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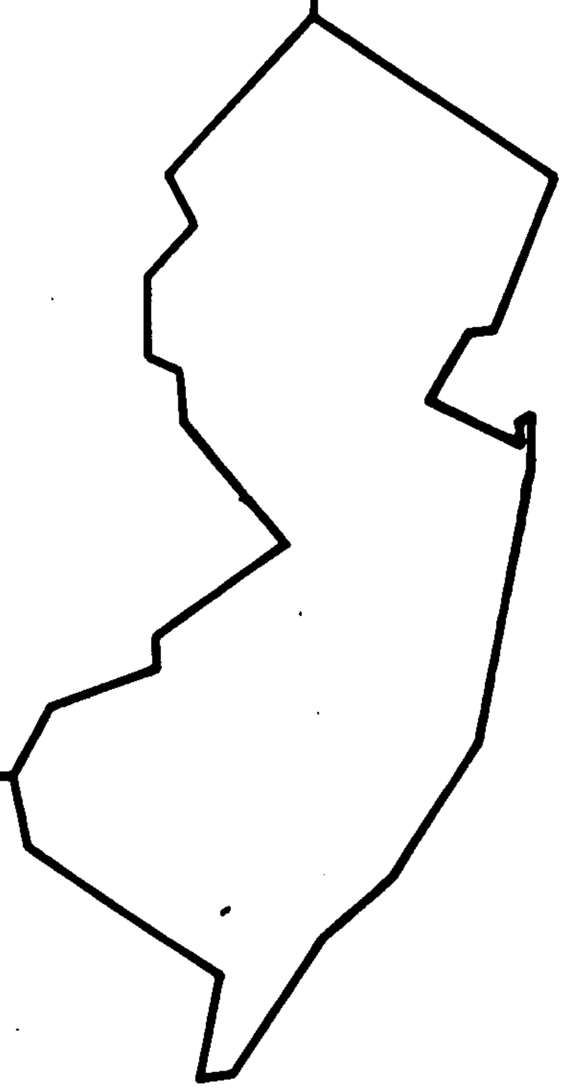
NEW JERSEY GEOLOGICAL SURVEY
TECHNICAL MEMORANDUM

REVIEW of the PERMEABILITY CHARACTERISTICS of the WOODBURY CLAY



Department of Environmental Protection
Division of Water Resources

1985

Thomas H. Kean, Governor
Robert E. Hughey, Commissioner

REVIEW OF THE PERMEABILITY CHARACTERISTICS OF THE WOODBURY CLAY

New Jersey Geological Survey
Technical Memorandum

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REVIEW OF THE PERMEABILITY CHARACTERISTICS OF THE WOODBURY CLAY

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ABSTRACT

The Woodbury-Merchantville confining layer overlies the Potomac-Raritan-Magothy aquifer system and underlies the Englishtown aquifer. It is one of the major hydrogeologic features of the New Jersey Coastal Plain. Prior to about 1950, the confining layer, particularly the Woodbury Clay, was believed to be impermeable. All water entering aquifers in the Potomac-Raritan-Magothy system was believed to come from west of the outcrop area of the confining layer. It has become clear, however, that considerable vertical leakage occurs through the Woodbury-Merchantville confining layer to the underlying aqiufers.

Although some of the vertical leakage may be due to flow through intergranular void space or high-permeability gaps through the formation, the primary component is more likely the result of fracturing. Field and remote sensing reconnaissance show pervasive fracturing in most areas of Woodbury Clay. Fractures are of two types, joints and faults. Joints are evident throughout the Inner Coastal Plain, but vary widely in outcrop expression. Open, mineralized joints may provide substantial permeability in places. Elsewhere joints are scarcely visible and may not be capable of transmitting significant amounts of water. Faulting appears to be more localized than jointing, but has the potential to cause high permeability.

INTRODUCTION

The Woodbury Clay is a geologic formation composed primarily of micaceous clayey silt and silty clay. It lies within the New Jersey Coastal Plain and through most of its extent forms a layer 50 or more feet thick. The Merchantville Formation underlies the Woodbury Clay, consists of silt and glauconitic sand and usually forms a layer 50 or more feet thick. Until recently the Woodbury and Merchantville together have been considered to form a nearly impermeable barrier to water. The Woodbury in particular has been considered virtually impervious (Kummel, 1903; Barksdale and others, 1943) and has been considered important in protecting the underlying Potomac-Raritan-Magothy aquifer system from contamination or salt water encroachment by vertical movement of water (Parker and others, 1964).

Since the 1950's geologists have come to realize that the Woodbury-Merchantville confining layer is not completely impermeable and that a significant proportion of the recharge to the Potomac-Raritan-Magothy aquifer system is by vertical leakage. In view of the increasing stress on Coastal Plain water resources and recognition of the dangers of ground water contamination, it is important to know what conditions control leakage.

This report describes the Woodbury Clay, reviews its geologic setting and summarizes permeability estimates. Reasons for the permeability based on geologic conditions are offered.

No attempt was made to evaluate the permeability of the formation across broad geographic areas or to identify areas of water movement upward or downward through the confining layer. Instead, areas believed to represent the range of conditions in the formation were investigated in reconnaissance to observe conditions which might contribute to permeability.

Geologic Setting

New Jersey Coastal Plain geology has been reviewed by Petters (1976), Perry and others (1975), Owens and others (1970) and Owens and Sohl (1969). Coastal Plain deposits (figure 1) form a wedge-shaped mass of southeast-dipping sedimentary formations which thickens from a feather edge at the fall line to over 6000 feet at Cape May. The formations are predominantly unconsolidated or semi-consolidated, layered units of sand, silt, clay, gravel, greensand marl or lime sand (table 1). They range in age from Upper Cretaceous to Holocene and lie unconformably on a pre-Cretaceous basement of consolidated bedrock. Depositional environments were marine, marginal marine and fluvial. The Woodbury Clay is a marine unit exposed near the inner edge of the Coastal Plain (figure 2) and dipping to the southeast at slightly more than 40 ft/mi.

Hydrology of the Coastal Plain has been summarized by Vowinkel and Foster (1981). Water flow in the subsurface is controlled by permeabilities of the layered geologic units. These range from highly permeable sand to tight clay. In very broad terms the Coastal Plain may be described as having five major aquifer systems separated by three major confining units (figure 2). The Woodbury and Merchantville formations together form the lowermost confining layer. This is underlain by the Potomac-Raritan-Magothy aquifer system and overlain in the subsurface by the Englishtown aquifer. Within its outcrop area the Woodbury-Merchantville confining layer is overlain in places by the Bridgeton, Pensauken and Cape May Formations.

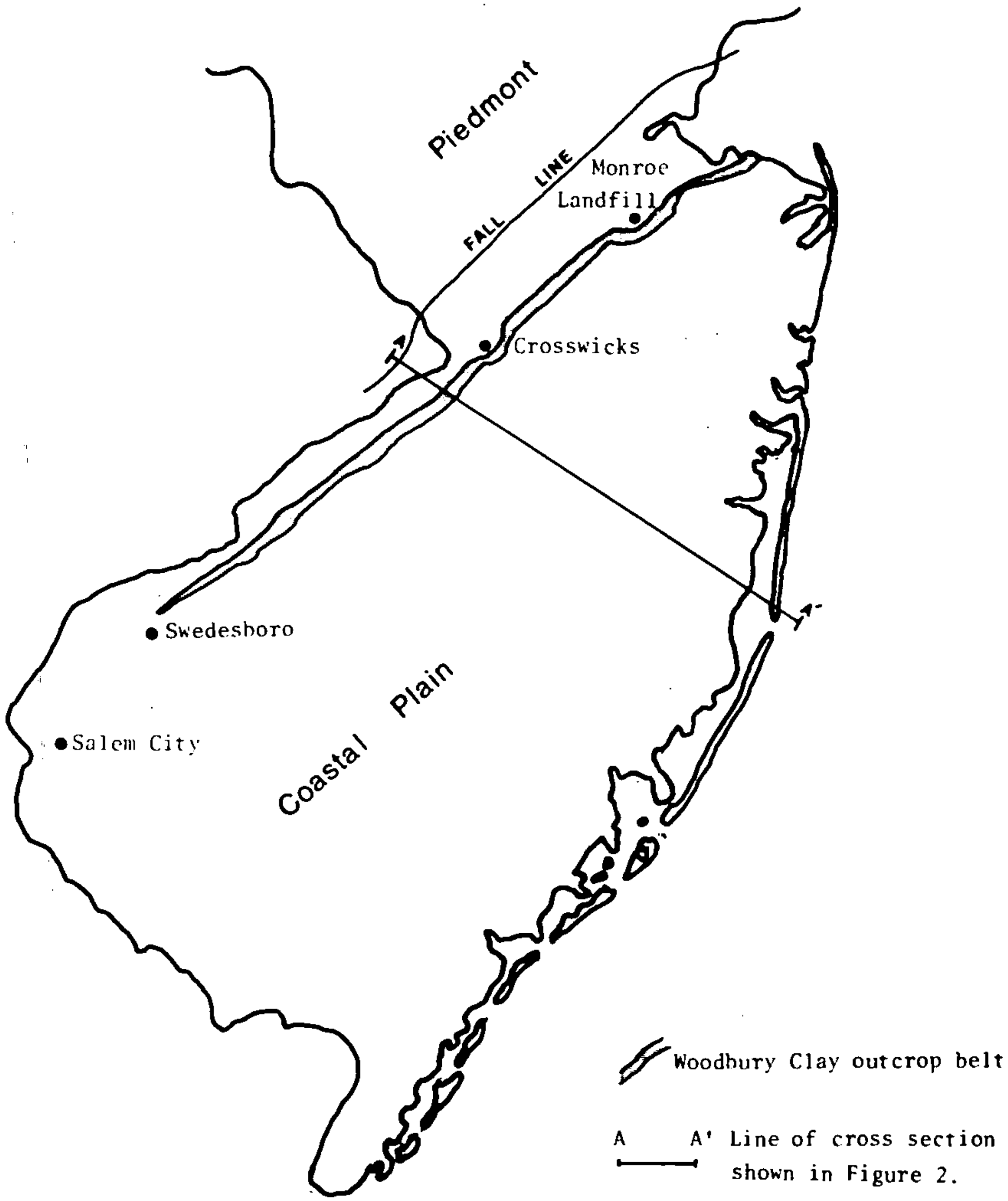
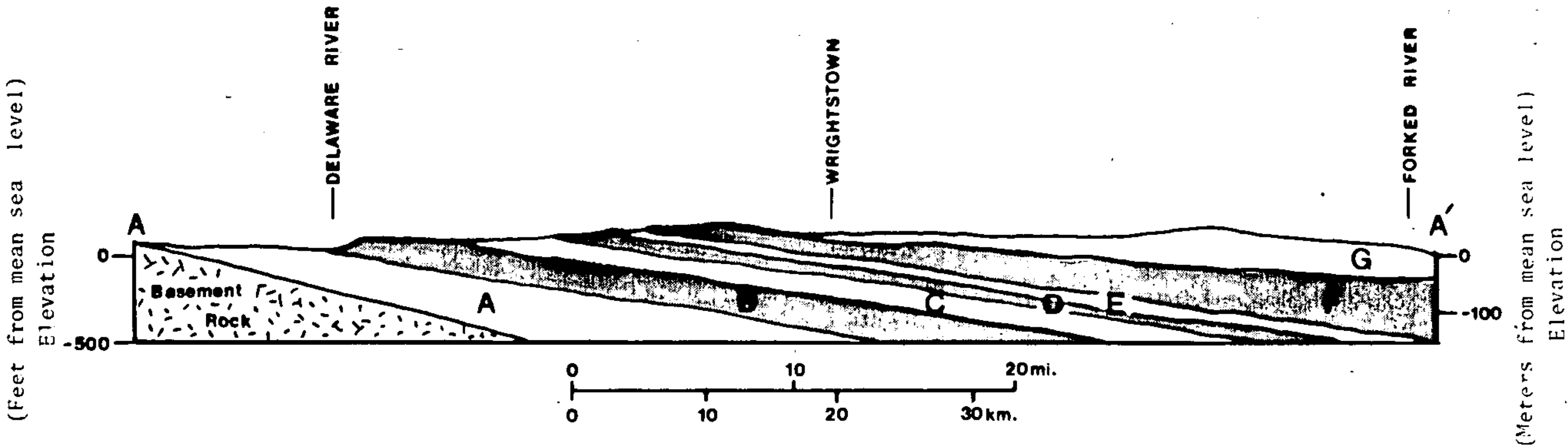


Figure 1. Map showing the New Jersey Coastal Plain and the Woodbury Clay outcrop belt. (from U. S. Geological Survey, 1967)



Aquifers		Confining Layers	
A	Potomac-Raritan-Magothy	B	Woodbury-Merchantville
C	Englishtown	D	Marshalltown
E	Mt. Laurel-Wenonah	F	Navesink-Hornerstown
G	Kirkwood and Cohansey		

Figure 2. Generalized cross-section of the New Jersey Coastal Plain (modified from Gill and others, 1968; line of section shown on Figure 1).

Table 1. Maximum thickness, lithology, and water-bearing characteristics of geologic formations of the Coastal Plain of New Jersey.

SYSTEM	FORMATION	MAXIMUM REPORTED THICKNESS	LITHOLOGY	WATER-BEARING CHARACTERISTICS
uater- nary	Alluvial deposits	80	Sand, silt, and black mud.	Locally may yield small quantities of water to shallow wells.
	Beach sand and gravel		Sand, quartz, light-colored, medium grained, pebbly.	
	Cape May Formation	200	Sand, quartz, light-colored, heterogenous, clayey, pebbly, glauconitic.	Thicker sands are capable of yielding large quantities of water.
	Pensauken Formation			
	Bridgeton Formation			
ertiary	Beacon Hill Formation	40	Gravel, quartz, light-colored, sandy.	No known wells tap this formation.
	Cohansey Sand	250	Sand, quartz, light-colored, medium to coarse-grained, pebbly; local clay beds.	A major aquifer. Ground-water occurs generally under water-table conditions. In Cape May, the aquifer is under artesian conditions. Inland from the coast and in the northern part of Ocean County, the upper part of the Kirkwood Formation is in hydraulic connection with the Cohansey Sand.
	Kirkwood Formation	750	Sand, quartz, gray to tan, very fine- to medium-grained, micaceous, and dark-colored diatomaceous clay.	Includes two aquifers. The principal artesian aquifer along the Atlantic Coast is the lower aquifer or the Atlantic City "800-foot" sand. The upper aquifer is artesian in Cape May. In the Atlantic City area it is also artesian but thin (10-20 feet) and not presently being used. Inland from the coast and in the northern part of the coast in Ocean County, the upper aquifer consists of the upper part of the Kirkwood Formation and the Cohansey Sand. Locally may be under semiartesian or artesian conditions.
	Piney Point Formation	220	Sand, quartz and glauconitic, fine- to coarse-grained.	Minor aquifer in New Jersey. Greatest thickness in Cumberland County.
	Shark River Marl	1400	Sand, quartz and glauconite, gray, brown, and green, fine- to coarse-grained, clayey, and green silty and sandy clay.	Locally may yield small quantities of water to wells.
	Manasquan Formation	160		Locally may yield small to moderate quantities of water to wells.
	Vincentown Formation	100	Sand, quartz, gray and green, fine- to coarse-grained, glauconitic, and brown clayey, very fossiliferous, glauconite and quartz calcarenite.	Locally may yield small to moderate quantities of water to wells.
	Hornerstown Sand	35	Sand, glauconite, green, medium- to coarse-grained, clayey.	Locally may yield small quantities of water to wells.
retaceous	Tinton Sand	25	Sand, quartz, and glauconite, brown and gray, fine- to coarse-grained, clayey, micaceous.	No known wells tap this sand.
	Red Bank Sand	150		Yields small quantities of water to wells in Monmouth County.
	Navesink Formation	50	Sand, glauconite, and quartz, green, black, and brown, medium- to coarse-grained, clayey.	Locally may yield small quantities of water to wells.
	Mount Laurel Sand	220	Sand, quartz, brown and gray, fine- to coarse-grained, glauconitic.	A major aquifer in the northern part of the Coastal Plain. A sand unit within the two formations forms a single aquifer.
	Wenonah Formation		Sand, quartz, gray and brown, very fine- to fine-grained, glauconitic, micaceous.	
	Marshalltown Formation	30	Sand, quartz and glauconite, gray and black, very fine to medium-grained, very clayey.	Leaky confining bed.
	Englishtown Formation	220	Sand, quartz, tan and gray, fine- to medium-grained; local clay beds.	A major aquifer in the northern part of the Coastal Plain. Two aquifer units in Ocean County.
	Woodbury Clay	325	Clay, gray and black, micaceous.	The two formations form a major confining unit throughout the New Jersey Coastal Plain. Locally the Merchantville may yield small quantities of water to wells.
	Merchantville Formation		Clay, gray and black, micaceous, glauconitic, silty; locally very fine-grained quartz and glauconitic sand.	
	Magothy Formation	4100	Sand, quartz, light-gray, fine-grained, and dark-gray lignitic clay.	Major aquifer system in New Jersey Coastal Plain. In the northern part of the Coastal Plain, two aquifers have been defined. They are the Farrington aquifer (mainly Raritan age) and the Old Bridge aquifer (Magothy age).
	Raritan Formation		Sand, quartz, light-gray, fine- to coarse-grained, pebbly, arkosic, red, white, and variegated clay.	
	Potomac Group		Alternating clay, silt, sand, and gravel.	
re- retaceous	Pre-Cretaceous Unconsolidated rocks and Wissahickon Formation	?	Precambrian and lower Paleozoic crystalline rocks, metamorphic schist and gneiss; locally Triassic basalt, sandstone, and shale.	Except along Fall Line, no wells obtain water from these consolidated rocks.

(from Vowinkel and Foster, 1981)

Previous Work

Since about 1950 there has been increasing awareness of the possible importance of vertical movement of water through the Woodbury-Merchantville confining layer. Knapp (1903) and Bascom and others (1909) refer to the Woodbury Clay as impermeable. According to Thompson (1932) the Woodbury and Merchantville together are "relatively impermeable ... Accordingly all the water that enters the Magothy and Raritan must do so west of the outcrop area of the Merchantville Clay." Barksdale and others (1943) similarly consider these formations to be a nearly impermeable layer.

In 1958, however, Barksdale and others mention that "vertical leakage may occur ... under suitable conditions of head." Vecchioli and Palmer (1962) recognize that "heavy pumpage of the aquifers of the Raritan and Magothy could establish a sufficient hydraulic gradient to enable water to percolate through the clays of the Woodbury and Merchantville ..." and "if such head differences were widespread considerable quantities of water could leak through the clays ..."

In the late 1960's a series of ground water reports on Coastal Plain counties (Jablonski, 1968; Rush, 1968; Anderson and Appel, 1969; Hilton, 1969; Roseneau and others, 1969) included laboratory measurements. It was recognized that "recharge to the Raritan and Magothy Formations from the Englishtown Formation takes place as the result of vertical leakage through the [Woodbury and Merchantville Formations]" (Rush, 1968).

Gill and Farlekas (1976) cite evidence of vertical leakage through the confining layer in that "The 1900 potentiometric surface map ... shows several ground water mounds that coincide with topographically high areas suggesting that the Potomac-Raritan-Magothy aquifer system is recharged by infiltration on the high level outcrop area northeast of Trenton and by leakage through the overlying semipervious confining layers downdip of the area."

Luzier (1980) in a hydrologic model study of the Potomac-Raritan-Magothy aquifer system characterizes the Woodbury and Merchantville as forming an "effective but leaky separation" between the Potomac-Raritan-Magothy and overlying aquifers. In response to increasing ground water usage he estimates the rate of recharge in a strip 20 miles wide from Trenton to Wilmington, Delaware, to have increased from 14.7 cfs (cubic feet per second) under natural conditions in 1900 to 68.8 cfs, 31 percent of the recharge to the Potomac-Raritan-Magothy aquifer system in this area, in 1973. The remaining 69 percent was from recharge through the outcrop area, much of it by infiltration through the bed of the Delaware River.

Acknowledgments

The original impetus for this work and many of the interpretations presented here were from Frank Markewicz. Review and comments were provided by Ian Walker, Bob Canace, Haig Kasabach and Bill Althoff. The report was edited by Dave Harper. Diagrams were prepared by Bill Graff and Ron Kuzma.

LITHOLOGY OF THE WOODBURY CLAY AND ENCLOSING FORMATIONS

Potomac Group, Raritan and Magothy Formations

The Potomac Group unconformably overlies pre-Cretaceous consolidated bedrock in Delaware and Maryland, but is not shown on the Geologic Map of New Jersey (Johnson, 1950). More recent maps (U. S. Geol. Survey, 1967) show the Potomac Group in southern New Jersey.

The Raritan Formation is conformable with and, in New Jersey, similar to the Potomac Group. Both consist of light-colored, quartzose sands, some gravels, and white, yellow, brown or red clays.

The Magothy Formation conformably overlies the Raritan Formation and consists of alternating beds or lenses of dark-gray or black clay and white, micaceous, fine to medium-grained sand. Gravel is occasionally present.

The Potomac-Raritan-Magothy aquifer system is one of the most productive and heavily pumped sources of ground water in the Coastal Plain and is of critical importance for public and industrial water supply along a strip approximately 20 miles wide extending from Salem County to Raritan Bay. South of a line extending from Salem City through Bridgeport, Gloucester County, to Waretown, Ocean County, water in this aquifer system is brackish or salty (Gill and Farlekas, 1976).

Merchantville Formation

The Merchantville Formation sharply and disconformably overlies the Magothy Formation. Its thickness is consistently about 50 feet along the outcrop belt but lithology varies along strike. In the Raritan Bay area the formation consists of dark-gray to black, massive, thick glauconitic sand beds interstratified with thin-bedded, micaceous clayey silts. In the vicinity of Trenton the thin-bedded clayey silts are absent. Within Camden County, a sand layer up to 30 feet thick has been mapped from geophysical logs (Farlekas and others, 1976).

As part of the Woodbury-Merchantville confining layer, the Merchantville Formation is generally recognized as less effective than the Woodbury in restricting vertical movement of water. Sand lenses near the top of the Merchantville Formation have been used in some areas for domestic water supply (Hardt and Hilton, 1969), but the total withdrawal is not large.

Woodbury Clay

The Woodbury Clay is conformable and intergradational with the underlying Merchantville and overlying Englishtown Formations. Its thickness is about 50 ft near the outcrop. Although commonly referred to as a clay, the Woodbury formation ranges in overall composition from silty clay to clayey silt. An appreciable amount of fine sand is usually present even within clayey samples. The upper zone, transitional with the Englishtown Formation, is commonly laminated and may include sand layers. At places this transitional zone is quite sandy, consisting of alternating, thin layers of light-brown clay and fine, white sand. Very little glauconite is present. Glauconite is most often found at or near the transitional contact with the Merchantville Formation. The predominant clay minerals from outcrop samples are kaolinite, chlorite and mica (Groot and Glass, 1960). Downdip, montmorillonite and glauconite are present. Color varies from beige or light gray on weathered surfaces to dark gray to black in fresh samples. Lignite is common and marine fossils occur at numerous localities. Weller (1907, p. 63-78) describes faunas from six localities in the Woodbury Clay in New Jersey.

In many exposures the Woodbury Clay has a blocky appearance due at least in part to fracturing. Fracturing is widely distributed and varies in intensity from exposure to exposure. Iron oxides commonly encrust or fill fractures, especially where the formation is highly fractured.

Minard (1965) has reclassified certain areas shown as Woodbury Clay on the Geologic Map of New Jersey (Johnson, 1950) as a clayey phase of the Englishtown Formation. The reclassification includes all of what was considered to be Woodbury Clay in Salem County and much in Gloucester County. According to this interpretation the Woodbury Clay pinches out at a point about 2.5 miles north of Swedesboro (U. S. Geol. Survey, 1967).

The Woodbury and Merchantville Formations are commonly not differentiated in subsurface work. The combined thickness of the two formations increases from about 100 ft near the outcrop to 300 ft along the coast and more than 500 ft offshore (Petters, 1976).

The Woodbury Clay is considered the most effective aquiclude in the New Jersey Coastal Plain (Barksdale and others, 1958). No wells are known to draw water from the Woodbury formation.

Englishtown Formation

The Englishtown Formation is conformable and intergradational with the underlying Woodbury Clay. In the northern part of the New Jersey Coastal Plain the Englishtown Formation is 50 to 150 ft thick and consists of cross-stratified sands interstratified with dark, carbon-rich silt. To the south the formation is approximately 40 ft thick and consists of massive, dark-colored silty sand.

The Englishtown Formation is a significant source of ground water for Ocean and Monmouth Counties. More than 10 million gallons of water per day are withdrawn from the formation (Vowinkel and Foster, 1981, figure 11).

In southern New Jersey where the Englishtown Formation consists of silty sand the formation acts as part of the confining layer overlying the Potomac-Raritan-Magothy aquifer system.

Bridgeton, Pensauken and Cape May Formations

The Bridgeton and Pensauken Formations are surficial, fluvial deposits of Miocene age (Owens and Minard, 1979) and unconformably overly older Coastal Plain formations. They are distributed as irregular areas of fine to coarse-grained quartzose sands and gravels. The Cape May Formation is a fluvial and marine deposit irregularly distributed at elevations of less than 50 ft in coastal areas and up to 150 ft in inland stream valleys. The formation is complex, compositionally variable and represents several depositional episodes. Subdivisions of the Cape May Formation have been proposed by Gill (1962), Owens and Minard (1975), and Owens and others (1979). Regional mapping has not been revised, however, from that shown on the Geologic Map of New Jersey (Johnson, 1950).

The surficial deposits of the Coastal Plain are commonly 30 to 50 ft thick and are minor aquifers for domestic supply.

PERMEABILITY MEASUREMENTS

Estimates and measurements of the permeability of Woodbury Clay and undifferentiated Woodbury-Merchantville samples have been made by laboratory testing of samples, digital simulation modeling, a pump test, and falling head tests. Permeabilities

Table 2. Permeability measurements of the Woodbury Clay and undifferentiated Woodbury-Merchantville Formations.

Geologic Unit	Permeability (cm/sec)	Source of Data
Woodbury-Merchantville	9.9×10^{-10} to 1.5×10^{-7}	Gill and Farlekas (1976)
Woodbury	4.7×10^{-8} to 1.9×10^{-5}	Farlekas and others (1976)
Woodbury-Merchantville	1.3×10^{-9} to 2.1×10^{-8}	Nichols (1977a,b)
Woodbury-Merchantville	6.6×10^{-8}	Geraghty and Miller, Inc. (verbal commun.)
upper Woodbury	6.5×10^{-5} to 7×10^{-6}	this study

have been variously reported in units of gallons per day per square foot, feet per day and meters per day. For ease of comparison, these have been converted to centimeters per second (table 2).

Laboratory Measurements

Laboratory measurements of the permeability of the Woodbury Clay have been reported in several U. S. Geological Survey publications. These are for outcrop and split spoon samples tested at pressures simulating those at the depth of recovery.

Gill and Farlekas (1976) report permeabilities from 12 split spoon samples from the more clayey parts of the Woodbury-Merchantville confining layer at three unspecified sites. These range from 9.9×10^{-10} to 1.5×10^{-7} cm/sec. Farlekas and others (1976) reported permeabilities from 10 samples from 10 ft intervals in the New Brooklyn Park well in Winslow Township, Camden County. These range from 4.7×10^{-8} to 1.9×10^{-5} cm/sec. Nichols (1977 a,b) tabulated permeability values from two wells, one at Fort Dix and one at Lakewood. Permeability values for the Woodbury-Merchantville confining layer ranged from 1.3×10^{-9} to 2.1×10^{-8} cm/sec.

The relatively low permeabilities found in many of these measurements are attributed by Luzier (1980) in part to bias in core recovery towards the finer-grained and therefore tighter horizons and in part to simulated depth of burial used during testing.

Digital Simulation Modeling

Estimates of the permeability of the Woodbury-Merchantville confining layer were used by Luzier (1980) during calibration of a digital simulation model of water flow in the Potomac-Raritan-Magothy aquifer system. Vertical hydraulic conductivities used in the final model ranged from 1×10^{-11} to 2×10^{-8} cm/sec and show marked decrease with increasing depth of burial. The range overlaps that found in laboratory measurements, but extends to lower values.

Pumping Test

Effective permeability of the Woodbury-Merchantville confining layer was calculated by Geraghty and Miller, Inc., (verbal commun.) on the basis of a large-scale pumping test performed at the site of a proposed major development in Old Bridge Township, Middlesex County.

A 310 ft deep test well was screened in the Magothy-Raritan aquifer. Several wells were available for observation at distances of 1000 to 4000 ft from the pumping well. These were screened at various levels in aquifers above and below the Woodbury-Merchantville confining layer.

The test well was pumped at 850 gpm for 48 hours. The observation wells were monitored during pumping and recovery periods. Permeability calculated by the consultant was 6.6×10^{-8} cm/sec, which is within the range obtained through laboratory measurements and the simulation model, but an order of magnitude greater than the median permeability from either method. The test well is near Monroe Township where the Woodbury Clay, as discussed below, is believed to be faulted. The slightly higher permeability may be a result of faulting.

Falling Head Tests

A series of falling head tests was performed as part of this study using methods described by Cedergren (1967). The tests were carried out within the Woodbury outcrop belt near the confluence of Rancocas and Parker Creeks, Moorestown Township, Burlington County. Nearby exposures of the Woodbury Clay consist of gray clayey silt and silty clay. No sandy layers or iron crusts were observed.

Falling head tests were conducted at three sites at the corners of a triangle 50 to 70 feet on a side. Borings were emplaced using a 3-inch auger.

At site #1, the boring was to 47 ft. No split spoon samples were taken. Cuttings were gray clayey silt and silty clay. At site #2 the boring was to 33 ft. Split spoon samples were taken. About 85% of the length of the recovered core consisted of silty clay. The remainder consisted of clean sandy silt. The elevation of the clean sandy silt beds was above the bottom of the boring at site #1. At site #3 the boring was to 26 ft and terminated approximately one foot above the elevation at which clean sandy silt was encountered at site #2. Split spoon samples consisted of homogeneous silty clay without any clean silts. No iron oxide crusts were noted in cuttings or split spoon samples from any of the sites.

Casings were sealed into unweathered Woodbury Clay and filled with water to several feet above the ground surface. Permeabilities were calculated from the rate of water level decline as 6×10^{-5}cm/sec at site #1, 9×10^{-5}cm/sec at site #2, and 7×10^{-6}cm/sec at site #3.

The relatively high measured permeability may in part be due to thin, nearly horizontal, sandy silt layers as were prominent in split spoon samples from site #2. The measurmements may therefore primarily reflect horizontal permeability. Vertical permeability at these same sites may be substantially less than the measured permeability.

NATURE OF THE PERMEABILITY OF THE WOODBURY CLAY

Fractures have long been noted as characteristic of the Woodbury Clay and provide the most obvious means by which large volumes of water might be transmitted through the formation. In places fractures are open and mineralized. Ground water movement through open, mineralized fractures was observed in trenches dug for leachate cutoff walls at the Monroe Township landfill.

Some leakage may also occur through sand or clean silt distributed either as facies of the Woodbury Clay or filling gaps through the formation. At no point in the course of this reconnaissance were either gaps or permeable materials noted through the entire thickness of the formation. Neither can be dismissed, however, as impossible. Facies changes are common in Coastal Plain formations, including the Woodbury Clay, and there is a reasonable possibility that clean silt or silty sand may, at places, extend through the entire thickness of the formation. Gaps are known to exist through a number of clayey formations and members in the Coastal Plain and the possibility that they exist through the Woodbury Clay cannot be dismissed without additional investigation.

FRACTURING OF THE WOODBURY CLAY

Fracture is a general term for any break in a rock whether or not displacement has taken place. The term includes joints and faults. A fault is a fracture along which movement has taken place, whereas little or no movement has occurred along a joint.

Fracturing is widespread within the Woodbury Clay and has been used as a criterion for recognizing the formation. Ries and others (1904) describe fracturing of the Woodbury as follows:

> [The Woodbury Clay,] when dry, breaks into innumerable blocks, large and small, frequently with conchoidal fracture. ... In some localities, as at Dobbs clay pit, near Camden, these joint faces are smoothed and polished in a striking manner. In its lower portion it is penetrated by numerous joints. Many of these are filled with crusts of limonite, which sometimes form huge honeycomb masses many feet in diameter and tons in weight.

Fracturing observed in the course of this study varies from place to place. A number of exposures were visited at which fracturing is not apparent. In many places fractures have a smooth and polished appearance and are not mineralized. Elsewhere, fractures are encrusted with limonitic iron oxide. The encrustations range from thin films to thick crusts. The crusts are usually thickest and most numerous where the clay is highly fractured.

Dessication has been identified as the probable cause of some fracturing in the basal beds of the formation (Owens and Minard, 1962).

Jointing due to stresses during Coastal Plain development is a likely cause for other fractures. Joints visible in clay pits in the vicinity of the Monroe Township landfill show no movement, extend to depths of greater than 50 ft and do not appear to have propagated downward from any identifieable surface.

Faulting is localized in occurrence and was most clearly observed in the Monroe and Crosswicks areas. Several of the characteristics of the faulting in these areas indicate slumpage as the probable cause of movement.

Features characteristic of slumpages include: 1) downslope concavity of fractures seen in horizontal section, 2) upward concavity of surfaces of detachment seen in vertical exposure, 3) fracture development parallel and perpendicular to the direction of sliding, 4) brecciation, 5) rotation of bedding, 6) cutting off of bedding and 7) repetition of stratigraphic units. All of these have been observed at or in the vicinity of the Monroe Township landfill. Some of the clearest examples were exposed in leachate cutoff walls at the landfill itself. As described by Canace (unpub. field notes):

> The excavation for the leachate cutoff wall uncovered various zones in the Woodbury Clay ranging from undisturbed "competent" clay to highly disturbed fracture zones. One trench exposed the following zones [figure 3]: A relatively undisturbed, "competent" zone of Woodbury Clay terminated by an inclined fracture zone about 8 to 12 inches wide. The fracture zone concaved upward and contained slickensides and iron encrustations which parallel the zone. The fracture zone dipped westerly under the next zone, a disturbed zone about 80 feet wide. This disturbed zone contained highly weathered silty to sandy clay. The silty, laminated character of the Woodbury here is distinctly contorted in this disturbed zone. Those laminations which could be identified as such are random and usually show a curved, twisted trend.
>
> Another fracture zone, about 6 to 10 inches wide, passes through the center of the disturbed zone. It also contains long iron encrustations parallel to the zone. Uncontaminated ground water visibly flows through this fracture zone demonstrating the secondary permeability that may be produced by such fracture zones.
>
> To the west, the disturbed zone grades into a more

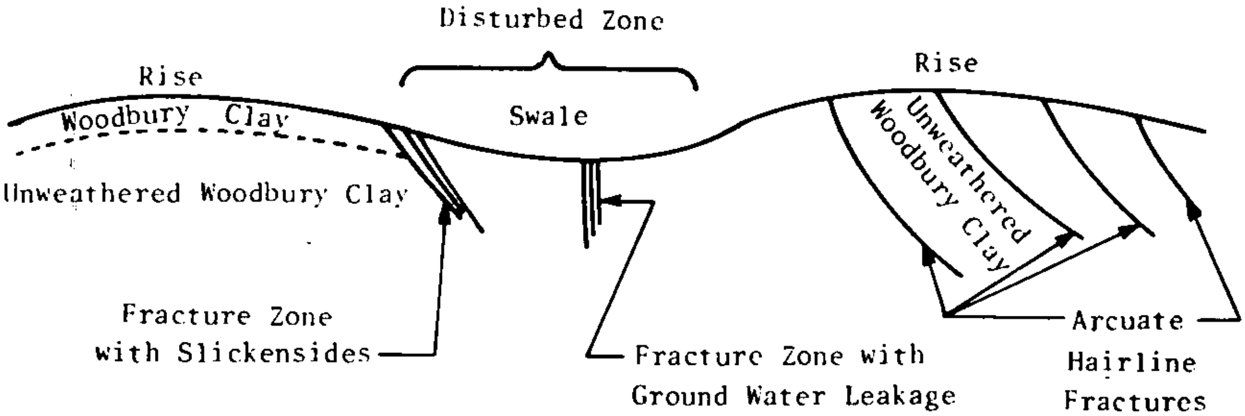


Figure 3. Field sketch showing features seen in excavations for a leachate cutoff wall at the Monroe Township Landfill. (from Canace, unpub.)

competent Woodbury Clay. Hairline fractures concaving upward cutthis otherwise competent clay. No ground water movement could be detected in these fractures.

An exploratory excavation to the north of the disturbed zone intercepted the iron-impregnated fracture zone. This was traced downward into the underlying Merchantville Formation. Overall, the fracture zone resembles an arcuate slump-block slide surface. The Merchantville Formation (normally about 50 ft thick) here is only 5 to 10 feet thick.

The disturbed zone formed a very obvious swale in the landscape. More competent Woodbury material makes up rises on either side of the swale. A similar swale east of the disturbed zone described above may represent another disturbed zone.

Other indications of the style of faulting were from borings at the landfill and from aerial photography. Borings at the landfill indicate a disturbed stratigraphic sequence. Merchantville clays, which normally underly the Woodbury, were found to overly as well as underly the Woodbury.

Aerial photography shows numerous arcuate lineaments in wooded areas within two miles of the landfill. These are 400 to 1000 ft long and are consistently concave to the northwest. Three of these join to form a short lineament trending N20°E. The orientation and sense of curvature of these lineaments, together with the upward-concave, westward-dipping fractures, existence of the Merchantville Formation both above and below the Woodbury Clay, and the other features seen in excavations in the Monroe Township landfill are strongly suggestive of slumping of sediment masses with the most probable direction of slump movement being to the northwest.

Other sites near the Monroe Township landfill at which slumping may have been active are a stripped area along Cornell Avenue, 4000 ft to the northeast of the landfill; and the Hoffman Station Road pit, 3.6 mi to the south south west.

The stripped area adjacent to Cornell Avenue shows evidence of faulting through arcuate fracture patterns on horizontal surfaces; an anomalous stratigraphic sequence in which the Woodbury Clay rests directly on the Magothy Formation in some spots and on Merchantville sections only a few inches thick at others, and by apparent drag structures within sands of the Magothy Formation.

At the Hoffman Station Road pit, unusual features within the Englishtown Formation which may be related to slumping include possible drag-folding and rotation of bedding to dips as great as 70°.

Numerous features commonly associated with slumping were also observed in the vicinity of Crosswicks, Burlington County. In this area faulting was first suspected on the basis of anomalous stratigraphic sequences revealed in water well drilling. Omissions and repetitions of units were noted in well logs and in suites of samples submitted to the New Jersey Geological Survey by drillers. Monitoring during drilling by Survey geologists confirmed the anolmalous stratigraphy (Markewicz, pers. commun.).

Direct examination of faults was later possible at the Franklin clay pit, one half mile west of Crosswicks. At this pit the Woodbury Clay has been seen in surface exposures and borings. The pit is, however, west of the outcrop belt of the Merchantville Formation and at an elevation at which exposure of Raritan and Magothy units would be expected. The Woodbury Clay appears, therefore, to have moved downward from its normal position. Many of the features characteristic of slumped material, in particular upwardly concave shear surfaces, stratigraphic anomalies, rotation of bedding, drag folding, and brecciation, were seen (Markewicz, pers. commun.). As described by Rhodehamel and Hilton (unpub.):

> Sediments within the Franklin pit posess considerable complexity of structure ... [figure 4].
>
> At various places both the Englishtown and Navesink formations are in contact with the Woodbury along angular unconformities.
>
> Intra or post-Navesink slumpage, flowage, side slippage and possibly some minor amounts of shearing are believed to have caused general folding in the Englishtown-Navesink sediments. The Woodbury formation, though generally flat-lying, has, in places, been tightly folded and even overturned (see diagram showing south wall of pit). Dip angles in the Navesink and Englishtown formations are similar and quite variable, the average dips being about 21 and 35 degrees on the north and south walls respectively.
>
> Absence of Marshalltown, Wenonah and Mt. Laurel sediments in the section demonstrates that a considerable period of erosion, with possible non-deposition in the area has occurred.

If the features in the pit have a common origin with those seen in water well drilling, slumpage may well have been active at a number of sites near Crosswicks.

Elsewhere along the Woodbury outcrop belt, evidence of faulting was not conspicuous, and fracturing seen in the formation is probably most often jointing. Lineaments seen in aerial photographs, SLAR (Side Looking Airborne Radar) and

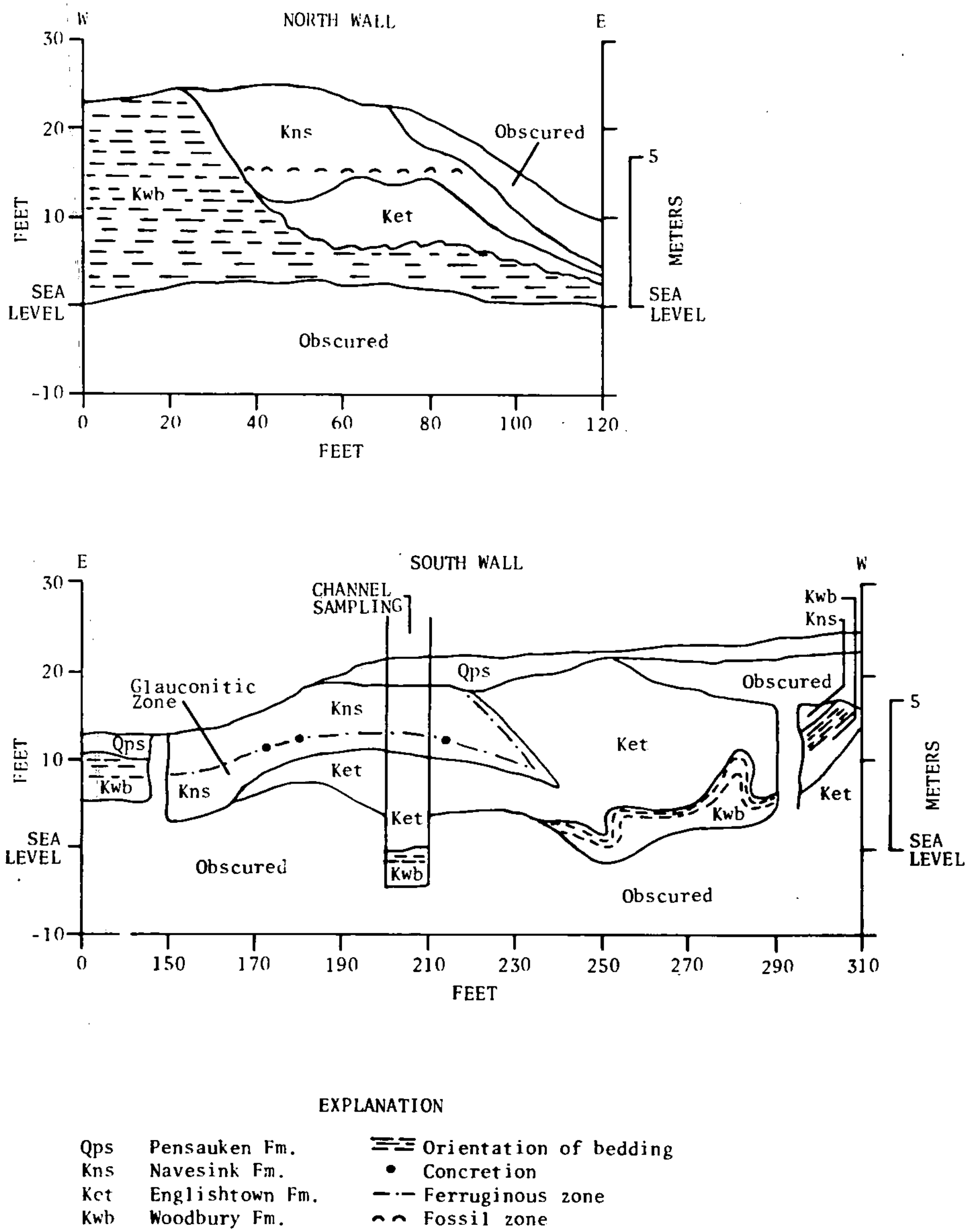


Figure 4. Cross sections showing features seen in the Franklin clay pit. (modified from Rhodehamel and Hilton, undated)

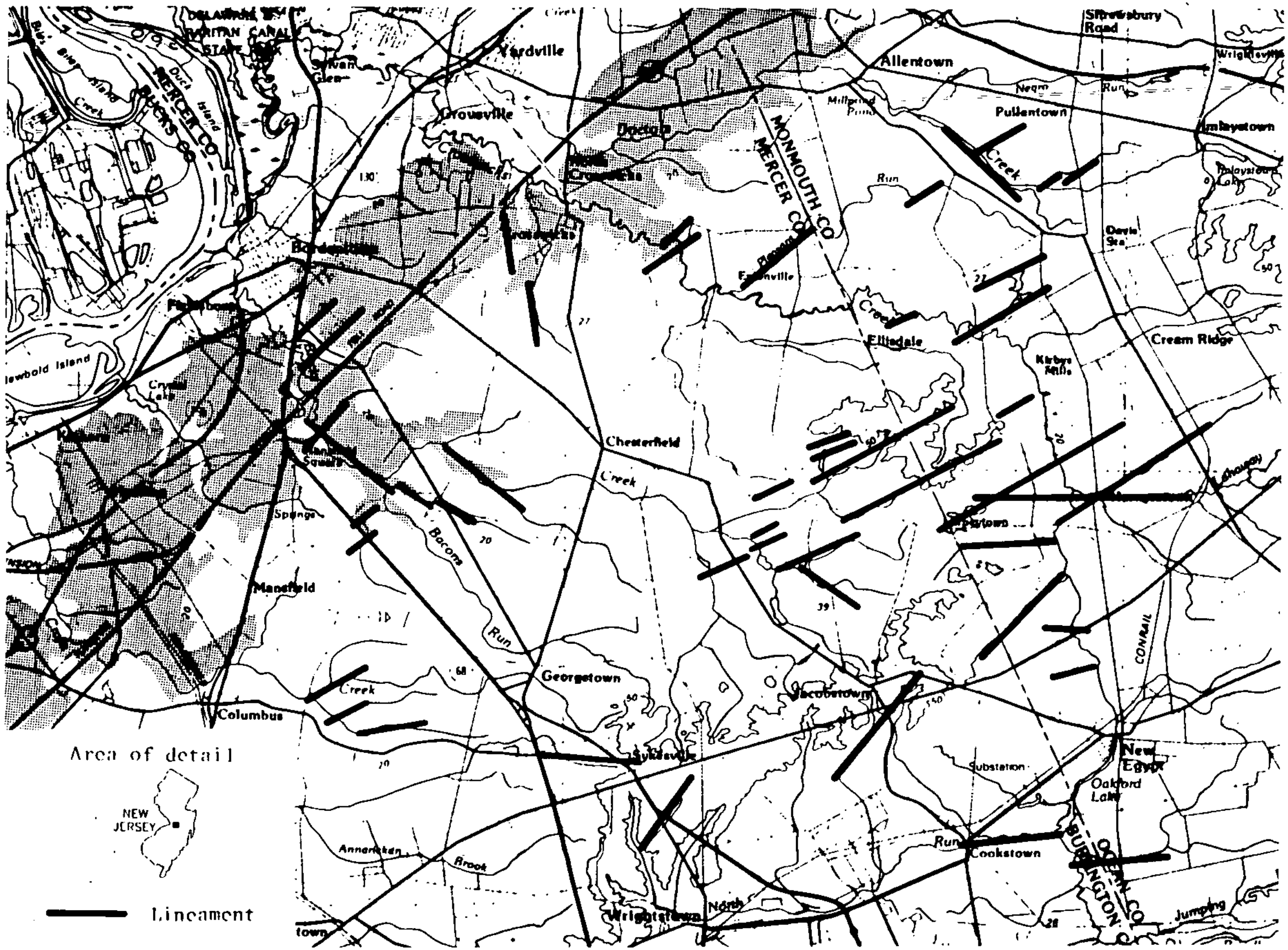


Figure 5. Lineaments on portions of the Trenton East, Allentown, Columbus and New Egypt quadrangles. Base map from Trenton, NJ, PA, NY Topographic Quadrangle, scale: 1 to 100,000, 1982. Shading shows Woodbury Clay outcrop belt.

satellite imagery and topographic maps show a consistent regional pattern throughout much of the Inner Coastal Plain which likely reflects regional, pervasive jointing. The lineaments are most clearly identifiable through a pronounced angular drainage network in which segments of headwater streams can often be matched across divides or trunk streams. The pattern can be seen in most areas directly underlain by clays and marls of the Inner Coastal Plain, but is difficult or impossible to identify where these are covered by surficial sands or gravels. This indicates that the lineaments are of geologic origin and reflect inhomogeneities within the pre-Miocene formations. At least three distinct lineament sets appear to be present (figure 5). The most prominent set trends northeast-southwest subparallel to the strike of the Coastal Plain formations. A second set trends northwest-southeast and a third trends east-west. Some of the lineaments in the set subparallel to the strike of the Coastal Plain formations may have formed by differential erosion along bedding units. The trend of the lineaments is not, however, exactly parallel to the trend of bedding in most areas. In the area shown in figure 5, for example, the trend of the lineaments differs from the strike of the bedding by about 10^{o}.

SUMMARY

Permeability values for the Woodbury-Merchantville confining layer are available from laboratory measurements, digital simulation modeling and pumping tests. Falling head tests were performed as part of this study. Permeability values range from 1.9×10^{-5} to 1×10^{-11} cm/sec and decrease with increasing depth of burial.

Within the Woodbury Clay, permeability appears to be primarily the result of fracturing. Fracturing appears to be of two types, jointing and faulting. Jointing is widespread within the Woodbury Clay, but intensity of jointing varies. In some areas, joints are open and mineralized and may provide pathways for water flow. Elsewhere jointing is scarcely visible and may contribute little to effective permeability. Faulting is limited, but appears to create the potential for high local permeability where it occurs.

The possibility also exists that sandy facies or gaps may penetrate the entire thickness of the Woodbury Clay and that significant local areas of high permeability of the confining layer may exist because of this.

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