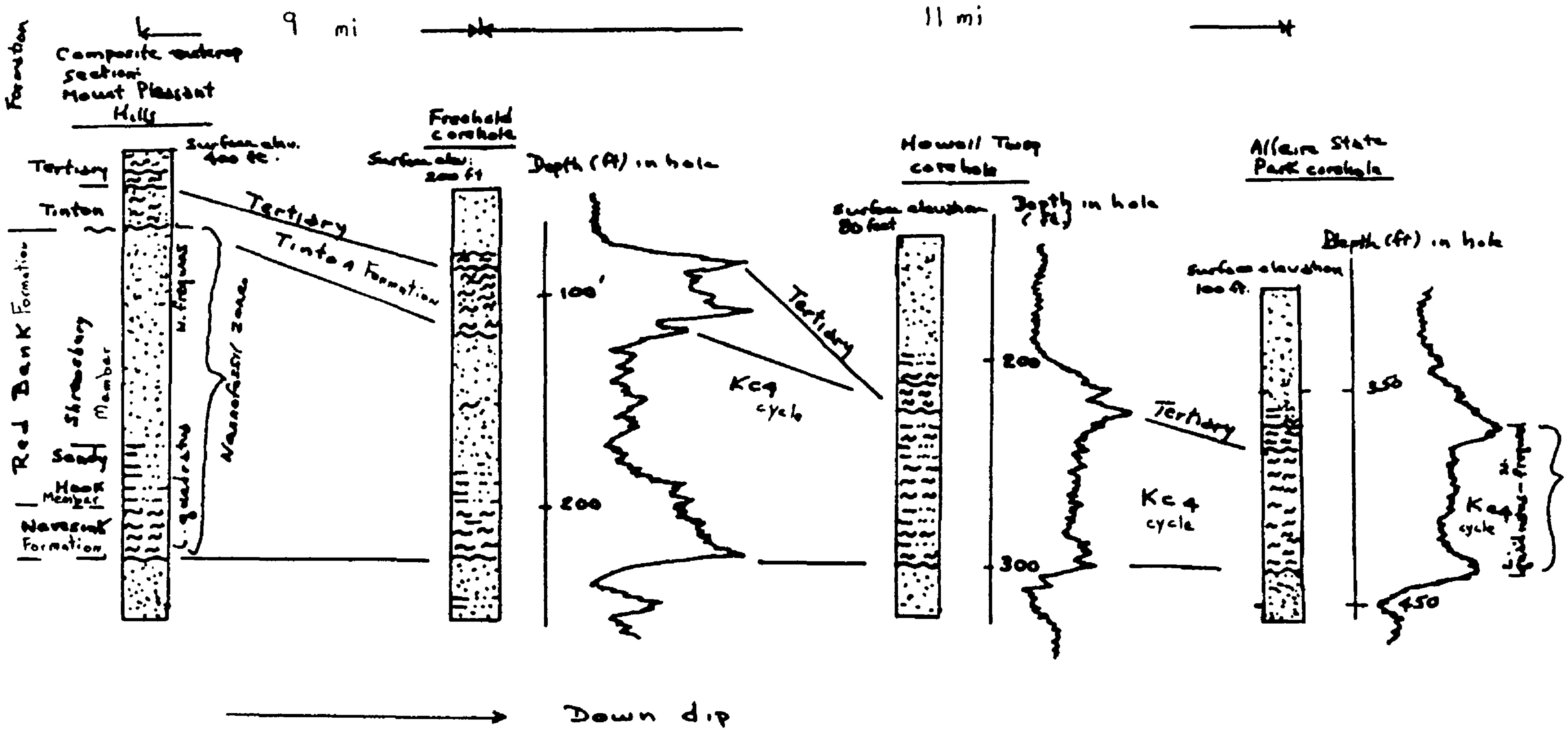

Figure 4. Facies changes exhibited within the Red Bank Formation and Navesink Formation cycle of sedimentation from a full cycle in outcrop and in the Freehold corehole to a single lithology in the deep subsurface of the Allaire corehole. The full cycle-single lithology are time equivalents. The downdip lithic change, therefore, represents a facies change to a deeper water lithology or a condensed section.

typical of this marine-non-marine transitional zone.

STRATIGRPAHIC NOMENCLATURE

Table 1 shows the surface to subsurface correlation for the Coastal Plain formations in the surface and subsurface. Eleven new or redefined stratigraphic units are shown on the central bedrock map. Most of these units are present only in the subsurface or in the subcrop areas (those covered by thinner alluvium).

Seven subsurface units are informally designed as cycles. The marine Upper Cretaceous cycles characteristically form a well developed asymmetrical pattern of sedimentation that consist of a basal transgressive glauconite-rich sand, a middle clayey or silty massive unit typically rich in mica and woody fragments, and an upper quartz-rich regressive sand. Many of the subsurface correlations are based on gamma-ray log patterns. Using this technique, the glauconite sands and clayey silts are indistinguishable in most cases. Additionally, the upper quartz tends to pinch out toward the down-dip areas. Consequently, distinguishing individual facies within the downdip area is not feasible and, for example, the three formations of the outcrop constituting a large scale cycle of sedimentation are correlated with a single cycle in the profiles. These cycles are given a numerical designation (Kc_1-Kc_4) with Kc_1 the oldest and Kc_4 the youngest. Three other unnamed units are Paleogene in age. Two of these units are a single lithology and represent mostly truncated sections. The other unit is also truncated, but also shows some facies effects. All three units are also considered to represent cycles. Detailed descriptions and age information for these cycles can be found in Description of Map Units. All new or redefined units are discussed below.

(A) Cheesequake Formation: This new formation is named for outcrops in numerous gullies in the eastern part of the South Amboy 7.5-minute quadrangle. This formation has a limited outcrop belt, but is widespread in the subsurface of the central sheet. The general lithology in outcrop is horizontal, very thin bedded, fine-grained micaceous quartz sand and dark clays. Siderite concretions are common (Litwin and others, 1993). The Cheesequake in outcrop is a maximum of about 45 ft in thickness. The formation unconformably overlies the Magothy Formation, and is overlain by the Merchantville Formation or the Kc_1 cycle in the subsurface. Geophysical logs from drill holes where the formation is thickest indicate a thick clay-silt at the base and a thin sand at the top.

(B) Kc_1 cycle: Informal name for sediments in the subsurface, which are equivalent to the Merchantville, Woodbury, and Englishtown Formations in outcrop. Typically, the Kc_1 cycle is widespread in the subsurface. Here it is mainly a massive dark gray clay-silt as determined from its geophysical signature and the few drill holes through this unit. The upper quartz sand of the outcrop tends to pinch out rapidly downdip. The cycle is unconformable on the underlying Cheesequake Formation and is unconformably overlain by the Kc_2 and Kc_3 cycle. The Kc_1 cycle is as much as 300 ft thick.

(C) Kc_2 cycle: Informal name for a unit that does not reach the outcrop belt but is widespread in the subsurface of the central bedrock sheet. The typical lithology is a dark greenish-gray, very clayey, micaceous and woody clay-silt at the base. Small fossils are common in these beds. The sand at the top has a similar color to the basal clay-silt, but has less clay and mica but similar abundance of woody fragments. Glauconite is a common constituent in the upper quartz sandy beds. The glauconite sand commonly found at the base of typical cycles were not found with the unit, but this may be, in part, due to the very few samples recovered from this unit. The Kc_2 cycle maximum thickness is approximately 150 ft.

(D) Kc_3 cycle: Informal name for the sediments in the subsurface equivalent to the Marshalltown, Wenonah, and Mount Laurel Formations in the outcrop belt. This cycle represents the typical pattern of sedimentation discussed earlier in the marine Cretaceous cycles. Like the Kc_1 cycle, the upper quartz sand (Mount Laurel) pinches out down dip and the typical subsurface lithology is a dark colored massive micaceous clay-silt. The Kc_3 cycle is widespread in the subsurface of the central bedrock sheet where its maximum thickness is about 150 ft.

(E) Kc_4 cycle: Informal name given to a subsurface unit equivalent to the Navesink and Red Bank Formations of the outcrop belt. This unit, unlike the underlying cycles, thins and changes facies more abruptly in the subsurface where it is typically a massive, dark-gray, clayey glauconite sand. Because of the very glauconitic nature of the subsurface formation, this unit may be a condensed section. The gamma ray patterns associated with this unit are atypical compared with the underlying marine units. Kc_4 is typically bounded by large gamma spikes, which indicate unconformities at the base and top. This pattern makes tracing this cycle in the subsurface relatively easy using the geophysical logs. Maximum thickness of the Kc_4 cycle is 110 ft.

(F) Te cycle: Informal name for a unit which does not reach the surface. Was formerly called the ACGS Alpha unit to the south (Owens and others, 1988). Only known in the extreme southeastern corner of the map where it is a maximum of 165 ft thick. Lithically, the lower part of the unit is a dark-brown, massive to finely laminated clay with numerous thin layers of broken shells. The upper part of the unit is a massive, medium- to coarse-grained, glauconitic quartz sand with a minor amount of quartz granules. To the south at Island Beach the unit is extensively bevelled and only the lower beds are present. The gamma patterns show no gamma spike at the base of the unit.

(G) To_1 cycle: Informal name for a subsurface unit which does not reach the outcrop belt. Was formerly called the Mays Landing unit to the south (Owens and others, 1988). To_1 cycle only occurs in the southeastern corner of the map. Here it is a massive, dark-gray, clayey to very clayey, fine-grained, quartz glauconite sand. Broken small, thin-walled fossils are common throughout the formation. Gamma log patterns are typical of those found with clayey units. There is no gamma spike at the boundary with the underlying unit. The To_1 cycle is a maximum of approximately 40 ft thick in the map area.

(H) To_2 cycle: Informal name for a unit which does not reach the outcrop belt. This unit was formerly called the ACGS Beta unit to the south (Owens and others, 1988). The To_2 cycle only occurs in the southeastern corner of the central bedrock sheet. The maximum thickness in this area is 175 ft. The unit is mostly a massive to thick-bedded, dark-gray (lower part of unit) to greenish-gray (upper part of unit), fine- to coarse-grained, quartz glauconite sand. Large worn shells are locally present. Geophysical logs show no gamma spike along the basal boundary.

(I) Kirkwood Formation and Shiloh Marl: The Kirkwood Formation was named by

Knapp (1904) for a light-colored, massive, quartz sand in outcrops near Kirkwood, New Jersey. The composition of the formation was amended and the outcropping Alloway and Asbury Park Clay Members were added to the formation (Kümmel and Knapp, 1904). The age of the Kirkwood in outcrop was determined from shells at the top of the formation in shallow pits along Stowe Creek near Shiloh, New Jersey. The Shiloh Marl was made a member of the Kirkwood Formation by Clark and others (1909). In our report, the Shiloh Marl is raised to formation rank because in the subsurface in the southern bedrock sheet the Shiloh can be separated from the underlying Kirkwood lithically, isotopically, and in the gamma logs. Details of this separation are discussed in detail in the text of the southern bedrock map. In the central bedrock map the Shiloh Marl is restricted to the southeastern corner of the map area where it is a maximum of 250 ft. Typically it subcrops beneath the thick Quaternary alluvium in this area. Lithically, the Shiloh here is a dark clayey-silt in the lower part and a light brown slightly clayey, fine- to coarse-grained, quartz sand with interbeds of gravelly coarse-grained sand in the upper part. There is sand in the basal Shiloh. The gamma log shows this sand overlying the more clayey Kirkwood with no gamma spike.

The underlying Kirkwood has a thickness of about 250 ft in the Island Beach corehole. The Kirkwood depositional basin is also much more widespread than the Shiloh basin, and in fact, reaches the outcrop belt. The Kirkwood in the deepest subsurface has a basal glauconite quartz sand which rapidly grades to a thick, locally fossiliferous, dark-gray, massive to thick-bedded, clayey silt. The upper beds are variable but are mostly fine to coarse quartz interbedded with thin gravelly beds. The basal Kirkwood commonly is a gravelly sand which shows as a sand in the gamma logs. There is no gamma spike along the basal boundary.

J) Wildwood Formation: New formation named for the sediments overlying the Shiloh Marl in the Wildwood, NJ corehole. The Wildwood only crops out where the overlying units have been stripped away along the Delaware Bay and the Atlantic Ocean. This formation lies within a basin which dips to the southeast. The Wildwood sediments are more than 200 ft thick in the deeper parts of the basin. Geophysical logs through this unit indicate it is characterized by shifting patterns of clay and sand. There is a tendency, however, to having clay in the base and sand at the top.

DESCRIPTION OF SUBSURFACE UNITS, COASTAL PLAIN
(Plates 2 and 3)

Tch Cohansey Formation (middle Miocene, Serravallian)--Sand, fine to coarse grained, locally gravelly, massive to cross-bedded, yellow to white where weathered to gray brown or dark gray where unweathered. Interbedded with thin to thick (several feet) massive to finely laminated clay or silty clay beds. Clay beds where weathered are white, yellow, or red, where unweathered are dark gray. The dark-gray beds commonly contain carbonized wood fragments, some of which are very large (log size). Locally, formation consists of several thin to thick upward coarsening sections (clay to sand). The Cohansey occurs in very large channels although the highly dissected nature of this unit makes determination difficult. The thickest sections (as much as 200 feet) occur within these channels along the southeastern border of the map area near Barnegat.

Because of its surface to near-subsurface position, most of the formation is highly dissected and weathered to varying degrees. Typically, the weathered sands are nearly all quartz or quartz-rich rock fragments (orthoquartzite). Where less weathered, small amounts (5 to 10 percent) of potassium feldspar are present. The heavy mineral suites are mostly the opaque minerals ilmenite, brown ilmenite (pseudorutile), and leucoxene. The pseudorutile and leucoxene content increases in the more weathered beds. In the non-opaque fraction, the most stable species dominate; zircon, tourmaline and rutile, staurolite, sillimanite and to a much lesser degree, kyanite are common to abundant, indicating an original metamorphic rock source for some, perhaps most, of the sediment in this unit. Clay minerals in the weathered clayey units are mostly kaolinite and illite. In the unweathered clay, illite/smectite is abundant in association with kaolinite and illite.

The age of the Cohansey was determined from its pollen content. The unit is considered to be Miocene, probably middle Miocene (Serravallian) in age (Owens and others, 1988).

Tw

Wildwood Formation (middle and lower Miocene, Langhian and Burdigalian)--The Wildwood Formation is equivalent to the upper clayey and silty beds of the Kirkwood Formation as described in the corehole near Mays Landing (Owens and others, 1988). The unit is named for a borehole at Wildwood, New Jersey to the south of the map area and is described in more detail in the southern bedrock map. The Wildwood is an unconformity bounded unit which lies on the underlying formation with a sharp contact. Very little reworked sediment is found in the basal beds. The upper contact in the map area is also sharp. In the updip areas the formation is overlain by the Cohansey Formation and along the shore it is overlain by Holocene sediments. The Wildwood is restricted to a small area in the southeastern corner of the map where it lies on the northernmost edge of a basin. The maximum thickness of the formation is somewhat in excess of 200 feet in this map area. Lithically the Wildwood is a clay-silt in the eastern part of its basin and is very sandy at the western basin edge. The best samples of the clay-silt were obtained from the corehole at Island Beach State Park (#290019). At this site the Wildwood is over 100 ft of gray-brown, massive to finely laminated, micaceous clay-silt except in the lower 20 ft of the formation where the unit consists of thick interbeds of fine- to medium-grained, massive to locally coarse-bedded, extensively bioturbated, micaceous quartz sand and dark-brown to grayish-brown silty clay. The middle part is mostly dark-gray to gray-brown, massive to finely laminated silt to clay. Sands, fine to coarse grained, locally fine gravelly and thin to thick bedded are interbedded with the clay and silt in the upper 20 ft. The Wildwood has common to abundant diatoms. Gamma logs of the facies are type F (fig. 2). To the west, the micaceous medium to coarse sands found in the upper beds at Island Beach thicken rapidly and are the major lithology. Clays, mostly thick bedded and dark gray, are common in this area. These clays often contain small to log-sized wood. The sandy facies is about 75 ft in this area. The gamma logs from this part of the formation are type F (fig. 3).

The clays in the Wildwood are a mixture of illite/smectite, illite and kaolinite. Kaolinite concentrations show an increase up section. Heavy mineral assemblages in sands of the clay facies are dominated by the opaque minerals ilmenite, pseudoilmenite and leucoxene in that order of abundance. In the non-opaque fractions, zircon, sillimanite, garnet, tourmaline, kyanite, chloritoid, staurolite and rutile are present in that order of abundance. Only trace amounts of the most weatherable mineral hornblende and epidote are present. The light mineral fraction is predominantly quartz. Feldspar (typically the potassic type) are present in very small amounts (less than ten percent). In general the sands in the sandy facies are similar mineralogically to those in the clay facies except where the sands have been post-depositionally altered. In the weathered sands the zircon content increases dramatically. The unweathered clays in the sand facies are similar compositionally to those in the clay facies. The weathered clays have a much higher kaolinite content.

The age of the Wildwood was determined in the map area by its diatom content. In general the diatom assemblage is Delphineis ovata, Rhaphoneis fusiformis, R. margaritaata, R. scalaris, Sceptroneis granidis and S. caduceus. These diatoms place the Wildwood within the East Coast Diatom Zone #2 of Andrews (1987, 1988) or lower Miocene (upper Burdigalian) and middle Miocene (Langhian). Strontium isotope analysis of shells from within this zone to the south yielded an age range of 17 to 15 Ma (Sugarman and others, 1993) which confirms the paleontologic age cited above.

Tsh

Shiloh Marl (lower Miocene, Burdigalian)--The corehole at Island Beach State Park revealed the presence of a unit which is equivalent to the middle beds of the Kirkwood Formation as described in the corehole at Mays Landing (ACGS#4, Owens and others (1988). The formation is well exposed in an outcrop along Stow Creek near Bridgeton, N.J. (in southern New Jersey) and was called by many other investigators the Shiloh Marl Member of the Kirkwood Formation. This unit is restricted to the southeastern corner of the map area where it lies at the northern end of a small basin. The maximum thickness in this area is 250 ft in a channel in the central part of the basin. In the Island Beach corehole the formation is more clayey in the base and more sandy at the top. In detail the lower 15 feet of the formation is a massive, extensively bioturbated, somewhat clayey, fine- to medium-grained micaceous quartz sand. Small woody fragments are common in these sands. The basal contact with the underlying unit is sharp but there is little reworked debris along this boundary. The lower sand grades upward into a sequence of horizontally bedded, light- to dark-gray clay and very fine grained, somewhat micaceous, quartz sands. Color banding in this interval is strong. A pale-gray, very coarse quartz sand with some granules is interbedded with this dominantly clayey sequence. This clayey sequence is overlain by a massive, medium-gray, medium-grained, bioturbated sand similar to the basal sand. This sand grades into a sequence of dark-gray-brown sand which increases to coarse to very coarse grained. These sandy beds are typically thin to thick bedded, massive to crossbedded. Near the top of the unit, quartz gravel is a common constituent in the very coarse sand bed. The mineralogy of the clays and the sands is very similar to that in the overlying Wildwood Formation.

No calcareous fossils were found in this unit. Diatoms were recovered, however, and these indicate equivalence with East Coast Diatom Zone #1 (Actinoptychus heliopelta Zone) of Andrews (1987, 1988). Essentially this would indicate an early Miocene age (Burdigalian). Strontium age determination at the ACGS #4 yielded ages of 20.9-19.7 Ma.

Tkw Kirkwood Formation (lower Miocene, Burdigalian to Aquitanian)--This formation typically consists of two thick lithofacies, a lower dark-gray to dark-brown, somewhat micaceous, fine sandy clay-silt and an upper light-colored sand, which locally has interbeds of dark-colored, woody silt-clay. The Kirkwood Formation underlies a much broader basin than the overlying Miocene unit and covers much of the Coastal Plain. The unit varies in thickness but is thickest, as much as 270 feet, in a belt running from wells #050676 (Coyle airport) to well #290453 (Lavelette well) and #290019 (Island Beach). South of this area, the Kirkwood apparently was removed during the emplacement of younger formations.

The basal bed of the Kirkwood Formation is a thin to thick layer of coarse sand with minor fine gravel. This sand is evident on the gamma logs, especially where the Kirkwood Formation overlies a clayey unit. This cycle unconformably overlies two Eocene units in the subsurface (Manasquan and Shark River Formations). Above the sandy basal unit, the lower clay-silt is readily traced updip on the gamma logs to where it merges with the outcropping Asbury Park Member of the Kirkwood Formation. The overlying sandy unit is readily traceable on the gamma logs where the overlying Wildwood Formation is present. Beyond the limits of the older Miocene unit, however, the Kirkwood Formation sand is overlain by the Cohansey Formation and separating these units with gamma logs is not possible. Where fully intact the most common gamma log is type B.

Typically the sands of the Kirkwood Formation are mostly quartz. Small amounts of potassium feldspar and siliceous rock fragments are present especially near the base of the upper sands. The opaque heavy-mineral fraction consists of nearly equal amounts of ilmenite and pseudorutile; leucoxene is present in small amounts. The non-opaque fraction is dominated by the most resistant minerals (zircon, tourmaline, and rutile) and other metamorphic minerals (staurolite, sillimanite, and kyanite). Zircon and sillimanite are particularly abundant. Zircon increases upward throughout the section, whereas sillimanite decreases. The clays from the basal facies is typically a mixture of illite/smectite, illite and kaolinite.

The age of the Kirkwood Formation in the subsurface is difficult to establish because of the general absence of foraminifera and diatoms. However, Woolman (1895) reported the diatom Actinoptychus heliopelta from this unit at Asbury Park. On this basis, the Kirkwood Formation is considered to belong to East Coast Diatom Zone 1 of Andrews (1987, 1988) and is early Miocene (Burdigalian) in age. Based on studies to the south where the basal beds are more marine, the Kirkwood Formation is within the lower Miocene planktic foraminifera zone N5 of Blow (1969) (Owens and others, 1988). Sugarman and others (1993) report strontium isotope ages of 22.6-20.8

Ma for this unit therefore extending the age of the lower part of the unit to Aquitanian.

To_2

To_2 cycle (upper Oligocene, Chattian)--Poorly sorted sands of late Oligocene age first described from a drill hole in Atlantic County (ACGS#4) were assigned to an informal ACGS Beta unit by Owens and others (1988). The designation To_2 cycle supplants this name. This unit is found only in the subsurface in the southeastern corner of the map area. It consists primarily of reddish-brown to olive-gray, silty to clayey, very fine to very coarse sand with concentrations of loose granules. Worn small shell fragments are common throughout. In easternmost deposits, cycle is massive, interbedded, dark-green and gray, clayey, fine to coarse quartz and glauconite sands that are sparingly fossiliferous. In the Island Beach well (#290019) the unit is about 175 ft thick. The gamma signature of the quartz glauconite sand is type C in this map area.

The clastic sand consists primarily of quartz with smaller amounts of feldspar (about 10 percent), siliceous rock fragments (about 5 percent), and glauconite (about 10-15 percent). Siderite crystals are common in the upper part of the quartz sand facies. Heavy minerals are common to abundant in this facies. The opaque heavies are principally ilmenite (about 75 percent), and leucoxene (about 25 percent), and less than 1 percent pseudorutile. The non-opaque heavy minerals constitute a full suite, containing a large variety of minerals. Hornblende and epidote are common (about 10% each), and the presence of these minerals distinguishes the To_2 cycle suites from those of the overlying Kirkwood Formation.

The glauconite sand facies contains essentially all glauconite with only small amounts of quartz. Quartz increases in some of the interbedded finer sands. The glauconite in this unit occurs in two colors, brown and dark green. Many of the brown grains are mottled with green. The glauconite grains are primarily botryoidal, but almost all have a polished surface. No heavy or light-mineral studies were conducted on the glauconite sand facies. Clay minerals in the glauconite sand facies are dominantly illite/smectite with smaller amounts of illite. Kaolinite is present in only trace amounts.

The age of the To_2 cycle was not determined in the map area because of the lack of diagnostic fossils. As determined to the southwest of this map, the Atlantic City is late Oligocene (Chattian) in age (Owens and others, 1988). Strontium isotope dated from this unit are about 26 Ma (Miller and others, 1990).

To_1

To_1 cycle (lower Oligocene, Rupelian)--Dark-gray to greenish, extensively burrowed, massive, clayey, fine- to medium-grained, quartz glauconite sand more clayey at the base; more glauconite sand at top. Overlies underlying unit with a sharp burrowed contact. A thin bed of glauconite sand is found along this boundary. Scattered thin wall small mollusks are common throughout. At Island Beach core hole (290019), the unit contains common to abundant reddish-brown siderite in the matrix. Where siderite is abundant the unit is indurated. To_1 only occurs in the southeastern corner of the map where it is as much as 40 ft thick or essentially the same thickness as found at the ACGS well to the southwest (Owens and others, 1988). The gamma log associated with this unit was associated with the very clayey unit (type C).

Mineralogically only the clays were analyzed from this unit. Illite/smectite is the major clay mineral, with lesser amounts of illite and kaolinite.

Nannofossils collected from this unit fall with the NP21 nannozone which is similar to that found in the ACGS corehole. At the ACGS well, this unit was assigned to the early Oligocene (Rupelian). Sr isotopic ages from this unit at Island Beach also suggest an early Oligocene age (33.0 to 32.0 Ma). This age is somewhat younger than the NP 21 age (~ 35 Ma). For the most part, the To_1 cycle at Island Beach is similar lithologically to the unit in the type well at Mays Landing (Owens and others, 1988).

Te

Te cycle (upper Eocene, Priabonian)--Dark-brown to brownish-gray clay, massive to finely laminated with scattered, thin, light-colored layers of broken small shells. Medium- to coarse-grained glauconite grains are scattered throughout the clayey sediment. The upper two feet of the unit is reddish to whitish red colored and extensively burrowed with glauconite sand extending downward into the burrows from the overlying unit. The basal contact with the underlying unit is sharp and has a thin one-foot bed of very fine- to coarse-grained quartz glauconite sand. This unit is equivalent to beds "B" or "C" in the alpha unit as described from the corehole to the south at Mays Landing (Owens and others, 1988). The unit is approximately 50 ft thick in the Island Beach corehole. This unit lies within a basin restricted to the southeastern corner of the map area. The unit thickens to the northeast where it is a maximum of 165 ft beneath the barriers at Seaside Park. Here, the upper beds contain more glauconite sand and fine quartz gravel (0.25 inch maximum diameter).

Mineralogically the clay minerals in this unit show a strong trend of kaolinite. In the lower beds, illite/smectite is the dominant mineral at the base. Kaolinite increases particularly in the upper half of the unit and in the upper reddened zone, kaolinite is the major mineral. The high kaolinite content in this unit is similar to the high kaolinite content found in this unit in the Mays Landing corehole (Owens and others, 1988).

The age of this unit was determined from its nannofossil content. Most of this unit falls within nannofossil zone NP 19/20, which is late Priabonian.

Tsr

Shark River Formation (upper and middle Eocene, Priabonian through Lutetian)--The Shark River Formation where fully developed consists of three lithofacies, a basal greenish-gray clayey glauconite sand, a middle dark-green to gray-green silty clay or clayey silt, and an upper medium-gray to gray-green, silty quartz sand. It lies within a basin which dips to the southeast. The Shark River basin is much larger than the overlying Eocene and Oligocene basins. On all the gamma-ray logs, the Shark River has a sharp kick at its base indicating a basal phosphate-glauconite lag deposit and, therefore, an unconformable relationship with the underlying formation. The gamma signature above the basal kick decreases upward (left sloping) in those holes where all the major lithofacies are present (type B). In general, however, the upper quartz sand is thickest in those areas where it has not been bevelled by the upper Eocene and

Oligocene units. The gamma signature for the lower glauconite sand and middle silt and clay facies is typically a flat pattern (type C) where the quartz sand has been removed.

The basal glauconitic sand facies typically is thin, in most cases less than 10 ft thick. The glauconite content is greatest at the base and decreases up section. Two suites of glauconite grains are present, a light-green and a dark-green variety. The middle clay and silt facies is typically the thickest lithofacies in most of the Shark River sections (as much as 125 ft thick). This facies is massive to thick bedded. The thick-bedded parts typically consist of intercalated silty and clayey beds that are extensively bioturbated. Macro- and microfossils are abundant in this facies. Most of the macrofossils are thin-walled pelecypods. The upper quartz-sand facies is gradational into the underlying silt-clay facies. The quartz sand is best developed in the Toms River to Butler Place area. This facies apparently was beveled off in the updip areas during emplacement of the overlying Kirkwood Formation. The quartz-sand facies is about 75 ft thick near Lavellette (well #290453). The maximum thickness of the Shark River is greater than 200 feet. The clastic sand grains in the Shark River are mainly quartz. Feldspar is present typically in small amounts (less than 10 percent of the sand fraction). The opaque heavy minerals suite is dominated by ilmenite. Leucoxene is present in small amounts, typically less than 10 percent of the opaque fraction. The non-opaque heavy mineral suites are characterized by a large variety of minerals (a full suite). In addition to the ZTR and SSK minerals, there are significant amounts of hornblende, epidote, and garnet and small amounts of chloritoid and andalusite.

The clay mineral suite is dominated by illite/smectite with smaller amounts of illite and kaolinite. The Shark River in the map area has more kaolinite than Shark River sections to the south. In addition to the major clay minerals, clinoptilolite (a zeolite) and cristobalite are present in some samples.

The Shark River Formation is middle to early late Eocene in age (Owens and others, 1988). In the map area, most of the Shark River lies within calcareous nannofossil zones NP14 to NP16 (middle Eocene, Lutetian and Bartonian). At Island Beach where the Shark River is the thickest, the upper part of the Shark River has a lower NP18 nannofossil assemblage and therefore is as young as early late Eocene (Priabonian).

The arrangement of the lithofacies in the Shark River is interpreted as an asymmetric transgressive-regressive cycle. This is true particularly where the three lithofacies are present in a single drill hole (as at Lavellette).

Tmq Manasquan Formation (lower Eocene, Ypresian)--The Manasquan Formation, like the overlying Shark River Formation, consists of more than one lithofacies. Unlike the Shark River, however, the distribution of lithofacies in the Manasquan is less predictable, especially in a vertical section. In the northwestern outcrop belt and shallow subsurface, the lower beds of the Manasquan Formation consist of bluish-green, somewhat clayey, fine to coarse glauconitic quartz sand. No calcareous fossils were found in this lithology. These lower beds are a maximum of 30 ft thick.

The glauconitic quartz sand is overlain to the southwest by a light- to dark-green, locally glauconitic, sandy clay-silt. This clay-silt is present at the base of the unit in the shallow subsurface. Eastward and in the intermediate subsurface, the Manasquan is primarily a clayey glauconite sand. In the deep subsurface, the Manasquan is primarily a light-yellow, massive to finely laminated clay-silt which has high concentrations of calcareous microfossils and has several hard indurated layers. Commonly there is a thin glauconite sand at the base in this region. The Manasquan lies within a basin which underlies the southern corner of the map. At its thickest, the Manasquan is over 200 ft thick in the Island Beach well (#290019). It would appear that the updip coarse glauconitic sand facies is only intact in small areas and the bulk of the Manasquan consists of the finer-grained facies.

The gamma signature of the Manasquan in the deep subsurface where it is fine grained is typically a flat, high-intensity log. In almost all holes, there is a sharp gamma kick at the base indicating a reworked zone. Updip, the gamma pattern is significantly different. In the area where the quartz sand is at the base, a typical low-gamma intensity is present. The gamma intensity increases upward where the clay and glauconite facies become dominant in this area.

The sand minerals in the basal sand facies, excluding glauconite, consist of quartz, approximately 10 to 25 percent feldspar, and a few percent of siliceous rock fragments. The opaque heavy minerals include ilmenite with much smaller amounts of pseudorutile and leucoxene. The non-opaque heavy minerals represent a full suite characterized by abundant epidote, garnet, hornblende, and staurolite. Zircon, tourmaline, rutile, kyanite, sillimanite, and andalusite are present in lesser amounts. The clays in the lower quartz sand and updip dark-clay facies are primarily an illite/smectite and kaolinite mixture. Illite is also present in significant amounts. The clays in the downdip clayey and silty facies are primarily illite/smectite with smaller amounts of illite. Additionally, small amounts of the zeolite clinoptilolite are locally present.

The age of the Manasquan is early Eocene. Calcareous nannofossil studies indicate that the Manasquan ranges from zone NP10 to zone NP13 (Ypresian). The bulk of the Manasquan is assigned to zone NP12, suggesting a major period of deposition during the middle Ypresian.

Tvt

Vincentown Formation (upper Paleocene, Selandian)--Sands of the Vincentown Formation are thickest in the northern part of the Coastal Plain where they are about 120 ft thick. Typically, they are fine to medium grained and coarsen upward through the section. Silt and clay increase toward the base of the formation. The sands are mostly quartz and have much smaller amounts of glauconite and feldspar. In general, glauconite increases toward the base of the formation where the Vincentown is basically a dark-green to gray, very clayey, somewhat quartzose glauconite sand. Locally at the base there is a shelly horizon principally composed of the brachiopod <u>Oleneothyris</u> <u>harlani</u>. In the western subsurface, the same lithologic association is present, but the upper quartz sand facies is much thinner.

Downdip, the overall grain size decreases throughout the Vincentown. At Allaire

State Park, for example, the bulk of the Vincentown is a dark-gray, clayey, very micaceous, slightly feldspathic quartz sand. Large fossils, which are abundant in the near-surface beds, are absent. In addition, the basal glauconite beds tend to thicken somewhat downdip. Farther basinward, the bulk of the formation is a gray-green to locally tan, unfossiliferous clayey silt or silty clay. Locally, a thin to thick glauconite sand occurs at the base. In the thickest downdip section penetrated at Island Beach, the Vincentown is mostly a pale-gray to dark-gray clay-silt throughout. No megafossils were observed in the Island Beach section.

The Vincentown maintains a thickness of about 70 ft from the extreme updip area to the deepest downdip section at Island Beach. The Vincentown is generally thinner in the western subsurface than in the Allaire-Island Beach area. The Vincentown unconformably overlies the Hornerstown Formation in the shallow subsurface and the Cretaceous Kc_4 cycle in the deep subsurface.

Gamma logs for the updip quartz sand facies of the Vincentown typically have a gamma kick at the base and a decrease upward in intensity, as is typical of quartz-sand units (type D).

The downdip clay-silt facies has a similar gamma ray signature, a large gamma kick at the base and flat featureless pattern above (type C), although the gamma intensity for the clayey unit is greater than that found in the overlying sand. These two gamma-ray patterns typify the Vincentown. The sand fraction of in the Vincentown, excluding the fossils and glauconite, is mainly quartz with smaller amounts of feldspar (usually less than 10 percent of the sand fraction) and even smaller amounts of siliceous rock fragments. The opaque heavy mineral suite is overwhelmingly ilmenite with much smaller amounts of leucoxene and pseudorutile. The non-opaque heavy mineral assemblage is dominated by hornblende, epidote and garnet. Smaller amounts of staurolite, sillimanite, kyanite, zircon, tourmaline, rutile, chloritoid, and andalusite are also present.

Clays in the Vincentown in the deep subsurface are primarily illite/smectite. Vincentown clays from the shallow subsurface also are dominantly illite/smectite with small amounts of illite and kaolinite.

The age of the Vincentown was determined from calcareous nannofossils The basal Oleneothyris harlani bed is assigned to upper zone NP5 and the upper part of the formation is assigned to lower zone NP9 (Bybell, 1992). The Vincentown, therefore, is late Paleocene (Selandian) in age in the subsurface.

Tht

Hornerstown Formation (lower Paleocene, Danian)--The Hornerstown Formation was truncated extensively before and(or) during the transgression represented by the basal beds of the Vincentown Formation. Only the lower part of the Hornerstown is still intact throughout the map area. The Hornerstown Formation lies in a basin which dips to the southeast.

The Hornerstown is thin, rarely exceeding 25 ft thick. The thickness varies widely throughout its subsurface distribution due to channeling by the overlying Vincentown.

The Hornerstown is primarily a massive, dark-gray (grading upward to light-green), locally clayey, glauconite sand. The dark-gray beds are the typical lithology in the subsurface. On gamma logs, the base of the Hornerstown has a large gamma spike that is typical of the Paleogene formations in this region. Above the gamma spike the Hornerstown gamma log has a flat field (type D). Samples recovered from this boundary show that the Hornerstown is extensively burrowed and phosphatic material is common. As noted earlier (Owens and others, 1977), the Hornerstown overlies a number of formations in the subsurface, the Tinton Formation in the north, the Red Bank Formation in the northwest, and the condensed Kc$_4$ cycle in most of the subsurface in the southwest.

The Hornerstown is nearly all glauconite sand except for minor clay. Detrital clasts are sparse; therefore no detailed sand petrology was determined for this unit. The clays are mainly glauconite in the light-green beds and illite/smectite in the dark-gray beds.

The Hornerstown yielded good calcareous nannofossil assemblages in almost all samples collected from this unit in the subsurface. The early Paleocene nannofossil zones NP2 and NP 4 are present with most samples yielding those of zone NP3 (all Danian). The transitional boundary of the Hornerstown with underlying Cretaceous units suggested by some (Olsson, 1963) was not confirmed by our subsurface investigation. This was particularly evident in subsurface samples near Sewell, where the Hornerstown was reported by many authors to be transitional with the underlying Cretaceous beds. The so-called "bone bed" found at this locality is a surface manifestation of the large gamma spike noted in the basal part of the Hornerstown in the subsurface.

Kt

Tinton Formation (Upper Cretaceous, Maastrichtian)--The Tinton Formation consists primarily of hard, siderite-cemented, reddish-brown to dark-gray quartz-glauconite sand. The Tinton was extensively dissected prior to deposition of the overlying Hornerstown Formation. The Tinton can be traced in the subsurface only as far downdip (south) as the Freehold area but not beyond. The Tinton, therefore, is restricted to the northern New Jersey Coastal Plain.

The Tinton in the Freehold core is about 25 ft thick and thickens to the east where at Rumson, it is 40 ft thick. The Tinton unconformably overlies the Red Bank Formation, but, because of cementation in the upper part of the Red Bank, the contact was difficult to determine in the subsurface. The contact was selected where glauconite dominates over quartz. Gamma logs of the Tinton, because of the widespread presence of siderite cement in the matrix, have a relatively high intensity and are similar in shape to gamma logs for clayey units (type D). The Tinton is more quartzose to the west and glauconitic to the east. The siderite cement, which imparts the hardness to the Tinton, is irregularly distributed throughout this unit. Because of its extensive induration, sand and clay mineralogy was not determined.

No fossils were found in subsurface samples of this formation. The Tinton represents an incomplete cycle of sedimentation as it consists only of subtidal marine beds and lacks nearshore sands.

Kc_4

Kc_4 cycle (upper Cretaceous, Maastrichtian)--As defined in the subsurface, this unit is equivalent to all the beds that occur in outcrop between the Hornerstown or Tinton Formation above and the Mount Laurel Formation below. The subsurface Kc_4 cycle is very distinctive on gamma logs. It appears on most gamma logs as a single lithology and has a marked gamma spike at its base. Above the gamma spike, the Kc_4 cycle has a flat high-value pattern (type D) common to clayey glauconite units. The notable exception is the Freehold corehole where the Red Bank Formation is still intact. There, the gamma log has a sloping pattern representing a clayey glauconite sand at the base and a well-sorted quartz sand at the top. At the Allaire State Park corehole and at Howell Township (#250635), the Kc_4 lithology is limited to dark-greenish-gray, clayey, fine to medium glauconite sand. This lithology persists throughout the rest of the northern subcrop and into the southwestern outcrop belt near Mullica Hill. In essence, the Kc_4 cycle represents a condensed section as compared with equivalent outcrop sections. The Kc_4 section thins into the deep subsurface from about 114 ft at Freehold to about 30 ft at Island Beach (#290019).

Calcareous nannofossils in the Kc_4 cycle were examined at several localities. At Allaire, most of the Kc_4 cycle fell within the *Nephrolithus frequens* Zone (CC 26) and the *Lithraphidites quadratus* Zone (CC 25). This would place the Kc_4 cycle in the middle and late Maastrichtian. In the Toms River well (#290045), the Hornerstown Formation overlies the Kc_4 cycle; here the Kc_4 cycle contains only the *L. quadratus* Zone. The same is true at Butler Place (#050683). It seems from these data that the latest Cretaceous beds in the subsurface have been beveled throughout their subcrop and, as noted above, in their outcrop belt.

No sand minerals were obtained from the Navesink Formation except glauconite. The clay minerals are dominated by illite/smectite and illite with smaller amounts of kaolinite.

Kc_3

Kc_3 cycle (upper Cretaceous, upper Campanian)--In the subsurface, all beds equivalent to the units between the base of the outcropping Navesink Formation and the top of the Englishtown Formation are included in the Kc_3 cycle. Like the overlying Kc_4 cycle, the Kc_3 cycle has a variably small or large gamma spike at its base and, like the Kc_4 cycle, is unconformity bounded.

Lithologically, the Kc_3 cycle differs from the overlying strongly glauconitic units. The lithology components found within the Marshalltown, Wenonah, and Mount Laurel Formations in outcrop can be found in the deep subsurface. At the Toms River Chemical Well (#290045), for example, the unconformity-bounded Kc_3 cycle includes a thin glauconite sand at the base, a thick, very silty micaceous quartz sand in the middle, and a thin, well-sorted, fine-grained quartz sand at the top. Variations in the thicknesses of the three lithofacies are common throughout the subsurface of the central sheet, but in most of the sampled wells the three lithofacies are present. Typical gamma logs for this cycle, therefore, have a low intensity in the upper quartz sand and a flat, high-intensity pattern in the clayey and silty sands of the lower beds (type B).

The Kc_3 cycle has a maximum thickness of 150 ft at Island Beach and is about 90 ft at the Freehold corehole. In general, this formation does not exhibit any great thickening or thinning from the outcrop into the subsurface.

The light sand minerals are mainly quartz with approximately 15 percent feldspar and siliceous opaque minerals. The opaque heavy mineral suite in this cycle is dominated by ilmenite and smaller amounts of leucoxene and pseudorutile. The non-opaque heavy minerals are a full suite. In general, the more labile epidote, hornblende, garnet, and chloritoid are relatively abundant with lesser amounts of zircon, tourmaline, rutile, staurolite, sillimanite and kyanite. A crystalline-metamorphic source for much of this sediment is indicated. The clay minerals are dominated by illite/smectite with smaller amounts of kaolinite and illite.

The age of the Kc_3 cycle is difficult to ascertain in the subsurface because of the general lack of calcareous material in the cores obtained from this cycle. In the shallow subsurface south of Runnemeade, the cephalopod Belemnitella americana was obtained from the sandy facies at the top of the formation. Strontium isotope ages from these fossils yielded ages of 72 to 70 Ma (Sugarman and others, 1995). B. americana, once thought to establish an early to middle Maastrichtian age, now is known in Campanian age beds. The Kc_3 cycle was surprisingly unfossiliferous, and so the latest Campanian age assigned to this unit by others could not be firmly confirmed.

Kc_2

Kc_2 cycle (Upper Cretaceous, middle Campanian)--This unit does not reach the outcrop but is widespread and is thickest in the northern Coastal Plain. The gamma logs for this formation are similar to those of the overlying Kc_3 cycle (type B) except that the Kc_2 cycle logs typically lack a gamma spike at the base. The general gamma-log configuration shows high-gamma-intensity clayey lithology in the bulk of the unit, and a low-intensity sand at the top. The greatest thickness of this unit is somewhat more than 150 ft.

The Kc_2 cycle consists of dark-greenish-gray, very clayey, somewhat glauconitic, sandy (quartz) clay-silt to very fine quartz sand. Mica and especially lignite are common constituents. The unit also has common thin-walled, small mollusks but otherwise has few other calcareous forms. Nannofossils were looked for but not found in samples from the type well. The sand at the top is the same color as the clay-silt but is less clayey and micaceous; it has a high lignitic content and more glauconite than the clay-silt. A glauconite sand of the type commonly found at the base of typical cycles is not present in those wells for which samples were available.

The sand in this cycle is primarily quartz with less than ten percent feldspar and siliceous rock fragments. The opaque heavy minerals are primarily ilmenite and leucoxene. The non-opaque assemblage is varied and has major concentrations of staurolite, tourmaline, epidote, garnet, and chloritoid. The clay mineral assemblage is mostly illite/smectite with somewhat smaller amounts of kaolinite and illite.

The age of the Kc_2 cycle is poorly known. Gohn (1992), in an evaluation of the ostracods from this unit, suggests a middle Campanian age.

Kc_1

Kc_1 cycle (Upper Cretaceous, lower Campanian)--The Kc_1 cycle is somewhat similar lithologically to the overlying Kc_2 cycle except that the basal glauconite unit is better developed.

In general the gamma pattern is similar; the bulk of the formation has a high-intensity pattern with a lower intensity pattern at the top (type B). The transition from the high to the low intensity is abrupt as was the case with the Kc_2 cycle and Kc_4 cycle.

Where it was best recovered, as in the Freehold core, the Kc_1 cycle resembles typical outcrop cycles in having a glauconite sand at the base, a clay-silt in the middle, and a quartz sand at the top. The lower glauconite beds are extensively cemented by siderite, the clay-silts have abundant shells, and the upper quartz sand has numerous interbedded, dark-gray, commonly very lignitic to woody clays or clay silt.

The Kc_1 cycle is thickest in the northern Coastal Plain where it attains a thickness of over 300 ft near Rumson in the Long Branch quadrangle. In general, the cycle thins to the south and southwest where it is less than 150 ft on average. The basal contact with the underlying unit in the subsurface is readily discerned in cores but is difficult to establish except locally from the underlying unit where cores are unavailable.

Sand minerals in this cycle are mostly quartz although feldspar (about 15 percent) and rock fragments (about 20 percent) are common constituents. The non-opaque heavy minerals compose varied assemblages having large amounts of chloritoid, garnet, and epidote and small amounts of zircon, tourmaline, rutile, hornblende, staurolite, sillimanite, and kyanite. The clay minerals in this cycle are a mixed suite with all three major clay groups present in significant amounts. An x-rayed sample from the basal Kc_1 cycle in the Freehold core showed that kaolinite was the major phase, whereas illite/smectite and illite are only minor constituents. This clay sample has weathered material (kaolinite) probably reworked from the underlying Cheesequake Formation.

The age of the Kc_1 cycle was determined using foraminifera from the Freehold hole. The foraminiferal faunas in the basal Kc_1 cycle includes Ventilabrella glabrata and Rugoglobigerina rugosa. R. rugosa does not range lower than Campanian and V. glabraba is confined to the Campanian (W. Poag, written comm., 1989). Coccolith ages obtained from this unit in the Manchester core hole range from zone CC-17 to zone CC-19 (D. Bukry, written comm., 1990). According to Perch-Nielsen (1985) these zones are earliest Campanian. The early Campanian zones CA2, CA3, and CA4 (Wolfe, 1976) are also present in the Kc_1 cycle.

Kcq

Cheesequake Formation (Upper Cretaceous, lower Campanian and Santonian)--The Kc_1 cycle is underlain by the Cheesequake Formation. This new formation is similar in its vertical succession of facies to the Kc_1 cycle consisting, where fully intact, of a thin, basal, dark-greenish-gray, clayey, fine-grained, quartz glauconite sand; a thick, middle, dark-gray, micaceous, very clayey silt to very fine quartz sand with scattered and varying amounts of glauconite sand, and an upper, thin, clayey, fine-grained, quartz sand. In most areas, particularly in the more updip sections, the upper sand has been eroded away. Distinguishing the Cheesequake from the overlying basal part of the Kc_1 cycle in such areas is very difficult. The Cheesequake Formation does not reach the outcrop belt in the Delaware River valley suggesting the post depositional erosion and removal of the Kc_1 cycle was not as extensive in the Raritan Bay area where the formation is exposed. The Cheesequake is as much as 110 feet thick being thickest in the northeast, but because of extensive erosion, it is typically much thinner. The gamma log pattern of the unit is locally characterized by a strong spike at the base. Locally, as in the Freehold corehole, a high intensity occurs in the glauconite sands and middle silt and a lower intensity in the upper sand (type B log).

Mineralogically the sands of this unit, excluding glauconite, are primarily quartz with small amounts of feldspar and mica. Sand minerals in the Cheesequake, excluding glauconite, are quartz with lesser amounts of feldspar and mica. The opaque heavy minerals include leucoxene (major) and pseudorutile and ilmenite (minor). A full suite of non-opaque minerals are present with the exception of epidote. The more labile minerals, hornblende, garnet, and chloritoid, are common as are staurolite, tourmaline, zircon, rutile, sillimanite, kyanite, and andalusite. The clay-mineral suite in this unit includes all the major clay minerals. On average, however, kaolinite is more abundant in this formation than in the overlying Kc_1 cycle.

The age of the Cheesequake was determined by nannofossils and pollen. Nannofossils obtained at Toms River and Freehold coreholes indicate that the Cheesequake Formation is latest Santonian at the base to earliest Campanian at the top (P. Valentine, personal commun., 1989) or equivalent to CC16 to CC17. Thus the Santonian-Campanian boundary lies within the Cheesequake Formation. Studies of the pollen (Litwin and others, 1993) in outcrop indicate a pollen assemblage containing elements of the ?Pseudoplicapollis cuneata-Semioculopollis Zone (Vc of Christopher, 1982) and the CA2 zone of Wolfe (1976). These data confirm the observations of the nannofossils cited above.

Thus, although some consider the Kc_1 cycle and Magothy Formation to interfinger downdip (notably Petters, 1976), the Cheesequake Formation lies between these units and is separated from the Magothy and Kc_1 cycle by unconformities.

Kmg Magothy Formation (Upper Cretaceous, lower Santonian)--The Magothy Formation is primarily a thick sand unit in the subsurface. This sand is traceable on nearly all gamma logs used to construct the cross sections except in the southeastern part of the map area. The Magothy is primarily a light-colored, fine sand in the updip areas but consists of interbedded clays and sands in the deep subsurface. The thickness of the lower part of the Magothy is variable but is greatest in the northern Coastal Plain where values of about 180 feet are typical. Gamma logs from this unit is type E.

The best recovered section of the Magothy is in the Freehold corehole. There, the basal bed of the Magothy is a thin quartz gravel (maximum clast diameter, about 1 in.). The lower part of the formation above the gravel consists of thin, white clays interbedded with thick, light-colored, poorly sorted, fine to coarse, somewhat micaceous quartz sands. The interbedded clays become dark gray upward through the section and, as noted above, the upper sands are slightly glauconitic and locally shelly. In general, when taken in conjunction with the upper part of the Magothy, this formation appears to be fluvial dominated near the base (upper delta plain) and gradually becomes more marine upward (shelf). The overall sedimentologic pattern suggests a net transgression during deposition of the Magothy with shelf deposits overriding a nonmarine (probably deltaic) facies. In the deepest well (#290019, Island Beach), the Magothy becomes more clayey and marine. Glauconite and shell fragments are present throughout much of the lower part of the formation here. In general, however, the Magothy there has fewer shells and less glauconite than the upper beds so that the upward trend to deeper water lithofacies is evident at Island Beach. The sand fraction in the Magothy is dominated by quartz, siliceous rock fragments, and, to a lesser degree, feldspar. The opaque heavy minerals are largely leucoxene, pseudorutile, and ilmenite. The non-opaque heavy minerals are mainly staurolite, chloritoid, garnet, hornblende, and tourmaline. Smaller amounts of zircon, rutile, sillimanite, andalusite, and kyanite are also present. The clay minerals are mostly kaolinite and illite. Illite/smectite is present only in small amounts.

The age of the Magothy in the subsurface is determined primarily from pollen and foraminifera collected from the Island Beach well (#290019). Christopher (1979) noted that the Magothy in outcrop could be assigned to three informal palynozones; from oldest to youngest, these are zones Va, Vb, and Vc. Zone Va typically occurs in the lower part of the Magothy. Zone Va subsequently was formalized as the Complexiopollis exiqua-Santalacites minor Zone, which is assigned an early Santonian age (Christopher, 1982).

Foraminifera collected from the Island Beach core at 1,805 ft are characterized by Marginotruncana marginata and Rosita fornicata, which indicate the Dicarinella asymetrica Zone. Because of the overall character of the foram assemblage it is probable that these fossils indicate a late Santonian rather than early Campanian age (H. Dowsett, written commun., 1992). The Magothy, therefore, is Santonian or older in age.

Kr

Raritan Formation (Upper Cretaceous, upper Cenomanian)--The Raritan Formation in the subsurface is a very heterogeneous unit. The formation contains both non-marine and marine facies. The best section containing both facies is from the Freehold corehole. In this corehole the Raritan is approximately 200 ft thick. The lower 40 ft consists of interrelated thin to thick beds of light- to dark-colored, fine- to medium-grained, quartz sand and light- to dark- colored clays or clayey silts. Small to large pieces of lignitized wood are characteristic and common to abundant in these beds. The middle 100 ft consists of laminated to thinly bedded, dark-gray, micaceous clays and light-colored, fine-grained, micaceous quartz sand. Reddish brown secondary cementation is common in the strata of this interval. Lignitized wood fragments are also locally abundant in these beds but on average the wood pieces are much smaller than in the basal beds. The upper 60 ft are also dominated by the laminated to thin-bedded sequences but have small amounts of glauconite sand. A thin layer of large fossils (primarily Exogyra woolmani) is present in these upper beds. At the very top of this interval some of the beds are cemented by siderite. In general, this unit appears to be fluvially dominated in the base, marginal marine in the middle and more marine at the top.

North and west of Freehold the Raritan is mostly non-marine interbeds of cross-bedded sands and black to variegated clays. At Island Beach the Raritan is wholly marine and consists largely of dark-gray, shelly, micaceous clays at the base to dark-gray, shelly, fine-grained, micaceous clays at the top.

The gamma logs of the Raritan vary in character and are widely dependent on the dominant depositional environment of the beds. Therefore, there is no typical Raritan gamma signature.

The mineralogy of the sands and clays also reflect the same depositionally controlled environmental imprint. The sands in the marine beds tend to be more feldspathic and contain a more immature heavy mineral suite (higher hornblende, epidote and chloritoid concentrations). The clay minerals follow the same trend of a more immature suite in the marine facies (characteristically the presence of I/S) and a dominance of kaolinite in the non-marine facies.

The age of the Raritan in the subsurface largely was determined by Petters (1976) from the foraminifera in the beds at Anchor-Dickenson well I in the southern New Jersey Coastal Plain. He considered the pre-P. helvetica beds (Raritan interval) to be Woodbinian (late Washitan and early Cenomanian) in age. The Raritan section according to this author would include planktonic zones Rotalipora greenhornensis/Praeglobotruncana delrioeneis (early Cenomanian) and Rotalipora cushmani (late Cenomanian). Samples at Island Beach were only available to 2,300 ft. These samples fell within the Rotalipora cushmani zone. Based on geophysical log interpretation the base of the Raritan was placed at 2,370 ft and the unit is considered to be late Cenomanian in the map area. Studies of the pollen in the Raritan at Island Beach suggest that the samples above 2,370 ft belong to zone IV (Complexiopollis-Atlantopollis assemblage).

KpIII Potomac Formation, unit III (Upper Cretaceous, lower Cenomanian)--The Potomac Formation is divided in the subsurface into three units designated Potomac Formation, unit I, II, and III. These designations conveniently match the numeric designation of the pollen zones of Doyle and Robbins (1977). Owens and Gohn (1985), utilizing this pollen zonation in the Potomac Formation, noted that the pollen zones became younger northward. Zone III, for example, is best developed in New Jersey, whereas zone I is thickest and best developed in Virginia to the south.

Unit III was cored in its entirety at Freehold where it is approximately 240 ft thick. The basal 20 ft consist of red or mottled red and white clays interbedded with fine gravel (pebbles up to 0.5 in in diameter) and fine to coarse sands. The clays are pervaded by reddish-brown siderite. Most of the overlying beds consist of interbedded dark-colored clays, locally weathered to pale yellow or white, and light-colored fine to medium sands. Layers containing fine black carbonaceous material to large lignitized wood pieces are common in unit III at this locality.

Samples from unit III are available only from a few downdip wells, including the Toms River Chemical, Butler Place, and Island Beach wells. At Toms River, the unit is about 150 ft thick. There, unit III consists of dark- to pale-gray clays, locally weathering to white or yellowish gray, and light-colored, micaceous sands. In general, the darker-colored clays are more common in the upper part of the section. Locally, the sands have very small amounts of glauconite which may indicate some local marine influence during sedimentation.

At Island Beach in the deepest part of the subsurface, core samples were available only above 2,300 ft within and above the Raritan Formation. Data regarding the thickness and lithic character of the Potomac Formation below this level at Island Beach are derived from Gill and others (1963) and Perry and others (1975). In the latter report, pollen zone III is approximately 400 ft thick. Thus, zone III thickens in the deep subsurface. Cuttings from this interval described by Gill and others (1963) consist of interbedded, olive-gray to greenish-gray, micaceous, calcareous, sparingly glauconitic, medium to coarse quartz sand. The clays are the same in the lower part of this zone but change color to light gray. If the calcareous and glauconitic materials are in place, it would indicate that unit III is marine in the deepest subsurface. However, the possibility of downhole contamination has to be considered. Overall, clayey beds are more abundant in the lower half of the unit, whereas sand is more abundant in the upper half.

Geophysical logs for unit III vary from locality to locality. At Freehold the gamma-ray log is characterized by sharp, narrow gamma highs and lows (type A). At Toms River and Butler Place, the gamma-ray logs are characterized by thick beds of high-intensity clay and low-intensity sand. At Island Beach, the gamma-ray pattern appears more like a marine unit with thick, relatively high gamma clay beds interfingering with thin sand beds in the lower half of the unit and predominant thick beds of sand layered with thin clay beds in the upper half.

The petrology of the unit III sands was examined only in the Freehold corehole. Most of the sand is quartz and siliceous rock fragments. The opaque heavy minerals are mostly ilmenite and leucoxene; small amounts of pseudorutile are also present. The non-opaque minerals are mainly staurolite, kyanite, garnet, hornblende, zircon, tourmaline, and rutile. The clay minerals are mostly kaolinite and illite. Illite/smectite is present in small amounts.

The age of pollen zone III was determined by Doyle and Robbins (1977) as early Cenomanian. This unit lacks the Normapollis and other zone-IV species found in the Raritan Formation.

KpII Potomac Formation, unit II (lower Cretaceous, Albian)--Unit II is present only in the subsurface beneath the southeastern corner of the map. The unit II basin is much smaller than the overlying unit III basin. It was only found in the Butler Place, Toms River chemical, and Island Beach wells. The designation of unit II used to identify this unit refers to the presence of pollen zones IIa, IIb, and IIc of Doyle and Robbins (1977).

The thickest sections available for study are from the Toms River chemical and Butler Place wells. In these wells, unit II is approximately 500 ft thick and consists of thick beds of clay-silt and sand. Strongly colored red, white, and yellow clay-silts are characteristic of this unit in both these holes. Dark-gray clays are interbedded locally, but they are uncommon. Downdip at Island Beach, this unit thickens to over 700 ft where it consists of thin- to thick-bedded, light-gray sands and medium- to light-gray clay-silts. Lignite and pyrite are common constituents in these beds, especially in the clay-silts. The highly colored clays of unit III that are so common at Toms River and Butler Place are absent in the Island Beach corehole.

The gamma-log patterns for KpII are similar at Toms River and Butler Place. They consist of thick, high-intensity sections (clays) interspersed with somewhat thinner lower intensity areas (sands) (type A). In the Island Beach well, the gamma-ray pattern is different. There, unit II consists of closely spaced gamma highs and lows, especially in the lower half of the unit. The upper half consists of a thick high intensity clay and an overlying thick low-intensity sand. The Island Beach pattern is characteristic of a delta front or lower delta plain whereas those at the Toms River and Butler Place wells are more indicative of a lower to upper delta plain (riverine) environment. Some marine influence is indicated, however.

The sand in the unit II is dominantly quartz, feldspar, and siliceous rock fragments. Glauconite is a common constituent in some of these sands, especially the younger beds. Whether glauconite is a contaminant is not known; if it is not, then parts of this cycle are marine. The opaque heavy minerals include ilmenite and, to a much lesser degree, leucoxene. The non-opaque heavy minerals include staurolite, and smaller amounts of zircon, garnet, tourmaline, rutile, kyanite, and andalusite. This is a limited mineral assemblage that suggests derivation from a crystalline terrain. The clay mineral suite in unit II is dominated by kaolinite and to a lesser degree, illite. In some samples illite/smectite is a major constituent.

This unit is Albian in age according to Doyle and Robbins (1977).

KpI Potomac Formation, unit I (Lower Cretaceous, Barremian)-- The oldest Coastal Plain unit in the map area is Potomac Formation, unit I. This unit was only penetrated in the deepest wells at Oxley, Butler Place, and Island Beach. The data from the Island Beach well was from the sources reported earlier; the Oxley section also is known only from cuttings.

The best description of the sediments found in this unit is from Gill and others (1963). Unit I is approximately 290 ft thick at Island Beach. The lower part of the unit is mottled in reds and whites and grades up into sediments which are overall a medium-gray to chocolate brown color. In the upper part of the unit, the sediments are less weathered than at the base. Like the other Potomac units, this unit consists of interbedded clayey, sandy, and gravelly sediments. Overall, the sands are more abundant than the gravels. Most of the sands are medium grained and fairly well sorted; mica and lignitic fragments are common constituents. Sands near the base have concentrations of siderite. The clays are hard, almost fissile. Like the sands, they have significant amounts of woody fragments, and pyrite masses are common.

The geophysical log from Island Beach indicates that the unit has large sand bodies interspersed with smaller clay units (type A).

The age of this unit is Barremian (pollen zone I; Doyle and Robbins, 1977).

See Description of Map Units for Piedmont and Newark basin rocks.

References Cited

Andrews, G.W., 1987, Miocene marine diatoms from the Kirkwood Formation, Atlantic County, New Jersey: U.S. Geological Survey Bulletin 1769, p. 1-14.

Andrews, G.W., 1988, A revised diatom zonation for marine strata of the southeastern United States: U.S. Geological Survey Professional Paper 1481, 29 p.

Barksdale, H.C., Johnson, M.E., Schaefer, E.J., Baker, R.C., and DeBuchananne, G.D., 1943, The ground-water supplies of Middlesex County, N.J.: New Jersey State Water Policy Commission Special Report 8, 160 p.

Berggren, W.A., Kent, D.V., Flynn, J.J., and Van Couvering, J.A., 1985, Cenozoic geochronology: Geological Society of America Bulletin, v. 96, p. 1407-1418.

Blow, W.H., 1969, Late middle Eocene to recent planktonic foraminiferal biostratigraphy, biochronology and paleoclimatology: 1st International Conference on Planktonic Microfossils, Geneva, Switzerland, 1967, Proceedings, v. 1, p. 199-422.

Bybell, L.M., 1992, Calcareous nannofossils--their use in interpreting Paleocene and Eocene geologic events in the New Jersey Coastal Plain, in, Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey Workshop on the geology and geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 9-13.

Christopher, R.A., 1979, Normapolles and triporate pollen assemblages from the Raritan and Magothy Formations (Upper Cretaceous) of New Jersey: Palynology, v. 3, p. 73-122.

_____1982, The occurrence of the Complexiopollis-Atlantipollis Zone (palynomorphs) in the Eagle Ford Group (Upper Cretaceous) of Texas: Journal of Paleontology, v. 56, p. 525-541.

Clark, W.B., Kümmel, H.B., and Miller, B.L., 1909, Description of the Trenton quadrangle, New Jersey and Pennsylvania: U.S. Geological Survey Geologic Atlas, Folio 167, 24 p.

Cobban, W.A., 1969, The Late Cretaceous ammonites Scaphites leei Reeside and Scaphites hippocrepis (Dekay) in the western interior of the United States: U.S. Geological Survey Professional Paper 619, 29 p., 5 pls.

Cobban, W.A., and Kennedy, W.J., 1990, Upper Cenomanian ammonites from the Woodbridge Clay Member of the Raritan Formation of New Jersey: Journal of Paleontology, v. 64, p. 845-846.

Doyle, J.A., 1969, Cretaceous angiosperm pollen of the Atlantic Coastal Plain and its evolutionary significance: Arnold Arboretum Journal, v. 50, p. 1-35.

Doyle, J.A., and Robbins, E.I., 1977, Angiosperm pollen zonation of the continental Cretaceous of the Atlantic Coastal Plain and its application to deep wells in the Salisbury embayment: Palynology, v. 1, p. 43-78.

Enright, Richard, 1969, The stratigraphy and clay mineralogy of the Eocene sediments of the northern New Jersey Coastal Plain, in Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: New Brunswick, N.J., Rutgers University Press, p. 14-20.

Gill, H.E., Seaber, P.R., Vecchioli, John, and Anderson, H.R., 1963, Evaluation of geologic and hydrologic data from the test-drilling program at Island Beach State Park, New

Jersey: New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Water Resources Circular, 1225 p.

Gohn, G.S., 1992, Preliminary ostracode biostratigraphy of subsurface Campanian and Maastrichtian sections, New Jersey Coastal Plain, in Gohn, G.S., ed., Proceedings of 1988 U.S. Geological Survey workshop on the geology and geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 15-21.

Goldstein, F.R., 1974, Paleoenvironmental analyses of the Kirkwood Formation: New Brunswick, N.J., Rutgers University, unpublished Ph.D. dissertation, 70 p.

Greller, A.M., and Rachele, L.D., 1984, Climatic limits of exotic genera in the Legler palynoflora, Miocene, New Jersey, U.S.A.: Review of Paleobotany and Palynology, v. 40, no. 3, p. 149-163.

Kennedy, W.J., and Cobban, W.A., 1993, Lower Campanian (Upper Cretaceous) ammonites from Merchantsville Formation of New Jersey, Maryland and Delaware: Journal of Paleontology, v. 67, no. 5, p. 828-849.

Kennedy, W.J., and Cobban, W.A., 1994, Ammonite fauna from the Wenonah Formation (Upper Cretaceous) of New Jersey: Journal of Paleontology, v. 68, no. 1, p. 95-110.

Knapp, G.N., 1904, Kirkwood Formation: New Jersey Geological Survey Annual Report to the State Geologist, 1903, p. 81-82.

Koch, R.C., and Olsson, R.K., 1977, Dinoflagellate and planktonic foraminiferal biostratigraphy of the uppermost Cretaceous of New Jersey: Journal of Paleontology, v. 51, p. 480-491.

Kümmel, H.B., 1940, The geology of New Jersey: New Jersey Dept. of Conservation, Geologic Series Bulletin 50, 203 p.

Kümmel, H.B., and Knapp, G.N., 1904, The stratigraphy of the New Jersey clays, in Ries, Heinrich, and Kummel, H.B., The clays and clay industry of New Jersey: New Jersey Geological Survey, v. 6 of Final report of the State Geologist, p. 117-209.

Lewis, J.V., and Kümmel, H.B., 1910-1912 (revised 1950), Geologic Map of New Jersey: New Jersey Geological Survey, scale 1:250,000.

Litwin, R.J., Sohn, N.F., Owens, J.P., and Sugarman, P.J., 1993, Palynological analysis of a new recognized Upper Cretaceous marine unit at Cheesequake, New Jersey: Palynology, v. 17, p. 123-135.

Martini, Erland, 1971, Standard Tertiary and Quaternary calcareous nannoplankton zonation: Proceedings of the Planktonic Conference, 2nd, Rome, 1969, p. 739-785.

Martino, R.L., and Curran, H.A., 1990, Sedimentology, ichnology, and paleoenvironments of the Upper Cretaceous Wenonah and Mount Lurel Formations, New Jersey: Journal of Sedimentary Petrology, v. 60, no. 1, p. 125-144.

Miller, K.G., Kent, D.V., Brower, A.N., Bybell, L.M., Feigenson, M.D., Olsson, R.K., and Poore, R.Z., 1990, Eocene-Oligocene sea-level changes on the New Jersey Coastal Plain linked to the deep-sea record: Geological Society of America Bulletin, v. 102, p. 331-339.

Minard, J.P., 1964, Geology of the Roosevelt quadrangle, New Jersey: U.S. Geological Survey Quadrangle Map GQ-340, scale 1:24,000.

Minard, J.P., and Owens, J.P., 1962, Pre-Quaternary geology of the New Egypt quadrangle, New Jersey: U.S. Geological Survey Quadrangle Map GC-161, scale 1:24,000.

Newell, W.L., Wyckoff, J.S., Owens, J.P., and Farnsworth, John, 1988, Cenozoic geology and geomorphology of the southern New Jersey Coastal Plain: Southern Friends of the Pleistocene, Guidebook for 2nd annual field conference, 51 p.

Olsson, R.K., 1963, Latest Cretaceous and the earliest Tertiary stratigraphy of New Jersey Coastal Plain: American Association of Petroleum Geologists Bulletin, v. 47, no. 4, p. 643-665.

_____, 1964, Late Cretaceous planktonic foraminifera from New Jersey and Delaware: Micropaleontology, v. 10, p. 157-188.

Olsson, R.K., Gibson, T.G., Hansen, H.J., and Owens, J.P., 1988, Geology of the northern Atlantic Coastal Plain; Long Island to Virginia: Geological Society of America, Decade of North American Geology, Chapter 6, v. 1-2, The Atlantic Continental Margin, p. 87-105.

Owens, J.P., 1983, Northwestern Atlantic Ocean margin, in, Moullade, M., and Nairn, A.E.M., eds., The Phanerozoic geology of the world, II--Mesozoic, B: Elsevier, North Holland Publishing Co., New York, p. 33-60.

Owens, J.P., and Minard, J.P., 1966, Pre-Quaternary geology of the Allentown quadrangle, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-566, scale 1:24,000.

Owens, J.P., and Sohl, N.F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain, in Subitsky, S., ed., Guidebook of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: New Brunswick, N.J., Rutgers University Press, p. 235-278.

Owens, J.P., Minard, J.P., Sohl, N.F., and Mello, J.F., 1970, Stratigraphy of the outcropping post-Magothy Upper Cretaceous formations in southern New Jersey and northern Delmarva Peninsula, Delaware-Maryland: U.S. Geological Survey Professional Paper 674, 60 p.

Owens, J.P., and Sohl, 1973, Glauconites from the New Jersey-Maryland Coastal Plains: their K/Ar ages and use in stratigraphic studies: Geological Society of America Bulletin, v. 84, p. 2811-2838.

Owens, J.P., Sohl, N.F., and Minard, J.P., 1977, A field guide to the Cretaceous and lower Tertiary beds of the Raritan and Salisbury embayments, New Jersey, Delaware and Maryland: American Association of Petroleum Geologists/Society of Economic Paleontologists and Mineralogists, Annual Convention, Washington, D.C., 111 p.

Owens, J.P., and Gohn, G.S., 1985, Depositional history of the Cretaceous Series in the U.S. Atlantic Coastal Plain - Stratigraphy, paleoenvironments, and tectonic controls of sedimentation, in Poag, C.W., ed., Geologic evolution of the United States Atlantic margin: New York, Van Nostrand Reinhold, p. 25-86.

Owens, J.P., Bybell, L.M., Paulachok, Gary, Ager, T.A., Sugarman, P.J., and Gonzalez, V.M., 1988, Stratigraphy of the Tertiary sediments in a 945 foot (288 m) corehole near Mays Landing in the southeastern New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1484, 78 p.

Perry, W.J., Jr., Minard, J.P., Weed, E.G.A., Robbins, E.I., and Rhodehamel, E.C., 1975, Stratigraphy of Atlantic Coastal margin of the United States north of Cape Hatteras - Brief Survey: American Association of Petroleum Geologists Bulletin, v. 59, p. 1529-

1548.

Perch-Nielsen, Katharina, 1985, Mesozoic calcareous nannofossils, in, Bolli, H.M., Saunders, J.B., and Perch-Nielsen, Katharina, eds., Plankton Stratigraphy: Cambridge University Press, New York, p. 329-426.

Petters, S.W., 1976, Upper Cretaceous subsurface stratigraphy of Atlantic Coastal Plain of New Jersey: American Association of Petroleum Geologists Bulletin, v. 60, no. 1, p. 87-107.

Rachele, L.D., 1976, Palynology of the Legler lignite: A deposit in the Tertiary Cohansey Formation of New Jersey, U.S.A.: Review of Paleobotany and Palynology, v. 22, p. 225-252.

Richards, H.G., 1958, The Cretaceous fossils of New Jersey, State of New Jersey, Department of Conservation and Economic Development, Bulletin 61, Part I, 364 p.

_____., 1967, Stratigraphy of Atlantic Coastal Plain between Long Island and Georgia: Review: American Association of Petroleum Geologists Bulletin, v. 51, p. 2400-2429.

Sugarman, P.J., Miller, K.G., Bukry, David, and Feigenson, M.D., 1995, Uppermost Campanian-Maestrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain: Geological Society of America Bulletin, v. 107, p. 19-37.

Sugarman, P.J., Miller, K.G., Owens, J.P., and Feigenson, M.D., 1993, Strontium isotope and sequence stratigraphy of the Miocene Kirkwood Formation, southern New Jersey: Geological Society of America Bulletin, v. 5, no. 4, p. 423-436.

Vokert, R.A., and Drake, A.A., Jr., 1993, Geology of the Trenton Prong, west-central New Jersey: Geological Society of America, Abstracts with Programs, v. 25, no. 2, p. 86.

Weller, Stuart, 1904, The classification of the Upper Cretaceous formations and faunas of New Jersey: New Jersey Geological Survey Annual Report 1904, p. 145-159.

_____1907, A report on the Cretaceous paleontology of New Jersey based upon the stratigraphic studies of George N. Knapp: New Jersey Geological Survey Paleontology Service, v. 4, 1107 p.

Wolfe, J.A., 1976, Stratigraphic distribution of some pollen types from the Campanian and lower Maastrichtian rocks (Upper Cretaceous) of the Middle Atlantic States: U.S. Geological Survey Professional Paper 977, p. 1-18.

Wolfe, J.A., and Pakiser, H.M., 1971, Stratigraphic interpretations of some Cretaceous microfossil floras in the Middle Atlantic States: U.S. Geological Survey Professional Paper 750-B, p. 35-47.

Woolman, Lewis, 1895, Report on artesian wells in southern New Jersey: New Jersey Geological Survey, Annual Report of the State Geologist for 1894, pt. 2, p. 151-304.