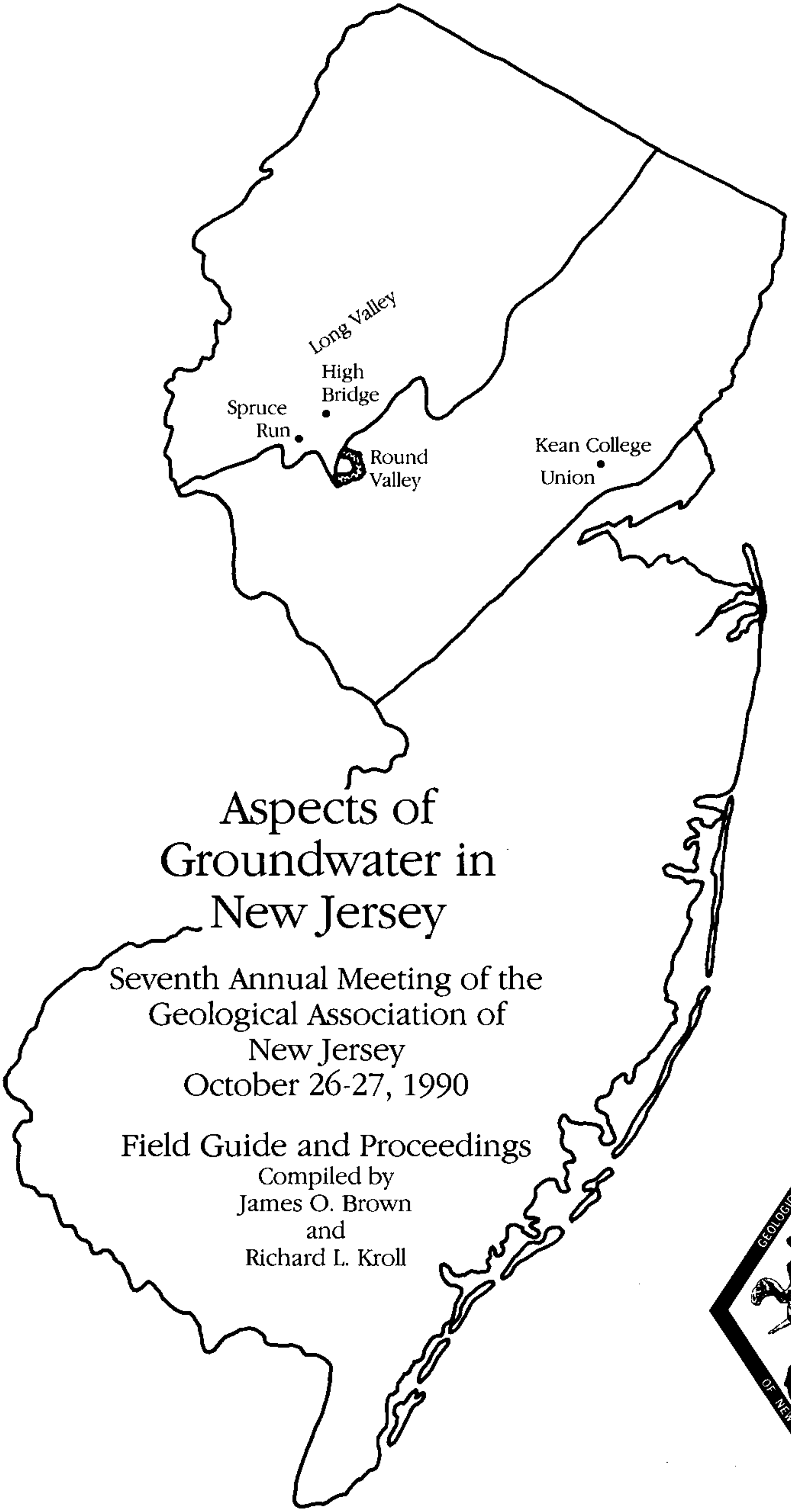


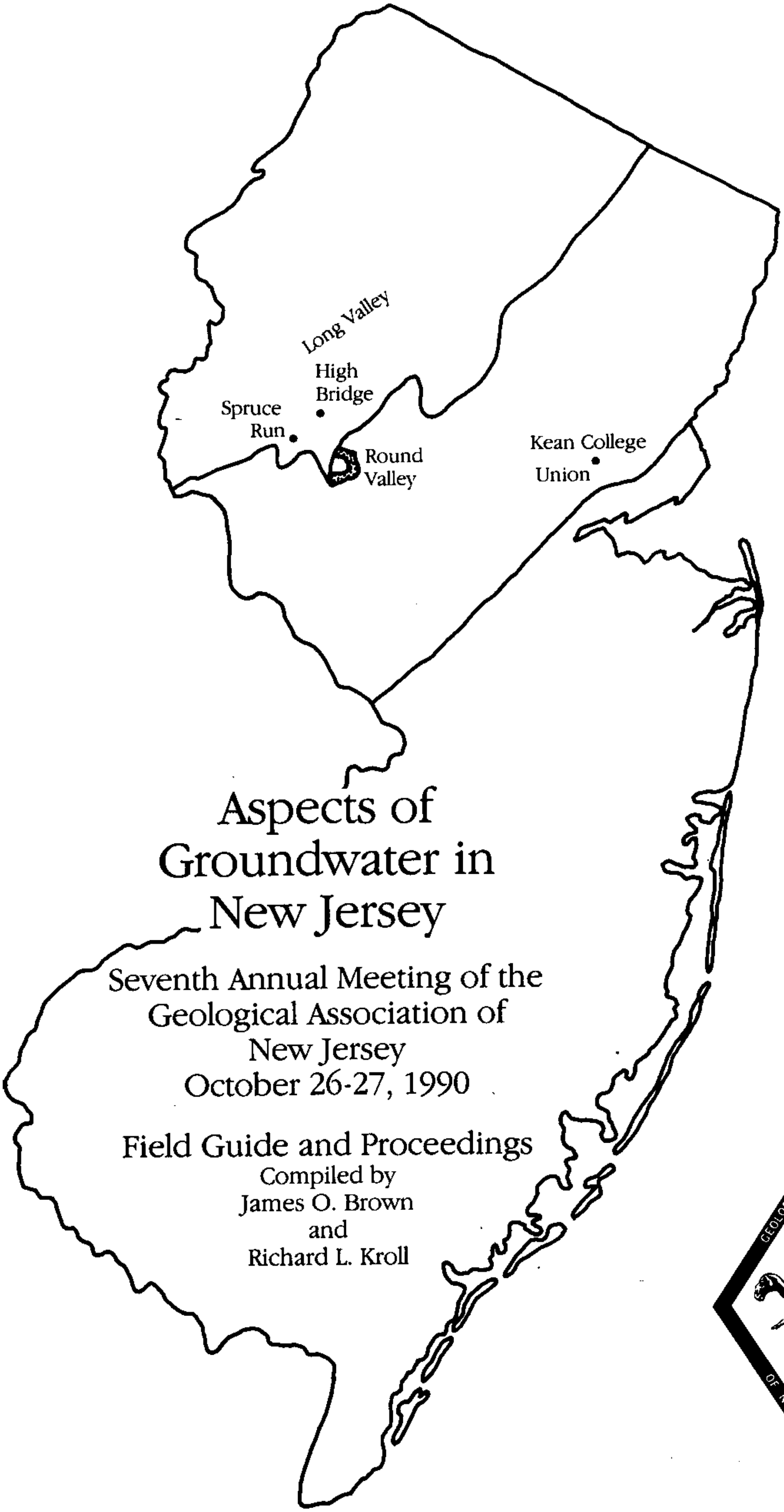
Aspects of Groundwater in New Jersey

Seventh Annual Meeting of the Geological Association of New Jersey
October 26-27, 1990

Field Guide and Proceedings

Compiled by
James O. Brown
and
Richard L. Kroll

GEOLOGICAL ASSOCIATION OF NEW JERSEY
FOUNDED 1984



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ASPECTS OF GROUNDWATER IN NEW JERSEY

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Kean College of New Jersey
Union, New Jersey 07083

ASPECTS OF GROUNDWATER IN NEW JERSEY

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FOREWORD

The Seventh Annual Meeting of the Geological Association of New Jersey (GANJ) is concerned with the topic of groundwater. After over one hundred years of severe abuse the problems related to a wide variety of pollutants, inadvertantly, or in some cases purposely, spread across the landscape, is being acutely recognized. Drinking water supplies are threatened, construction and siting of structures is subject to contamination evaluation, and clean up problems are myriad.

Knowledge of the amounts and quality of groundwater that are available is the realm of the - groundwater geologist - hydrogeologist - geohydrologist - groundwater consultant - (pick one to suit) - but if it's in the ground, then geology is involved.

This conference brings together a wide range of groups interested in some aspect of the groundwater phenomenon - researchers, well drillers, teachers, environmentalists, consultants and others to review, and view, several aspects of groundwater. In addition to groundwater, the field trip will visit sites that involve substantial surface water supplies, namely the Round Valley and Spruce Run Resevoir systems.

The Geological Association of New Jersey thanks all who participated in and contributed to this conference.

Dr. Richard L. Kroll, President
GANJ

Geological History of New Jersey's Coastal Plain Aquifers

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Stockton State College
Pomona, New Jersey 08240

Abstract

The geologic events that marked the history of New Jersey since the Triassic resulted in the development of the aquifers of the New Jersey coastal plain. The disintegration of *Pangaea*, the development of the Baltimore Canyon trough, and the formation of the New Jersey coastal plain, the continental shelf, and continental slope resulted in a series of sedimentary deposits that contain the aquifers under study. A sequence of aquifer types developed that reflected the sea level history of the coastal plain. The coastal plain subsided from late Cretaceous through Eocene time. An aquifer system first developed. It was replaced by individual aquifers, then restricted aquifers, then no aquifers. The coastal plain emerged after the Eocene resulting in an inversion of the sequence previously developed.

Introduction

The New Jersey coastal plain was formed by a series of geological events that left as a legacy the aquifers of the New Jersey coastal plain. This paper is an attempt to put the origin of these aquifers into an historical context in order to demonstrate the relationship between groundwater hydrogeology and its parent discipline-geology.

The first major geologic event involved in the development of the aquifers of the New Jersey coastal plain was the disintegration of *Pangaea*, which led to the development of the Baltimore Canyon trough and the Atlantic Ocean. The Baltimore Canyon trough filled and was subsequently buried by deposits that make up the New Jersey coastal plain. These deposits are cyclic reflecting changes in sea level. The coastal plain subsided from early Cretaceous through Eocene time, then emerged after Eocene time. The deepening and shallowing of the coastal plain altered the texture of its cyclic deposits, thereby altering the volume of coarse textured sediment deposited within each cycle. The volume of coarse textured sediment, in turn, determined the magnitude of the aquifer produced.

Early History : The Baltimore Canyon Trough

The world continent *Pangaea* began to disintegrate in late Triassic to early Jurassic time, giving rise to *Laurasia* and *Gondwana*. Regionally, what are now the middle

Atlantic states separated from northwest Africa. Locally, this event is marked by the development of the Newark Basin in what is now northern New Jersey (Manspeizer, W., 1988), and the development of the Baltimore Canyon trough currently buried beneath continental shelf deposits east of the southern New Jersey coastal plain (Grow, J.A., 1980; Poag, C.W., 1979) (figure 1).

As *Laurasia* separated from *Gondwana* and then split into the continents of today, the geography of the area currently occupied by the New Jersey coastal plain changed dramatically. The earlier stages of these changes are described in detail by W. Manspeizer (1988). Overall geographic changes are depicted in published paleocontinental maps (Smith, A.G. & J.C. Briden, 1977) (figure 2).

New Jersey was situated in the interior of *Pangaea* and drifted from near equatorial to subtropical latitudes during Triassic through early Jurassic time (Manspeizer, W., 1988) (figure 2). (This is quite different from its current temperate maritime position.) Basement rocks subsided during this interval, resulting in the development of the Baltimore Canyon trough (Bayer, K.C. & R.E. Mattick, 1980) (figures 1 & 3), a narrow, shallow basin northeast of *Laurasia* and southwest of *Gondwana*. The Baltimore Canyon trough became a permanent part of the *Tethys Seaway* by, at least, the onset of the Cretaceous as the result of the separation of the African/Arabian plates from the Eurasia plate and the separation of the North American plate from the South American plate. [Tethyan sea water had invaded the trough area for brief periods of time previously (Manspeizer, W. *& others*, 1978).] Subsequently, the trough connected to the South Atlantic Ocean, as the African and South American plates separated, and later became part of the North Atlantic Ocean by early Cretaceous time (figure 2).

The early history of the Baltimore Canyon trough is recorded in the deposits buried beneath the current continental shelf and slope of the Atlantic Coastal Plain. The Baltimore Canyon trough developed along a boundary where subsiding continental crust from the North American plate met subsiding oceanic crust from the newly created Atlantic Ocean (Grow, J.A., 1980) (figure 3). This trough began as a site of swamp, river and lake deposition during late Triassic time. Next, the trough became a site of restricted, shallow marine deposition in the lower Jurassic (Mattick, R.E. & K.C.Bayer, 1980). But throughout most of the Jurassic, the Baltimore Canyon trough consisted of a sequence of environments that included alluvial plains on its western margins to coastal regions in the east, where carbonates and evaporites accumulated. This culminated in the development of reefs along the eastern margin by late Jurassic time.

Establishment of the New Jersey Coastal Plain

The Baltimore Canyon trough filled with sediments by the early Cretaceous (figure 3). From then on, sediments passed further offshore, resulting in the formation and development of the New Jersey coastal plain, the continental shelf and the continental slope .

The New Jersey coastal plain was the result of continental deposition from the North American plate and marine deposition from the Atlantic Ocean. Owens *and others* (1988) describe a sequence of environments that served as bridges between the North American continent and the Atlantic Ocean. These environments include either a delta/shelf sequence, consisting of an upper delta plain followed by a lower delta plain, delta front, prodelta, inner shelf and outer shelf, or a barrier island/shelf sequence, consisting of a lagoon and barrier island complex followed by an inner and outer shelf.

The shelf segments of these sequences consist of more homogeneous, spatially extensive deposits. For example, coarse textured, inner shelf deposits are homogeneous along strike but gradually give way to fine textured, outer shelf deposits downdip. Nearshore segments, however, consist of more heterogeneous, spatially restricted facies. The textural and spatial properties of these deposits, in turn, effect the nature of the aquifers and confining beds within them. This idea will be developed further on.

An environment's location on the New Jersey coastal plain at a particular time was a function of the location of the shoreline. However, the shoreline's location changed in a cyclic manner. Sea levels rose and the shoreline migrated to the west, flooding the coastal plain. Subsequently, the shoreline receeded to the east as sediments filled the flooded area.

The history of the New Jersey coastal plain can be divided into three general phases based on the location of the shoreline and the resultant dominant environment. The location of the shore line during the early phase of the coastal plain's development was similar to its location today (Owens, J.P. & N.F. Sohl, 1968; Olsson, R.K., 1980). The coastal plain was covered by rivers and nearshore environments. This was followed by a long period of submergence, when continental shelf environments covered the coastal plain. The coastal plain once again emerged during the final phase.

The development of aquifers and confining units during each phase is also a reflection of the dominant environments present. *Aquifer systems* (i.e., a series of several hydraulically connected aquifers separated by discontinuous confining units) formed during the first and last phases while individual aquifers and confining units developed during the middle phase.

Phase I : The Establishment of the New Jersey Coastal Plain and the Development of the Potomac-Raritan-Magothy Aquifer System

The Potomac-Raritan-Magothy Aquifer System (referred to as the PRM) is composed of three stratigraphic units. These are the Potomac Group, the Raritan Formation and the Magothy Formation. In addition, the Raritan and Magothy Formations have subdivided into several members that persist through much of the coastal plain (Zapecza, O.S., 1989) (figure 4).

Initially, floodplains and, perhaps deltas, covered the westernmost edges of the Baltimore Canyon trough in early Cretaceous time. This resulted in the deposition of the Potomac Group, which occupied the southern part of the New Jersey coastal plain.

A major transgression flooded this region from the final stages of the early Cretaceous through the earliest stages of the late Cretaceous (i.e., Albian through Turonian). The Potomac Group gave way to the Raritan Formation, which covered all of what is now the New Jersey coastal plain with sediments deposited primarily in rivers, deltas and nearshore environments (Owens, J.P. & N.F. Sohl, 1969). The maximum extent of this trangression was reached in the Turonian with the deposition of sediments laid down in the brackish to saltwater environments of the Woodbridge Clay Member of the Raritan Formation (Petters, S.W., 1976; Olsson, R.K., 1980). Next, a regression lowered sea levels, removing some of the previously deposited sediments of the Raritan Formation during Coniacian time. A second transgression followed during Santonian and early Campanian time, resulting in the deposition of the nearshore shore Magothy and offshore Merchantville Formations.

The lower aquifer of the PRM is composed of the coarse textured horizons of the Potomac Group and lower Raritan Formation, confined between basement bedrock and fine textured horizons within these stratigraphic units. This aquifer, restricted to the southern coastal plain, was the result of the initial spread of continental deposits. These were the first sediments deposited on the New Jersey coastal plain.

The middle aquifer is equivalent to the Farrington Member of the Raritan Formation and is overlain and confined primarily by the Woodbridge Clay Member of the Raritan Formation (Zapecza, O.S., 1989). The Woodbridge Clay is a shallow marine salient of its downdip equivalent -the Bass River Formation (Petters, S.W., 1976). The middle aquifer and its overlying confining bed are the result of the marine transgression that covered the New Jersey coastal plain during the interval from Albian to Turonian time.

The upper aquifer is equivalent to the Old Bridge Sand Member of the Magothy Formation and is, for the most part, overlain by the Merchantville-Woodbury confining bed (Zapecza, O.S., 1989). The upper aquifer and its overlying confining bed represent the results of the second transgression that took place.

The three aquifers of the PRM Aquifer System are hydraulically connected to one another (Luzier, J.E., 1980; Gill, H.E. & G.M. Farlekas, 1976). The confining beds between them are discontinuous so that aquifers respond uniformly to pumping. This is the basis for referring to them as an *aquifer system* rather than as three separate aquifers. The lack of confining unit continuity may be accounted for by their depositional environment. The deposition of fine textured sediments nearshore, which make up confining units, occurs in tidal embayments, wetlands and in floodplain backswamps. These environments are restricted spatially, cut by coarse textured channel deposits, or surrounded by coarse textured nearshore deposits. Their position at or above sea level also makes them vulnerable to subseqeunt erosion. The movements of groundwater from one aquifer to another through these confining units is easy to comprehend. However, the confining units which form offshore on continental shelves are more extensive, homogeneous and, therefore, more confining. Consequently, the continental and nearshore environments of the Potomac, Raritan and Magothy strata gave rise to a combined *aquifer system* simply because they were deposited in environments where confining units were likely to be discontinuous. (This situation did not arise again until the last phase of the development of the New Jersey coastal plain during Miocene time.)

Phase II : Cyclic Sedimentation and the New Jersey Coastal Plain

A series of regional and local aquifers overlie the PRM Aquifer System (Zapecza, O.S., 1989) (Table 1 and figure 4)). These aquifers, and their intervening confining beds, are artifacts of a series of sea level fluctuations that took place during the second phase of coastal plain development during late Cretaceous to Eocene time.

Cyclic sedimentation has been reported and described in the stratigraphic units of the New Jersey coastal plain (Dorf, E. & S.K. Fox, 1957; Owens, J.P. & N.F. Sohl, 1969; Olsson, R.K., 1980; Fox, S.K., 1981; Owens, J.P. *& others*, 1988). Each cycle represents an initial rapid rise in sea level followed by a gradual decline in sea level. Furthermore, each cycle consists of a disconformable, transgressive unit, often of glauconite sand, that is conformably overlain by a regressive, or at least aggrading, silty or clayey unit that grades upward into an upper quartz sandy unit (Owens, J. P. & N.F. Sohl, 1969; Owens, J.P. *& others*, 1988). This is described as a "coarsening upward" cycle.

The shoreline represents the elevation of the ocean surface and, as mentioned previously, migrated back and forth across the New Jersey coastal plain. But the sediments laid down on the continental shelf are deposited on the sea bottom and the elevation of the sea bottom subsided during the second phase of coastal plain development. This is suggested by the deepening of facies through time reported by C.W. Poag (1980) and by R.K. Olsson (1980). Consequently, the depositional environment at a particular point on the coastal plain became generally deeper from one cycle to the next. Furthermore, continental and nearshore coarse textured sediments were deposited further west, following the shorelines, also as the coastal plain deepened. Many of these coarse textured sediments were lost during subsequent episodes of erosion by virtue of their western, marginal location near the highest elevations of the coastal plain. In other words, as the New Jersey coastal plain deepened, the magnitude of the aquifers formed decreased.

The Englishtown and Wenonah-Mount Laurel Aquifers were deposited early in the second phase of coastal plain development during the Late Cretaceous. The Englishtown is made up of river and nearshore deposits while the overlying Wenonah-Mount Laurel Aquifer is primarily composed of nearshore deposits (Owens, J.P. & N.F. Sohl, 1968). The next overlying aquifers, the Redbank and Vincentown Aquifers, are made up entirely of nearshore deposits (Owens, J.P. & N.F. Sohl, 1968). However, they are restricted to the northern part of the coastal plain and are only local sources of water supply. Coarsening upward cycles persist through the remainder of the second phase of coastal plain development but lack sufficient coarse textured units required to produce aquifers. Thus, the overlying Manasquan and Shark River Formations, considered middle to outer shelf deposits (Owens *and others*, 1988), are too fine textured to be considered aquifers. Thus aquifers dwindle in significance as result of the deepening of the New Jersey coastal plain from late Cretaceous to late Eocene time.

Phase III : The Emergence of the New Jersey Coastal Plain

Sediments laid down on the New Jersey coastal plain after Eocene time continue to show a cyclic nature but also indicate progressively shallower depositional environments (Poag, C.W., 1980; Olsson, R.K., 1980). One consequence of this is the development of more significant aquifers with the passage of time. This is the inverse of the situation in previous phase.

Recently, a nearly complete section of early Eocene through Oligocene sediments were discovered beneath Miocene and younger deposits at Mays Landing, New Jersey. This was the first such section discovered on the U.S. Atlantic coastal plain (Owens & *others*, 1988). The oldest units, the Manasquan and Shark River Formations, as mentioned previously, show cyclic sediments but are considered middle to outer shelf deposits, containing little coarse material. The next three units, given informal names by Owens & *others*, are, from the oldest to youngest, the ACGS Alpha Unit (late Eocene-early Oligocene), the Mays Landing Unit (early Oligocene), and the ACGS Beta Unit (late Oligocene). Each unit is made up of cyclic, coarsening upward deposits and shows progressively shallower environments from cycle to cycle. The ACGS Alpha Unit represents a change from middle to inner shelf, while the Mays Landing Unit represents a change from inner shelf to prodelta. Next, the ACGS Beta Unit represents nearshore environments.

The ACGS Beta Unit is also referred to as the Piney Point Formation (Zapecza, O.S., 1989; Olsson, R. K. & *others*, 1980). It makes up the Piney Point Aquifer, the first major Tertiary aquifer in the New Jersey coastal plain.

The Kirkwood Formation (early to middle Miocene), unconformably overlying the ACGS Beta Unit, is made up of three coarsening upward sequences considered to be deltaic (Owens & *others*, 1988) or nearshore deposits (Isphording, W.C., 1970). Four water bearing zones are associated with the Kirkwood Formation (figure 5). These are, from oldest to youngest, the lower Atlantic City 800 Foot Sand, the upper Atlantic City 800 Foot Sand (Mullikin, L.G. & *others*, 1989), the Rio Grande Water Bearing Zone, and the Kirkwood-Cohansey Aquifer System (Zapecza, O.S., 1988). The Atlantic City 800 Foot Sand Aquifer and the Rio Grande water-bearing zone, are individual aquifers. They represent shallow continental shelf, nearshore deposits. These segments probably merge updip with the Kirkwood-Cohansey Aquifer System inland (Mullikin, L.G., & *others*, 1989)

The Cohansey Formation (middle Miocene) conformably overlies the Kirkwood Formation. It consists of at least two regressive cycles representing environments associated with barrier islands overlain by tidal channels and flats (Carter, C.H., 1978). The Cohansey Formation is unconformably overlain by the Bridgeton Formation (late Miocene?) which is composed of river sand and gravel deposits (Owens, J.P. & J.P. Minard, 1979). These stratigraphic units make up the Kirkwood-Cohansey Aquifer System, which consists of several water-bearing zones separated by leaky confining units (Epstein, C.M., 1989; Gill, H.E., 1962). This aquifer system is the youngest aquifer of the New Jersey coastal plain, except on the Cape May peninsula.

The last phase in the development of the New Jersey coastal plain was a reversal of the first and second phases. A sequence of aquifers developed through time from aquifer systems (i.e., the PRM), to individual aquifers (i.e., Englishtown and Wenonah-Mount Laurel), to spatially restricted aquifers (i.e., the Red Bank and Vincentown) to no aquifers as the coastal plain deepened in the first two phases. In the last phase, the sequence of aquifer types was inverted, changing from individual aquifers (i.e., the

Piney Point, Atlantic City 800 Foot Sand, and Rio Grande) to aquifer systems once again (i.e, the Kirkwood-Cohansey) as the coastal plain emerged.

Conclusions

The development of the aquifers of the New Jersey coastal plain was controlled by the deposition of the sediments in which they were contained. The development of the sediments of the New Jersey coastal plain was controlled by the geological events that stimulated their deposition.

First, the disintegration of *Pangaea* resulted in the development of the Baltimore Canyon trough, which filled to overflowing by early Cretaceous time. The subsequent disintegration of *Laurasia* and *Gondwana* resulted in the development of the North Atlantic Ocean. The continental margin of that ocean filled with sediments creating the coastal plain, the continental shelf, and continental slope from late Cretaceous time on. Sea level fluctuations coupled with subsidence of the coastal plain, continental shelf and continental slope resulted in cyclic sedimentation. Nearshore and continental deposits of these cycles contained the coarse textured units that make up the aquifers of the New Jersey coastal plain.

The coastal plain at first subsided through Eocene time and then began to emerge. The subsidence of the coastal plain resulted in a sequence of aquifer types starting with an aquifer system, followed by individual aquifers, then by spatially restricted aquifers. This sequence reversed as the coastal plain emerged. One consequence of this is that the most significant aquifers of the New Jersey coastal plain, the Potomac-Raritan-Magothy Aquifer System and the Kirkwood-Cohansey Aquifer System, developed during periods of nearshore and continental deposition when the coastal plain was emergent. The significance of the aquifers of the New Jersey coastal plain decreased as the coastal plain became submerged.

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Figure 1. Location map of the Baltimore Canyon Trough (taken from C.W. Poag, 1979).

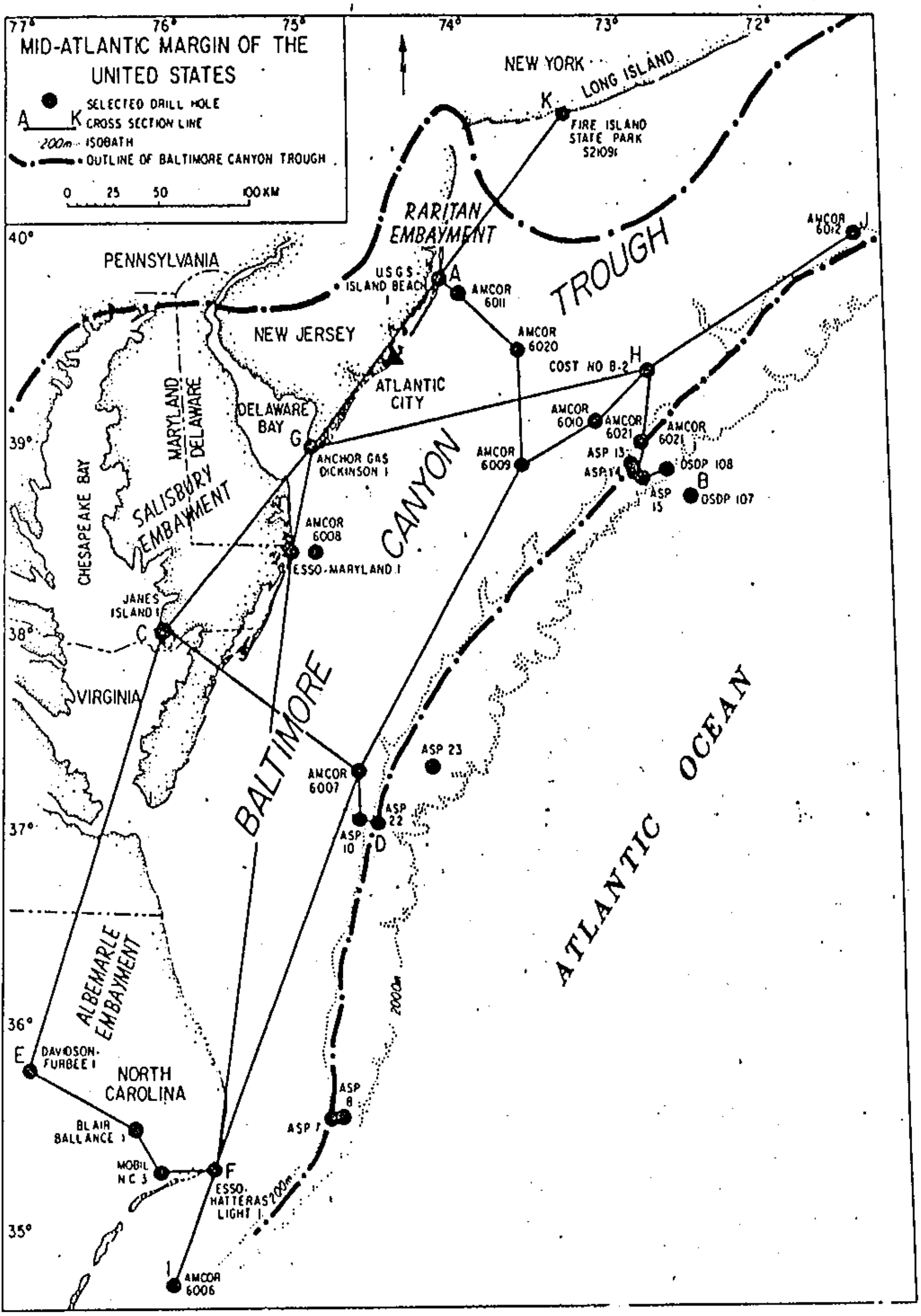
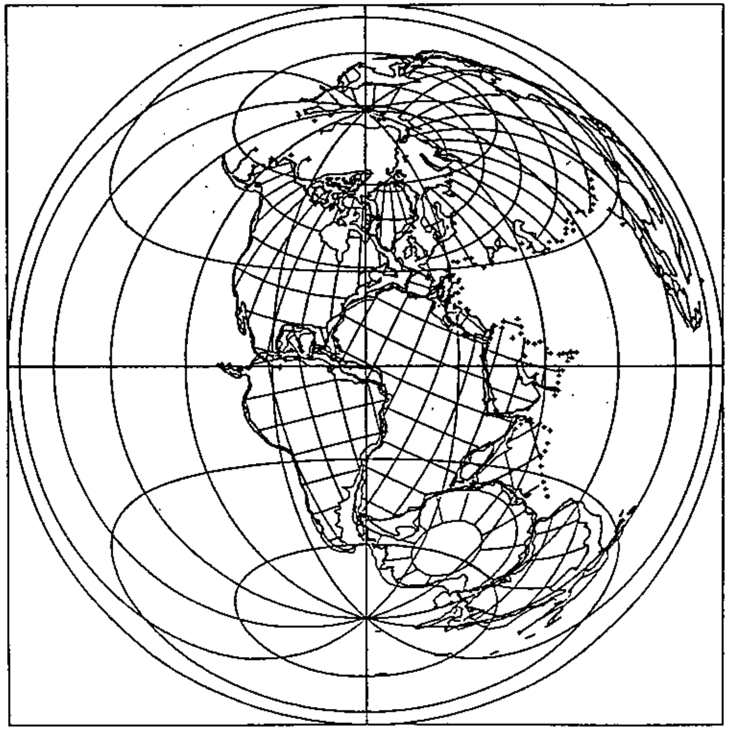


Figure 2. Lambert equal-area projection maps of the continents during the early Jurassic, the late Jurassic, the early Cretaceous, and the late Cretaceous (taken from Smith, A.G. & J.C. Briden, 1977).

Map 50
180 million years
Pliensbachian (early Jurassic)

Lambert equal-area
$N = 32$ Alpha-95 = 7·5



Map 48
140 million years
'Tithonian' (late Jurassic)

Lambert equal-area
$N = 33$ Alpha-95 = 5·4

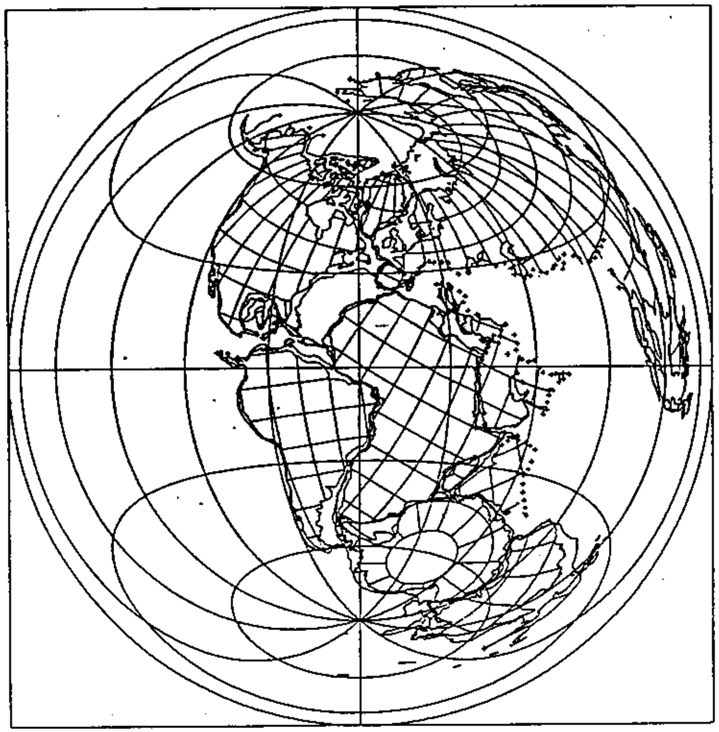
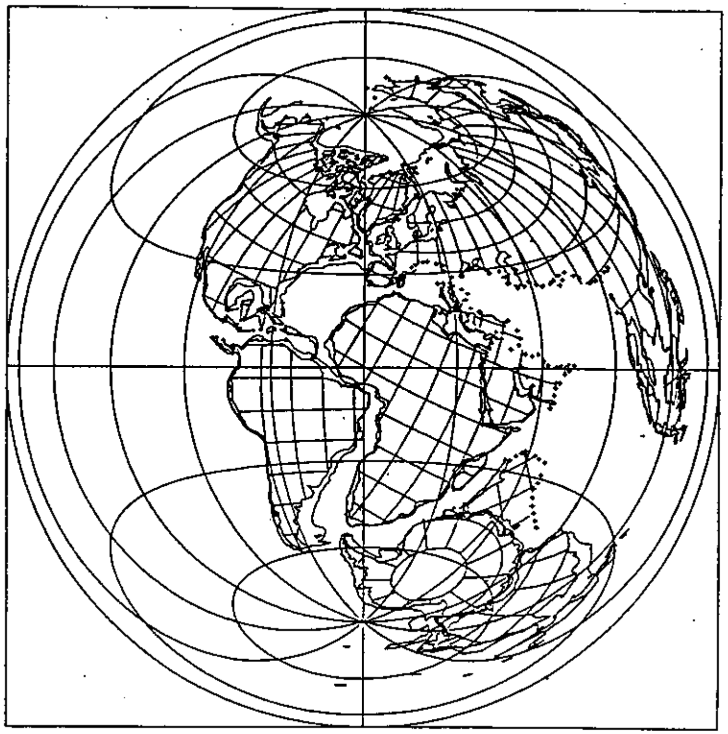


Figure 2. Lambert equal-area projection maps of the continents during the early Jurassic, the late Jurassic, the early Cretaceous, and the late Cretaceous (taken from Smith, A.G. & J.C. Briden, 1977).

Map 47
120 million years
Hauterivian (early Cretaceous)

Lambert equal-area
$N = 27$ Alpha-95 = 6·2



Map 45
80 million years
Santonian (late Cretaceous)

Lambert equal-area
$N = 25$ Alpha-95 = 6·0

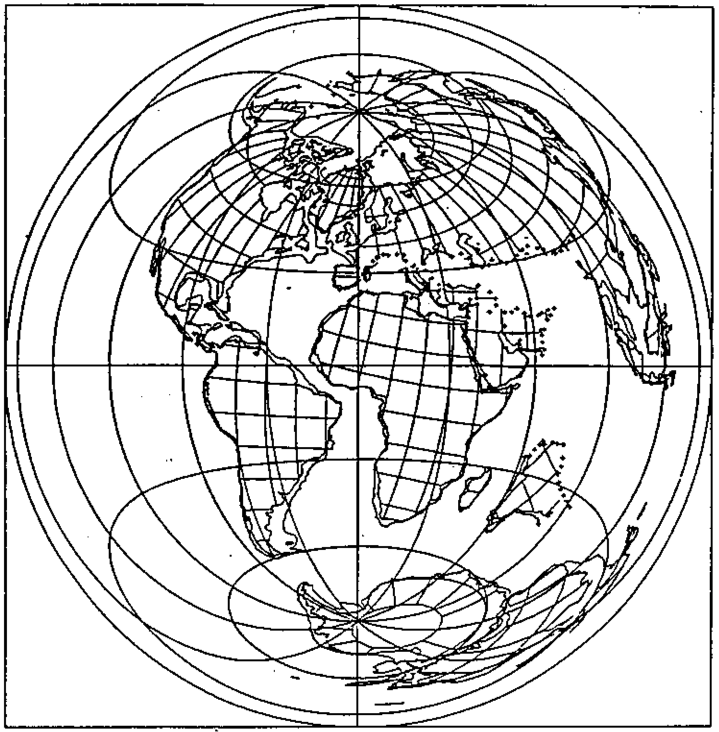


Figure 3. Geologic cross section of the Baltimore Canyon Trough from near Atlantic City, New Jersey southeastward toward the COST No. B-3 well to beyond the edge of the continental shelf (taken from Grow, J.A., 1980).

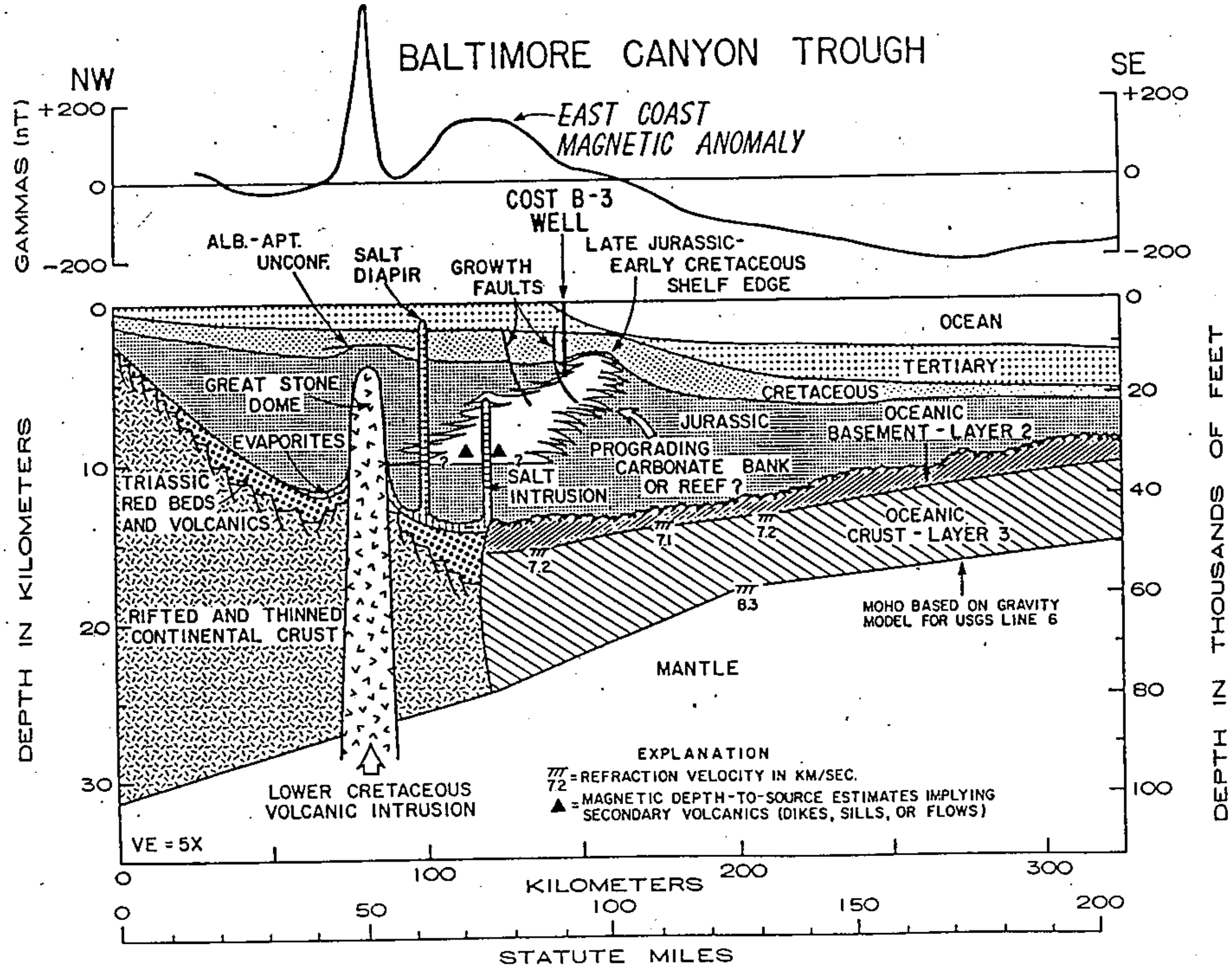


Figure 4. Stratigraphic correlations of Cretaceous formations of the New Jersey coastal plain (upper diagram taken from Mattick, R.E. & K.C. Bayer, 1980 as adapted from Perry & others, 1975; lower diagram taken from S.W. Petters, 1976).

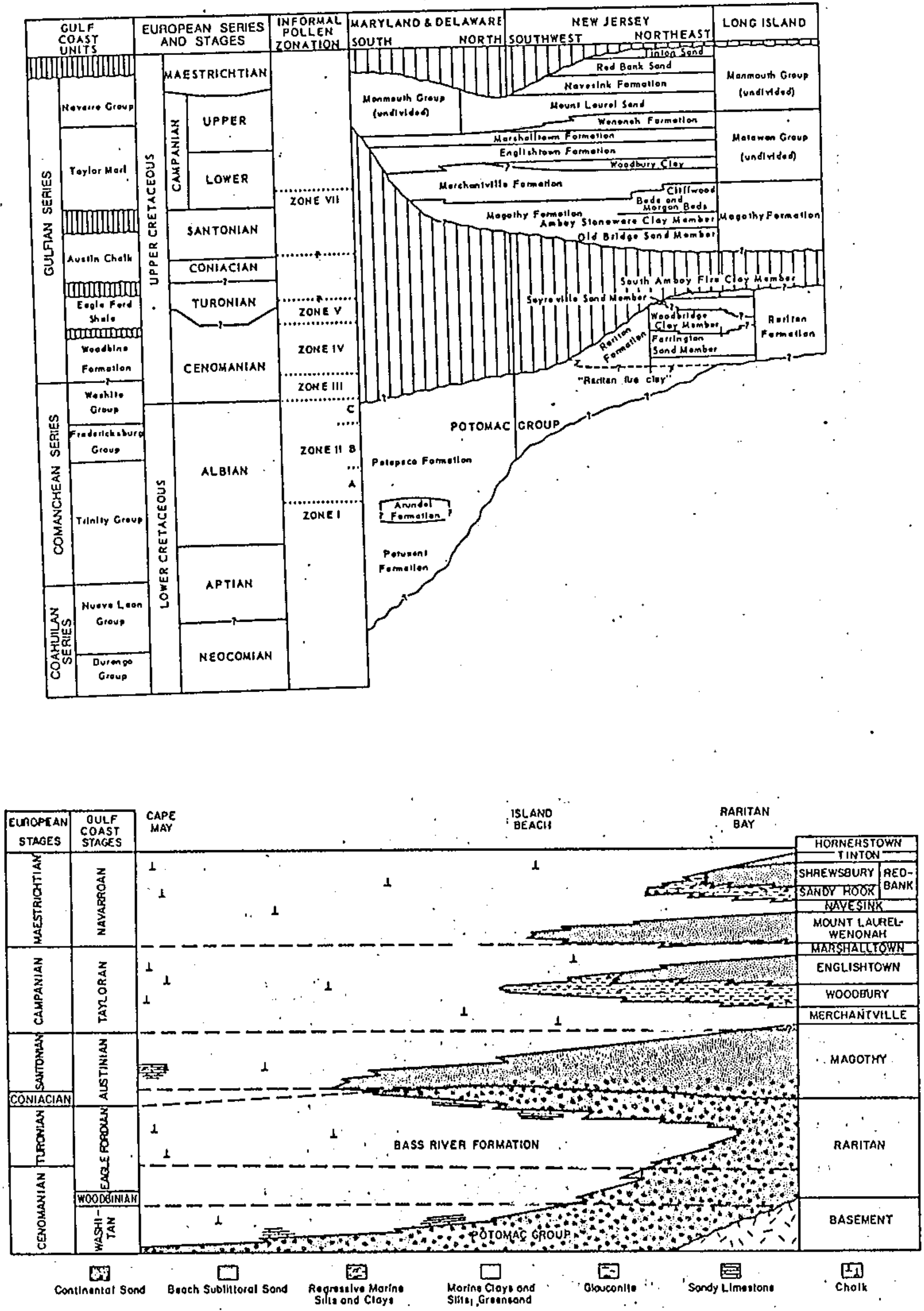


Figure 5. Geologic cross section of the formations of the New Jersey coastal plain from Camden to Atlantic City (taken from Clark, J.S. & G.N. Paulachok, 1989, NJ Geol.Surv. Open-File Report 88-3).

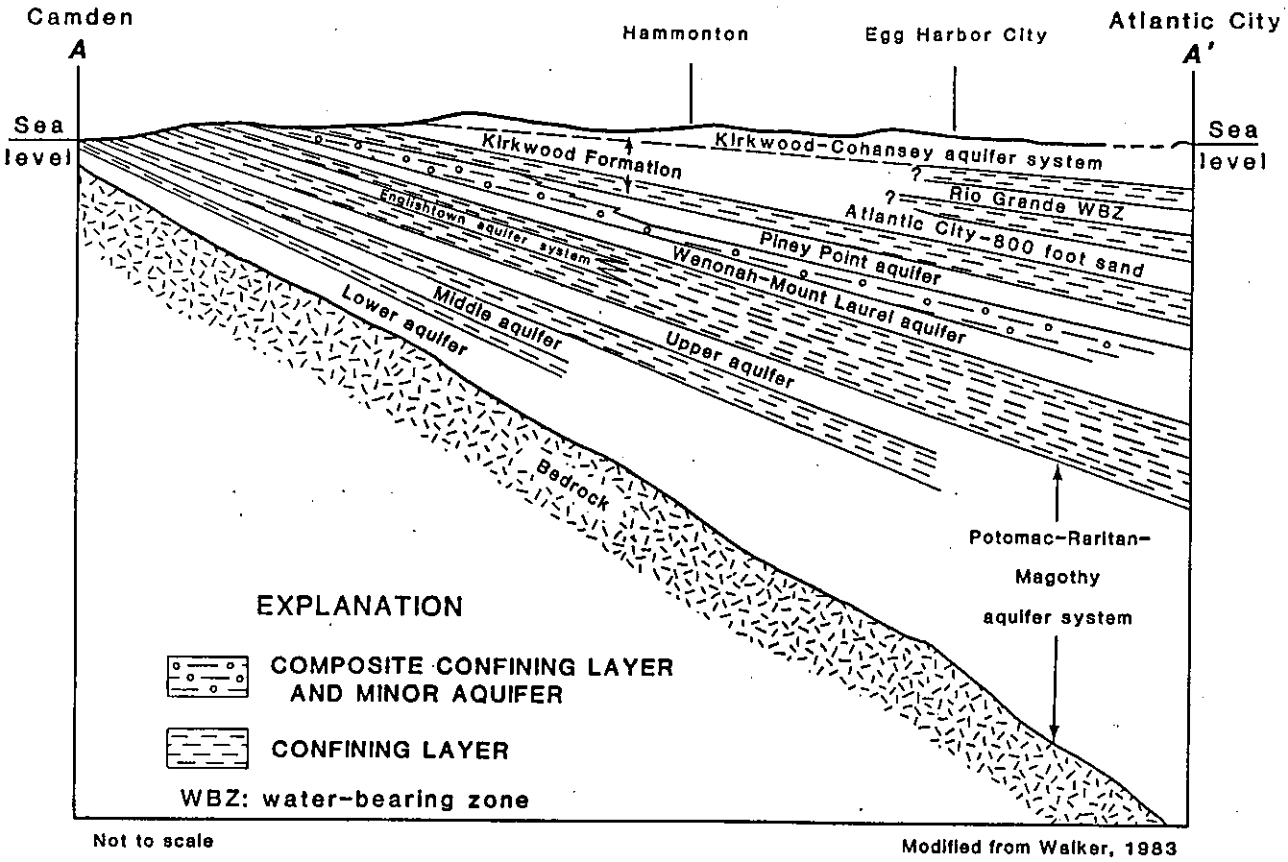


Table 1. Geologic and hydrogeologic units of the New Jersey coastal plain (taken from Zapecza, O.S., 1989).

SYSTEM	SERIES	GEOLOGIC UNIT	LITHOLOGY	HYDROGEOLOGIC UNIT		HYDROLOGIC CHARACTERISTICS
Quaternary	Holocene	Alluvial deposits	Sand, silt, and black mud.	Undifferentiated		Surficial material, commonly hydraulically connected to underlying aquifers. Locally some units may act as confining units. Thicker sands are capable of yielding large quantities of water.
		Beach sand and gravel	Sand, quartz, light-colored, medium-to coarse-grained, pebbly.			
	Pleistocene	Cape May Formation	Sand, quartz, light-colored, heterogeneous clayey, pebbly.			
Tertiary	Miocene	Pensauken Formation				
		Bridgeton Formation		Kirkwood-Cohansey aquifer system		A major aquifer system. Ground water occurs generally under water-table conditions. In Cape May County the Cohansey Sand is under artesian conditions.
		Beacon Hill Gravel	Gravel, quartz, light colored, sandy.			
		Cohansey Sand	Sand, quartz, light-colored, medium to coarse-grained, pebbly; local clay beds.			
		Kirkwood Formation	Sand, quartz, gray and tan, very fine-to, medium-grained, micaceous, and dark-colored diatomaceous clay.	Confining unit		Thick diatomaceous clay bed occurs along coast and for a short distance inland. A thin water-bearing sand is present in the middle of this unit.
				Rio Grande water bearing zone		
				Confining unit		
				Atlantic City 800-foot sand		A major aquifer along the coast.
				Composite confining unit		Poorly permeable sediments.
	Oligocene	Piney Point Formation	Sand, quartz and glauconite, fine-to coarse-grained.		Piney Point aquifer	Yields moderate quantities of water.
	Eocene	Shark River Formation				
		Manasquan Formation	Clay, silty and sandy, glauconitic, green, gray and brown, fine-grained quartz sand.			Poorly permeable sediments.
	Paleocene	Vincentown Formation	Sand, quartz, gray and green, fine-to coarse-grained, glauconitic, and brown clayey, very fossiliferous, glauconite and quartz calcarenite.		Vincentown aquifer	Yields small to moderate quantities of water in and near its outcrop area.
		Hornerstown Sand	Sand, clayey, glauconitic, dark green, fine to coarse-grained.			Poorly permeable sediments.
Cretaceous	Upper Cretaceous	Tinton Sand	Sand, quartz, and glauconite, brown and gray, fine-to coarse-grained, clayey, micaceous.			
		Red Bank Sand			Red Bank sand	Yields small quantities of water in and near its outcrop area.
		Navesink Formation	Sand, clayey, silty, glauconitic, green and black, medium-to coarse-grained.			Poorly permeable sediments.
		Mount Laurel Sand	Sand, quartz, brown and gray, fine-to coarse-grained, slightly glauconitic.	Wenonah-Mount Laurel aquifer		A major aquifer.
		Wenonah Formation	Sand, very fine-to fine-grained, gray and brown, silty, slightly glauconitic.	Marshalltown-Wenonah confining unit		A leaky confining unit.
		Marshalltown Formation	Clay, silty, dark greenish gray, glauconitic quartz sand.			
		Englishtown Formation	Sand, quartz, tan and gray, fine-to medium-grained; local clay beds.	Englishtown aquifer system		A major aquifer. Two sand units in Monmouth and Ocean Counties.
		Woodbury Clay	Clay, gray and black, micaceous silt.	Merchantville-Woodbury confining unit		A major confining unit. Locally the Merchantville Formation may contain a thin water-bearing sand.
		Merchantville Formation	Clay, glauconitic, micaceous, gray and black; locally very fine-grained quartz and glauconitic sand.			
		Magothy Formation	Sand, quartz, light-gray, fine-to coarse-grained. Local beds of dark-gray lignitic clay.	Potomac-Raritan-Magothy aquifer system	Upper aquifer	A major aquifer system. In the northern Coastal Plain, the upper aquifer is equivalent to the Old Bridge aquifer and the middle aquifer is equivalent to the Farrington aquifer. In the Delaware River Valley three aquifers are recognized. In the deeper subsurface, units below the upper aquifer are undifferentiated.
		Raritan Formation	Sand, quartz, light-gray, fine-to coarse-grained, pebbly, arkosic, red, white, and variegated clay.		Confining unit	
					Middle aquifer	
	Lower Cretaceous	Potomac Group	Alternating clay, silt, sand, and gravel.		Confining unit	
					Lower aquifer	
Pre-Cretaceous		Bedrock	Precambrian and lower Paleozic crystalline rocks, metamorphic schist and gneiss; locally Triassic sandstone, shale and Jurassic basalt.	Bedrock confining unit		No wells obtain water from these consolidated rocks, except along Fall Line.

AN OVERVIEW OF NEW JERSEY GROUND-WATER HYDROLOGY

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INTRODUCTION

This report summarizes New Jersey ground-water facts, issues, and conditions. It was compiled primarily from the 1984, 1986 and 1987 National Water Summaries (U.S. Geological Survey, 1985, 1988, and 1990, respectively) and U.S. Geological Survey files. It includes information on water use, the geohydrology of aquifers, ground-water quality, and ground-water management, and presents a list of selected references on ground-water hydrology in New Jersey.

WATER USE

Ground water is the source of water for about 50 percent of New Jersey's population. In 1987, about 729 Mgal/d (million gallons per day) of ground water was withdrawn within the State for public supply, industrial/commercial, domestic, and agricultural uses.

Of the 630 public-water-supply systems in the State (which include more than 1,900 wells), 90 percent obtain all or part of their supplies from ground-water sources. An additional 16,000 self-supplied irrigation and industrial/commercial wells, and about 400,000 rural domestic-supply wells, are used in the State (Robinson, 1986). In 1987, about 407 Mgal/d of ground water was pumped for public-supply use, 226 Mgal/d was pumped for self-supplied industrial/commercial and irrigation use, and about 96 Mgal/d was pumped for rural domestic-supply use (N. J. Department of Environmental Protection, 1987).

NEW JERSEY AQUIFERS

The principal aquifers in New Jersey are of two types--Coastal Plain aquifers south of the Fall Line and non-Coastal Plain aquifers north of the Fall Line. The aquifers are described below and in table 1, from youngest to oldest; their areal distribution is shown in figure 1.

Coastal Plain Aquifers

The New Jersey Coastal Plain is a seaward-dipping wedge of unconsolidated sediments of Cretaceous to Quaternary age. These sediments, generally consist of clay, silt, sand, and gravel and are of continental, coastal, or marine origin. The Coastal Plain sediments thicken seaward from a featheredge at the Fall Line to greater than 6,500 ft (feet) at the southern tip of Cape May County (fig. 1C). This sedimentary wedge forms a complex ground-water system in which the sands and gravels function as aquifers and the silts and clays function as confining units. Water-bearing

Table 1. Aquifer and well characteristics in New Jersey

[Mgal/d = millions of gallons per day; gal/min = gallons per minute; ft = feet.] **Modified from U.S. Geological Survey, 1985.**

Aquifer name and description	Aquifer withdrawals 1985 (Mgal/d)	Well characteristics			Remarks
		Depth (ft)	Yield (gal/min)		
		Common range	Common range	May exceed	
Coastal Plain aquifers:					
Kirkwood-Cohansey aquifer system: Sand, quartz, fine to coarse grained, pebbly; local clay beds. Unconfined.	130	20 - 350	500 - 1,000	1,500	Ground water occurs generally under water-table conditions. Aquifer system extends from southern Monmouth County to Delaware Bay and from 12 mi southeast of the Delaware River to the Atlantic Ocean. Aquifer thickness can exceed 350 ft. Brackish and salty water may occur in coastal areas.
Atlantic City 800-foot sand: Sand, quartz, medium to coarse grained, gravel, fragmented shell material. Confined.	20	450 - 950	600 - 800	1,000	Principal confined artesian aquifer supplying water along the barrier beaches in Cape May, Atlantic, and Ocean Counties. Aquifer thickness generally ranges between 100 and 150 ft. Water quality suitable for most uses.
Wenonah-Mount Laurel aquifer: Sand, quartz, slightly glauconitic, very fine to coarse grained, layers of shells. Confined.	6	50 - 600	50 - 250	500	Important confined aquifer in the northeast and southwest part of the Coastal Plain. Aquifer thickness generally range between 60 and 120 ft. Water quality suitable for most purposes.
Englishtown aquifer: Sand, quartz, fine to medium grained, local clay beds. Confined.	11	50 - 1,000	300 - 500	1,000	Important source of water for Ocean and Monmouth Counties. Confined aquifer thickness generally ranges between 60 and 140 ft. Excellent water quality.
Potomac-Raritan-Magothy aquifer system: Alternating layers of sand, gravel, silt, and clay. Confined.	235	50 - 1,800	500 - 1,000	2,000	Highly productive and most used confined aquifer in the Coastal Plain. Aquifer system extends throughout Coastal Plain and attains maximum thickness of 4,100 ft. Includes two aquifers in northern Coastal Plain: Farrington and Old Bridge aquifers. Salty water increases with depth and in downdip direction. Excellent water quality but large iron concentrations in some areas.
	Aquifer withdrawals 1987 (Mgal/d)				
Non-Coastal Plain aquifers:					
Glacial valley-fill aquifers: Sand, gravel, interbedded silt and clay. Generally unconfined except where overlain by lake silt and clay or till.	69	10 - 300	100 - 1,000	2,000	North of terminal moraine occur principally as channel fill in preglacial stream valleys; south of moraine, as outwash plains and valley trains. Important aquifers in Bergen, Essex and Morris Counties. Water quality suitable for most uses.
Aquifers in the Newark Group: Shale and sandstone: Shale, sandstone, some conglomerate. Unconfined to partially confined in upper 200 ft; confined at greater depth.	82	30 - 1,500	10 - 500	1,500	Most productive aquifers in Essex, Passaic and Union Counties. Water generally hard; may have large concentrations of iron and sulfate. Saltwater has intruded areas of large ground-water withdrawal near bays and estuaries.
Valley and Ridge sedimentary units: Predominantly limestone and shale; some dolomite, calcareous sandstone and siltstone, sandstone, conglomerate and slate. Confined and unconfined.	9	150 - 400	5 - 500	1,500	Highest yields from cavernous limestones and in weathered and fractured zone within 300 ft of land surface. Locally excessive iron, hardness, and low pH.
Highlands crystalline units: Gneiss, marble, quartzite, pegmatite; some schist, amphibolite and granite. Includes thin belts of conglomerate, sandstone, not significant as aquifers. Confined and unconfined.	13.5	35 - 800	5 - 50	400	Most water obtained from weathered and fractured zone in upper 300 ft; high yields in or near major fault zones. Excellent source of water for domestic use in some areas.

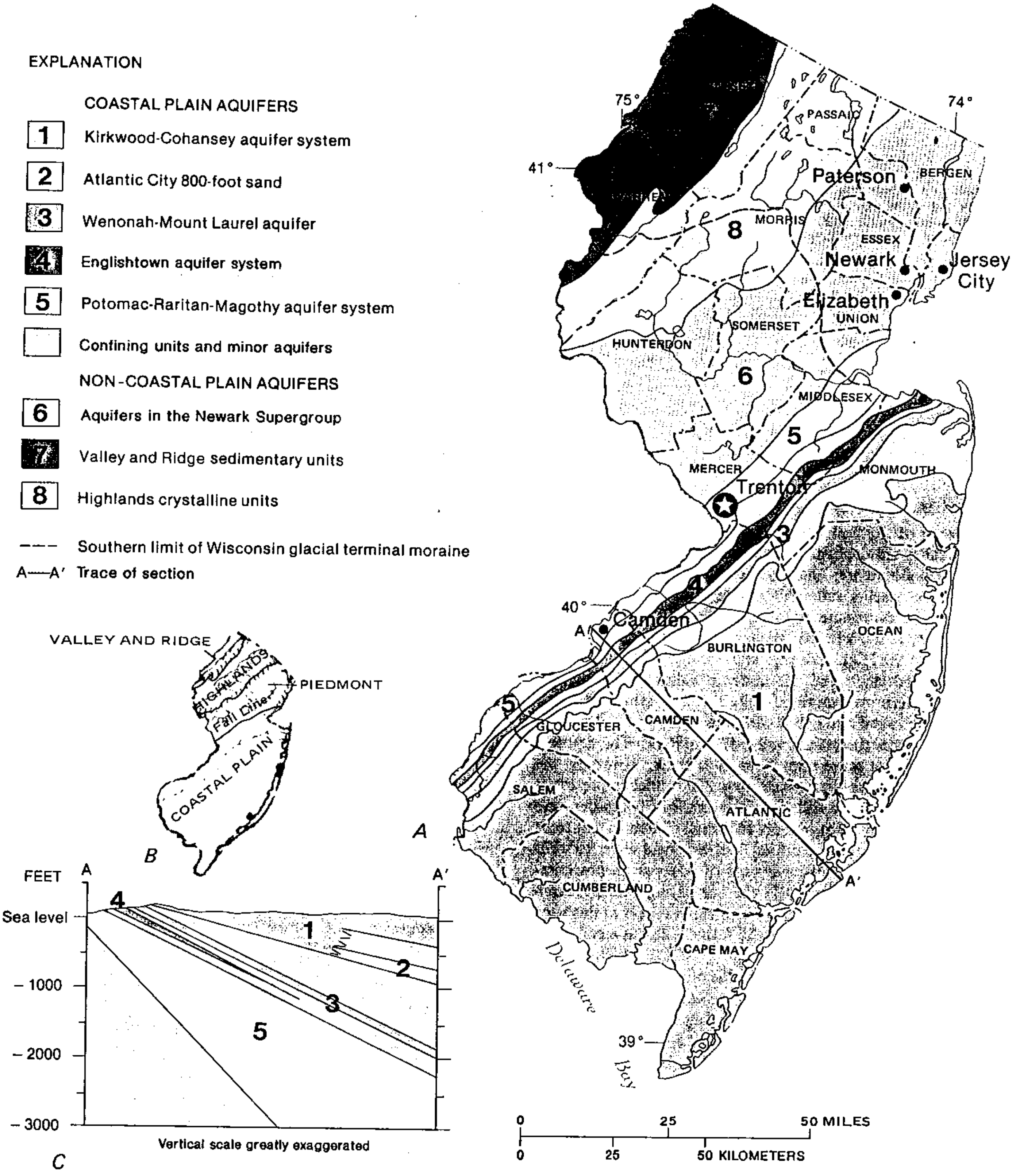


Figure 1. Principal aquifers in New Jersey. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized section (A-A′) of the Coastal Plain. (See table 1 for more detailed description of the aquifers.
Modified from U.S. Geological Survey (1985)

properties are a function of the lithology, thickness, and lateral extent of the various geologic formations.

The five principal Coastal Plain aquifers or aquifer systems in New Jersey are the Kirkwood-Cohansey aquifer system, the Atlantic City 800-foot sand of the Kirkwood Formation, the Wenonah-Mount Laurel aquifer, the Englishtown aquifer system, and the Potomac-Raritan-Magothy aquifer system. All but the Kirkwood-Cohansey aquifer system are confined except where they crop out or are overlain by permeable surficial deposits. The aquifers generally receive recharge directly by precipitation in outcrop areas, by vertical leakage through confining units, and by seepage from surface-water bodies.

More than 75 percent of the freshwater supply in the New Jersey Coastal Plain is ground water. High-capacity production wells used for public supply commonly yield 500 to 1,000 gal/min (gallons per minute), and some yield more than 2,000 (gal/min).

Non-Coastal Plain Aquifers

North of the Fall Line, the principal aquifers consist of glacial valley-fill deposits; fractured shales, limestones, sandstones, and conglomerates; and crystalline rocks. These aquifers include the glacial valley-fill aquifers, the Newark Supergroup aquifers, the carbonate aquifers within the Valley-and-Ridge sedimentary units, and the igneous and metamorphic crystalline rocks of the Highlands crystalline units. Ground water provides about 20 percent of the freshwater supply north of the Fall Line.

Stratified drift and till underlie valleys north of the Wisconsin terminal moraine (fig. 1a). The stratified drift--poorly sorted sand and gravel with interbedded silt, silty sand, and clay--forms the glacial valley-fill aquifers. The aquifers (in places) comprise channels up to 300 ft thick in pre-Pleistocene stream valleys. These glacial valley-fill aquifers are narrow, beltlike deposits of small areal extent. The stratified drift can yield water to wells and can retain substantial amounts of water from precipitation, which increases yields in the underlying bedrock aquifers. In some areas, till, which consists of a veneer of unsorted clay, silt, sand, and gravel 10 to 30 ft thick, acts as a confining unit.

Glacial valley-fill aquifers are the most productive source of ground water in some northeastern counties in New Jersey (Vecchioli and Miller, 1973). These aquifers can yield as much as 2,000 gal/min to public supply and industrial wells.

The most productive aquifers in the Newark Supergroup in the Piedmont physiographic province (fig. 1a) consist of shale and sandstone. Water generally is present in weathered joint and fracture systems in the upper 200 or 300 ft (Barksdale and others, 1958). Below a depth of 500 ft, fractures are fewer and smaller than in the upper part of the system, and water availability is reduced, depending on rock type. In coarse-grained sandstones, ground water also is present in intergranular pore spaces. In several counties, the shale and sandstone aquifers of the Newark Supergroup yield as much as 1,500 gal/min (Carswell and Rooney, 1976; Nemickas, 1976a). Basaltic rocks, diabase and the resistant black mudstones commonly are poor producers. Water from these units is used primarily for domestic purposes. Well yields of less than 5 gal/min are common.

In the Valley and Ridge sedimentary units, the most productive aquifers consist of carbonate rocks that commonly yield large supplies of water, especially where they are overlain by stratified glacial deposits. Cavities and solution channels in the rock provide storage and avenues for water movement. In the crystalline Highlands, water is available in weathered and fractured zones, usually within 300 ft of the land surface. With the exception of carbonates, yields from other consolidated sedimentary rocks (poorly fractured sandstones and shales) and from crystalline rocks are limited by the degree of weathering and fracturing and do not exceed a few hundred gallons per minute.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL DECLINES

In 1987, total reported ground-water withdrawals in New Jersey amounted to 230,997 million gallons, or 633 Mgal/d. The New Jersey Department of Environmental Protection (1987) estimates an additional (unreported) 96 Mgal/d of ground water was withdrawn through domestic wells, bringing the total 1987 ground-water usage in New Jersey to about 729 Mgal/d.

The percentage of reported ground-water withdrawals from Coastal Plain and non-Coastal Plain aquifers during 1987 is shown in figure 2. Coastal Plain aquifers contributed almost 70 percent of all ground water withdrawn. Newark Supergroup aquifers and glacial valley-fill aquifers together contributed about 24 percent, the remaining 6 percent was withdrawn from Highlands, Valley and Ridge, and undifferentiated aquifers.

Increases in population (fig. 3A) and changes in population distribution (fig. 3B) have affected the distribution of water use in New Jersey. According to the U.S. Bureau of the Census (1987), in 1985 New Jersey was ninth in population in the United States (about 7.5 million residents) and first in population density (more than 1,000 people per square mile). North of the Fall Line, high population density in northeastern New Jersey has resulted from the development of business, industry, and transportation, and from proximity to New York City. Although aquifers north of the Fall Line yield significant amounts of water, ground-water supplies over large areas are insufficient to meet public needs, therefore, public-supply systems in northeastern New Jersey have always relied primarily on surface water.

South of the Fall Line, water supplies are obtained primarily from ground water. In 1985, about 235 Mgal/d of water was withdrawn from the Potomac-Raritan-Magothy aquifer system, 130 Mgal/d was withdrawn from the Kirkwood-Cohansey aquifer system, and 37 Mgal/d was withdrawn from the Atlantic City 800-foot sand, the Wenonah-Mount Laurel aquifer, and the Englishtown aquifer system, combined.

Ground-water withdrawals from Coastal Plain aquifers in New Jersey have increased steadily since the turn of this century. Withdrawal rates

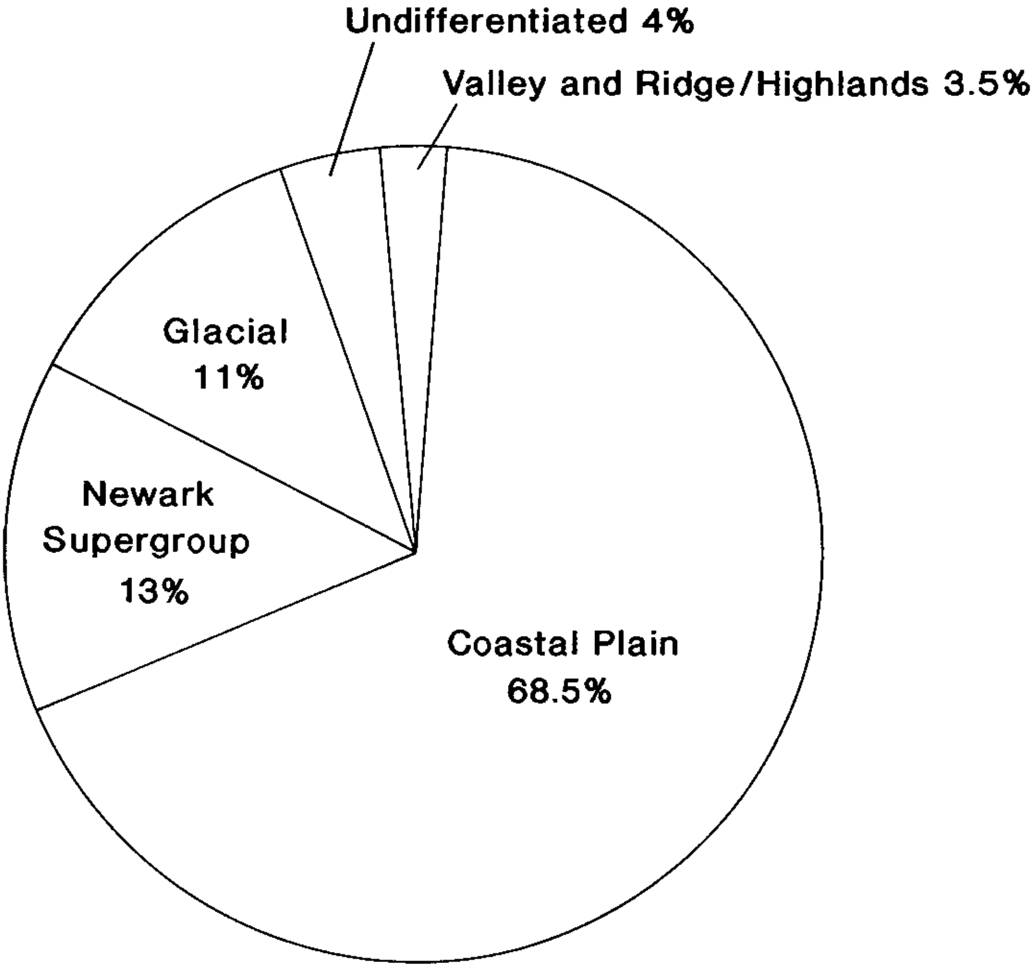


Figure 2.--Percentage of 1987 reported ground-water withdrawals from Coastal Plain and non-Coastal Plain aquifers.

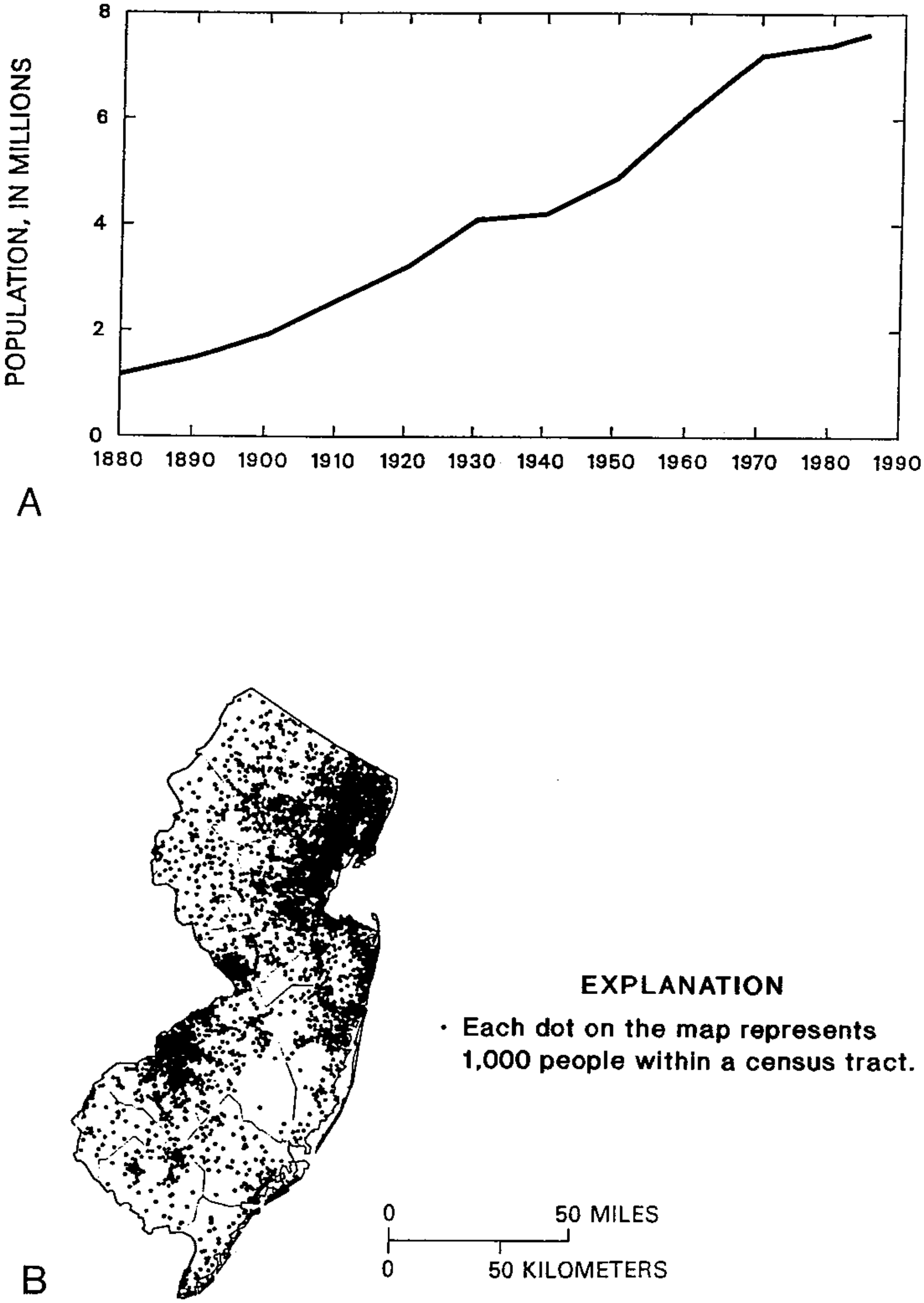


Figure 3.--A, Population trend, 1880 to 1985. B, Population distribution, 1985. (Compiled by U.S. Geological Survey, from U.S. Bureau of the Census data.

have increased from less than 50 Mgal/d before 1920 to more than 400 Mgal/d in 1985 (fig. 4). In response to increasing ground-water withdrawals, ground-water levels in major confined aquifers have steadily declined and large regional cones of depression have formed.

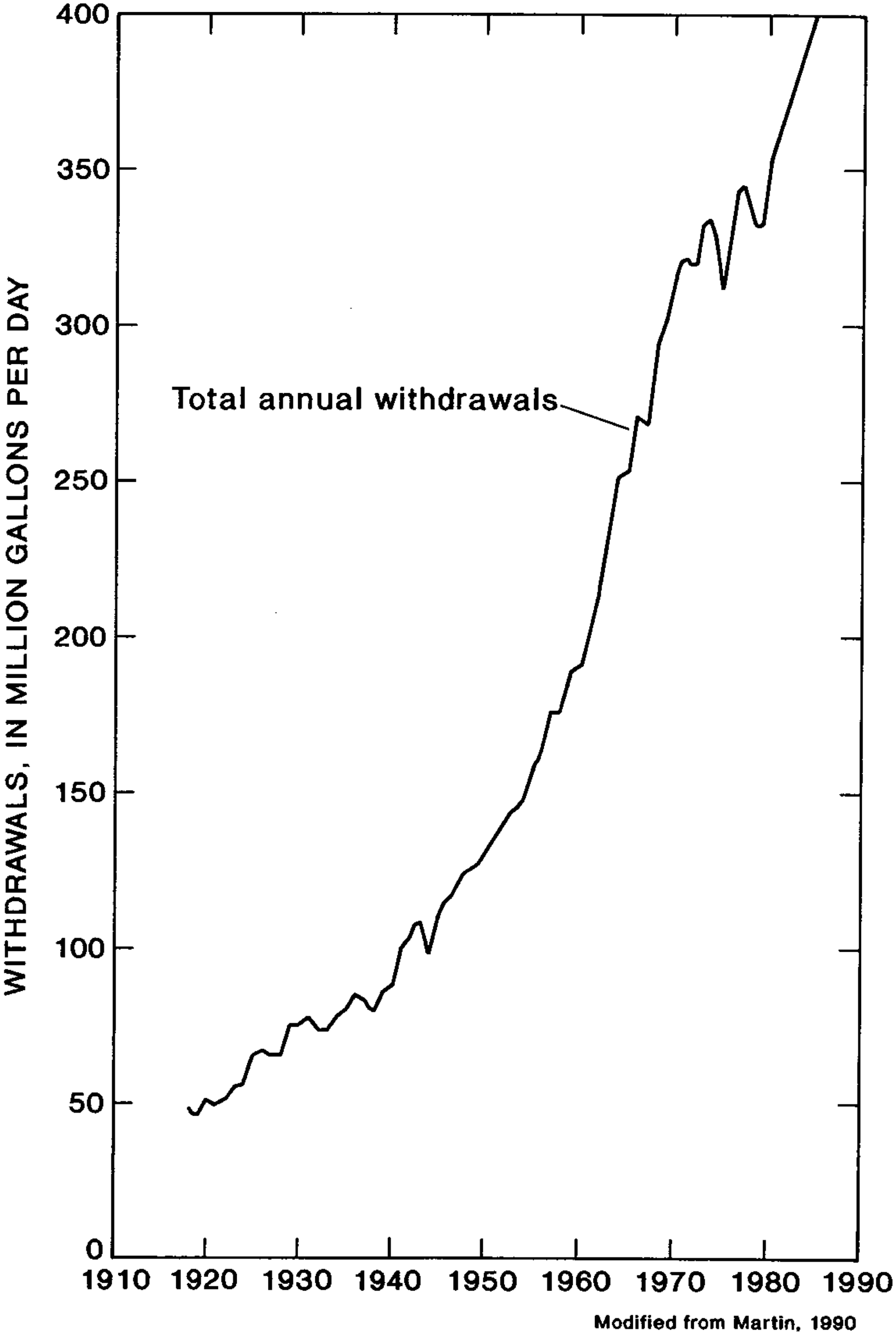
The map in figure 5 shows regional cones of depression in which water levels were more than 50 feet below sea level in 1988. The response of water levels to withdrawals in the vicinity of these cones of depression is illustrated by the associated long-term water-level hydrographs (fig. 5).

The greatest water-level declines in New Jersey have occurred in the Englishtown aquifer system. Water levels in the Allaire State Park observation well in Monmouth County (hydrograph 1, fig. 5) have declined about 95 ft from 1965 through 1990. Water levels recorded in the Englishtown aquifer system in the late 1890's indicate that flowing wells (as much as 35 ft above land surface) were common in coastal areas of Ocean and Monmouth Counties (Zapecza and others, 1987). In 1988 static water levels as great as 240 ft below sea level were recorded in wells in the center of the cone of depression in the Englishtown aquifer system near the boundary of Monmouth and Ocean Counties along the Atlantic Coast. Withdrawals from the Englishtown aquifer system have induced leakage of water from the overlying Wenonah-Mount Laurel aquifer. Water levels as much as 200 ft below sea level in the Wenonah-Mount Laurel aquifer were recorded in 1988 in the same vicinity as the cone in the Englishtown aquifer system. On the basis of a ground-water flow model, Nemickas (1976b) concluded that the major cause of water-level decline in the Wenonah-Mount Laurel aquifer is withdrawals from the Englishtown aquifer system, and that only one-third of the decline is caused by direct withdrawals from the Wenonah-Mount Laurel aquifer.

In addition to declining water supplies, declining water levels in confined aquifers have caused reversals in natural hydraulic gradients. These reversals can induce movement of brackish or saline water from surface-water bodies or adjacent aquifers.

More than 140 Mgal/d of ground water is withdrawn from the Potomac-Raritan-Magothy aquifer system in Burlington, Camden, and Gloucester Counties. Water-level hydrographs from observation wells screened in the Potomac-Raritan-Magothy aquifer system in Burlington and Camden Counties show water-level declines of about 50 ft since the mid-1960's (hydrographs 2 and 3, fig. 5). Heavy pumping of the aquifer system in the Camden area has reversed the normal flow of water from the aquifer to the Delaware River; the river now recharges the aquifer. In the event of a severe drought, decreased streamflow in the Delaware River could allow the saltwater front in the Delaware Bay to advance upstream to the Camden area, thereby allowing the intrusion of saltwater into the aquifer system.

In the northern part of the Coastal Plain two aquifers have been defined within the Potomac-Raritan-Magothy aquifer system--the Farrington aquifer and the Old Bridge aquifer. Large ground-water withdrawals near Raritan Bay in Middlesex and Monmouth Counties have caused water levels to decline. As a result, the bayward hydraulic gradient that existed prior to well development has reversed, allowing saltwater to flow laterally into the Old Bridge aquifer from Raritan Bay (Schaefer and Walker, 1981).



Modified from Martin, 1990

Figure 4.--Total annual ground-water withdrawals from the New Jersey Coastal Plain, 1918 through 1985.

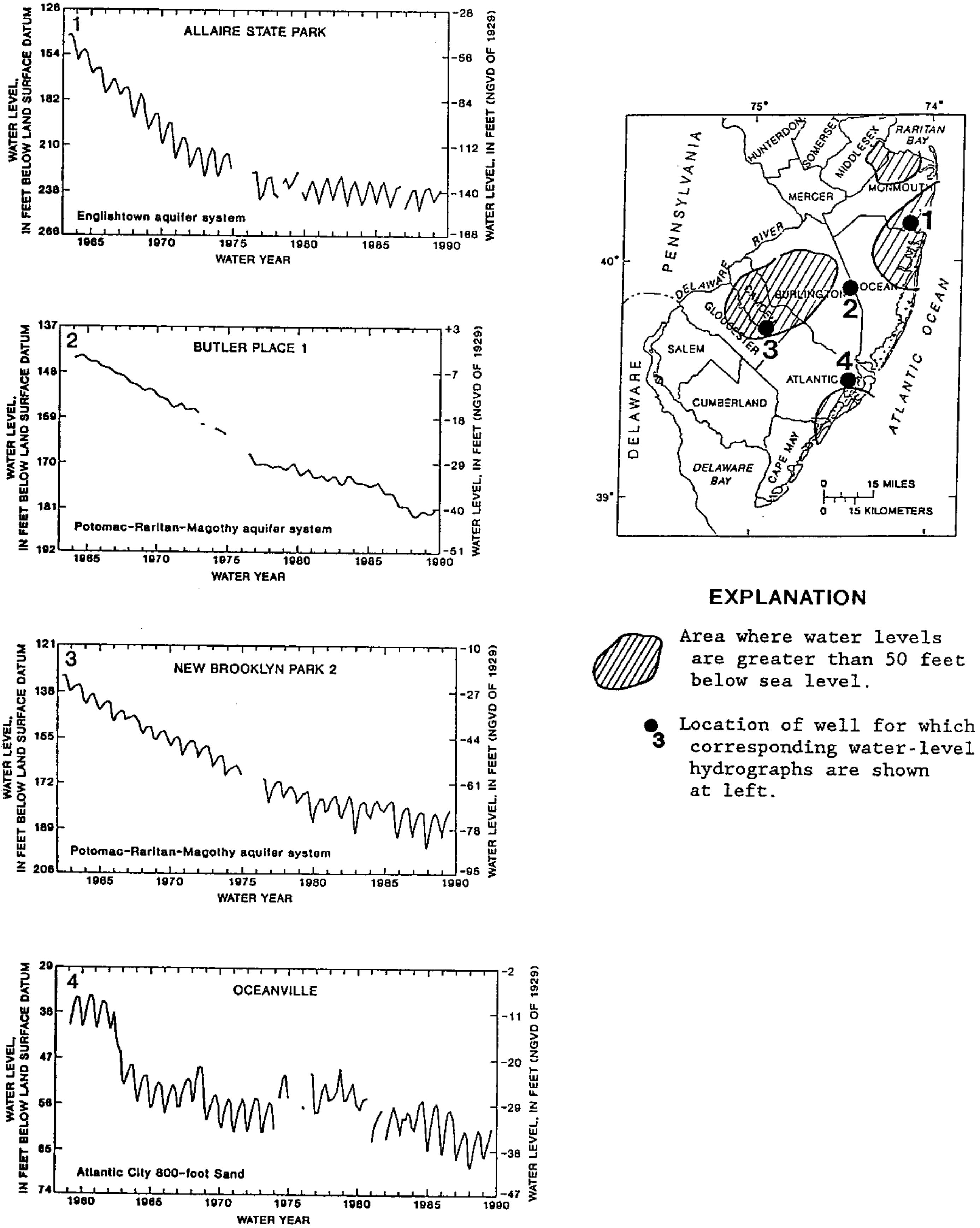


Figure 5.--Areas of water levels more than 50 feet below sea level; and four selected hydrographs showing long-term water-level trends.

The Atlantic City 800-foot sand is pumped heavily along the Atlantic Coast in Cape May, Atlantic, and Ocean Counties. Water-level fluctuations in the aquifer are represented in the hydrograph of the Oceanville observation well (hydrograph 4, fig. 5). Ground-water-withdrawal rates fluctuate seasonally. In 1986, withdrawals from the Atlantic City 800-foot sand ranged from 13 Mgal/d in December to 36 Mgal/d in July. In the 1890's water levels were about 20 to 25 ft above sea level at Atlantic City prior to development of the 800-foot sand for water supply (Thompson, 1928). In April 1986, under conditions of annual minimum pumping stress, water levels in the deepest part of the Atlantic City cone were more than 70 ft below sea level. In September 1986, under conditions of annual-maximum pumping stress, water levels in the deepest part of the cone were 100 feet below sea level (Clark and Paulachok, 1989).

In an effort to evaluate the likelihood of saline-water intrusion into the 800-foot sand in the vicinity of Atlantic City, the U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, constructed two marine observation wells in 1985 at sites 1.9 and 5.3 miles offshore of Atlantic City. Results of water-quality sampling in both wells suggest that a large body of freshwater in the 800-foot sand extends seaward of Atlantic City. In 1985, chloride concentrations in water from the 1.9-mile well and the 5.3-mile well were measured at 15 parts per million and 77 parts per million, respectively. Continued measurements from specific-conductance sensors permanently installed in each well indicate that saline water has not contaminated the aquifer in the vicinity of the wells (Clark, 1989).

GROUND-WATER QUALITY

Ground-water studies prior to 1970 indicated that New Jersey's ground water was suitable for most uses, although locally saltwater intrusion, toxic-metal or other inorganic contamination, objectionable odor and taste, and excessive iron content were problems. These studies focused only on inorganic quality because an awareness of organic ground-water contamination was not developed until the advent of improved organic-compound analytical capability in the 1970's. By 1977, reports of incidents of organic contamination resulting from chemical-waste storage, production, disposal, and (or) spills were reaching the N. J. Department of Environmental Protection regularly.

As of 1990, New Jersey had 1,400 known or suspected hazardous-waste sites (fig. 6a) where a minimum of a site inspection or preliminary assessment had been made in response to suspected ground-water contamination. As of July 1990, 103 sites were included on the "Superfund," or National Priorities List for cleanup as part of the comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, and another 6 sites were proposed for inclusion. Also, monitoring is required at 183 sites under the Federal Resource Conservation and Recovery Act of 1976 (RCRA) program (N. J. Department of Environmental Protection, 1989). A total of 310 county, municipal, and privately owned landfills (fig. 6b) were known to exist in New Jersey as of July 1990; most of these are not included among the 1,400 sites noted above.

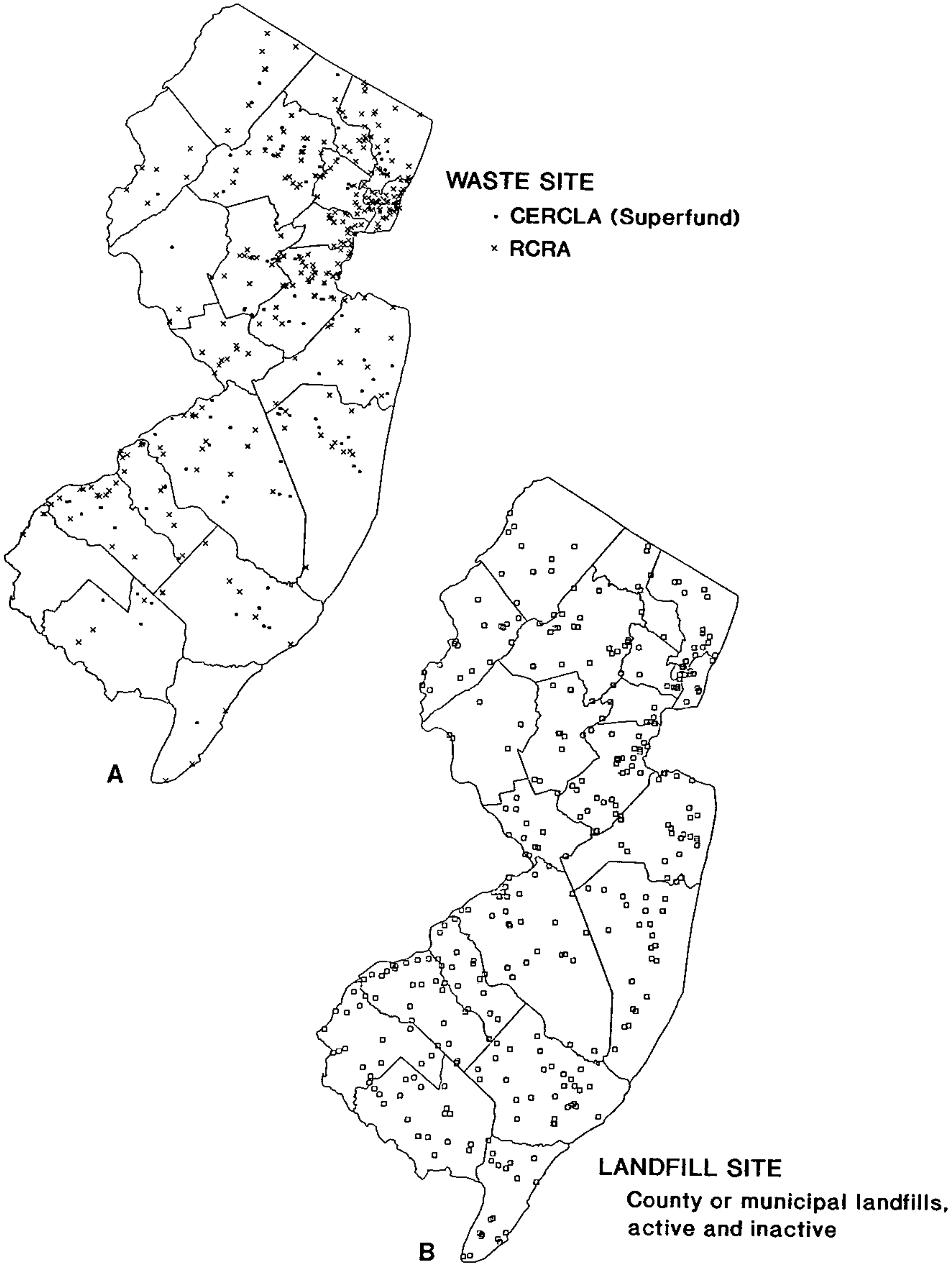


Figure 6.--A, Selected waste sites in New Jersey. B, County and municipal landfills as of 1986.

Despite the fact that ground-water contamination, especially from organic compounds, is a serious problem locally, New Jersey continues to have a sufficient supply of ground water of adequate quality for most users throughout the State. Furthermore, in-place management practices in the State indicate a comprehensive approach to ground-water protection whereby all known and potential sources of contamination are subject to regulatory controls.

Background Ground-Water Quality

The inorganic water quality of the nine principal aquifers in New Jersey is summarized in graphs (fig. 7) compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). The graphs show dissolved-solids, hardness, iron, nitrate plus nitrite (as nitrogen), and sulfate concentrations in water samples collected from 1923 to 1986. Percentiles of these constituents are compared to national standards that specify the maximum concentration or level of a contaminant allowable in drinking-water supply as established by the U.S. Environmental Protection Agency (USEPA) (1986a, b). The primary maximum contaminant level regulations, which are health-related and are legally enforceable, include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen). The secondary maximum contaminant level regulations, which apply to esthetic qualities and are recommended guidelines, include maximum concentrations of 500 mg/L dissolved solids, 300 µg/L (micrograms per liter) iron, and 250 mg/L sulfate. The data in figure 7C are presented without consideration to sample depth or whether the aquifer is confined or unconfined. Where more than one sample was analyzed per site, the median value of the constituent was used.

Median dissolved-solids concentrations (fig. 7) ranged from 32 to 219 mg/L, which did not exceed the USEPA drinking-water regulation. In the Coastal Plain the dissolved-solids concentrations in ground water from the Atlantic City 800-foot sand, Wenonah-Mount Laurel aquifer, and the Englishtown aquifer system reflect the longer residence time of water expected under predominantly confined conditions and show less variation than the dissolved-solids concentrations in ground water from Kirkwood-Cohansey aquifer system, which is predominantly unconfined.

The predominant ions in most New Jersey ground waters are calcium, magnesium, and bicarbonate. A gradual change to sodium bicarbonate dominance is observed about 30 to 40 miles downdip in the confined Coastal Plain aquifer systems as a result of cation-exchange mechanisms. The Atlantic City 800-foot sand is a sodium bicarbonate-dominated system except where it contains saltwater at the southern tip of Cape May County. The Potomac-Raritan-Magothy aquifer system contains saltwater in the southern part of the Coastal Plain (fig. 8).

The soils overlying the Kirkwood-Cohansey aquifer system are very sandy and permeable, leaving little time and potential for mineralization of recharge water. Consequently, dissolved-solids concentrations near those of rainfall are found in the ground water in this system. Water in this aquifer system also is poorly buffered (median alkalinity 3 mg/L) and naturally acidic (median pH 5.2). Ion dominance in this aquifer system is

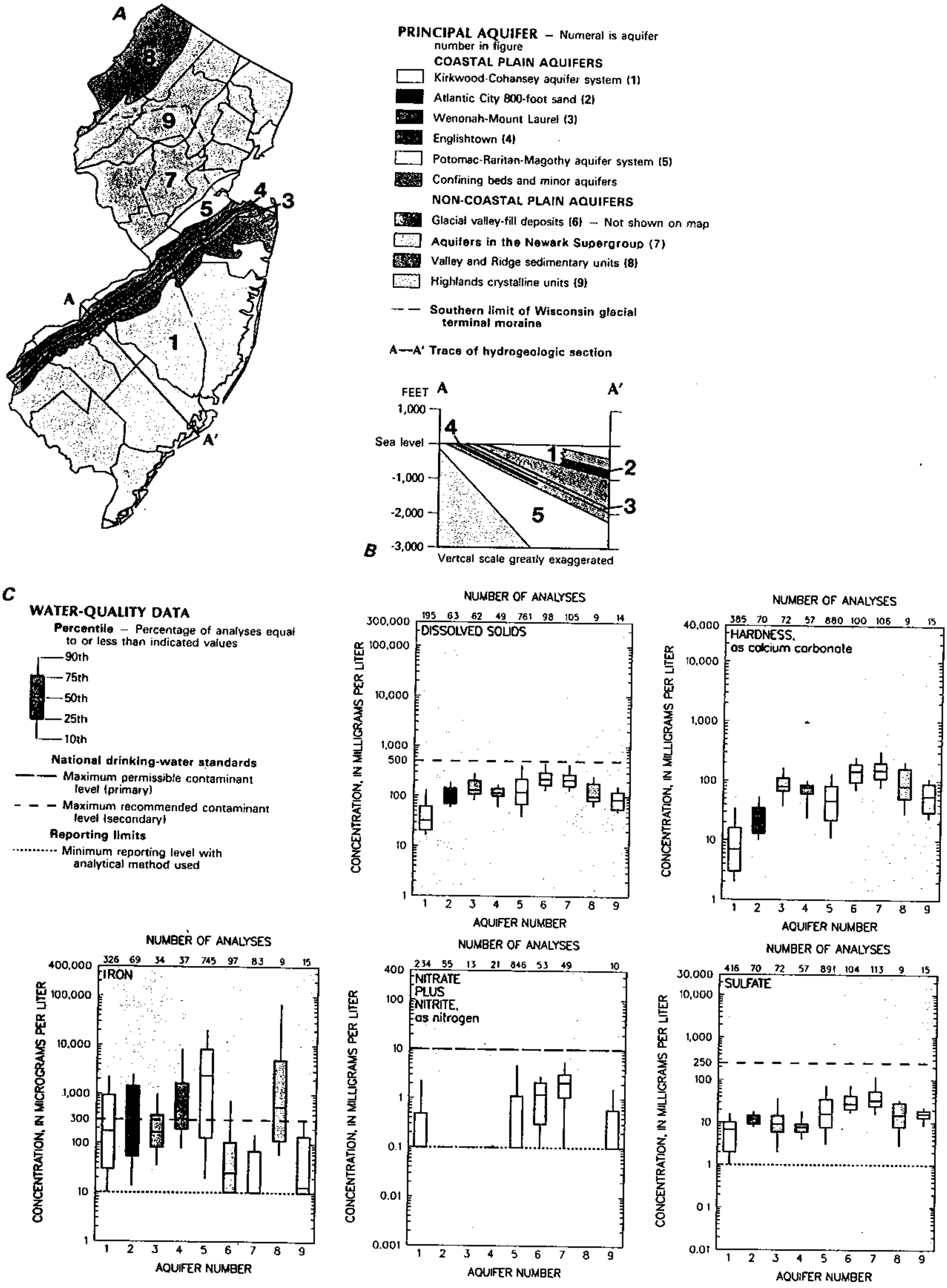
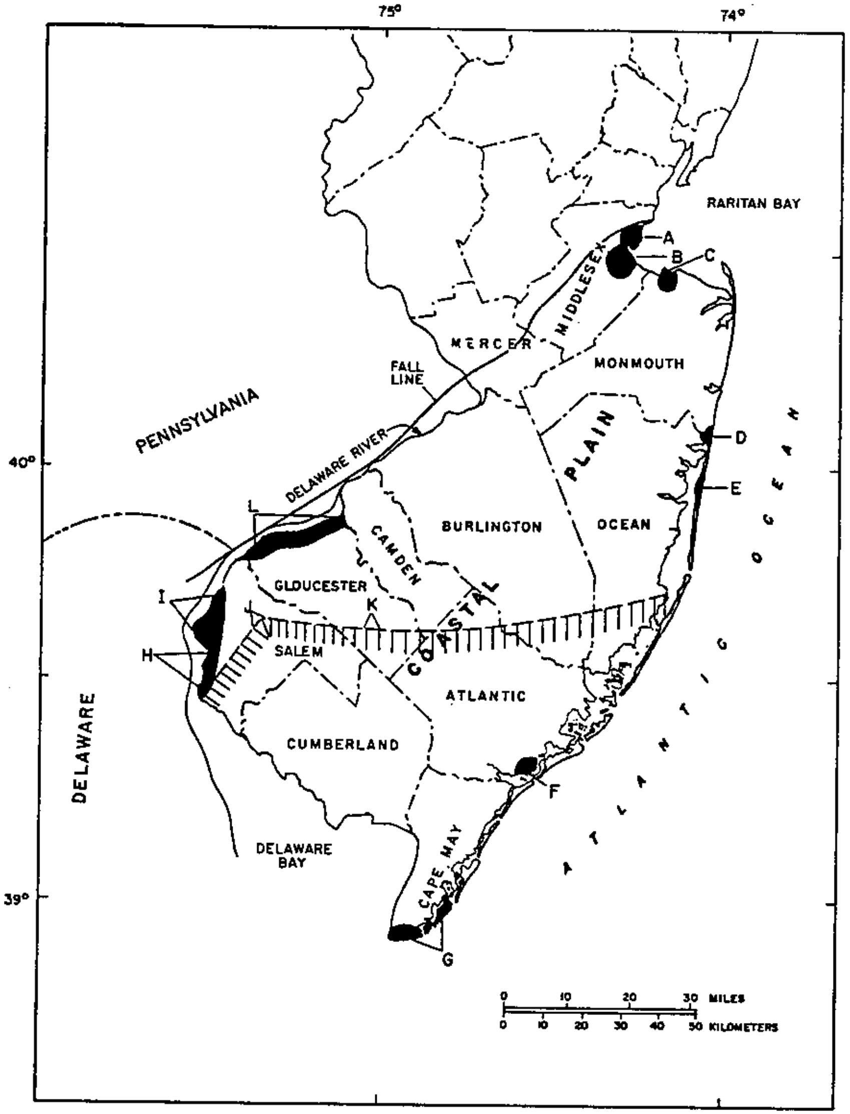


Figure 7.—Principal aquifers and related water-quality data in New Jersey. *A*, Principal aquifers; *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1923-86. Modified from U.S. Geological Survey (1988)



EXPLANATION

● A Areas of saltwater intrusion in principal aquifers. Letter identifies locations listed below.

Area	Location	County	Aquifer affected
A	Perth Amboy City and Woodbridge Township	Middlesex	Farrington aquifer
B	Sayreville Borough and South Amboy City	Middlesex	Farrington and Old Bridge aquifers
C	Keyport and Union Beach Boroughs	Monmouth	Old Bridge aquifer
D	Point Pleasant Beach Borough	Ocean	Kirkwood-Cohansey aquifer system
E	Seaside Heights Borough	Ocean	Kirkwood-Cohansey aquifer system
F	Somers Point City	Atlantic	Kirkwood-Cohansey aquifer system
G	Cape May City and surrounding areas	Cape May	Cohansey Sand
H	Salem City and surrounding areas	Salem	Wenonah-Mount Laurel aquifer
I	Areas between Penns Grove and Salem City	Salem	Potomac-Raritan-Magothy aquifer system
J	Woodstown Borough and surrounding areas	Salem	Potomac-Raritan-Magothy aquifer system
K	Clayton Borough and surrounding areas	Gloucester	Potomac-Raritan-Magothy aquifer system
L	Areas between Paulsboro and Gibbstown	Gloucester	Potomac-Raritan-Magothy aquifer system

ПППП Line of 250-milligrams-per-liter chloride concentration near the top of the Potomac-Raritan-Magothy aquifer system (from Luzier, 1980, p.6). South and east of this line, chloride concentrations increase.

From Schaefer, 1983

Figure 8.--Areas of significant saltwater intrusion in the principal aquifers of the New Jersey Coastal Plain.

variable, depending on depth and location relative to wetlands (Rhodehamel, 1979).

The Potomac-Raritan-Magothy, the glacial valley-fill, and the Newark Supergroup aquifer systems have median chloride concentrations of 11.6, 30.5, and 16.0 mg/L, respectively. All other aquifers in New Jersey have median chloride concentrations less than 7.0 mg/L. Chloride is a problem only in some coastal areas (fig. 8) where extensive ground-water withdrawals have induced saltwater intrusion (Schaefer, 1983).

Using Hem's (1985) classification ranges for hardness, the Kirkwood-Cohansey, Atlantic City 800-foot sand, Potomac-Raritan-Magothy, and Highlands crystalline aquifer systems have soft ground water (0-60 mg/L as calcium carbonate); the Wenonah-Mount Laurel, Englishtown, and Valley and Ridge aquifer systems have moderately hard ground water (61-120 mg/L); and the glacial valley-fill and Newark Supergroup aquifers have "hard" ground water (212-180 mg/L) (fig. 7). Hardness is easily treatable for those ground waters with concentrations greater than 100 mg/L.

Median iron concentrations (fig. 7) commonly exceed the USEPA drinking-water regulation of 300 μg/L in all aquifers except the glacial valley-fill deposits, the Newark Supergroup, and the Highlands crystalline systems. Iron concentrations are extremely variable within each aquifer system because of large variations in local conditions controlling the dissolution of iron minerals. Iron is a local or subregional problem and usually is treatable.

Sulfate (fig. 7) follows a pattern similar to dissolved solids, as does chloride. Sulfate is not perceived to be a water-quality problem in New Jersey ground water. Certain soils in the Coastal Plain appear to be saturated with respect to sulfate, however, and current research indicates that sulfate mobility through soils to shallow ground-water and surface-water systems probably facilitates the mobilization of aluminum. Aluminum in the ionic form can be toxic to some plants and fish.

Median concentrations of nitrate plus nitrite (fig. 7) in the confined Coastal Plain aquifer systems are consistently 0.11 mg/L or less, which is considerably lower than the USEPA drinking-water regulation of 10 mg/L. Although median concentrations in the Kirkwood-Cohansey and Potomac-Raritan-Magothy aquifer systems are low (0.1 mg/L), the data are extremely variable because of the large number of samples from unconfined wells, which are more susceptible than confined wells to the effects of land use. The glacial valley-fill and Newark Supergroup aquifer systems generally are water-table systems overlain by soils more fertile than soils overlying the other New Jersey aquifer systems; therefore, the median concentrations of nitrate plus nitrite are higher than in the other systems. Several dozen rural-domestic wells have been closed statewide because of increased nitrate levels resulting from the intensity of agricultural practices or septic systems in some areas.

Human-Induced Contamination

Ground-water quality in some areas of New Jersey has been degraded, in some instances severely, as a result of the effects of urbanization, transportation, industrialization, agriculture, land disposal of wastes, ground-water pumpage, and, possibly, atmospheric deposition. Between 10,000 and 15,000 firms in New Jersey are engaged in the manufacture of chemical and petrochemical products. New Jersey also generates about 8 percent of the nation's hazardous waste--more than 40 million pounds annually--which is the largest of any State (Stevenson and others, 1986). The use, transport, and storage of organic and other hazardous chemicals is pervasive throughout much of the state. Consequently, aquifers have been contaminated in many locations through poor industrial housekeeping, spills and accidents of all types, deliberate dumping, illegal discharges, leaks from subsurface storage tanks, landfills, and other factors.

In two regional ground-water studies of toxic contaminants (metals, pesticides, and volatile organic compounds (VOC's)), researchers found that VOC's present the most serious and pervasive contamination threat to New Jersey's ground water (Tucker, 1981; Fusillo and Hochreiter, 1982). Testing for 22 organic compounds, Tucker (1981) found one or more of eight VOC's with a concentration higher than 10 μg/L in about 20 percent of the 315 Coastal Plain wells sampled. The three most common contaminants were trichlorethylene, tetrachloroethylene, and benzene.

In an overview of the State's ground-water-quality program, Kasabach and Althoff (1983) reported that nearly 70 percent of the ground-water-contamination cases involved industrial solvents. The principal contaminants were trichloromethane, 1,1,1-trichloroethane, tetrachloroethylene, trichloroethylene, carbon tetrachloride, and methylene chloride. Where gasoline discharges had occurred, dissolved benzene, toluene, and xylene were common ground-water contaminants.

Since 1970, about 200 wells in the State have been closed because of chloride, arsenic, nitrate, mercury, lead, hexavalent chromium, biological, or radiological (both natural and human-caused) contamination (John Preczewski, N. J. Department of Environmental Protection, oral commun., 1986). Also since 1970, nearly 1,200 wells have been closed because of contamination by organic compounds. Private wells accounted for 80 to 90 percent of the well closures.

New Jersey's experiences with ground-water contamination indicate that wells in unconsolidated, water-table aquifers near population and industrial centers are most likely to have contamination problems. Organic compounds, especially volatile organic compounds, are the most common and pose the most serious human-induced contamination threat to ground-water supplies.

Natural Contamination

In addition to human-induced contamination, elevated concentrations of some naturally occurring elements, or simply the naturally occurring geochemistry of the ground-water system, can contaminate drinking-water supplies. Naturally occurring radionuclides and naturally corrosive ground water have affected the quality of drinking water locally. Elevated concentrations of dissolved radium, radon, and uranium in ground water are associated with uranium-rich rocks which comprise some Newark Supergroup aquifers. (Zapecza and Szabo, 1987; Szabo and Zapecza, 1987). Elevated concentrations of naturally occurring radium dissolved in ground water also have been identified throughout large parts of the Kirkwood-Cohansey aquifer system in the southwestern Coastal Plain (Zapecza and Szabo, 1989). Elevated levels of radioactivity in ground water may increase cancer risks if the water is ingested, therefore, water treatment prior to consumption may be necessary.

In Ocean and Atlantic Counties, corrosive ground water in the Kirkwood-Cohansey aquifer system has been linked to leaching of trace metals from plumbing materials (Kish and others, 1987, 1989). Increased residence time of naturally occurring, soft, acidic ground water in new-home-plumbing systems resulted in elevated concentrations of lead and copper in tap water.

GROUND-WATER MANAGEMENT

A thorough evaluation of the State's ground-water resources is critical to effective ground-water management. The U.S. Geological Survey has conducted investigations of ground-water conditions in New Jersey since the late 1920's. The U.S. Geological Survey provides technical support for ground-water regulation through cooperative and federally funded data-collection and hydrologic-investigation programs.

The N. J. Department of Environmental Protection, Division of Water Resources (NJDEP/DWR), is the primary agency responsible for managing and regulating water resources in the State. State control of surface-water use began in 1910. In 1947, the State was authorized to delineate areas where the control of diversions of subsurface and percolating waters was necessary to protect their natural replenishment (New Jersey Law 1947, c. 375). This statute required users withdrawing more than 100,000 gallons per day (gal/d) in delineated areas to obtain a permit and to report withdrawal information to the State. Another measure adopted in 1947 required well drillers to be licensed and to acquire a State permit prior to drilling a well. Since January 1981, all users of 100,000 gal/d or more of surface water, ground water, or both are required to obtain a permit and to report monthly withdrawal rates to the NJDEP/DWR.

Since 1974, the New Jersey legislature has rewritten all laws pertaining to water supply and water quality. The New Jersey Water Supply Management Act (1981), the Water Supply Bond Act (1981), and the New Jersey Water Supply Authority Act (1981) are elements of the State program to protect and manage ground-water resources. Every 5 years, NJDEP/DWR revises and updates the State Water Supply Plan. Procedures to handle emergency conditions caused by droughts are included in the Management Act.

In addition to NJDEP/DWR, other State governmental agencies have an interest in water supply. The New Jersey Water Supply Authority, established in 1981 by the New Jersey Water Supply Authority Act, controls specific State water supplies and issues bonds to finance water-supply projects. The North Jersey District Water Supply Commission, established in 1916 to provide water to counties in northern New Jersey, is one of the largest purveyors of potable water in the State. The Delaware River Basin Commission, established in 1961, has as members the Federal Government and the States of Delaware, New Jersey, New York, and Pennsylvania. In New Jersey, the Commission has regulatory responsibility over the area draining into the Delaware River and its tributaries; this area covers approximately

40 percent of the State. The agency has broad powers over the planning, development, and control of water and related natural resources of the Delaware River basin.

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CORROSIVE GROUND WATER IN THE NEW JERSEY COASTAL PLAIN

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Acidic, low-alkalinity water is corrosive to metallic substances. In the presence of corrosive ground water, metals may leach from plumbing materials into drinking water, and underground storage tanks may be breached. Corrosion indices calculated from existing water-quality data for two major aquifer systems in the unconsolidated sediments of the New Jersey Coastal Plain show that highly corrosive, low-pH (4.0 to 5.5), low-alkalinity (less than 6 milligrams per liter as calcium carbonate) ground water is widely distributed in the Kirkwood-Cohansey aquifer system, but generally is found only north of Camden County in the Potomac-Raritan-Magothy aquifer system.

Interactions of water from the Kirkwood-Cohansey aquifer system with plumbing and other metallic substances were investigated. Analyses of first-draw tap water sampled from houses in Ocean, Atlantic, and Gloucester Counties show that lead and copper concentrations commonly were greater than the concentrations of those metals in ground water. Lead concentrations in tap water exceeded 50 micrograms per liter in some samples.

Corrosion rates of copper and of carbon steel in ground water from the Kirkwood-Cohansey aquifer system were measured by corrosion probes installed in observation wells. For carbon steel, high concentrations of dissolved oxygen (10.7 milligrams per liter) combined with low pH (4.8) contributed to high rates of corrosion (greater than 0.005 inch per year). Lower rates (less than 0.001 inch per year) were measured for copper in similar water and for carbon steel in water with low concentrations of dissolved oxygen (0.13 milligrams per liter).

DETERMINING AQUIFER CHARACTERISTICS

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ABSTRACT

Because most geologic and groundwater investigations are conducted as a response to a discharge of some material to the environment, hydrologic conditions are evaluated only insofar as current environmental protection regulations require. As a result, investigations tend to focus on water quality first, with only secondary consideration of groundwater hydrology. This approach does not provide the data needed to estimate groundwater behavior, predict contaminant movement, to expand a monitoring network, or to design groundwater remediation systems. Solving these problems requires extensive understanding of an aquifer, its hydraulic parameters and aquifer responses to induced changes (pumping) - an understanding which must be derived from test results. Conducting initial investigations which yield the data needed to interpret and understand aquifer conditions, while complying with regulatory schedules and staying within the budget allotted, requires careful planning and design before field work begins.

Comprehensive approaches to groundwater studies are discussed and methods to estimate and determine aquifer parameters, while observing project restrictions, are explored. Methods include collecting hydrogeologic data which allow estimation and calculation of hydraulic conductivity, transmissivity, flow rate, well yield, potential drawdown, radius of pumping influence, and determining optimum placement of additional wells.

INTRODUCTION

The accepted approach to groundwater investigations related to contamination studies has been to install a prescribed number of monitoring wells, analyze groundwater samples, decide if there is a problem, and, if there is, install additional wells at random locations, generally down hydraulic gradient of the discharge. Determining aquifer hydraulic characteristics has only been considered if groundwater remediation is necessary, or if prediction of contaminant migration is required. At that time, a separate phase of field work is planned so the necessary data can be collected.

Rather than this unplanned approach the hydraulic properties of aquifers can be determined, within a reasonable margin of error, while installing, developing and sampling a groundwater monitoring system, with almost no impact on project schedule or budget. This paper describes the hydrogeologic observations which can be performed in the field, and which will yield sufficient data to estimate aquifer hydraulic properties. In many cases, these estimates will provide all of the hydrogeologic data needed for the investigation. When comprehensive aquifer tests are needed, the estimates can be used to design the tests and specify the equipment needed.

THE HYDROGEOLOGIC INVESTIGATION

In a strict sense, a hydrogeologic study involves investigation of the inter-relationship between the geology and aquifer hydrology of a region or area, without consideration of other parameters such as groundwater quality. Recent investigations conducted as part of contamination studies, have focussed primarily on groundwater quality with little or no consideration of aquifer characteristics.

The objectives of determining the characteristics of an aquifer are to provide a hydrogeologist with enough data to predict the direction and flow rate of groundwater through an aquifer, the amount of water in storage, the sustainable yield from a pumping well, the drawdown of the aquifer in response to pumping, and the radius of influence of a pumped well (cone of depression). The hydrogeologic parameters which must be determined are defined briefly, below.

Hydraulic Gradient: The change in vertical head over a known distance (between two observation points), usually expressed in ft/ft

$$I = \frac{h_1 - h_2}{L}$$

Where h_1 and h_2 are static water elevations at two measured observation points and L is the linear distance between the two points.

Hydraulic Conductivity: The amount of water which will pass through a unit cross section of an aquifer in a unit period of time, under a hydraulic gradient of 1 (100%), expressed in gallons per day per square foot (gpd/ft^2).

Transmissivity: The amount of water which will pass through a unit section of the aquifer and extending the entire vertical thickness of the saturated zone, under a hydraulic gradient of 1.

Coefficient of Storage: The volume of water taken into, or released from storage, per unit change in head per unit area.

These hydrologic parameters are determined by conducting physical tests on an aquifer (pump tests or slug tests) after wells are installed. The tests induce a stress on the aquifer by either removing or injecting water. The response of the aquifer to the stress over time is measured and interpreted to calculate the hydraulic characteristics. Various types of aquifer tests, the methods to conduct them and interpretation of the resulting data are described in great detail in numerous works (Driscoll, 1986, Kruseman and DeRidder, 1989, Walton, 1988) to which the interested reader is referred.

To design aquifer tests, a geologist must estimate certain hydrologic parameters, and, if possible, measure some of the physical characteristics of the hydrogeologic skeleton of the aquifer to improve any pre-test estimation. A high degree of training or experience in hydrogeology is not needed to collect the data needed, but the interpretation of test results requires both.

DESIGNING A HYDROGEOLOGIC STUDY

Because most groundwater investigations are conducted in response to a spill or discharge (such as an underground storage tank leak) the number and approximate location of initial monitoring wells are determined by regulation rather than science. Although this approach is often limiting, in that there is little flexibility in siting wells, more wells will usually be required if contamination is identified. To prepare for this later work, and to assure that any subsequent wells will be installed in locations which complement the system properly, hydrogeologic data should be gathered while installing, developing and sampling the initial wells. This will avoid a costly and time consuming test period after well installation. The measurements and observations needed to make hydrogeologic determinations are conducted during well installation, well development and during subsequent monitoring.

Hydrogeologic Measurements During Well Installation

Drilling monitoring wells for contaminant studies in New Jersey (see Brown, 1990) involves soil sampling at various depths in the borehole to determine the presence or absence of contamination. In addition to these samples, a geologist will usually collect samples at some regular interval to identify stratigraphy.

For hydrologic purposes, at least two samples from the saturated zone should also be retained for grain size distribution analysis, and porosity determination. Masch and Denny, 1966, Shepard, 1989, and Driscoll, 1986, describe methods by which hydraulic conductivity can be estimated using grain size distribution, expressed as a percent of the sample which is either passed or retained by various mesh sizes in a stacked sieve column. Other methods to determine hydraulic conductivity are discussed in later sections of this work.

To calculate transmissivity, the saturated thickness of the aquifer must be known. At least one boring should be drilled through the entire saturated thickness of the aquifer, and a complete stratigraphy should be determined. Having a complete stratigraphy will help in interpreting data collected during groundwater sampling/testing, and can be used with the grain size distribution data to select proper gravel pack and screen slot size to maximize well efficiency.

At least one monitoring well should be screened across the entire saturated thickness of the aquifer. Aquifer tests conducted in fully penetrating wells are easier to interpret than those using partially penetrating wells. Using a fully penetrating well is also more conducive to conducting full pump tests if the number and spacing of observation points are limited.

Determining groundwater flow directions and pathways in bedrock aquifers is difficult to estimate, and usually relies on sparse structural geology data regarding fracture/joint/fault orientations. When installing bedrock wells at least one borehole should be cored, and oriented core samples should be collected to determine the orientation of fractures, joints, faults and bedding planes, if present. Also, after each rock well is installed, an automatic water level recorder should be installed and operated during drilling and developing of all subsequent wells. Any fluctuation in water levels recorded in the existing wells during installation of another well will indicate a hydraulic connection, and the attitude of at least one joint/fracture is established.

Hydrogeologic Measurements After Well Installation

After wells are installed they must be developed to ensure that the aquifer matrix is not permanently impacted by the drilling process. Well development involves pumping water from a well, or surging compressed air into the casing. The objective is to clear the matrix of the aquifer of any foreign material introduced during drilling. As a result, development induces a stress on the aquifer, much the way an aquifer test does. To achieve preliminary estimates of hydraulic parameters, well development can be treated as an aquifer test. Discussion of various development techniques are beyond the scope of this work. The interested reader is referred to Driscoll, 1986.

Wherever possible, wells should be developed by pumping rather than air purging because pumping produces a steady discharge and drawdown. The static water level should be measured in all wells before development begins. This establishes the datum against which subsequent measurements are compared.

Because the wells will not yet be developed while they are being pumped, well efficiency will be reduced, so the results of the test should not be considered absolute. However, when the pump is turned off, development is complete and the recovery of the piezometric surface to static level can be measured, over time (rising head recovery test).

In wells which are not fully penetrating only a rising head recovery test should be conducted. After the development pump is turned off it should be removed from the water column immediately. Head recovery measurements should be made with automatic equipment unless recharge is slow. Pump tests in these wells will suffer from the effects of partial penetration. This problem is compounded by the close well spacing common in contamination studies.

If the pumped well is fully penetrating, it is possible to conduct a pump test. In this test, the well is pumped at a known discharge rate and drawdown is measured in the other monitoring wells. The drawdown data are plotted on distance/drawdown and time/drawdown plots, and the various hydraulic parameters can be calculated. After pumping is complete, rising head recovery measurements should be collected to achieve a better estimate of aquifer parameters. This, again, is important because until the well is developed aquifer conditions around the pumping well will not represent ambient conditions accurately.

If wells have an extremely low yield and are easily pumped dry, development will likely be conducted by hand bailing or using compressed air. It is still possible to conduct rising head recovery tests by evacuating all water from the well and measuring the rate of recharge to static water level. If well development proceeds rapidly and if the aquifer is not complicated hydrogeologically, this test might suffice for all future requirements.

Hydrogeologic Measurements After Well Development

Once the wells are developed, the depth to groundwater from a surveyed datum on each well is measured to determine the direction of groundwater flow. Using these measurements the hydraulic gradient can be determined. However, unless the two wells used to measure the gradient are parallel to groundwater flow the true gradient must be calculated from the apparent gradient (see Ragan, A Manual of Structural Geology, for applicable techniques).

Many times a geologist will inherit a groundwater monitoring system which was installed during an earlier phase of an investigation by another geologist or another geological firm. When this is the case, one does not have the opportunity to collect the hydraulic data as the project proceeds. Rather, the data must be gleaned from drillers' boring logs, well construction summaries or well permits. During this research one must determine the depth of each well, the length of the well screen and whether any well penetrates the entire saturated thickness of the aquifer. If this information can not be determined one borehole should be drilled to determine the aquifer thickness and to verify the stratigraphy which was originally compiled by someone else. (New Jersey Department of Environmental Protection, Division of Water Resources requires a separate well permit for borings greater than 25 feet below grade.)

In many instances, wells are not developed adequately, or they might collect silt in the screened interval. To avoid generating erroneous data the wells should be re-developed. Re-development will also provide the opportunity to collect some of the data discussed earlier.

SUMMARY

By collecting hydrogeologic data while performing tasks which are routinely completed during groundwater investigations, a hydrogeologist can address most situations which require solutions to hydrologic problems, without remobilizing field crews to conduct additional tests. Except in complicated aquifers, or situations which require numerical simulation, the estimates which can be made from the measurements described in this work will be sufficient to estimate contaminant migration, to locate additional wells and even to design groundwater recovery or interceptor systems. These estimates can also be used to design aquifer tests which will yield specific data required for any situation, without needing a trial-and-error period of test start-up.

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HYDROGEOLOGY OF THE EARLY MESOZOIC ROCKS OF THE NEWARK BASIN,NEW JERSEY

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ABSTRACT

The Newark basin formed as a continental rift associated with the opening of the Atlantic ocean during late Triassic and early Jurassic time. The basin was filled in succession with arkosic sandstone deposited by braided streams (Stockton Formation), gray and black siltstone, mudstone, and argillite deposited in lake and lake margin environments (Lockatong Formation), and red siltstone sandstone, and mudstone deposited in fluvial and playa lake settings, and lava flows (Brunswick Group). Recent field mapping in the Newark basin has produced a highly detailed picture of both structure and lithofacies.

Diverse rock types in the Newark basin have highly variable hydrologic properties. Coarser sandstones can have significant primary porosity, whereas much of the finer-grained, well-cemented sedimentary rocks and the igneous rocks have mainly secondary, fracture porosity. Fracture porosity in sedimentary rock sequences is controlled by the thickness of beds with either closely spaced bedding plane fractures or primary porosity; these aquifers are bedding-parallel and form dipping tabular aquifers. Most aquifers in the basin are semi-confined; shallow aquifers are commonly unconfined.

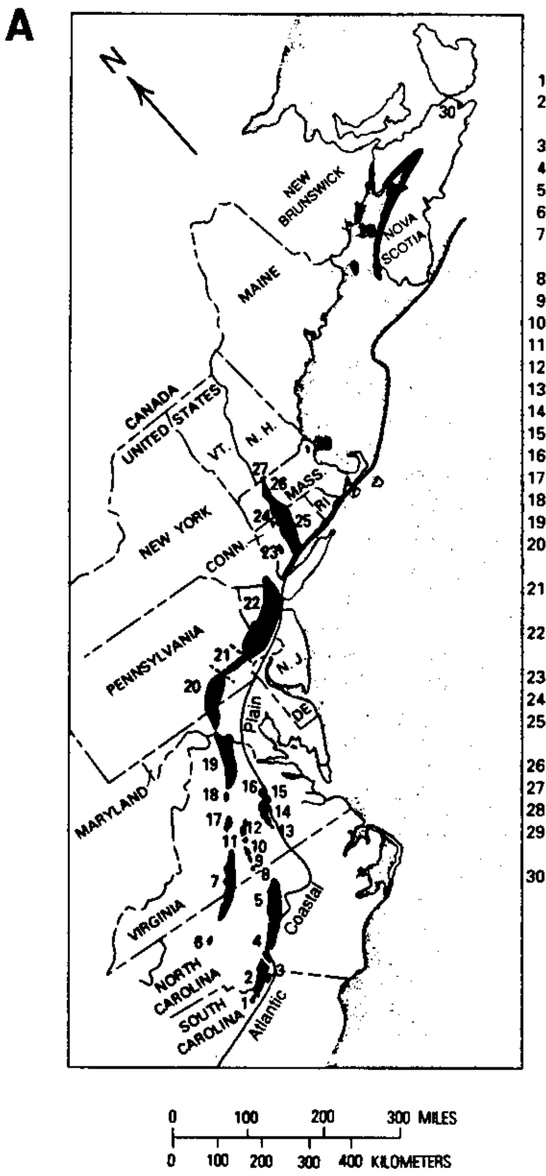
INTRODUCTION

Geologic Setting

The Newark basin is an elongate (130 by 35 miles) northeast-southwest trending fault trough filled with fluvial and lacustrine sediments of latest Triassic and earliest Jurassic age (Figs. 1,2; Cornet, 1977; Olsen, 1986), and basalt flows and diabase sills and dikes of early Jurassic age (Seidemann et al., 1984; Dallmeyer, 1975). Beginning in early Mesozoic time, the basin developed as part of a series of inland rifts parallel to ocean-floor forming rifts along which the North Atlantic oceanic crust was generated (Van Houten, 1977). A series of these rift basins developed along the eastern seaboard of North America, from Florida to Nova Scotia (Fig. 1). Sediments that accumulated within these basins have been assigned to the Newark Supergroup (Olsen, 1978).

Stratigraphic Units

The first comprehensive study of the stratigraphy of the Newark basin was by Kummel (1897, 1898), who named the three principal Triassic formations (Stockton, Lockatong, and Brunswick). Since 1977, the names of the Jurassic units have been under revision as a result of work done on pollen (Cornet, 1977) and vertebrate fossils (Olsen, 1980a; Olsen et al., 1982). The revised nomenclature of Olsen (1980a) has gained general acceptance in academic usage and is becoming more widely used by the general public. The present status of names for the Newark basin rock units is given below (Table 1).



EXPLANATION

1. Crowburg basin, South Carolina
2. Wadesboro basin, South Carolina-North Carolina
3. Ellerbe basin, North Carolina
4. Sanford basin, North Carolina
5. Durham basin, North Carolina
6. Davie County basin, North Carolina
7. Dan River-Danville basin, North Carolina-Virginia
8. Scottsburg basin, Virginia
9. Randolph basin, Virginia
10. Roanoke Creek basin, Virginia
11. Briery Creek basin, Virginia
12. Farmville basin, Virginia
13. Richmond basin, Virginia
14. Flat Branch basin, Virginia
15. Deep Run basin, Virginia
16. Taylorsville basin, Virginia
17. Scottsville basin, Virginia
18. Barboursville basin, Virginia
19. Culpeper basin, Virginia-Maryland
20. Gettysburg basin, Maryland-Pennsylvania
21. The narrow neck of the Newark-Gettysburg basin, Pennsylvania
22. Newark basin, Pennsylvania-New Jersey-New York
23. Pomperaug basin, Connecticut
24. Cherry Brook outlier, Connecticut
25. Hartford basin, Connecticut-Massachusetts
26. Deerfield basin, Massachusetts
27. Northfield basin, Massachusetts
28. Middleton basin, Massachusetts
29. Fundy basin, New Brunswick-Nova Scotia
30. Chedabucto Bay, Nova Scotia

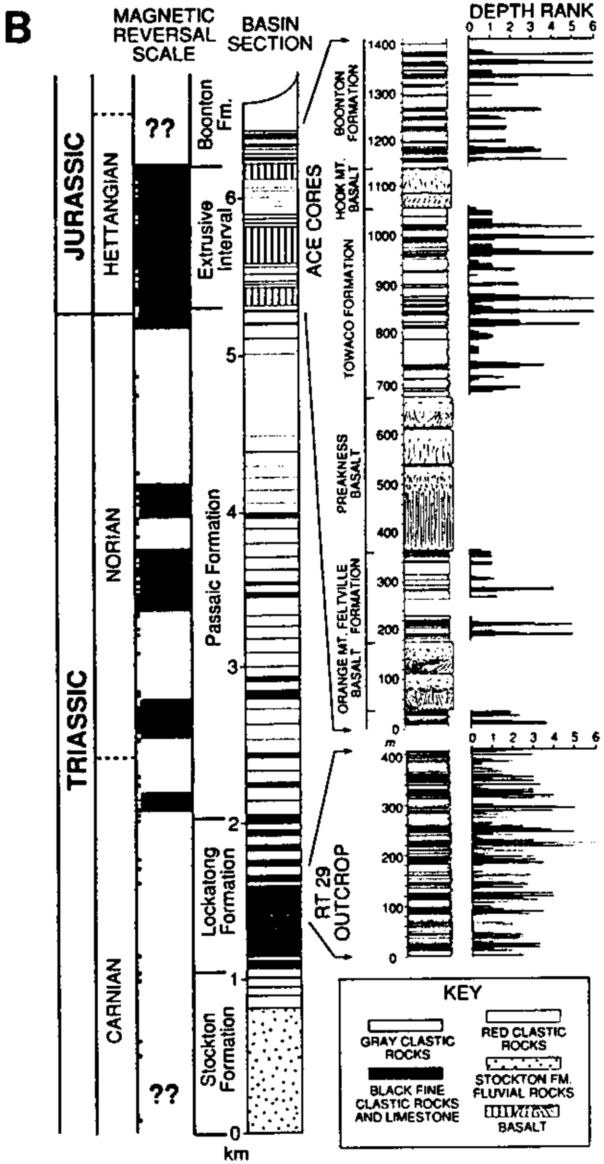


Figure 1. The Newark Supergroup and stratigraphic data for the Newark basin. A. Location map of Early Mesozoic basins of eastern North America, from Luttrell (1989). B. Stratigraphic data columns for the Newark basin, from Olsen and Kent (1990). ACE refers to Army Corps of Engineers cores.

TABLE 1
STRATIGRAPHIC NOMENCLATURE IN THE NEWARK BASIN

Kummel, 1898	Olsen, 1980	USGS Geologic Names Committee, 1985	
		Brunswick Group:	
Brunswick Shale	Boonton Fm.	Boonton Fm.	
Third Watchung Mt.	Hook Mt. Basalt	Hook Mt. Basalt	
Brunswick Shale	Towaco Fm.	Towaco Fm.	
Second Watchung Mt.	Preakness Basalt	Preakness Basalt	
Brunswick Shale	Feltville Fm.	Feltville Fm.	
First Watchung Mt.	Orange Mt. Basalt	Orange Mt. Basalt	JURASSIC
Brunswick Shale	Passaic Fm.	Passaic Fm. or "Brunswick Group, undivided"	TRIASSIC
Lockatong Argillite	Lockatong Fm.	Lockatong Fm.	
Stockton Arkose	Stockton Fm.	Stockton Fm.	

Recent mapping in the Newark basin in New Jersey for a revised State geologic map by geologists from the New Jersey and U.S. Geological Surveys has resulted in a detailed picture of both lithofacies distribution and structural framework of the basin (Fig. 2). The distribution of gray lakebed sequences in the Passaic Formation reveals details of the mostly open folds in three main fault blocks of the Newark basin in New Jersey. Tighter folds occur in the vicinity of major fault zones. Broad regional warping occurs within each of the intrabasinal fault blocks. The major fault systems are more complex than previously depicted, and consist of parallel and en echelon segments, splays, and braided systems with both synthetic and antithetic displacements.

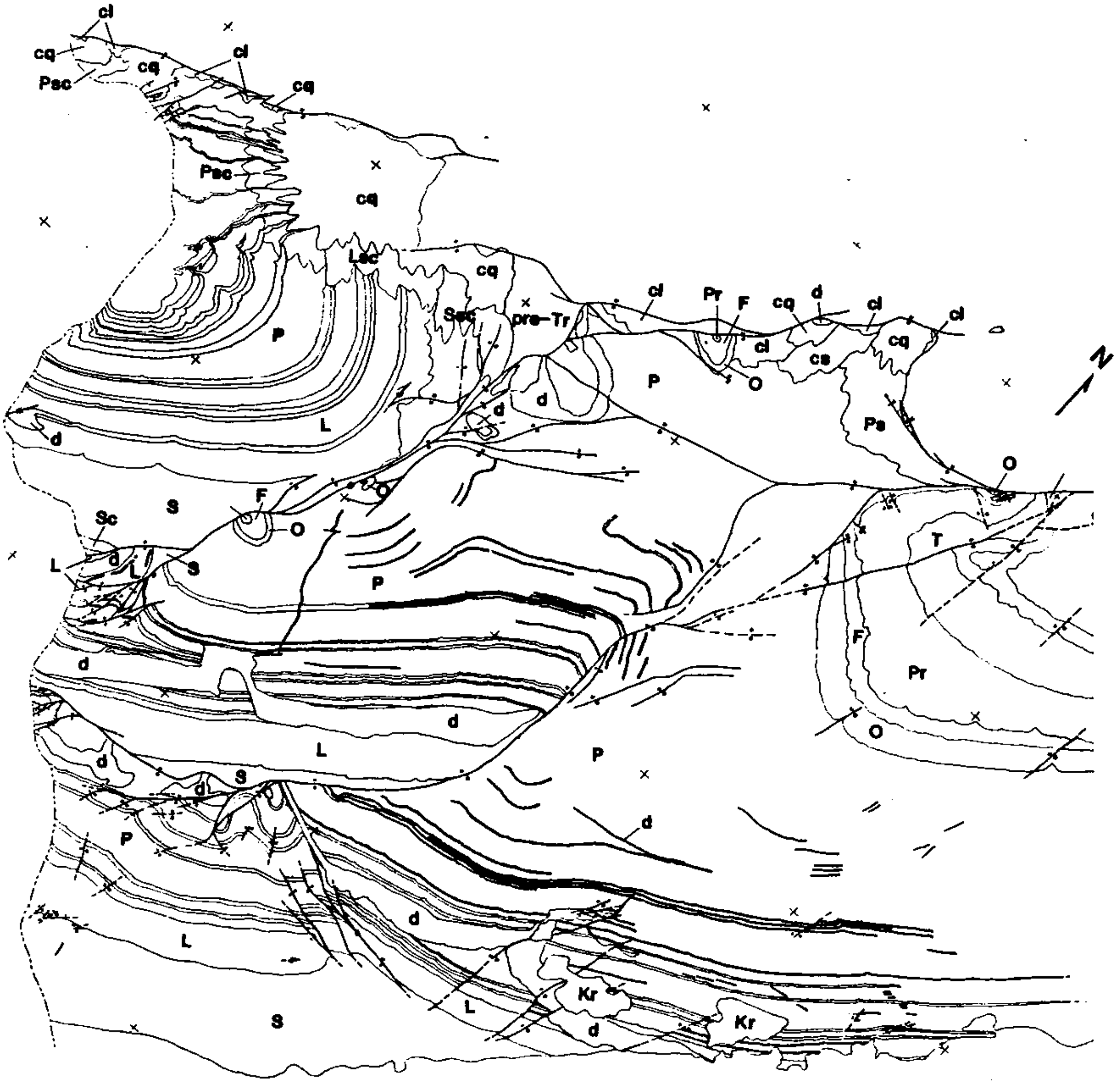


Figure 2. Draft geologic map of the New Jersey part of the Newark basin. Data compiled from unpublished field maps of Kummel (1897b), Parker (1990), Houghton (1990), Herman (1990), interpretations of bedrock elevation data by Stone (1990), and published geologic quadrangles (Drake et al. 1961, 1967). Lithologic unit abbreviations are: B - Boonton Formation, cb - basalt-clast conglomerate, cg - gneiss-clast conglomerate, cl - limestone-clast conglomerate, cq - quartzite-clast conglomerate, cs - shale-clast conglomerate, d - diabase, F - Feltville Formation, H - Hook Mountain Basalt, Kr - Raritan Formation, L - Lockatong Formation, La - Lockatong Formation arkosic sandstone facies, Lsc - Lockatong Formation sandstone and conglomerate, O - Orange Mountain Basalt, P - Passaic Formation, Pc - Passaic Formation quartz pebble conglomerate and pebbly sandstone, Pr - Preakness Basalt, Ps - Passaic Formation sandstone, Psc - Passaic Formation sandstone and pebble conglomerate, S - Stockton Formation, Sc - Stockton Formation quartz pebble conglomerate, Ssc - Stockton Formation sandstone and quartz pebble conglomerate.

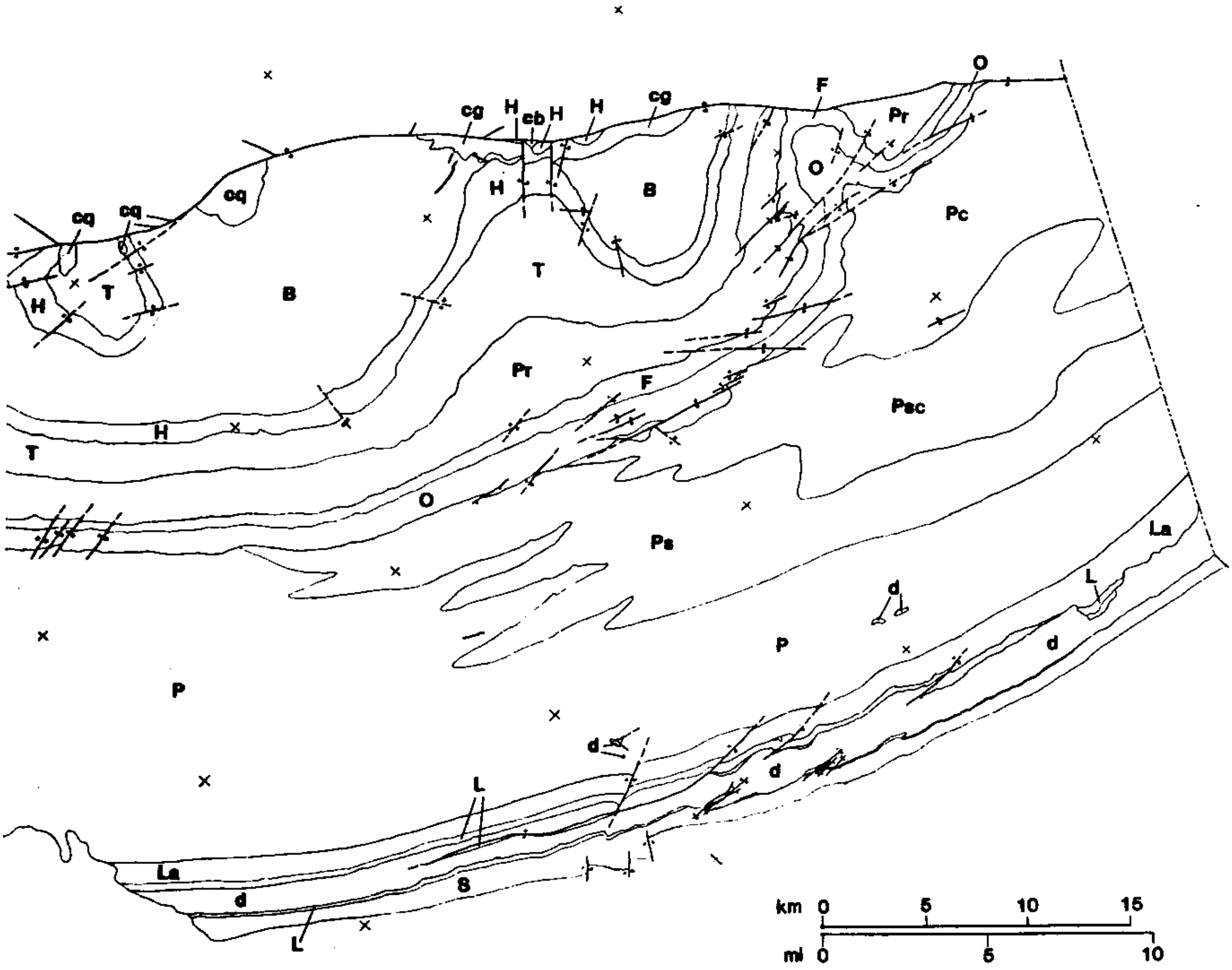


Figure 2. (Cont'd)

Two stratigraphic columns are depicted for the Newark basin in figure 3. Figure 3a is a composite of the Delaware River section, originally measured by McLaughlin (1945) and modified by recent well-record data (discussed below). Only the lower part of the Passaic Formation is preserved in the Delaware River section, along with the Lockatong and Stockton Formations. The complete Passaic Formation exposed east of the Flemington fault is about 10,000 feet thick. Figure 3b represents the stratigraphy north of New Brunswick, where the entire late Triassic and early Jurassic section is present. The vertical scale varies in the two stratigraphic columns.

GEOLOGY

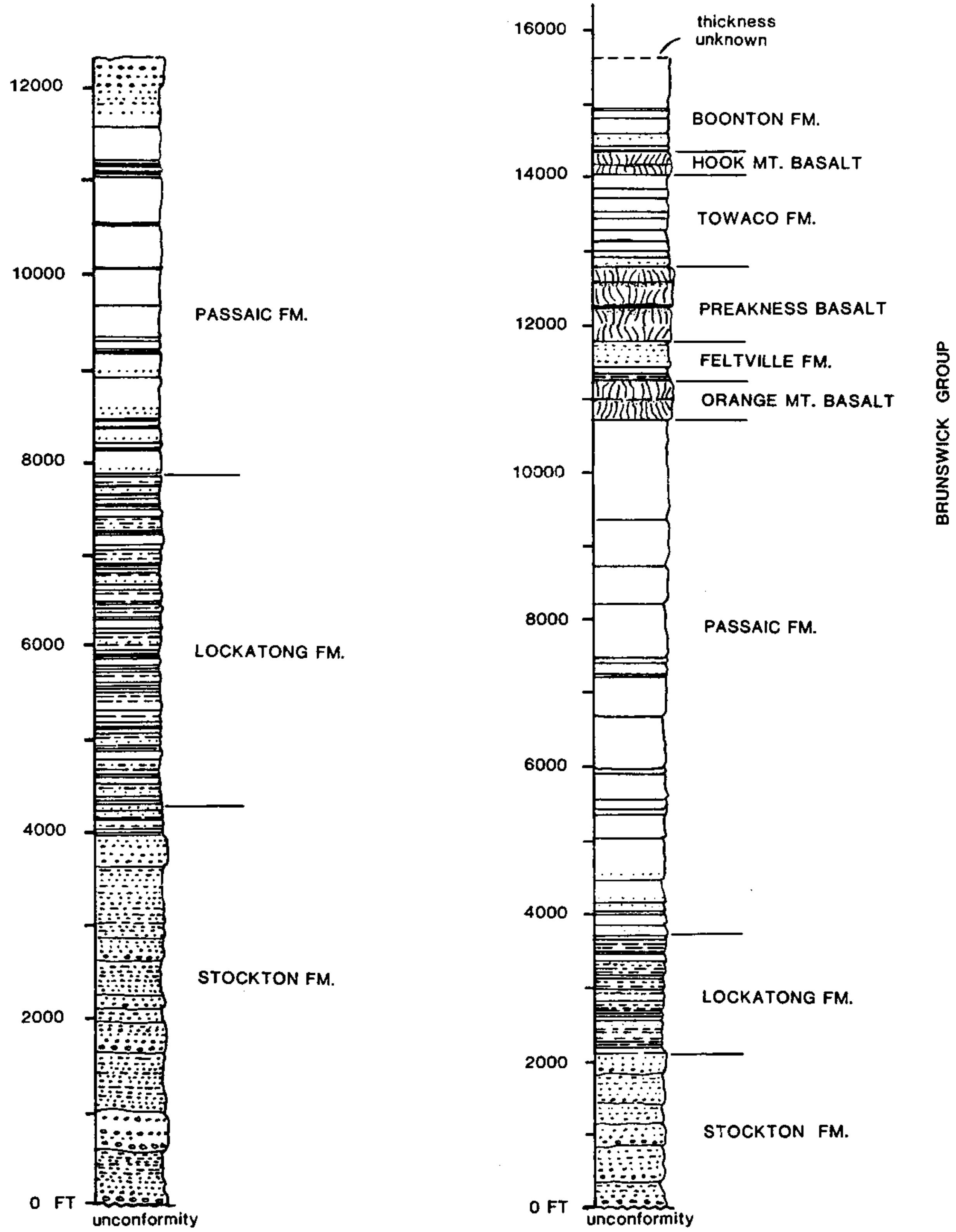
Stockton Formation

Lithology

The Stockton Formation consists of three main lithologies. In order of decreasing abundance they are arkosic sandstone, red siltstone and mudstone, and light-colored conglomerate.

The characteristic rock type of the Stockton Formation is feldspathic sandstone or arkose, typically medium to coarse grained, buff or tan colored, thick-bedded, with medium to large-scale cross bedding. The coarse sandstones are moderately sorted and contain sand grains which are texturally immature (sub-angular to sub-rounded) and mineralogically immature (abundant fresh feldspar).

The sandstones are channel deposits of streams which trans-



a. Triassic stratigraphy, central Newark basin. Modified from Van Houten (1969).

b. Composite stratigraphic section, north-central Newark basin.

Figure 3. Generalized stratigraphic sections, Newark basin. Diabase sills not depicted.

ported sediment mainly as bedload, as indicated by coarseness and moderately good sorting of grains and by abundance of low-angle trough cross-beds. Stacks of channel deposits up to tens of meters thick are common. The base of channel-fill sequences are in some places marked by shale rip-ups, undulating scour surfaces, or pebble lags. Tops of channel fill sequences may consist of burrowed micaceaous siltstone or cross-laminated very fine grained sandstone.

Overbank and floodplain deposits of the Stockton consist of reddish-brown, fine-grained sandstone interbedded with ripple cross-laminated, burrowed, and mudcracked siltstone and silty mudstone. Floodplain deposits of the Stockton Formation are indistinguishable from floodplain facies of coarser-grained fluvial sequences of the Passaic Formation. Floodplain deposits in the Stockton Formation are increasingly abundant near the center of the Newark basin and toward the top of the formation.

Distribution and Thickness

The Stockton Formation is the basal sedimentary sequence throughout the Newark basin. The formation reaches a maximum thickness of 4100-5000 feet in the Hunterdon plateau fault block along the Delaware River, and thins to less than 1000 feet near the northeast end of the basin in New York State. The Stockton is overlain by the Lockatong Formation throughout most of the basin, except in the area north of Alpine, New Jersey, where the Lockatong Formation pinches out (Fig 4.). In this region the Stockton and Passaic Formations are in gradational contact.

Light-colored arkose indistinguishable from Stockton Formation sandstone occurs in detrital-type cycles of the Lockatong Formation in the northern Newark basin, where they were mapped as part of the Stockton Formation by Kummel (Lewis and Kummel, 1912). These beds are now being mapped as an arkosic sandstone member of the Lockatong Formation.

Lockatong Formation

Lithology

The base of the Lockatong Formation is marked by the sudden appearance in the stratigraphic column of gray to black siltstone beds. The drab (green, gray) or black bedding sequences were deposited in lakes, lake margin mudflats, or deltas. Lake sequences occur in discrete units which record the periodic flooding and drying out of the lake basin. The rhythmic alternation from humid to arid climatic conditions recorded in the Lockatong sequence has been described at length by Van Houten (1962, 1964) and by Olsen (1980b, 1984).

Van Houten (1962) identified two fairly distinct types of lake cycles in the Lockatong. The differences between so-called "detrital" cycles and "chemical" cycles are many, but most are subtle and not easily seen in outcrop. The most apparent difference is in thickness. Detrital cycles average 5 meters (17 feet) thick, while the average chemical cycle is only 3 meters (10 feet) thick.

Studies by Olsen (1980a,1980b) in the Newark basin, and Houghton (1984) in the Culpeper basin show that lake sequences can be divided into three parts which record (1) transgression of fluvial and lake facies, (2) lake-bottom deposition, and (3)

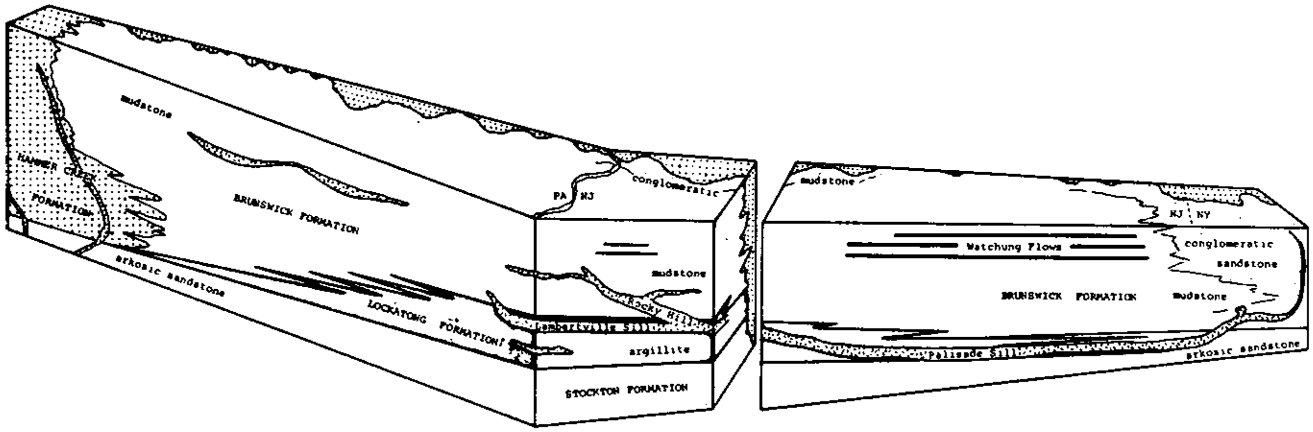


Figure 4. Schematic block diagram of lithofacies and formations of the Newark basin, from Van Houten (1969). Shown as restored before faulting; view looking toward the northwest.

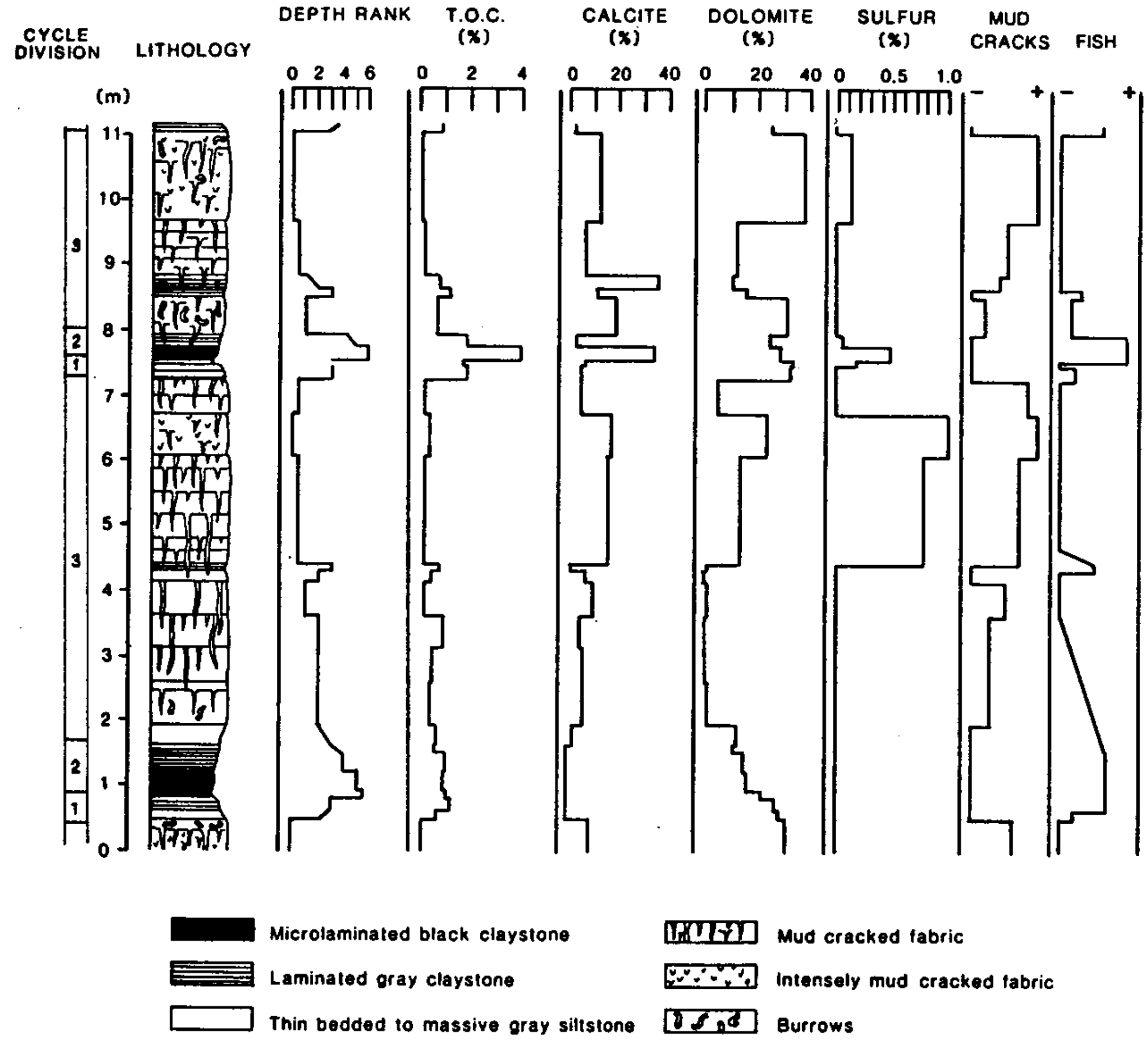


Figure 5. Major features of Lockatong detrital cycles, slightly modified from Olsen (1986).

regression of lake facies (Fig. 5). Division 1 usually begins with deposition of drab sandstone beds (green to olive-tan, gray, or purplish-gray) containing shallow-water sedimentary structures such as cross-lamination or disturbed bedding. Desiccation cracks are common in the upper part of division 1. During the next stage, the lake basin fills with water; the lake water is mostly fresh during "detrital" lake episodes and mostly saline during "chemical" lake depositional cycles. Filling of the lake basin is accompanied by the deposition of dark gray to black mudstone to claystone, often thinly laminated (division 2). The second division corresponds with optimum trophic conditions in the lake: the water was at its lowest salinity and highest nutrient content. Division 2 beds vary in character, depending on how deep, fresh, and eutrophic the lake became during that particular climate cycle.

The upper part of lake cycles (division 3) records a drying out of the lake, with abundant mudcrack breccias, massive bioturbated siltstones, and often fine-grained sands or silts deposited in delta complexes which prograded over the dry lake plain. A modified version of Olsen's (1986) figure shows the three divisions of a typical detrital-type cycle (Fig. 5).

An important aspect of the Lockatong facies, from the applied geology standpoint, is the occurrence of "argillite" beds. These are extremely hard, chemically-cemented siltstones (cemented with dolomite and/or calcite, mixed-layer clays, and in some beds, analcime). Argillite beds are abundant throughout the Lockatong sequence; they occur mostly in division 3, above the laminated lake-bottom beds. In thick detrital cycles, massive argillite beds can range up to 5-8 meters thick or more. Fractures are very sparse in these beds, resulting in generally poor ground-water yields.

Distribution and Thickness

The Lockatong Formation crops out in three belts. The southern belt runs from Wilburtha, north of Trenton, nearly to the New York State line. The Lockatong Formation thins from about 3100 feet near Trenton, to less than 300 feet thick north of Fort Lee, New Jersey where the narrow outcrop belt flanks the Palisades diabase sill. Lockatong beds cannot be traced as far north as the NJ-NY boundary; apparently they pinch out somewhere north of Alpine, NJ. The central (Hopewell fault block) belt forms part of Sourland Mountain and, where the Sourland-Lambertville sill cuts up-section, underlies uplands south of the diabase ridge. Kummel (1897) reports a thickness of 3,630 feet for the Lockatong Formation in the vicinity of Sourland Mountain. This estimate may not have been corrected for the effects of faulting. The Lockatong Formation reaches a maximum thickness of 3515 feet in the Chalfont-Flemington fault block. In the New Jersey part of the fault block, the Lockatong Formation crops out in an arcuate belt from the Delaware River near Byram to the border fault north of Pittstown. The thickness reported here is taken from the record of a "new field wildcat well" drilled in Nockamixon Township, Pennsylvania in 1985. This was drilled as an exploratory gas well; it was a dry hole. Total depth reached was 10,500 feet. A summary of the formation log for this well is given below.

Depth	Formation	Thickness	Comment
Surface-2925 ft.	Passaic	2925 ft.	Water from 0-600 ft.
2925-6440 ft.	Lockatong	3515 ft.	
6440-10500 ft.	Stockton	4060 ft.	

The well record does not indicate whether the entire thickness of the Stockton Formation was penetrated; if it was, the thickness of the Stockton Formation at this point (403230N/750730W) is 4060 feet (bedding is essentially horizontal at this locality).

Passaic Formation

Lithology

The contact between the Lockatong and the overlying Passaic Formation is defined as the horizon at which red beds make up more than 50% of the section. Gray beds decrease in frequency near the top of the Lockatong Formation until the section is about 50/50 gray/red beds. Above the highest gray beds in this mixed color interval the rocks are almost entirely red for nearly 1000 feet. Gray lacustrine sequences occur higher up in the Passaic Formation in the central Newark basin, notably in the Graters and Perkasie Members of McLaughlin (1959). The lake intervals become thinner toward the northeast, but can be traced as far as the New Brunswick area.

Sedimentary cycles driven by periodic climatic change can be identified throughout most of the Passaic Formation in the central Newark basin. The cycles are not easily seen because color changes are subtle or lacking in most sequences. Variation from dry to wet climate is expressed as assemblages of sedimentary structures formed in dry playas, floodplains, and playa lakes. Dry environments produced mostly massive-appearing red mudstone; wet environments produced laminated siltstone and mudcrack breccia. Laminated parts of cycles in the Passaic Formation may be red-brown, or can range in color from purple to greenish gray, gray, or black. Cycle thickness in the Passaic Formation is on the same scale as Lockatong cycles, generally 2-8m (about 6-25 feet). Cycles become less apparent in the upper Passaic Formation, where color variations are rare and massive-looking, highly fractured, irregularly fissile mudstone is the predominant lithology.

In the northern part of the Newark basin the Passaic Formation consists mostly of fine to coarse sandstone. The predominance of relatively energetic fluvial environments indicates that higher stream gradients persisted in the northern basin during late Triassic time. The Passaic Formation in the northern Newark basin has been divided into four informal stratigraphic units (Fig. 2) which are mappable on the basis of lithology (Parker et al., 1988). These units consist mainly of, in ascending order:

1) siltstone and mudstone, with subordinate sandstone,
2) sandstone - fine to medium grained, commonly trough cross-bedded in fining-upward cycles 1.5 to 5 m thick,
3) pebbly sandstone - medium to coarse sandstone with pebbles in scour lags at the base of fining-upward cycles
4) conglomeratic sandstone - coarse conglomeratic sandstone

and bedded conglomerate.

A similar sequence of lithofacies was mapped in the northern end of the Newark basin in New York by Savage (1968).

Distribution and Thickness

The areal distribution of the Passaic Formation is similar to that of the two underlying units, forming three belts bounded on the northwest by the Hopewell, Flemington, and border faults. In the northern Newark basin, the Passaic Formation is bounded to the northwest either by the Orange Mountain Basalt or by the Ramapo fault (Fig. 2).

The total thickness of the Passaic Formation can only be calculated where it is overlain by the Orange Mountain Basalt. Along the Delaware River, the upper part of the Passaic Formation is cut off by faults or has been disrupted by intrusion of diabase. The previously mentioned exploration gas well in Bucks County, Pennsylvania penetrated 2925 feet of Passaic Formation, stratigraphically below the Coffman Hill diabase. There may be several hundred more feet of Passaic beds above the sill in this region, for a total of about 3500 feet. The high structural relief of the Chalfont-Flemington fault block resulted in erosional stripping of about 6000 thousand feet of the Passaic Formation in this area.

In the Hopewell fault block, there is a continuous sequence of Passaic Formation extending from the north slope of Sourland Mountain to either the lower basalt flow at Sand Brook or the basalt flow at Flemington. The geometrically calculated thickness of the formation in that area, based on dip measurements, is in the range of 9800 feet (Sourland to Sand Brook) to 11,000 feet (Sourland to Flemington). The Flemington fault zone east of Flemington probably repeats the uppermost part of the Passaic Formation, which means the actual thickness is close to the lower number.

Farther north, the Passaic Formation thins to less than 8000 feet. Between the Orange Mountain flow at Plainfield and the base of the Passaic Formation in Highland Park, the dip of the bedding is relatively uniform, averaging about 10 degrees. This gives a maximum thickness of about 7800 feet, without accounting for faulting.

Jurassic Formations

The early Jurassic formations of the Newark basin consist of three basalt flow units, each made up of two to four individual flows, and three sedimentary rock sequences overlying the basalts. Each of the six units has been given formation status. Rock cores made by the Army Corps of Engineers in 1984-86 for the proposed Passaic River diversion tunnel have given an accurate picture of the lithology and thickness of the units.

Orange Mountain Basalt

The Orange Mountain Basalt forms the base of the Watchung syncline and is composed of two major flows, each about 265 feet thick with thin (0-15 feet) interbedded volcaniclastics and, in some places, red siltstones (Michael S. Fedosh, Army Corps of Engineers, New York, spoken communication, 1987). Smaller outlying basalt flows with the same chemical composition as the Orange Mountain flow occur at Oldwick, Flemington, and Sand Brook, New Jersey, and at Jacksonwald, Pennsylvania (Geiger et al., 1980).

Feltville Formation

Sedimentary rocks overlying the Orange Mountain Basalt have been named the Feltville Formation after that locality along Green Brook in the east-central Watchung syncline. The poorly exposed 18-meter-thick type section contains about 70% siltstone, mostly red, and 30% buff, gray, and red sandstone, medium to fine grained. There is a small amount of limestone and gray to green shale in the type section, which is near the bottom of the formation. The middle and upper part of the Feltville Formation contains much hard brownish-red to pinkish-tan sandstone, usually arkosic and commonly trough cross-bedded. There are numerous small quarries in the Feltville Formation from which building stone was formerly taken.

The Feltville Formation is reported by Olsen (1980a) to average 170 meters (560 feet) thick. Core recovery shows a thickness of about 510 feet in the northern Watchung syncline (Fedosh, 1986). Red beds overlying smaller basalt flows in the Newark basin have been correlated with the Feltville Formation on the basis of position and palynology (Cornet, 1977; Olsen, 1980a).

A bed of black carbonaceous limestone near the base of the formation varies from 0-6 feet thick and contains thermally mature hydrocarbons. This layer constitutes an oil-prone source rock. Analysis of this material was largely responsible for a flurry of exploration activities by major and minor oil companies in the mid-1980s.

Preakness Basalt

The Preakness Basalt consists of three major flow sequences which are geochemically distinct (Puffer, 1989). The lower flow is about 475 feet thick and is overlain by 10 to 30 feet of sedimentary rock, mostly red siltstone. The second flow is about 450 feet thick; the third flow is about 90 feet thick. The total thickness of the Preakness Basalt is about 1030 feet (Fedosh, 1986).

Basalt in the Preakness Formation is highly variable in texture and minor structures, but generally has more extensive columnar jointing than the Orange Mountain Basalt. The basal 65 feet of the first flow is commonly highly vesicular or brecciated. The upper 5-20 feet of each flow is highly vesicular.

Red siltstone beds above the first series of flows have been mapped along part of the basalt outcrop belt. The siltstone was apparently deposited on an irregular or undulating surface on top of the first Preakness flows.

Towaco Formation

The Towaco Formation comprises about 1250 feet of red siltstone, gray and buff sandstone, and black, gray, and green calcareous siltstone (Fedosh, 1986). Much of the section is composed of fining-upwards cycles of buff to gray sandstone and red siltstone 6-16 feet thick (Olsen, 1980a). Well-laminated dark gray to black carbonaceous lake beds 1.5 to 16 feet thick occur singly or in clusters throughout most of the formation.

These beds contain mature to immature hydrocarbons and differ from the Feltville lake beds in the predominance of quartz siltstone, rather than limestone.

Hook Mountain Basalt

The third series of basalt flows in the Watchung syncline forms the S-shaped Hook Mountain folds and folded ridges in the Bernardsville area, including the New Vernon anticline. The total thickness of the Hook Mountain basalt is about 280 feet, comprised of two geochemically distinct flow sequences (Puffer, 1988). Tops of flows are brecciated and have textures indicating weathering and paleosoil development (M. S. Fedosh, spoken communication, 1987). The Hook Mountain flows are not continuously exposed, but aeromagnetic data indicate their continuity in the subsurface (Henderson et al., 1966).

Boonton Formation

The sedimentary rocks overlying the Hook Mountain flows are named after the type section on the Rockaway River east of Boonton, New Jersey. Outcrops of the Boonton Formation are predominantly purplish or brownish-red fine sandstone and siltstone in indistinctly laminated fining-upward cycles. Also present are numerous thin (1-6 feet) greenish-gray to olive silty mudstone beds, a few gray to brown sandstone and conglomerate beds, and at least one lake sequence with a one-meter-thick black, calcareous siltstone laminite containing fish fossils (the "Boonton Fish Bed") which occurs near the middle of the section given by Olsen (1980a).

Olsen (1980a) estimates the thickness of the Boonton Formation to be 1600 feet or greater. Core data do not constrain thickness estimates for the Boonton Formation.

Within one mile of the Ramapo Fault, conglomerates are a prominent feature of the Boonton Formation. Conglomerates with pebbles to cobbles of gneiss, basalt, and quartzite in a red sandstone and siltstone matrix occur at Montville, New Jersey. These deposits contain well-graded pebble to silt layers with ripple lamination at the top, interpreted as sheet flood units, and thick, poorly sorted beds representing debris flows. This facies association is interpreted as an alluvial fan sequence (Manspeizer, 1980).

Diabase

Diabase occurs in the Newark basin predominantly in the form of nearly concordant, thick (1000 to 1500 feet in most places) sills. The Palisades sill extends from the northernmost end of the Newark basin (where it becomes discordant near its terminus) to Monmouth Junction, where it again becomes somewhat discordant and continues to the west as the Rocky Hill diabase. The Palisades sill intrudes the lower to upper Lockatong Formation; at Rocky Hill, it cuts up-section, into the lower Passaic Formation. The Sourland diabase is about 1400 feet thick and is nearly concordant to the bedding attitude of the enclosing Lockatong Formation. In the vicinity of Woodsville (near Route 31), the Sourland diabase cuts up-section, intruding the lower Passaic Formation. Outlying diabase bodies west of the Rocky Hill sill, include Pennington Mountain and Baldpate Mountain diabases, are strongly discordant to the enclosing sediments. The ring-shaped intrusion at Round Valley, northeast of Flemington, is also discordant. Diabase also occurs in some areas as thin dikes (generally less than 20 feet thick).

Compositionally the diabase is a quartz tholeiite (Walker, 1969), consisting mostly of calcic plagioclase and augitic pyroxene. The euhedral to subhedral mineral grains are tightly intergrown, forming a very hard, fracture-resistant material. The hardness and lack of bedding in the diabase sills result in marginal conditions for ground water occurrence. Joints and faults in the diabase sills are usually widely spaced and have a wider range of orientation than those in the sedimentary rocks.

HYDROGEOLOGY

Aquifer characteristics

Well records and aquifer tests in the rocks of the Newark basin indicate the following hydrologic properties:

1) Ground water occurs principally in secondary fractures in most of the early Mesozoic rocks. In addition to fracture porosity, sandstone in the Stockton Formation and in the Passaic Formation of the northern Newark basin commonly has moderate primary or intergranular porosity,

2) Multiple, semi-artesian aquifers are usually intercepted by wells. Typical vertical spacing of water-bearing zones is 30-100 feet. The upper water-bearing zone is usually unconfined.

3) Storage coefficients of water-bearing zones are low, indicative of artesian or semi-artesian conditions, under which ground-

water flows by hydraulic pressure within the aquifer rather than by hydraulic head loss.

4) Flow is horizontally anisotropic. Under pumping conditions, flow direction tends to be aligned in a direction which coincides either with strike of bedding or the direction of principal high-angle fractures.

5) Boundary conditions of semi-artesian aquifers can range from nearly impermeable to leaky, to constant head (very leaky). Varying conditions reflect differences in lithologic sequence and fracture patterns. Constant-head boundaries have been encountered in wells located near streams.

6) High-yielding zones in some instances coincide with what drillers call "seams", usually marked by calcite and epidote mineralization. These are fault zones.

Semi-artesian conditions in the rocks of the Newark basin can arise in two ways:

1) Inclined beds or layers with relatively high permeability interlayered with beds or thick sequences with relatively low permeability - it is likely that most semi-artesian aquifers occur in dipping layered sequences with permeability contrast sufficient to produce aquifer/confining-layer conditions. Aquifer and confining bed lithology varies according to sequence as given in table 2. Note that mudstone beds can act as confining layers when they bound permeable sandstone beds, or can behave as aquifers when bounded by massive, well-cemented siltstone or argillite.

2) Fracture system interconnection - fractures are connected

over a finite range and form discrete three-dimensional networks. The highest level of an interconnected system will correspond to the maximum piezometric elevation. The confining mechanism is long-range discontinuity of fractures; these systems are inherently leaky. Such interconnections have little storage volume, but may provide high-velocity flow paths from pumped wells to distant semi-artesian aquifer zones.

Both types of confining conditions can occur simultaneously in rock sequences of the early Mesozoic basin, giving rise to very complex hydrogeologic systems.

Table 2. - Layered semi-artesian aquifer sequences

Aquifer	Confining layers	Formations
sandstone	mudstone	much of Stockton; Passaic in northern basin; upper Passaic
fissile mudstone, fissile siltstone	massive argillite or siltstone	Lockatong; Passaic
vesicular basalt	massive basalt	Watchung basalts

Water-table aquifers commonly occur in the uppermost zone of water-saturated subsoil, weathered and broken bedrock, and competent bedrock. Pores and fractures in this material are commonly well connected, and contain water under atmospheric pressure. At increasing depth in typical fractured bedrock of the Newark basin, fractures become more widely spaced and more poorly interconnected. Below a certain depth, which may vary from around 50 feet to more than 150 feet, semi-artesian conditions occur in fracture systems which are isolated from the overlying water-table aquifer.

Shallow observation wells usually show water levels and flow directions corresponding to those in the water-table aquifer. The slope of the water table follows topographic contours, with more gentle gradients than the land surface.

Lithologic and Structural Controls of Ground Water Occurrence

Lithologic Controls

The physical and hydraulic properties of Newark basin rocks vary considerably among lithologies ranging from massive diabase to thin-bedded mudstone. The spacing, orientation, and extent of fractures depend upon the mechanical properties of the rocks and their sequence. Rock types will be discussed in general order of increasing fracture permeability.

Massive, hard, sparsely jointed rock: This lithology is represented by diabase. Joints are widely spaced (0.3 to 2 m), except in fault zones, where joints and fault planes may be spaced less than 0.1 m apart. Fracture permeability of diabase is low to very low, except in fault zones or other areas where strain concentration produced closely-spaced joints. Reported yields of diabase wells generally reflect pumping from borehole storage. Yields from wells in diabase are generally insufficient for commercial or public supply uses.

Hard, sparsely fractured rock with some beds or layers with higher permeability: These rocks include most of the Lockatong Formation, the lower part of Passaic Formation in the central

Newark basin, some of the Jurassic sedimentary rocks, and parts of the Watchung basalt flows. In the sedimentary rocks, mudstone or fissile siltstone beds have higher fracture porosity and probably higher storage coefficient than the more abundant argillite or well-cemented siltstone. These beds enhance the recharge capability of wells. In basalt, both the basal portions and the upper parts of flows can be vesicular and have enhanced porosity. Vesicles in basalt can be connected by tectonic joints or joints formed by contraction due to cooling.

Sparsely fractured rock interbedded with much highly fractured rock, or all highly fractured rock: These lithologies occur in the upper part of the Stockton Formation, throughout much of the Passaic Formation, and in parts of the Jurassic formations. The ratio of sparsely to highly fractured rock generally increases going upward in the Passaic Formation. Well yields and specific capacity are moderate to high, generally increasing with higher proportion of well-fractured rock. Water supply is adequate for most commercial/industrial and public supply requirements.

Sparsely to highly fractured rock and rock with moderate intergranular porosity: These lithologies occur widely in the Stockton Formation and in the Passaic Formation in the northern Newark basin. Ground water is produced both from fractures and from permeable sandstone beds. Average yields and specific capacities are the highest of all Newark basin rocks. These rocks tend to weather deeply, producing thick, sandy soils which enhance recharge to the aquifer.

Structural Controls

Joints and Faults: High-angle joints and faults occur throughout the basin and are especially well-developed in the harder rock types. The joints are systematic, with the most common orientation being northeast-striking and southeast-dipping. The high-angle joints are nearly normal to bedding throughout the basin, regardless of the dip angle of the beds. This indicates that the joints were emplaced after diagenesis of the rocks, but before the basin had been tilted to a large degree. The joints are thus post-early Jurassic in age. The predominant joint direction is parallel to the long axis of the basin, with the most common strike orientation ranging from 015-050 degrees.

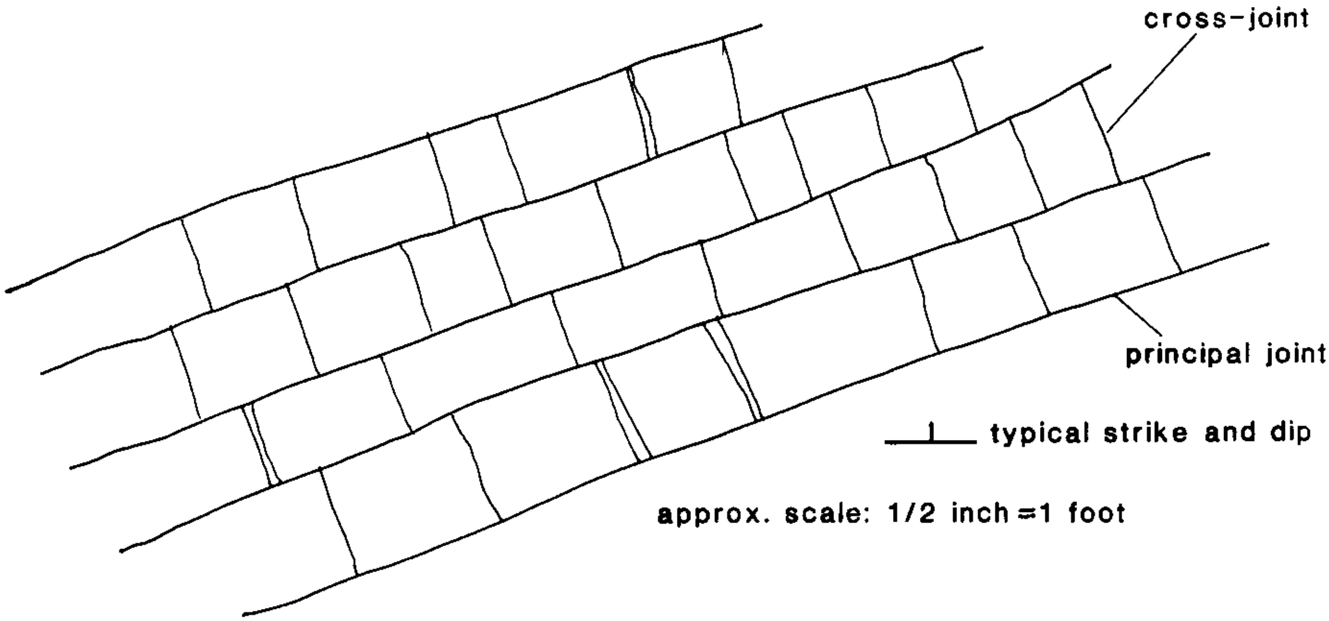
Fracture orientation can influence ground water flow directions in semi-artesian aquifers, particularly where hard, massive, jointed lithologies are predominant. In ground water investigations, knowing the principal fracture directions can help in locating observation and monitoring wells.

Outcrop evidence indicates that principal joints (perpendicular to bedding and sub-parallel to strike, most commonly) are extensive vertically and horizontally. Vertically, such joints commonly traverse entire outcrops, where lithology is homogeneous, or penetrate thick-bedded units, terminating in shaly beds. Horizontal extent is difficult to assess, but aquifer tests suggest lateral interconnection over thousands of feet (Rima et al., 1962; Vecchioli et al., 1969; J. Boyle, NJGS, oral communication). Secondary joint sets include two general types:

1) High-angle-to-bedding joints with different average

strike orientation from principal joints: There can be one, two, or rarely, three or more additional joint sets in some areas(especially, but not necessarily in fault zones). These secondary joints are extensive, vertically and horizontally.

2) Cross-joints: These are usually seen only in bedding-plane outcrops (from above). They are nearly perpendicular to bedding and to principal joints. They are not extensive vertically or horizontally. Vertically, they commonly penetrate one bed or a few thin beds. Horizontally, they generally are terminated at both ends by principal joints. A sketch view of a bedding plane outcrop shows the relationship between secondary cross-joints and principal joints.



Sketch of bedding-plane outcrop showing principal joints and cross-joints, viewed from above

Cross-joints add to the fracture porosity and permeability of rock aquifers and provide interconnection between principal joints. The flow paths of ground water along cross-joints are highly tortuous compared to flow paths in principal high-angle joints. Cross-joint flow paths are also short and truncated by the principal joints. Net fracture flow in a system with this geometry is expected to be nearly parallel to the direction of principal joints.

In addition to the high-angle-to-bedding joints discussed above, the sedimentary rocks of the Newark basin also have bedding plane joints. The spacing of these joints depends on lithology, varying from very far apart (several feet or more) in the most massive rocks to very close (fractions of an inch) in mudstones and shales. Basalt flows have some bedding plane discontinuities, including flow boundaries. Bedding plane joints are laterally continuous, particularly in lacustrine and playa-mudflat facies, and in basalt flows.

The use of photolineament analysis to locate fracture zones has not been documented in the Newark basin. Wood (1980) found that 19 non-domestic wells located on fracture traces (photolineaments) in the Gettysburg basin had specific capacities and yields that were not significantly different from other wells in the same lithology.

Dip of Bedding: In most of the Triassic rocks of the Newark basin, rocks with different hydraulic properties are interbedded. Ground-water flow within more permeable, dipping beds increases the anisotropic character of the aquifer. Because the strike orientation of bedding in much of the basin is within the same quadrant as the principal joint sets, horizontal anisotropy is reinforced.

Statistical studies of well performance in the Gettysburg Formation (nearly identical in lithology to the Brunswick Group sediments) shows a decline in average yield and specific capacity with increasing dip angle (Wood, 1980, p.32).

Water Well Statistics

A compilation of published well yield data for the Newark basin in New Jersey is given in table 3. The order of increasing average yields for Newark basin aquifers is: diabase, Lockatong, basalt, Passaic, Stockton. Data are not available for individual Jurassic formations. The Jurassic sedimentary aquifers probably have mean yields similar to that of the Passaic Formation.

Table 3. Summary of yield data for domestic wells in the Newark basin. Yield given in gallons per minute (gpm). Number of wells included in mean indicated by letter n.

Aquifer	Mean yield (gpm)
Diabase (n=141)	7.4
Basalt (n=94)	11.8
Passaic Formation (n=1196)	16.3
Lockatong Formation (n=393)	9.5
Stockton Formation (n=309)	20.0

Sources of data: Carswell (1976), Carswell et al. (1976), Kasabach (1966), Miller (1974), Nemickas (1976), Widmer (1965)

Average yields vary considerably in different areas. In Hunterdon County (Kasabach, 1966), average yield in the Brunswick Formation varied by township from 27 gpm to 15 gpm. Highest yields were in Raritan Township, where most of the Brunswick wells were adjacent to the Flemington Fault. The data summary from Kasabach (1966) is given below.

SUMMARY OF HUNTERDON COUNTY DOMESTIC WELLS

Formation	*No. of Wells*	*Yield In Gallons Per Minute*			
		Maximum	*Minimum*	*Average*	*Median*
Diabase Intrusives (Trdb) and Basalt Flows (Trbs)	65	55	0	8	5
Brunswick Shale (Trb)	528	100	0	19	15
Lockatong Formation (Trl)	186	78	½	12	6
Stockton Formation (Trs)	162	70	1½	20	18
Border Conglomerates (Trc)	94	87	0	15	12
Baked Brunswick Shale (Baked Trb)	64	35	½	9	6
Argillite, siltstone and gray shale within the Brunswick Shale (Trba)	32	45	1½	10	7
Martinsburg Shale (Omb)	23	95	2	17	12
Kittatinny Limestone (COk)	70	50	½	17	15
Precambrian (pC) and Hardyston (Ch)	203	66	0	14	15

Hydraulic properties

Rocks of all the early Mesozoic basins of eastern North America formed in similar geologic settings and have similar physical properties. Hydrogeologic observations from other basins supplement those from the Newark basin and provide a more complete data set.

Porosity

Average porosity of 12 samples from the Stockton Formation in Pennsylvania was 15.7% (range = 7.1 to 30.6 percent) (Rima et al., 1962). One sample was a siltstone which had a porosity of 9.7 percent; all other samples were sandstone (9 samples) or conglomerate (2 samples). These data are included in table 4, below.

Table 4. *Laboratory determination of hydraulic properties of rock samples from the Stockton formation*

(From Rima et al., 1962)

Sample no.	Location no.	Description	Porosity (n) (percent)	Specific yield (percent)	Coefficient of permeability (K) in gpd/ft^2	
					Horizontal	Vertical
57PA1	J23a-7423	Conglomerate, very coarse-grained	17.3	11.0	0.009	0.007
57PA2	J23a-7423	Arkose, very coarse-grained	10.9	6.2	.01	.007
57PA3	J23a-7423	do.	19.4	12.8	.01	.009
57PA4	J23a-5724	Arkose, medium-grained	30.6	19.1	.3	.2
57PA5	J23a-5724	Arkose, fine-grained	14.4	9.5	.03	.003
57PA6	J23a-5724	Arkose, coarse-grained	19.2	16.2	.03	.04
57PA7	J23a-1801	Conglomerate, very coarse-grained,arkosic	7.1	3.1	.003	.004
57PA8	J23a-4113	Sandstone, arkosic, very fine-grained, brick-red	10.5	0	1/ .4	....
57PA9	J23a-3823	Siltstone, sandy grayish-red	9.7	0	.0022	.003
57PA10	J22b-5160	Arkose, medium-grained, buff	25.6	19.3	.02	.01
57PA11	J22b-5061	Arkose, medium-grained, tan	16.1	4.0	.001	.001
57PA12	J22b-5061	Arkose, coarse-grained, tan	7.9	1.0	2/	.0003

1/ Sample 57PA8 could not be cored without fracturing. Permeability is probably high. Porosity was determined on "undisturbed" chunk.

2/ Could not obtain two cores from sample 57PA12.

Credit for this table is given to the Pennsylvania Geological Survey.

Twenty samples of Stockton sandstone from central and northern New Jersey had porosities ranging from 0.7 to 12.5%, with an average of 4.4 percent (Rose, 1950). Higher porosities in this study were mostly from samples characterized as weathered.

Ten samples of Triassic sedimentary rocks from the Deep River basin, North Carolina had porosity ranging from 0.88 to 26.4 percent, with an average of 7.59% (Bain and Brown, 1981). Average gas porosity of 5 samples of argillite and siltstone from the Durham basin, North Carolina was 2.4 percent (range = 0.9 to 4.7 percent). This compares with an average of 6.9 percent gas porosity for 5 sandstone samples (range = 2.3 to 12.0 percent) (Bain and Brown, 1981). Porosity measurements discussed above are all from unfractured samples and represent intergranular, rather than fracture, porosity. The Stockton Formation samples of Rima et al. (1962) and Rose (1950) were taken from outcrop and may have enhanced porosity due to weathering. Samples from the Durham basin (Bain and Brown, 1981) were from rock cores, and are probably more representative of sandstone porosity in typical wells.

The sample set for siltstone and argillite is small, showing a porosity range from 0.9 to about 10 percent, averaging 3.2% (7 samples). Reported porosity values for sandstone range from 0.7% to more than 30%, with an average of 8.2% (34 samples). More experimental data are needed from fine grained lithologies.

Permeability

Hydraulic conductivities of Stockton Formation samples are given in table 4, from Rima et al. (1962). Range of hydraulic conductivity is from 0.001 to 0.3 gpd/ft^2 horizontally (average of 10 samples = 0.042 gpd/ft^2), and from 0.0003 to 0.2 gpd/ft^2 vertically (average = 0.028 gpd/ft^2). The ratio of average horizontal to vertical conductivity is 1.5:1. Higher conductivity parallel to bedding surfaces is expected from the usual fabric of competent, bedded sedimentary rock. These values are from unbroken rock samples; fracture permeability may be much higher than the values given above.

Nine rock core samples from the Deep River basin (North Carolina) had an average test permeability of 4.2 X 10^{-4} um^2 (420 microdarcies) (Bain and Brown, 1981). Other permeabilities reported by Bain and Brown (1981) for Triassic rocks ranged from

8 to 100 microdarcies. These permeabilities are all extremely low, typical of very tightly cemented, indurated sedimentary rocks.

Transmissivity

A summary of published transmissivity values for early Mesozoic basin rocks is given in table 5.

Table 5. - Summary of published transmissivity values of early Mesozoic rocks.

Basin and location	Formation or rock type	Transmissivity (gpd/ft)	Comment	Reference
Newark basin, PA	Brunswick	6,700	entire well	Sutton (1983)
"	"	830	single zone	"
"	"	270	single zone	"
Newark basin, PA	Brunswick	9,000	median, 19 tests	Longwill and Wood (1965)
"	"	32,047	mean, 19 tests	"
Newark basin, PA	Stockton	16,500	median, 14 tests	Rima et al. (1962)
"	"	16,360	mean, 14 tests	"
Durham basin, NC	sandstone	8,275	17m zone at 250m depth	Bain and Brown (1981)
"	mixed lithologies, some shale	30,600	134m zone at 1000m depth	"

The greatest range of transmissivity values from any study was that reported by Longwill and Wood (1965) for the Brunswick Formation in Pennsylvania. They reported values ranging from 100 to 180,000 gpd/ft, which demonstrates the extreme variability of fractured aquifers in rocks of this type. The median (9,000 gpd/ft) varied greatly from the mean (32,000 gpd/ft) due to positive skewing effects of several wells with very high transmissivities. If the upper and lower 20% of values are deleted from this data set, the mean transmissivity of 11 well tests is 19,900 gpd/ft, which is more in accord with other results. The mean and median transmissivities reported by Rima et al. (1962) for the Stockton Formation were nearly the same, around 16,500 gpd/ft.

Storage coefficient

Storage coefficients determined from pumping tests in the Stockton Formation ranged from 2×10^{-5} to 1.4×10^{-3} (Rima et al., 1962). The average of 11 observations was 4.3×10^{-4}. Storage coefficients from aquifer tests in the Brunswick Formation in Pennsylvania ranged from 3.3×10^{-5} to 2.9×10^{-4}, with an average of 9.5×10^{-5} for 12 tests (Longwill and Wood, 1965).

The reported storage coefficients for wells in both Stockton and Brunswick (Passaic) Formations are within the expected range for confined aquifers (Heath, 1983).

Specific Yield

Specific yields of Stockton Formation rocks given by Rima et al. (1962) range from 0 to 19.3% (Table 4), with an average of 10.1%. Two samples with zero specific yield were a very fine-grained, red sandstone and a siltstone. These values were determined experimentally and reflect the volume of water drained by gravity from a rock sample, divided by the total volume of the rock. The discrepancy between storage coefficients (storativity) and specific yields reported for Newark basin rocks arises from the conditions under which the measurements are made.

Storage coefficients computed during aquifer tests reflect compression of the aquifer and water expansion under semi-artesian conditions. Specific yield is measured under unconfined conditions and reflects drainage of pores by gravity.

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GROUND WATER IN NEW JERSEY: LEGAL/POLITICAL ISSUES

by

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- an outline -

I - Environmental Protection In New Jersey - Some History
II - Programs/Acts/Laws/Regs - An Overview
III - Bureaus/Divisions/Elements - Who's Who
IV - Standards
V - Preservation/Permitting/Protection
VI - Cleanup
VII - Enforcement
VIII - Economics

Under the foregoing headings, the speaker will present his views on a number of ground water issues and programs including the Toxic Substances Control Program, the Spill Compensation and Control Act, Underground Storage Tank Programs, the Toxic Catastrophe Prevention Act, ECRA, the Solid Waste Management Program, the Hazardous Waste Management Program, CAFRA, Wetlands, Stream Encroachment, and NJPDES.

URANIUM, RADIUM, AND RADON IN GROUND WATER FROM THE ROCK AQUIFERS OF THE PIEDMONT PROVINCE AND THE KIRKWOOD-COHANSEY AQUIFER SYSTEM OF THE COASTAL PLAIN PROVINCE, NEW JERSEY

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INTRODUCTION

The concentrations of uranium, radium, and radon in ground water used for drinking-water supply is of major concern because each of these radionuclides is a known human carcinogen on ingestion (Mays and others, 1985; Cothern, 1987). The USEPA (U.S. Environmental Protection Agency) has established an interim drinking-water standard of 5 pCi/L (picoCuries per liter) for the sum of radium-226 and radium-228 concentrations, and has proposed to regulate uranium and radon-222 concentrations (U.S. Environmental Protection Agency, 1986). Since 1985, the U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection has been studying the distribution of uranium, radium, and radon in ground water from selected rock aquifers of the Piedmont province and from the Kirkwood-Cohansey aquifer system of the Coastal Plain province of New Jersey. The objectives of this study are to (1) determine the concentrations of uranium, radium, and radon in ground water in selected areas of New Jersey, and (2) identify causes of elevated concentrations of these radionuclides in the ground water. This paper (1) compares the concentrations of uranium, radium, and radon in ground water from the rock aquifers of the Piedmont province with those in ground water from the Kirkwood-Cohansey aquifer system of the Coastal Plain province in New Jersey, and (2) discusses the influences of the four factors listed below on the distribution of these radionuclides in these two ground-water systems.

Concentrations of naturally occurring uranium, radium, and radon in ground water are controlled primarily by (1) the concentrations and distribution of these radionuclides or their radioactive parents in the source rock; (2) the geochemical environment, which affects the solubility of each radionuclide differently; (3) ground-water flow paths, which can control the geographic distribution of the radionuclides in solution; and (4) the half-life of the radionuclide and its relative position within the radioactive-decay series of which it is a member. The length of the half-life of a radionuclide imposes a maximum on the residence time of the radionuclide in solution. The distribution and abundance of daughter radionuclides in ground water is determined, in part, by the abundance of the parent radionuclide in both the solid and aqueous phases in the aquifer.

HYDROLOGY

The Piedmont province (Fenneman, 1938), located in central and northeastern New Jersey (fig. 1), is defined by the outcrop of the interbedded arkosic sandstones and red and black mudstones of the Newark Supergroup (Olsen, 1980). Uranium-enriched strata are present in permeable

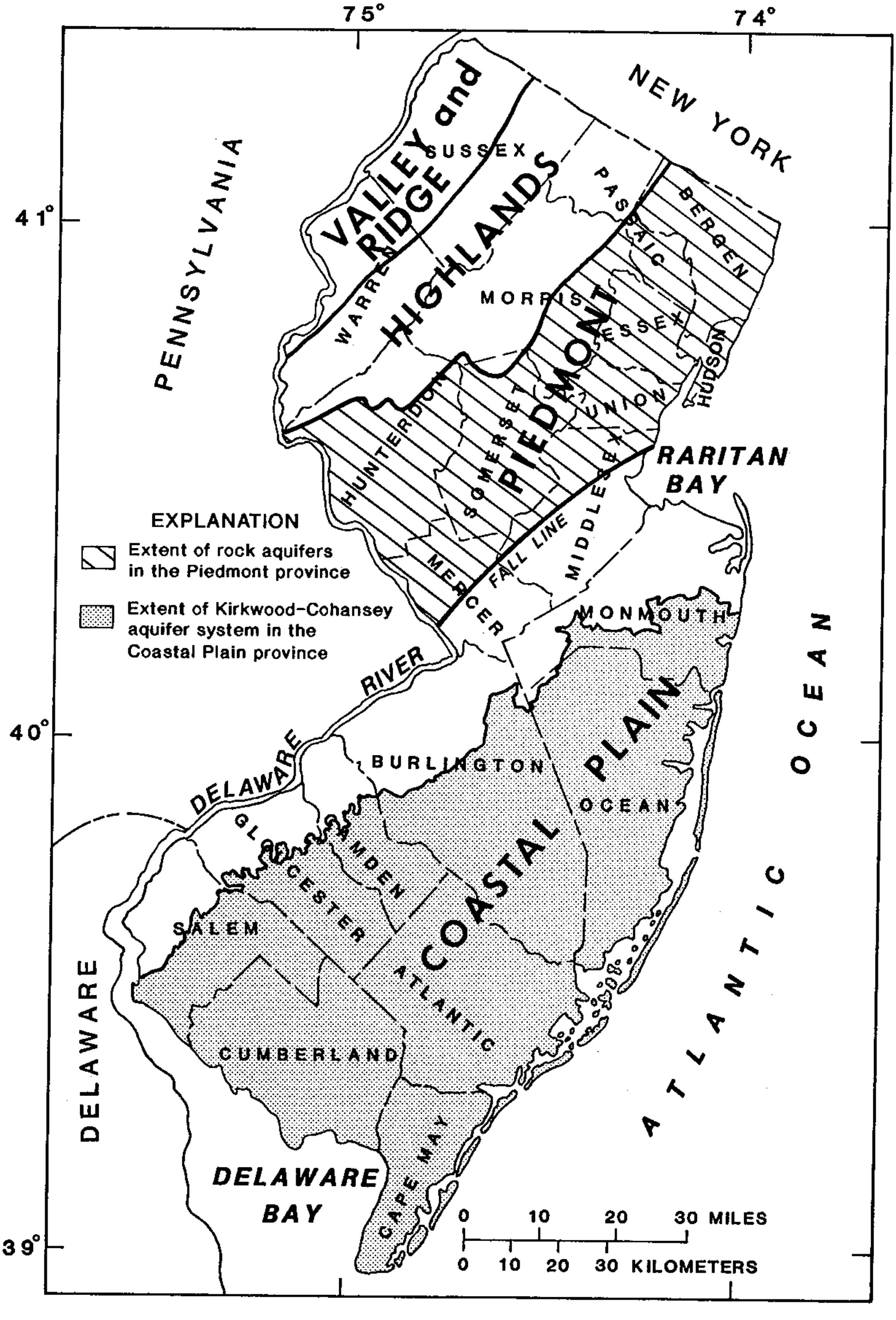

Figure 1.--Location of physiographic provinces in New Jersey. (Modified from Fenneman, 1938).

zones adjacent to organic-matter-rich horizons in both arkosic sandstones (Turner-Peterson, 1980) and black mudstones (Muessig and Houghton, 1988). Ground water is stored primarily in the weathered overburden and is transmitted through the rock through interconnected openings formed along bedding plane partings, faults, fractures, and joints. Ground water flows from openings with higher hydraulic heads to openings with lower heads. The length of ground-water flow paths in fractured rocks varies with the complexity of the interconnected openings and usually increases with depth (Gerhart and Lazorchick, 1988). Wells screened at varying depths in the rock aquifers of the Piedmont province were sampled, to represent ground water with various residence times.

The Kirkwood-Cohansey aquifer system (Zapecza, 1989) is the most important unconfined aquifer in the Coastal Plain province (Fenneman, 1938) in southern New Jersey (fig. 1) in terms of water supply. The aquifer system consists of a wedge of unconsolidated sands and gravels dipping and thickening to the southeast. The sands and gravels are composed primarily of quartz grains (Zapecza, 1989). Trace quantities of minerals that contain uranium and thorium, such as zircon and monazite, are present; however, no uranium-enriched strata are present. Ground water is stored in, and transmitted through, pore spaces between the grains of the aquifer matrix. Ground-water flow within the aquifer is controlled primarily by topography, and moves from areas of high elevation to areas of low elevation. Flow paths generally are short but lengthen with depth (Rhodehamel, 1970). Most of the ground-water samples collected for this study from the Kirkwood-Cohansey aquifer system of the Coastal Plain, were withdrawn from shallow wells so that the samples would be representative of ground water with short residence times.

RADIONUCLIDES

Decay Series

Radionuclides are found as trace elements in most rocks and soils and are formed principally by the radioactive decay of uranium-238 and thorium-232, the long-lived parent elements of the radioactive-decay series that bear their names. The parent radionuclides, uranium-238 and thorium-232, produce intermediate daughter radionuclides, such as radium and radon with shorter half-lives than those of the parents. Uranium-238 and thorium-232 decay through numerous daughter radionuclides to become stable lead-206 and lead-208, respectively. Radium-226 is an intermediate decay product in the uranium-238 decay series; its immediate radionuclide parent is thorium-230. Radium-226 decays to produce radon-222. Radium-228 is the direct decay product of thorium-232.

One half-life is the time required for half of the initial amount of the radionuclide to decay. The length of the half-life is highly variable from radionuclide to radionuclide. Isotopes of uranium have very long half-lives that range from 10^6 to 10^9 years. Radium-226 has a long half-life (1,622 years) compared to that of radium-228 (5.75 years). Radon-222, an inert gas, has a short half-life of only 3.82 days.

Concentrations of Dissolved Uranium, Radium, and Radon in Ground Water

Uranium concentrations in ground-water samples collected from wells completed in the fractured rocks of the Piedmont province ranged from 0.05 to 74 μg/L (micrograms per liter); most samples contained from 2 to 4 μg/L of uranium (fig. 2a). Concentrations of radium-226 ranged from less than 0.05 to 22.5 pCi/L; most samples contained from 0.1 to 0.5 pCi/L of radium-226 (fig. 2b). Concentrations of radon-222 ranged from less than 70 to 26,000 pCi/L, and most samples contained from 1,500 to 3,500 pCi/L of radon-222 (fig. 2b). Concentrations of radium-228 ranged from less than 0.5 to 3.4 pCi/L, and most samples contained less than 0.5 pCi/L of radium-228 (fig. 3). Less than 5 percent of the ground-water samples contain concentrations of radium in excess of the USEPA drinking-water standard.

Concentrations of uranium in ground-water samples collected from wells completed in the Kirkwood-Cohansey aquifer system of the Coastal Plain province ranged from less than 0.01 to 0.62 μg/L, and most samples contained less than 0.03 μg/L of uranium (fig. 2a). Concentrations of radium-226 ranged from 0.02 to 9.2 pCi/L, and most samples contained from 1 to 4 pCi/L of radium-226 (fig. 2b). Concentrations of radon-222 ranged from less than 70 pCi/L to 1,900 pCi/L, and most samples contained from 200 to 400 pCi/L of radon-222 (fig. 2a). Concentrations of radium-228 ranged from less than 1 to 10 pCi/L, and most samples contained from less than 1 to 3 pCi/L of radium-228 (fig. 3). About 30 percent of the ground-water samples contained concentrations of dissolved radium in excess of the USEPA drinking-water standard.

Comparison of Radionuclide Concentrations Between the Piedmont Province Rock Aquifers and the Coastal Plain Kirkwood-Cohansey Aquifer System

Concentrations of uranium and radon-222 generally are 1 to 2 orders of magnitude higher in ground water from rock aquifers of the Piedmont province than in ground water from the Kirkwood-Cohansey aquifer system of the Coastal Plain province (fig. 2a). The highest concentrations of uranium and radon-222 measured in ground water from the Kirkwood-Cohansey aquifer system generally are equal in order of magnitude to the lowest concentrations of these radionuclides measured in ground water from the rock aquifers, primarily because the solid minerals in the arkosic sandstones and mudstones of the Piedmont province are significantly richer in uranium than are the quartzose sands of the Kirkwood-Cohansey aquifer system. The uranium-rich aquifer material of the Piedmont province thus can generate greater amounts of radium-226 and radon-222 than the relatively uranium-poor sediments of the Coastal Plain province. Uranium-rich strata are common in rocks of the Piedmont province (Turner-Peterson, 1980; Zapecza and Szabo, 1987; Muessig and Houghton, 1988), but are absent from the quartzose sands of the Kirkwood-Cohansey aquifer system. Concentrations of uranium and radon-222 in ground water from the rock aquifers of the Piedmont province are highest in areas of uranium-rich strata (Zapecza and Szabo, 1987).

Concentrations of radon-222 are approximately 10 to 100 times the concentrations of its radioactive parent, radium-226, in ground water from the Kirkwood-Cohansey aquifer system. By contrast, radon-222 concentrations are approximately 1,000 to 10,000 times the concentrations of radium-226 in ground water from the rocks of the Piedmont province. Because radon-222

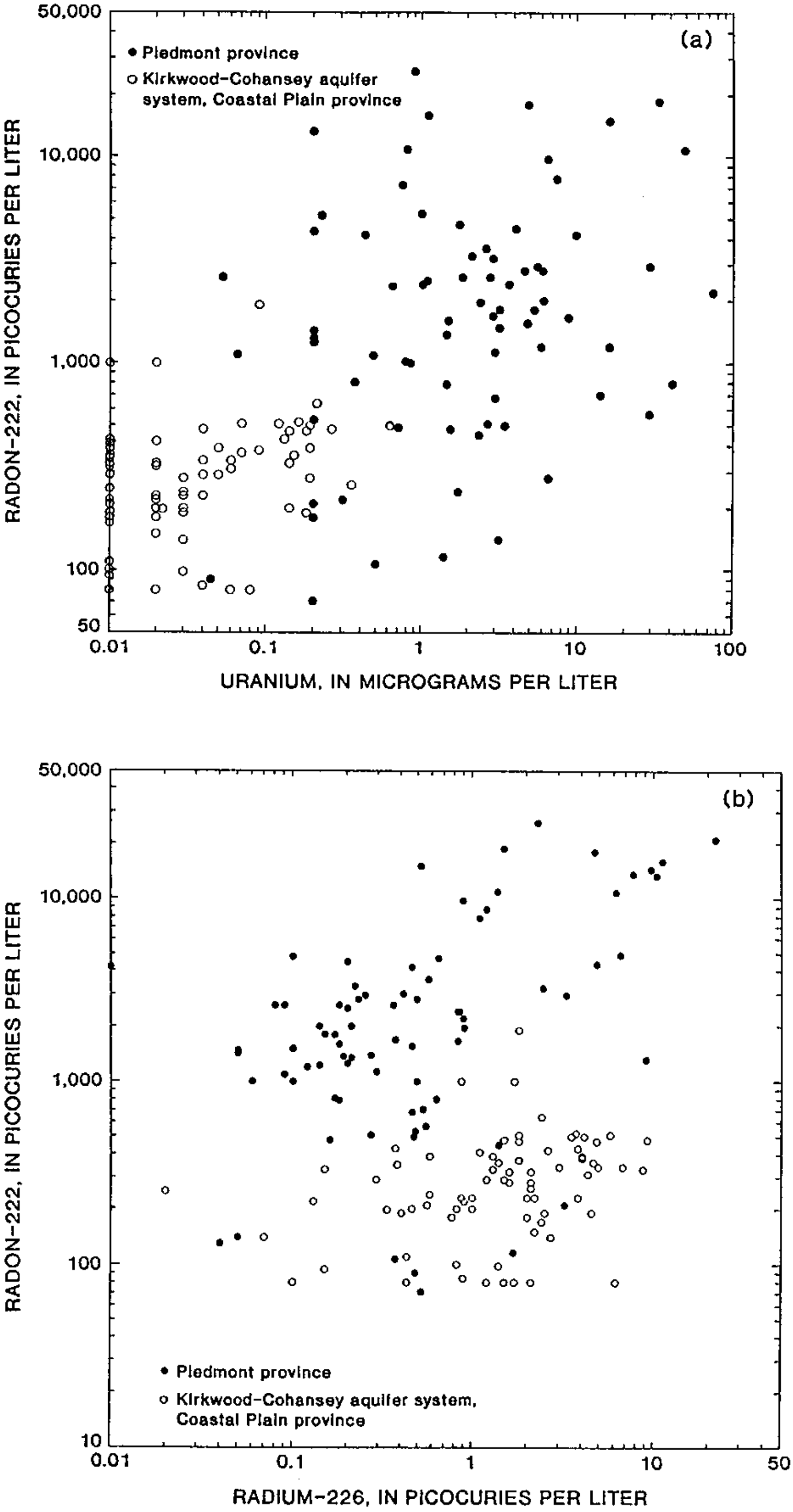

Figure 2.--Relation of concentration of radon-222 to (a) uranium concentrations, and (b) radium-226 concentration in ground water from the rock aquifers of the Piedmont province and the Kirkwood-Cohansey aquifer of the Coastal Plain province, New Jersey, 1985-89.

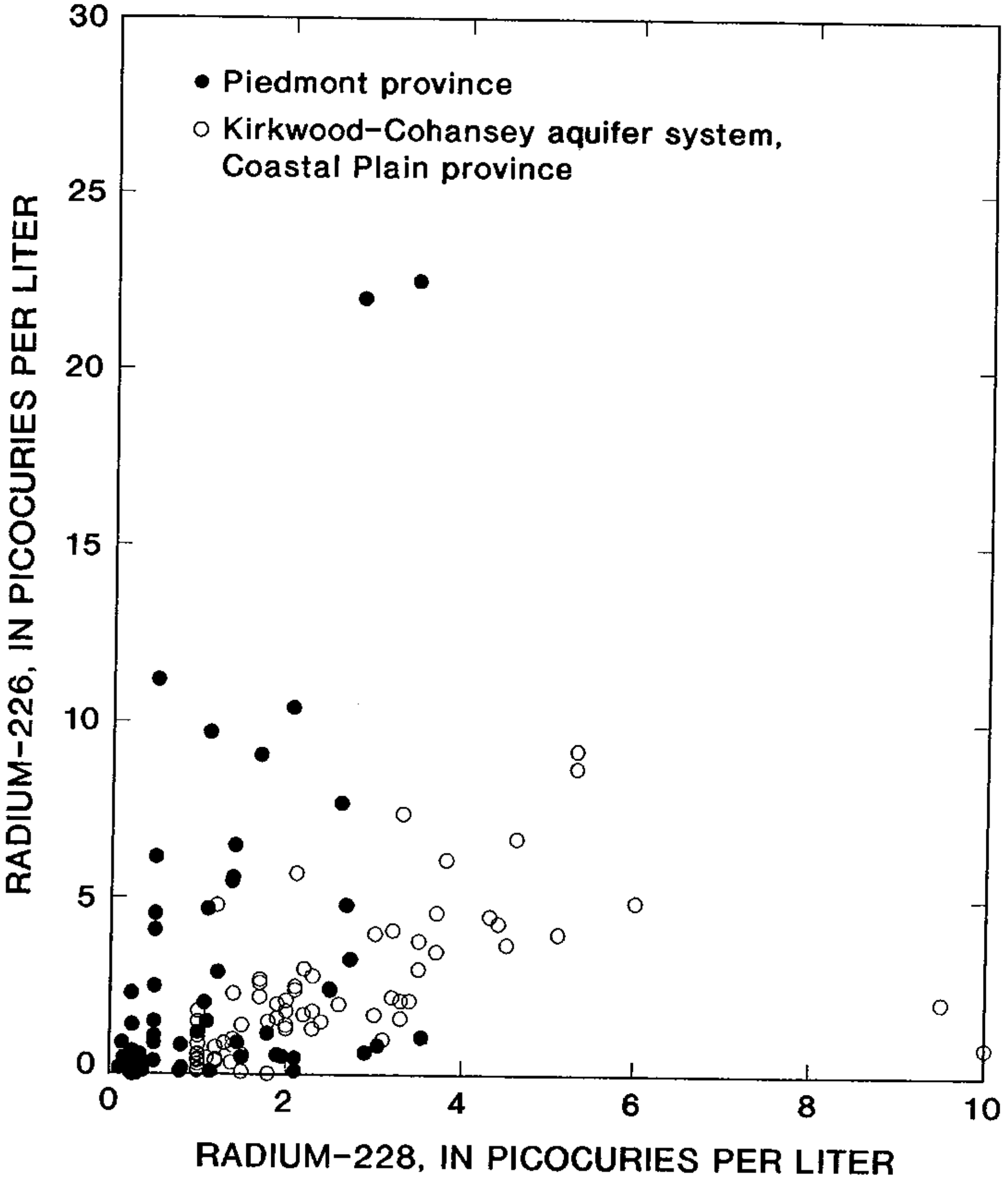

Figure 3.--Relation of concentration of radium-226 in ground water to radium-228 concentration in ground water from the rock aquifers of the Piedmont province and the Kirkwood-Cohansey aquifer system of the Coastal Plain province, New Jersey, 1985-89.

concentrations in ground water that exceed the amount that can be generated from radioactive decay of aqueous radium-226 must be supplied from the radioactive decay of radium-226 in the aquifer material itself, the radium-226 content of the aquifer material must be greater in the matrix of the rocks of the Piedmont province than in the matrix of the quartzose sands of the Kirkwood-Cohansey aquifer system.

The highest concentration of radium-226 measured in ground water from the rocks of the Piedmont province (22.5 pCi/L) exceeds the highest concentration of dissolved radium-226 measured in ground water from the Kirkwood-Cohansey aquifer system (9.5 pCi/L). This result is consistent with the higher uranium concentrations present in the matrix of rocks in the Piedmont province than in the matrix of the Kirkwood-Cohansey aquifer system. Concentrations of radium-226 in the majority of ground-water samples from the Kirkwood-Cohansey aquifer system, however, were approximately an order of magnitude greater than radium-226 concentrations in ground-water samples from the rocks of the Piedmont province (fig. 2b). This implies that a significantly greater part of the radium-226 generated by radioactive decay in the aquifer system is present in solution, rather than in the solid matrix of the aquifer material, in the Kirkwood-Cohansey aquifer system than in the rocks of the Piedmont province.

In the southeastern United States, the ratio of radon-222 concentration to radium-226 concentration also is much greater in ground water from rock aquifers of the Piedmont province than from sand-and-gravel aquifers in the Coastal Plain province (King and others, 1982). This indicates that in the eastern United States in aquifer systems of the Coastal Plain province relative to the rock aquifers of the Piedmont province a greater proportion of the total amount of radium-226 generated by radioactive decay in the aquifer system is in solution rather than in the solid matrix of the aquifer material.

Relations Among Concentrations of Dissolved Uranium, Radium, and Radon

In ground water from the uranium-rich rock aquifer of the Piedmont province in New Jersey, concentrations of radon-222 relate weakly with concentrations of uranium (fig. 2a) and relate more with concentrations of radium-226 (fig. 2b). Radon-222 concentrations are not strongly related with uranium and radium-226 concentrations, primarily because the concentrations of uranium and radium-226, both chemically active elements, depend on the geochemistry of the ground water as well as on the uranium content of the aquifer material.

Because radon-222 has a half-life of only 3.8 days, the radon-222 detected in the ground water must be derived from radium-226 in the aquifer material immediately adjacent to the well screen. In contrast, uranium isotopes have long half-lives that allow them to travel great distances along ground-water flow paths, and to accumulate along convergent flow paths or to disperse along divergent flow paths, so that the length of the ground-water flow path can influence uranium concentrations in ground water. Therefore, uranium in ground water is not necessarily derived from the aquifer material immediately adjacent to the well screen, and uranium concentrations relate only weakly with radon-222 concentrations. Where radium-226 is soluble, radium-226 is more likely to be derived from the aquifer material adjacent to the well screen than is uranium because the half-life of radium-226 is much shorter than that of the isotopes of uranium. Radon-222 and radium-226 concentrations may be more strongly related than radon-222 and uranium concentrations because the half-life of radium-226 is closer in magnitude to the half-life of radon-222 than the half-lives of uranium isotopes.

Concentrations of radon-222 relate weakly with concentrations of uranium (fig. 2a) and radium-226 (fig. 2b) in ground water from the Kirkwood-Cohansey aquifer system. Because the relatively short ground-water flow paths in the Kirkwood-Cohansey aquifer system preclude significant dispersal of long-lived uranium, the solubilities of all three radionuclides in the local geochemical environment adjacent to the well screen largely control their concentrations in the ground water.

In ground water from the rock aquifers of the Piedmont province, radium-226 concentrations generally exceeded radium-228 concentrations by a factor of two or three (fig. 3). The ratio of radium-226 concentration to radium-228 concentration suggests that the aquifer material is enriched in uranium relative to thorium. This hypothesis is consistent with the presence of numerous uranium-enriched strata in this area (Turner-Peterson, 1980; Muessig and Houghton, 1988).

In ground water from the Kirkwood-Cohansey aquifer system in the Coastal Plain province, the ratio of radium-226 concentration to radium-228 concentration is nearly one (fig. 3). This ratio suggests that the aquifer material contains uranium and thorium in ratios similar to typical crustal-abundance ratios. This hypothesis is consistent with the absence of any known uranium enrichment in this area.

Because the uranium concentration in the aquifer material in the rocks of the Piedmont province is substantially higher than that in the aquifer material of the Kirkwood-Cohansey aquifer system, concentrations of uranium, a fairly soluble element, are greater in the ground water from the rock aquifers (fig. 4). Concentrations of radium-226, a chemically reactive element that is less soluble than uranium, generally are much lower in ground water from the rock aquifers of the Piedmont province than in ground water from the Kirkwood-Cohansey aquifer system, because the chemically reactive aquifer materials of the Piedmont province inhibit the mobility of radium-226 to a greater degree than the much less chemically reactive aquifer materials of the Coastal Plain province. These results are similar to those obtained for ground-water samples collected from rock aquifers of the Piedmont province and from the unconfined sand-and-gravel aquifers of the Coastal Plain province in the southeastern United States (King and others, 1982).

Uranium concentrations greater than 10 μg/L and radium-226 concentrations of less than 1 pCi/L were detected in numerous samples of ground water from the rock aquifers of the Piedmont province. Many other samples contained uranium concentrations of less than 1 μg/L and radium-226 concentrations greater than 5 pCi/L (fig. 4). Though both uranium and radium-226 in the ground water originate from uranium in the aquifer material, the aqueous concentrations of these two radionuclides are inversely related (fig. 4), implying that uranium and radium-226 are

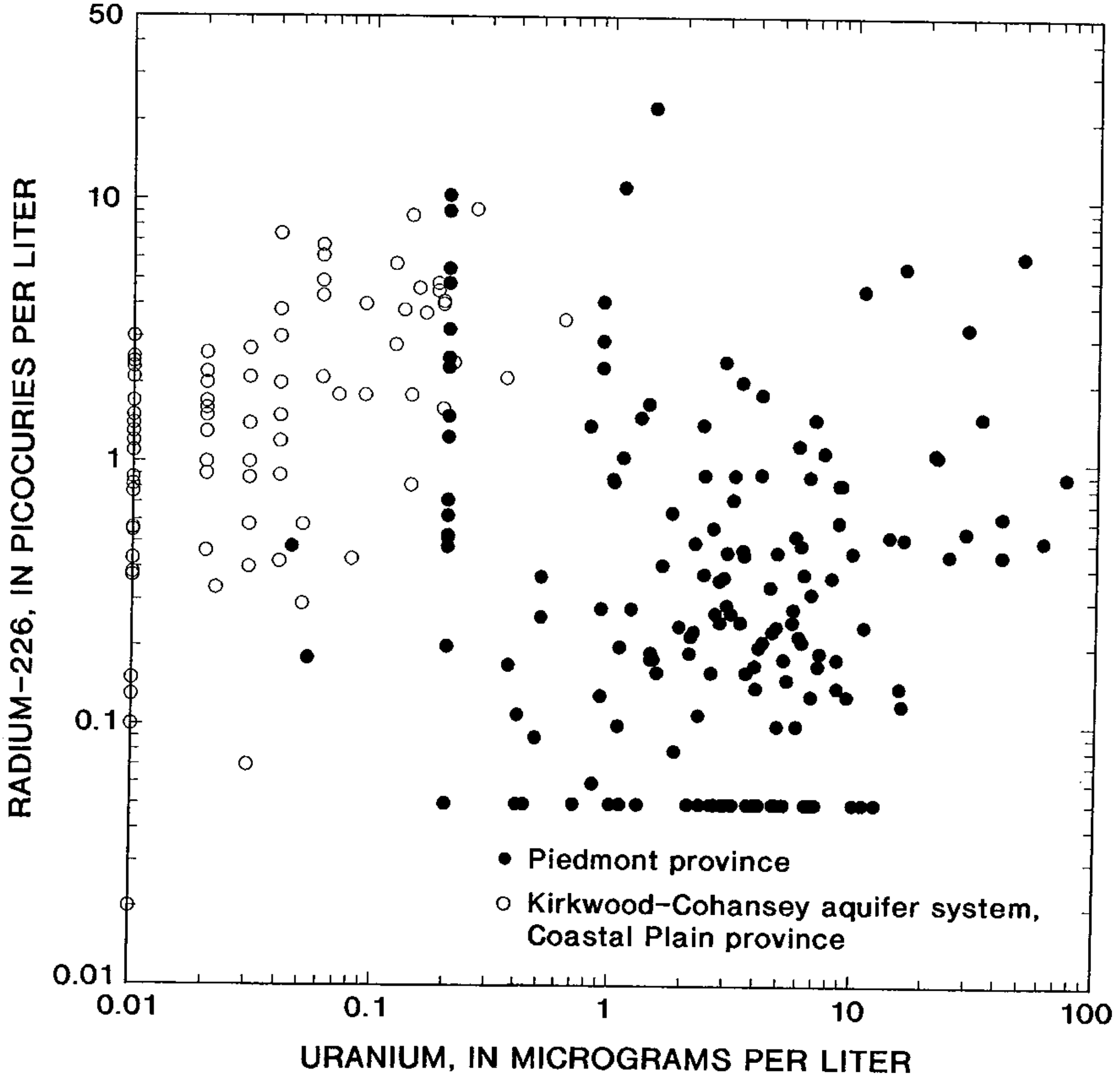

Figure 4.--Relation of concentration of radium-226 to uranium concentration in ground water from the rock aquifers of the Piedmont province and the Kirkwood-Cohansey aquifer system of the Coastal Plain province, New Jersey, 1985-89.

mobilized in the ground water in different chemical environments. In the majority of the samples from the rock aquifers of the Piedmont province, concentrations of uranium exceeded those of radium-226 by an order of magnitude (fig. 4), indicating that the geochemical environment of ground water in the Piedmont favors the mobilization of uranium relative to radium.

Concentrations of uranium and radium-226 in ground water from the Kirkwood-Cohansey aquifer system are positively correlated (fig. 4), implying that the geochemical environment facilitates the mobilization of both uranium and radium-226. Radium-226 concentrations exceeded uranium concentrations in all of the ground-water samples from the Kirkwood-Cohansey aquifer system, however, indicating that the geochemical environment of ground water from the Kirkwood-Cohansey aquifer system favors the mobilization of radium relative to uranium.

The difference between the mobility of radium relative to that of uranium in ground water from the rock aquifers of the Piedmont province and in ground water from the Kirkwood-Cohansey aquifer system in the Coastal Plain province is the result of the differing geochemical behavior of these two elements (Zapecza and Szabo, 1988) and of the geochemical differences between the ground water and the aquifer materials from these two terranes.

CONCLUSIONS

The concentrations of uranium, radium, and radon in ground water in the rock aquifers of the Piedmont province and in the unconfined Kirkwood-Cohansey aquifer system of the Coastal Plain province in New Jersey are controlled by geologic factors, such as the concentration and distribution of parent radionuclides in the rock; by geochemical factors, such as the solubility of each radionuclide in differing geochemical environments; by hydrologic factors, such as the length of ground-water flow paths; and by the physical principles of radioactivity, such as the half-lives of the radionuclides, which control their residence times in solution.

The concentrations of uranium, radium, and radon in ground water in rock aquifers of the Piedmont province and in the unconfined Kirkwood-Cohansey aquifer system of the Coastal Plain province in New Jersey are similar to the concentrations of these radionuclides in ground water in the Piedmont and Coastal Plain provinces of the southeastern United States (King and others, 1982; Zapecza and Szabo, 1988). This similarity indicates that the factors controlling the concentrations of these radionuclides in ground water, identified in studies in New Jersey, also are applicable to the Piedmont and Coastal Plain provinces of the southeastern United States.

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Alternate Concentration Limits for Groundwater Discharge Standards

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Alternate Concentration Limits (ACL's) offer New Jersey industrial facilities an opportunity to establish groundwater discharge permit limits which are different from the familiar Drinking Water Standards or Maximum Concentration Limits (MCL). The authority for establishing ACL's can be found under NJAC 7:14A-6.15, with the New Jersey Pollutant Discharge Elimination System (NJPDES) regulations.

In order for a facility to establish an ACL several important conditions must be met. First, there must be "no substantial present hazard" from the compounds discharged by the facility. Second, there must be a point of compliance (POC) and a point of exposure (POE) established by the facility. Finally, the selected ACL for each compound must be based upon some set of scientific criteria, either those specified by USEPA guidance documents or other criteria developed by the permittee and approved by the Department.

Portions of the data required to develop an ACL can be taken directly from the normal hydrogeologic investigations which are performed during NJPDES permit activities. Other portions of the data must be developed by the facility or retrieved from existing literature and records.

Groundwater related information which is required for establishing an ACL are:

Characteristics of the hazardous wastes.

Hydrogeology of the facility.

Quantity, rate and direction of groundwater flow.

Proximity too, and withdrawal rates of, groundwater users.

Current and future uses of groundwater in the area.

Existing quality of groundwater, including other sources of contamination.

The potential health risks caused by human exposure.

Potential damage to wildlife, crops and structures.

The persistence and permanence of the potentially adverse effects from any ACL discharge.

In addition to groundwater, the facility must provide similar information on the effect of the discharge on the surface water environment. Some of this information is from outside the realm of normal geologic investigations. Specifically these are:

The volume and characteristics of the wastes.

Hydrogeology of the facility.

Quantity, quality and flow direction of groundwater.

Rainfall patterns.

Proximity of the regulated unit to surface waters.

Current and future uses of surface waters and the cumulative impact of this discharge on the Surface Water Quality Standards.

Federal guidance documents provide a starting point for preparation of an ACL petition. In New Jersey, the Department of Environmental Protection has the authority to apply Federal guidance within it's own policy objectives.

As of June 1990, only one facility has established an ACL in New Jersey. A review of this facility's file shows that establishing an ACL provided some relief from the existing groundwater standards, while clearly protecting the NJDEP's right to take enforcement actions for other nearby potential groundwater pollution sources.

GROUND WATER MONITORING WELLS AND SAMPLING IN NEW JERSEY

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ABSTRACT

In New Jersey, ground water monitoring wells are installed and sampled to abide by many laws including ECRA, RCRA, SARA, NJPDES and UST. The two basic types of monitoring wells installed are placed in either a rock or soil medium. Typical design in each of these media is reviewed. Ground water samples collected from a monitoring well will be analyzed for target parameters that are dependent on the regulatory reason for well installation and the surrounding environmental conditions. Sampling procedures are standardized as best as possible, but will vary according to the type of well, target parameters and site conditions present.

1. INTRODUCTION

The following is an introduction, but by no means complete review of ground water monitoring wells and their sampling as performed in New Jersey. Monitoring wells are undoubtedly the most common type of well being installed in the state of New Jersey today due to our industrial heritage. Monitoring wells are an essential way to evaluate ground water conditions to detect or determine ground water pollution. Earth science teachers should be able to utilize this paper in showing what a monitoring is well is and how it is used.

A monitoring well is a type of well installed according to regulatory standards to determined ground water quality through the collection of water samples and water elevations. In contrast, are the typically larger diameter water supply wells used to obtain massive quantities of water for industrial and drinking water purposes. An observation well, sometimes referred to as a piezometer, is another type of well usually with a smaller diameter that is restricted to the measurement of water level elevations. A key semantic difference between an "observation" versus "monitoring" well is that the former does not meet all standards or criteria for acquiring potentially defensive legal chemical ground water quality data. A recovery well, while less common than the above types of wells, is used to pump out contaminated water during clean-up operations. A recovery well may have originally been installed as a monitoring well prior to its use in obtaining ground water. Injection wells, as the term implies, pump fluids back into the ground. A water supply well is the only type of well listed above that necessitates being installed within an bona fide aquifer, if an aquifer is considered as a hydrostatic unit yielding large quantities of water. The type of hydrogeologic units necessary for the other types of wells will depend on the objective of installing the well.

2.0 WHY MONITORING WELLS?

Public awareness of the need to protect our subsurface water resources has lead to the creation of several laws on a federal and state level requiring the installation of hundreds of monitoring wells across the state of New Jersey over the past decade. Some of the more common acronyms for laws and regulations involved with monitoring wells include RCRA (Resource Conservation and Recovery Act), SARA (Superfund Amendments and Reauthorization Act of 1986, NJPDES (New Jersey Pollutant Discharge Elimination System), ECRA (Environmental Cleanup Responsibility Act of New Jersey), and UST (Underground Storage Tanks). RCRA monitoring wells are for hazardous and solid waste facilities where known, suspected or potential contaminants may be found from the site's past or current activities. SARA or Superfund monitoring wells are installed where known or highly suspected ground water contamination exists. NJPDES monitoring wells include all RCRA wells, some superfund wells and any other monitoring wells where a NJPDES discharge permit is required. ECRA monitoring wells are installed to assure that no ground water contamination has occurred at an industrial facility where a real estate transaction is about to occur. If ground water contamination has indeed occurred, it is highly likely NJPDES, RCRA and/or state or federal Superfund criteria for the monitoring wells may be necessitated at the ECRA site. UST site monitoring wells are installed where existing or former underground storage tank(s) are present. If ground water contamination has occurred, a NJPDES permit is required and depending on the contents of the tank(s), RCRA may also be involved. If the UST site owners go bankrupt and the site is a serious enough problem, Superfund may also become involved. Hopefully, the above acronyms show how legal phenomena have created the science of contaminant hydrogeology and how a specific hydrogeologic study will be "limited" by what is legally mandated.

The parameters a monitoring well is targeted for will vary among the regulatory groups. For example, RCRA, ECRA, NJPDES and Superfund sites may require monitoring for what chemical constituents are known to exist at a site or if unknown a complete priority pollutant analysis. Among the items in a priority pollution analysis are several dozen volatile organic and base neutral organic compounds, eight heavy metals, polychlorinated biphenyls (PCBs), pesticides and herbicides. These priority pollutant parameters are known or suspected carcinogens. Some NJPDES wells, especially those associated with landfills, may be more concerned with how potable the water is and may require analysis for such things as iron, pH, odor, total dissolved solids and hardness. Unless the underground storage tank stored a specific type of chemical, most underground storage tanks contain petroleum hydrocarbons such as gasoline, diesel fuel, and heating oil. Petroleum hydrocarbon-bearing tanks are typically monitoring for volatile organics, especially benzene, toluene, ethylbenzene, and xylene (BTEX), and base neutral organics.

3.0 MONITORING WELL INSTALLATION

Monitoring wells fall under two basic types: rock and unconsolidated. Both the method of installation and final design of each type of monitoring well differs.

A typical rock monitoring well (Figure 1) will consist of steel casing set in and grouted with a bentonite/cement slurry in an oversized hole. Upon settling and hardening of the grout, the interior of the steel casing is cleaned and a borehole, typically 6 inches in diameter, is drilled beneath the casing (Figure 2). Ground water is derived from the borehole. At stop 2 of the GANJ field trip, the operation of a rotary drill rig to install a small, 6-inch diameter water supply well will be observed. Methodology and equipment use here, including the well diameter size of 6 inches, are basically the same as for the installation of a rock monitoring well. Not all rock monitoring wells can be installed using steel casing and an open borehole. This is usually due to complications from structural geology, the close proximity of rock to the surface, a water table that straddles the bedrock-soil interface and the semi-consolidated nature of the rock unit. Therefore, the design of the rock monitoring well (Figure 3) may be similar to that discussed below for unconsolidated monitoring rock wells. However, the drilling method of these wells is typically accomplished with an air or mud rotary rig method rather than the hollow stem auger method.

A typical unconsolidated monitoring well (Figure 4) is installed by the hollow stem auger method (Figure 5). The augers typically have an inner diameter space of approximately six inches and are able to drill a borehole of approximately eight inches. The lead auger is modified with teeth to assist with drilling through the sediments. In addition, a plug connected to rod pipe is lowered through the annulus of the augers to hinder sediments from entering inside the augers.

When a desired depth is reached, typically 4-inch diameter schedule 40 PVC or stainless steel well screen and riser pipe is installed through the stem of the augers. The well screen has slots typically 0.01 or 0.02 inches in width and 2 or 3 inches in length which will allow the intake of water but not sediments. Threaded joints are used to connect all screen and riser pipes. No glues or solvents are used due to the potential of their contents dissolving in the well and giving biased analytical data.

After the insertation of the PVC or stainless steel screen and pipe a filter pack of sand is introduced through the augers along the outside of the riser pipe and screen. This sand is uniform (i.e., well sorted) and slightly larger in grain size than the screen slot width to avoid its entrance into the annulus of the well. The augers are periodically raised two to three feet to allow the sand to spread out within the borehole. This process is repeated until a sand filter pack is installed extending one or two feet above the top of the screen. A one or two foot thick bentonite pellet seal is then placed through the augers. Bentonite pellets are a clay product that expand to ten times their volume when they come into contact with water. The bentonite pellet seal, therefore, assures that no vertical migration of contaminants from overlying water-bearing units migrates along the borehole and well casing. Finally, a slurry of cement-bentonite grout is tremmied in the borehole to the ground surface and allowed to hardened. A locking cap and steel protective casing is installed around a monitoring well to assure that no one tampers with the well.

4.0 WELL DEVELOPMENT

After a well is installed, it needs to be developed to assure that hydraulic communication with the surrounding hydrostratigraphic unit occurs. This is accomplished by removing several times the volume of the well's water column either by a pump, bailer or air compressor. The initial water removed from the well will be "dirty" with fine particulates, typically of clay, silt and fine sand size, but a properly installed monitoring well should eventually be clean of this material. A problem with well development is what to do with the potentially contaminated water derived from the monitoring well. Depending on the site conditions and suspected contaminants, this water is either drummed or placed in a tank for later treatment or disposal, discharged to the surface, or poured down a storm or sanitary drain.

5.0 THE POTENTIAL OF EXPOSURE

The logistical problem of what to do with well development water also brings up another overall problem when installing monitoring wells: there is the potential of being exposed to hazardous materials. Therefore, the personnel working at the installation of a monitoring well, both geologist and driller, need to be trained according to Occupational Safety and Health Administration (OSHA) standards. This entails attending a 40-hour training course and yearly 8-hour refresher courses as well as having regular physicals.

The potential of being exposed to hazardous substances necessitates proper decontamination procedures both from a personnel and equipment perspective. Personal protection of personnel includes wearing gloves, suits and boots that will prevent exposure to any potential hazards encountered. In additional, respiratory protection with an air filter or oxygen supply may be needed. Equipment needs to be decontaminated not only from the perspective of protecting personnel, but also to avoid cross-contamination of additionally installed wells on and off site. Typically, decontamination procedures of the drill rig and drilling equipment is accomplished by steam cleaning. More sophisticated decontamination procedures of special equipment, such as a split spoon or bailer sampler, may entail a soap and water wash, distilled/deionized water rinse, dilute nitric acid rinse, distilled/deionized water rinse, acetone rinse and final distilled/deionized water rinse. These procedures are necessary if analytical samples are to be taken. The actual decontamination procedure(s) to be used will also be dependent on the type of laboratory analysis to be performed. Again, the disposal of the water generated from steam cleaning as well as waste generated from other decontamination procedures will need to be addressed.

6.0 Well Sampling

The actual sampling of a monitoring well will be dependent on various aspects reviewed so far such as regulatory authority, analyses to be performed, degree of known or suspected contamination including well water disposal, and overall site conditions. The latter problem is at times the most interesting: weather, too cold in the winter where one's water sample freezes or too hot in the summer while encased in a protection "moon-suit" with an oxygen tank, may be a problem. Site security, activities and tidal conditions may also come into play affecting the opportune time of sampling. Despite the variables of each sampling event, several standard procedures have been outlined by the NJDEP and EPA.

Prior to sampling a monitoring well, a water level is obtained to assess ground water conditions. Ground water flow direction within a hydrostratigraphic unit can be determined only if three or more properly screened and sufficiently spaced wells are present at a site. This explains why most sites require a minimum of two downgradient and one upgradient well.

A monitoring well needs to be purged prior to sampling. This is standardized by removing 3 to 5 volumes within the well's water column. The volume of water removed is computed by knowing the length of the water column (determined by knowing the depth to the bottom of the well and water level elevation) and diameter of the well. A conversion chart for computing well casing volumes is presented in Table 1. An exception to removing 3 to 5 volumes is when a well has a low yield and is purged dry. In this case the well is allowed to sufficiently recharge prior to sampling. The purging of the well is typically done using either a bailer, peristaltic (suction lift) pump, bladder pump, or submersible pump.

Sampling of the monitoring is commonly, though not always, accomplished using a stainless steel or teflon bottom fill bailer. If volatile organics are to be analyzed for, the volatile organic sample vials are collected first to assured that gases within the well water, theoretically representative of ambient ground water conditions in immediate vicinity to the well, do not volatilize. If petroleum hydrocarbons are to be analyzed for, then the groundwater sample is obtained from the top of the well column to assess the presence floating free product. All sampling devices need to be properly decontaminated as previously discussed to assure that no outside source of contamination has occurred. Additional Quality Assurance/Quality Control (QA/QC) of a collected ground water sample includes documentation with a field book and chain of custody form. The chain of custody form will note the number of bottles collected from each well and may also list the analyses to be performed by the analytical laboratory. All analytical laboratories are certified with the NJDEP if legally defensible ground water analysis is required.

Additional QA/QC of ground water samples is obtained by the analysis of field and trip blank samples. A field blank is a sample obtained by running laboratory supplied distilled/deionized water over a decontaminated sampler. This will help to assess whether unusual analytical results may be derived from a contaminated sampler. A trip blank is used when volatile organic analysis is to be performed. The trip blank is prepared in the laboratory and transported with the sample vials to and from the field. The trip blank assures that air borne volatiles do not contaminant the sample vials and subsequent samples while in transport.

7.0 SUMMARY

Hopefully, this paper has been informative about some of the aspects of monitoring wells and their sampling. As stressed earlier, monitoring wells are a legal phenomenon: most monitoring wells would not be installed without the potential legal ramifications. The hydrogeologic science of detecting and delineating ground water contamination is a consequence of what parameters are legally required to be analyzed for. Except for water level readings, there is no way to correlate monitoring wells throughout the state, since no parameters are, justifiably, standardize for all wells.

My personal experience is that most monitoring wells in New Jersey are installed within the water table. However, the water table is not always a bona fide aquifer, if an aquifer is considered as a hydrostratigraphic unit yielding substantial quantities of water. Therefore, monitoring wells should not be considered as strictly used for protecting drinking water sources, but as protecting all ground water.

In addition to this paper and handouts at the workshop, I suggest educators contact the NJDEP (and ask for a copy of their Field Procedures Manual) and obtain copies of the Ground Water Monitoring Review published four times a year by the Water Well Journal Publishing Company of Dublin, Ohio for additional information. The latter has state-of-the-art information on monitoring well installation, sampling and contaminant hydrogeologic studies that can be utilized as class projects.

8.0 ACKNOWLEDGEMENTS

I wish to thank Marianne Covin of LESI for typing, Pat Cibellis of Langan Engineering Associates for assistance with the diagrams and Gerry Malack of Empire Soil Investigations, Inc. for discussions on this document.

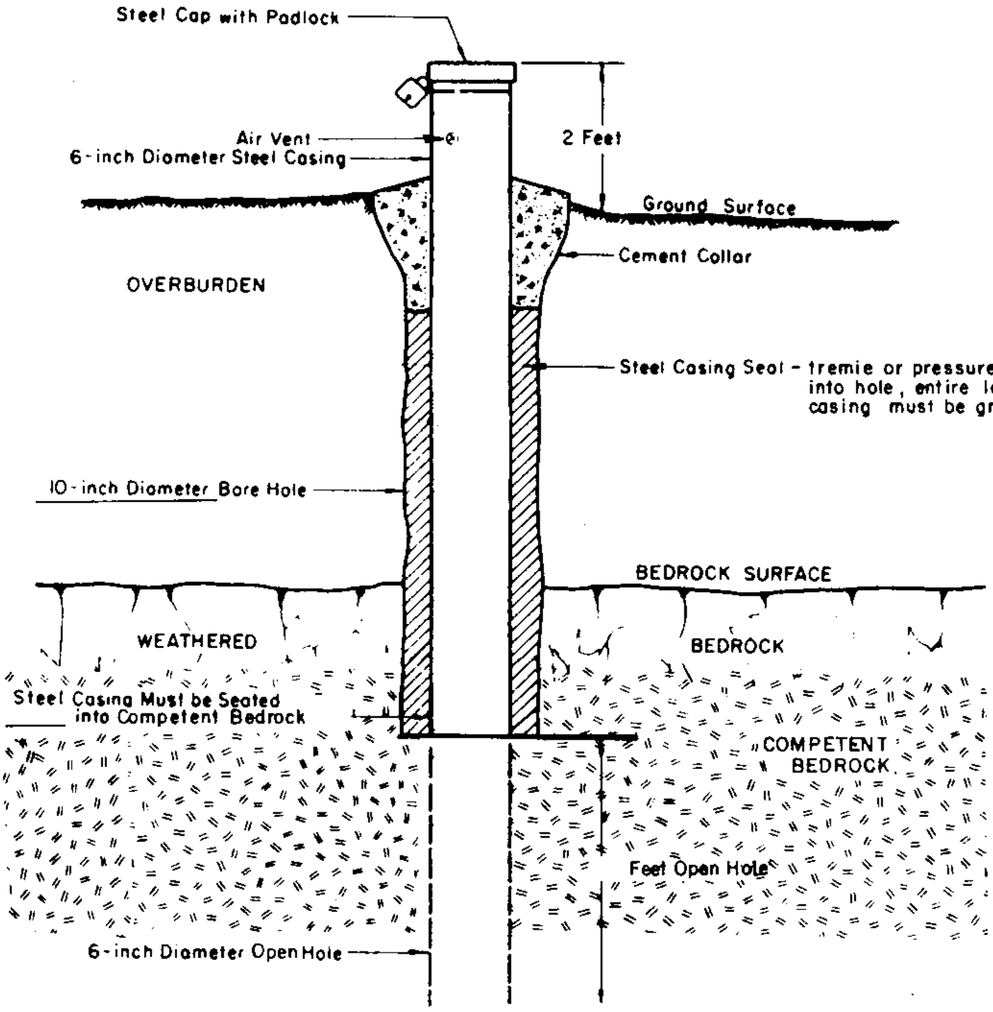
TABLE 1

WELL CASING VOLUME CONVERSION CHART (Gallons)

WELL CASING DIAMETER (INCHES)

WATER COLUMN (FEET)	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	24.0	36.0	48.0
.1	.004	.009	.016	.037	.065	.15	.26	.41	.59	.80	1.04	1.32	2.35	5.29	9.40
.5	.02	.05	.08	.18	.33	.73	1.3	2.0	2.9	4.0	5.2	6.6	11.7	26.4	47.0
1.0	.04	.09	.16	.37	.65	1.5	2.6	4.1	5.9	8.0	10.4	13.2	23.5	52.9	94.0
2.0	.08	.18	.33	.73	1.3	2.9	5.2	8.2	11.7	16.0	20.9	26.4	47.0	105.8	188.0
4.0	.16	.36	.65	1.5	2.6	5.9	10.4	16.3	23.5	32.0	41.8	52.9	94.0	211.5	376.1
6.0	.24	.45	.98	2.2	3.9	8.8	15.7	24.5	35.3	48.0	62.7	79.3	141.0	317.3	564.1
8.0	.33	.73	1.3	2.9	5.2	11.7	20.9	32.6	47.0	64.0	83.6	105.8	188.0	423.1	752.2
10.0	.41	.92	1.6	3.7	6.5	14.7	26.1	40.8	58.8	80.0	104.5	132.2	235.1	528.9	940.2

BEDROCK MONITORING WELL SPECIFICATION



NOTE:

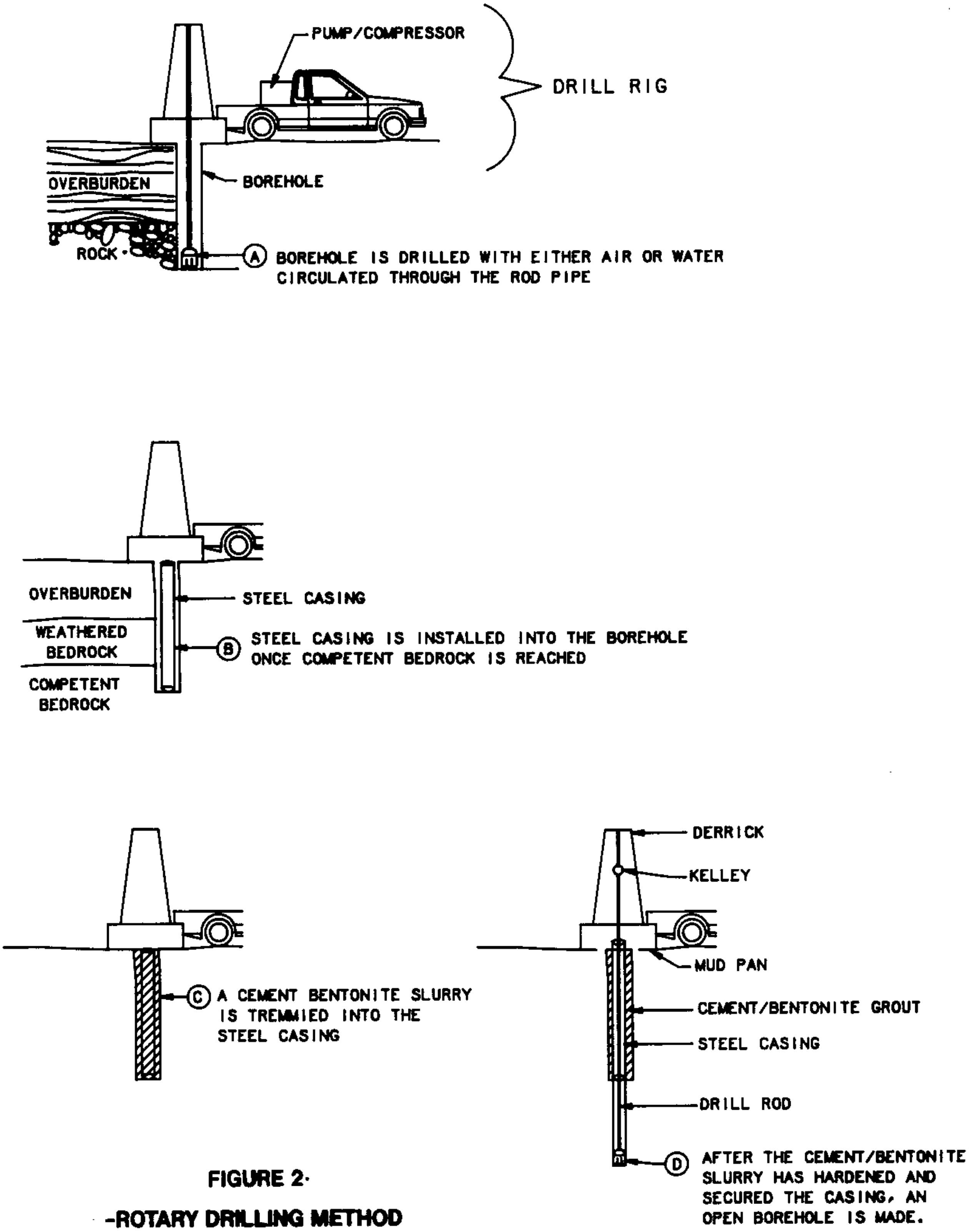
THIS SPECIFICATION BASED ON " NJDEP BEDROCK MONITOR WELL SPECIFICATIONS"

LESI Langan Environmental Services, Inc.

Elmwood Park, NJ • New York, NY • Miami, FL

TYPICAL BEDROCK MONITORING WELL INSTALLATION

PROJ	SCALE N.T.S.	DATE	FIG. NO 1



Ⓐ BOREHOLE IS DRILLED WITH EITHER AIR OR WATER CIRCULATED THROUGH THE ROD PIPE

Ⓑ STEEL CASING IS INSTALLED INTO THE BOREHOLE ONCE COMPETENT BEDROCK IS REACHED

Ⓒ A CEMENT BENTONITE SLURRY IS TREMMIED INTO THE STEEL CASING

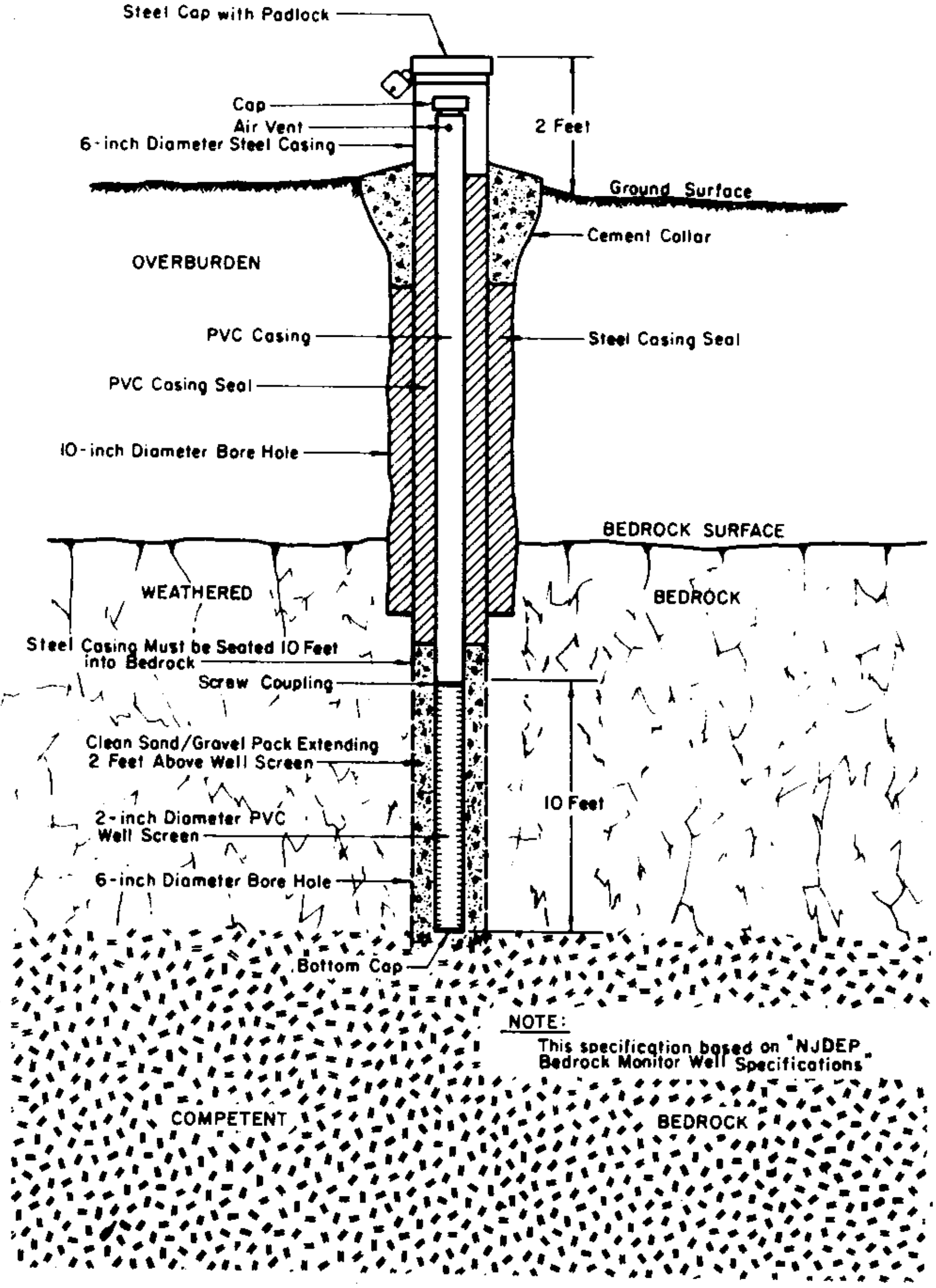
Ⓓ AFTER THE CEMENT/BENTONITE SLURRY HAS HARDENED AND SECURED THE CASING, AN OPEN BOREHOLE IS MADE.

FIGURE 2-

-ROTARY DRILLING METHOD

123997

INNER PVC CASING / SCREENED BEDROCK MONITORING WELL SPECIFICATION



NOTE:
This specification based on "NJDEP Bedrock Monitor Well Specifications"

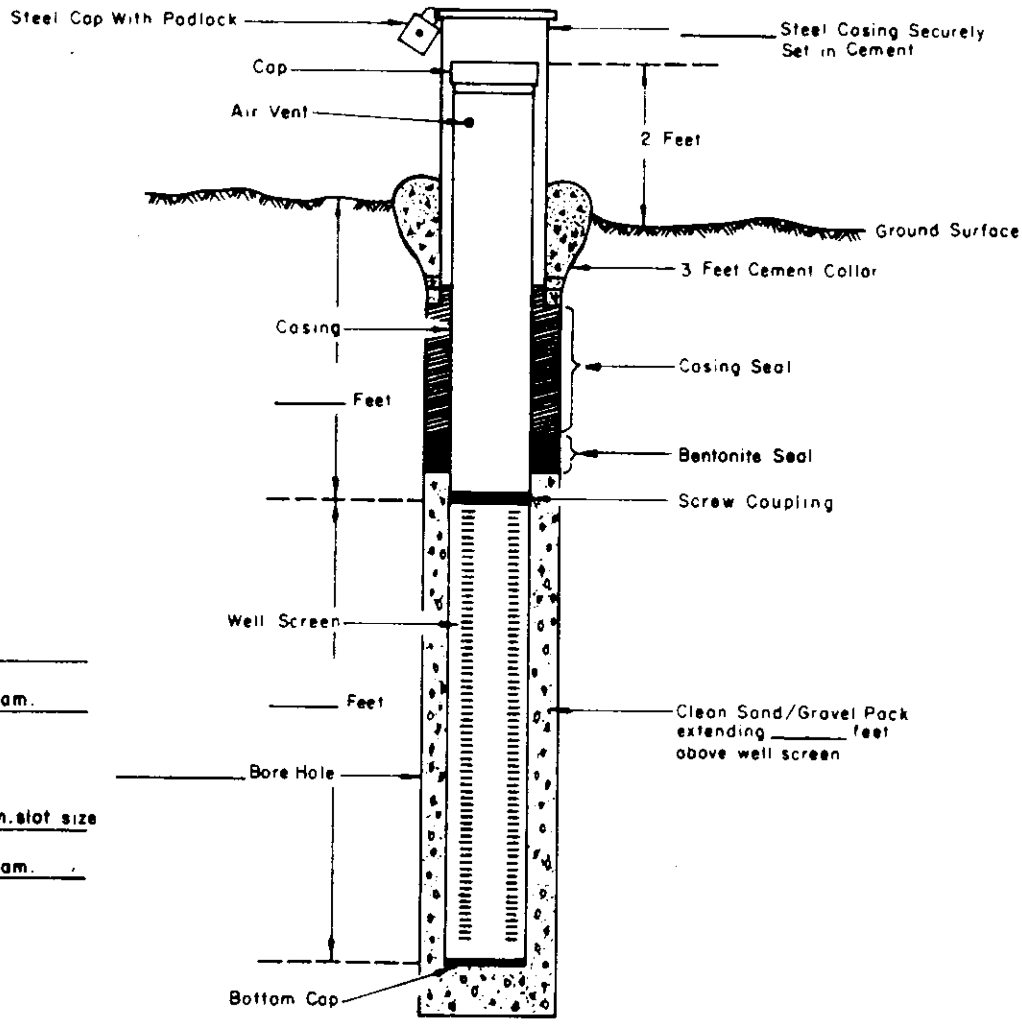
LESI Langan Environmental Services, Inc.

Elmwood Park, NJ • New York, NY • Miami, FL

INNER PVC CASING / SCREENED BEDROCK MONITORING WELL SPECIFICATION

PROJ	SCALE N.T.S.	DATE	FIG NO 3

UNCONSOLIDATED MONITORING WELL SPECIFICATION



SPECIFICATIONS

Well Casing PVC

4 in. diam.

Well Screen PVC in. slot size

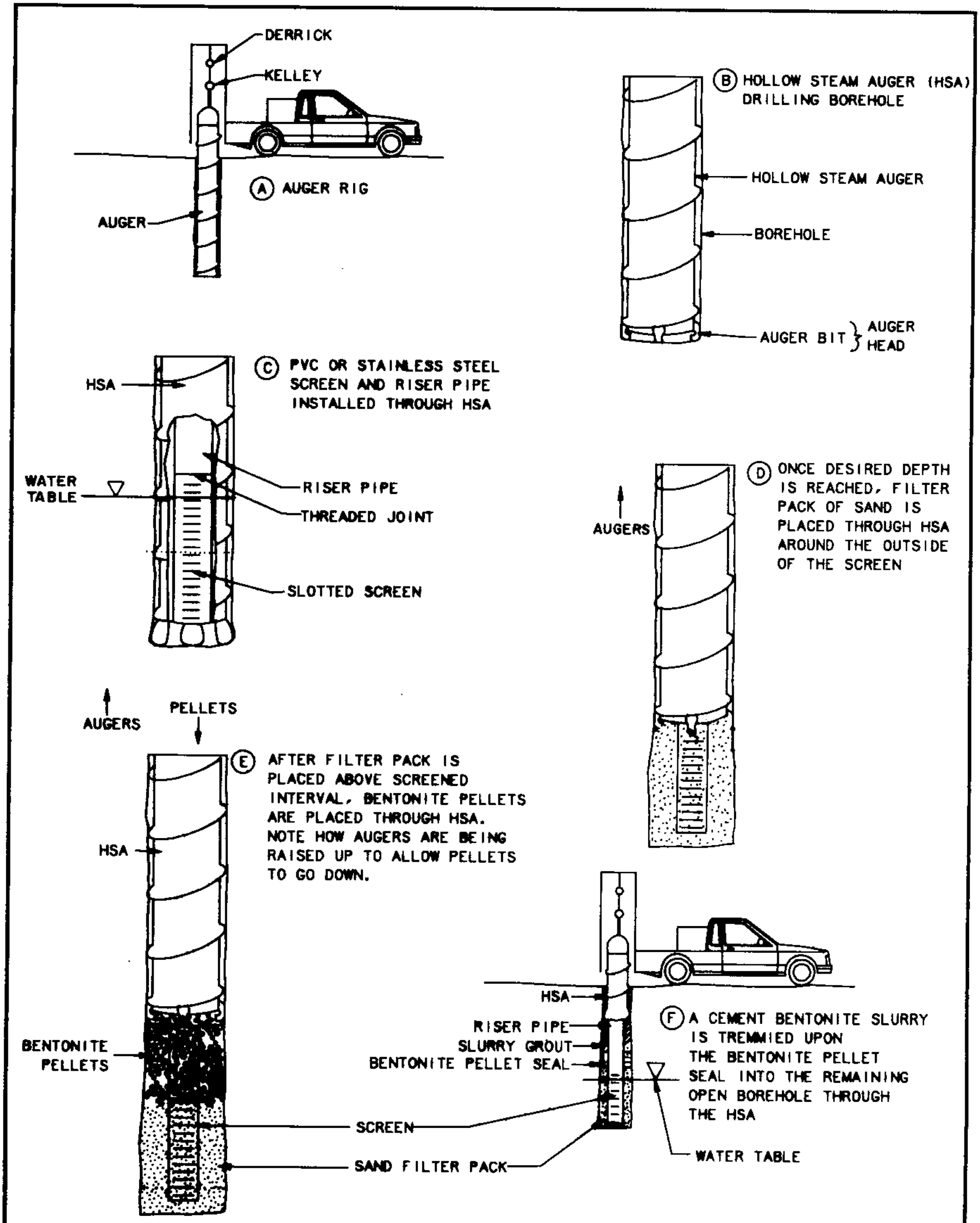
4 in. diam.

NOTE:
This specification based on "NJDEP Unconsolidated Monitor Well Specifications."

ESI Langan Environmental Services, Inc.
Elmwood Park, New Jersey • Miami, Florida

TYPICAL UNCONSOLIDATED MONITORING WELL INSTALLATION

PROJ
SCALE N.T.S.
DATE
FIG NO 4



Ⓐ AUGER RIG

Ⓑ HOLLOW STEAM AUGER (HSA) DRILLING BOREHOLE

Ⓒ PVC OR STAINLESS STEEL SCREEN AND RISER PIPE INSTALLED THROUGH HSA

Ⓓ ONCE DESIRED DEPTH IS REACHED, FILTER PACK OF SAND IS PLACED THROUGH HSA AROUND THE OUTSIDE OF THE SCREEN

Ⓔ AFTER FILTER PACK IS PLACED ABOVE SCREENED INTERVAL, BENTONITE PELLETS ARE PLACED THROUGH HSA. NOTE HOW AUGERS ARE BEING RAISED UP TO ALLOW PELLETS TO GO DOWN.

Ⓕ A CEMENT BENTONITE SLURRY IS TREMMIED UPON THE BENTONITE PELLET SEAL INTO THE REMAINING OPEN BOREHOLE THROUGH THE HSA

FIGURE 5 HOLLOW STEAM AUGER METHOD

USER-JOHN FILE-TEMP WIN-LES1:1

Cave Exploration in New Jersey:
Tools, Techniques, and Experiences

Kathy Jordan

Northern New Jersey Grotto/National Speleological Society

Caves may be found in various rock types, both nonsoluble and soluble. Several caves occur in nonconsolidated sediments.

The nonsoluble rocks include granites, gneisses, basalt, diabase, shales, sandstones and quartzites. Caves in this rock type fall into two categories. The first formed when the rock was molten. Fissure caves and lava tubes are examples of this group.

The second category are those caves formed by the tectonic or weathering process, or some combination of these processes. Representative of such caves are the fracture and talus caves. Ice frequently forms within cold air pockets of talus caves giving rise to the popular term ice caves. Also included in this category are sandstone caves forming at the base of sandstone cliffs.

Typical of caves formed in nonconsolidated sediments are those found in sand or clay, created by runnoff water which found its way, through small cracks in the caprock, into the nonconsolidated sediments. Slowly, the passage of the runoff removed particles of sand and clay, leaving behind a cave.

In soluble rock formations such as limestone, dolomite and marble, caves are usually formed by solution. As most New Jersey caves have formed in soluble rock, the solution process of cavern formation shall be emphasized.

Meteoric water combines with carbon dioxide of the atmosphere and decaying organic matter to form a weak solution of carbonic acid. When this acid penetrates the surface and comes in contact with limestone, a series of open channels will be created and continue to enlarge as the acidic water moves through them. The channel form will be governed by fractures, bedding planes or joint system of the rock formation.

Solution cave passages can be grouped into several categories. A fissure passage is one in which the height is several times the width and is controlled by the fractures and joints in the rock. A bedding plane passage is wider than high and is controlled by the bedding in the rock. A key hole passage has a classic keyhole shape created by prior passage sedimentation, channel development above the sediment and subsequent scouring/removal of prior sedimentation.

When ground water highly concentrated in calcium bicarbonate begins to evaporate along cave passages, calcium carbonate is deposited, creating stalactites and stalagmites. Ceiling deposits are termed stalactites, those accumulating on the floor of the passage are called stalagmites. When the stalactites grow down to meet the stalagmites, a column is formed. Helictites are a unique type of stalactite that can grow in any direction.

Life within New Jersey's caves may be divided into zones. The twilight zone, as its name implies, is located near the cave entrance. In this dimly lit zone may be found several varieties of flora, as well as frogs and bats which regularly visit caves (trogloxenes). Just beyond the twilight zone is the middle zone, home of the troglophiles. These dwellers (i.e. millipedes and spiders), live their entire life in the cave, but their species may also be found living outside caves. Beyond the middle zone is the dark zone, the realm of the troglobites. These are permanent cave dwellers, such as blind cave fish, species of which are never found outside the cave.

Cave exploration requires the proper equipment. Durable clothing with full length sleeves and trousers, gloves, construction grade boots, thermal underwear and hard hats are necessary for any cave trip. As the cave temperature in New Jersey is a constant 50° to 55° and humidity at 100%, warmth is an important factor.

At least three sources of light per person are required. These may be battery powered, carbide, or candles as a third back-up source.

If the cave has pits or exposed trenches which need to be traversed, vertical caving equipment is required. This includes repelling and ascending devices, caving or climbing rope, and various climbing harnesses.

When visiting any cave, permission is usually required from the landowner. Care must be taken while on private property, making certain that it is left in the same condition as when the caver arrived.

While in the cave, care must be taken not to disturb any forms of cave life. Bats usually hibernate in caves and should never be touched. Avoid touching or damaging cave formations. Oils from the hand will permanently discolor all cave formations.

When exploring caves, safety should be of utmost conceren. Drugs or alcohol are never to be used while caving. Warm clothing must be worn to avoid hypothermia. Exploration of a complex cave system may require a cave map. No matter how complex a cave, a minimum of three experienced cavers is required on any trip. Each should carry first-aid kit.

It is highly recommended that anyone seriously interested in cave exploration should join the National Speleological Society. This organization addresses every aspect of caving, from safety, techniques, equipment and conservation to cave research and scientific studies.

TYPES OF SURFACE- AND BOREHOLE-GEOPHYSICAL EQUIPMENT AND METHODS USED IN HYDROLOGIC AND GEOLOGIC INVESTIGATIONS IN NEW JERSEY

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INTRODUCTION

The six major types of geophysical methods used in geologic and hydrologic investigations are;

gravimetric,
magnetic,
electrical,
electromagnetic,
seismic, and
radiometric.

The purpose of this workshop is to display typical field equipment used to collect geophysical data. In addition, there will be a brief explanation of how each instrument works, typical examples of the type of investigation that could benefit from the use of the geophysical technique, methods of data collection in the field, data interpretation, and advantages and limitations of each technique. References on the use of geophysics in typical geologic and hydrologic studies in New Jersey will be presented.

Geophysical methods can be divided into surface and borehole methods. Identical geophysical principals are used in both surface and borehole applications; only the construction of the instruments is different. Some geophysical techniques, such as gravity, magnetics, and seismics, are much more applicable to, and therefore are more frequently used, at the surface, whereas radiometric, electrical, and electromagnetic techniques can be used equally at the surface and in boreholes.

Two or more types of geophysical methods commonly are used to survey an area or to log a borehole to provide redundant data, to identify a nonunique response, and (or) to explore more than one target. Simultaneous collection of land-use, geologic, hydrologic, and in certain cases biological, climatological, or borehole- and well-construction data will help to ensure accurate interpretation of geophysical data.

TYPES AND USES OF SURFACE- AND BOREHOLE-GEOPHYSICAL EQUIPMENT

Gravimetric: The most common type of gravimeter uses a zero-length spring with a small mass attached to it. In areas of low density, such as a bedrock valley filled with unconsolidated sediment, the small mass in the gravimeter is deflected less than in areas of high density, so that a gravity low anomaly is detected in the valley center. A gravity-high anomaly is detected over a massive body, such as an igneous intrusion like the Palisades Sill. The gravity map of New Jersey (Bonini, 1965) shows regional gravity anomalies. Gravity data collected in Mercer County Park, New Jersey (Ghatge and others, 1989), was coupled with other geophysical techniques to determine the depth to bedrock. Gravimetric techniques are time-consuming and are rarely used in investigations of a local scale or as a borehole technique. Gravity surveys can be used in an urban environment where nearly all other surface-geophysical techniques fail.

Magnetic: The most commonly used magnetometer is a proton precession magnetometer. The instrument detects the precession (spin as in a child's top) of a proton. Magnetometers can be used to delineate areas of high magnetism, such as basaltic outcrops or buried steel drums, from areas of low magnetism. A magnetic map of northern New Jersey (Henderson and others, 1958) delineates the magnetic-high basalt bodies from the magnetic-low sedimentary rocks. Site-specific hydrologic applications of magnetic techniques include surveys conducted at hazardous-waste sites to detect a buried metallic target (Geraghty and Miller, Inc., 1985). Magnetic surveys are inexpensive and easy to conduct. Field surveys are, however, very sensitive to overhead and underground surface lines, chain-link fences, and so on. Because many areas contain these interference sources, use of this method requires discretion. Magnetic methods are used only infrequently for typical borehole applications.

Electrical: The most commonly used electrical-survey equipment consists of a power source, voltmeter, ohmmeter, four electrodes, and appropriate lengths of wire. The four electrodes can be aligned in numerous arrays. The ohmmeter essentially controls the amount of electric current that is induced to flow into the ground, and the voltmeter measures the resulting voltage. By applying a modification of Ohms Law it is possible to calculate the electrical resistance of the subsurface. Qualitatively, the following various subsurface materials are pairs of high-low-resistance materials, respectively: dry and wet, sand and clay, freshwater and saltwater, and freshwater and contaminated water. Surface electrical surveys are used at hazardous-waste sites to delineate contaminated and uncontaminated areas or to differentiate sand from clay (Lacombe, 1986). Borehole electric logs are used to delineate aquifers and confining units and saltwater from freshwater (Zapecza, 1989). Typical surface surveys are relatively inexpensive and very versatile but cannot be conducted in areas influenced by electrically conductive service lines, chain-link fences, guard rails, and train tracks. Borehole electric techniques commonly are used in conjunction with gamma-ray and driller's logs; however, they cannot be used in a dry hole or in cased wells.

Electromagnetic: Since studies of hazardous waste sites have become common, various electromagnetic (EM) techniques have become some of the more frequently used surface-geophysical tools used to delineate ground-water-contamination source areas and contamination plumes. The instrument typically consists of a transmitter, transmitting antenna, receiver, and receiving antenna. For an apparent-conductivity survey, a radio-frequency EM field is created around the transmitting antenna. The primary EM field creates a secondary EM field around a local conductive body. The second EM field is intercepted and measured by the receiving antenna. The relative size, location, and conductivity of the body determines its apparent conductivity. Typical electromagnetic-conductivity surveys to delineate ground-water contamination have been conducted at numerous waste sites in New Jersey (Lacombe and others, 1986). Ground-penetrating-radar (GPR) surveys are a second type of EM survey. The emitted EM signal is reflected from subsurface contacts and the configuration of subsurface features is displayed. A buried, peat-filled channel and dipping beds were detected by the author using this technique in New Jersey. A conductivity survey is moderately expensive. It is an excellent initial investigation tool in areas unaffected by service lines and metallic material. GPR equipment is very expensive. EM borehole tools are gaining recognition as appropriate tools to use in hazardous-waste-site investigations to delineate lithology and to differentiate contaminated from uncontaminated areas. The advantage of the EM borehole-logging tool over electric logging tools is that it can be used in dry holes and in wells cased with polyvinyl chloride.

Seismic: Typical seismic field surveys use a 12- or 24-channel engineering seismograph, an equivalent number of geophones, and a sound source, such as a sledge hammer, weight drop, or explosive. The two types of surface seismic surveys are refraction and reflection. Seismic-refraction surveys are most commonly conducted to detect the bedrock surface (Lacombe and others, 1986 and Lacombe and Duran, (1981988). Seismic-reflection surveys frequently are conducted to detect significant changes in the strata. A seismic survey can be relatively expensive but is inexpensive when compared with the cost of exploratory drilling to determine the depth to bedrock. Refractive surveys are difficult to conduct where depth to bedrock is greater than 500 feet, in urban settings, or along highways, where ambient noise is very high. Refractive surveys are easier to interpret than reflective surveys. Reflection surveys are typically not conducted as part of small-scale investigations because the techniques are time-consuming. Although borehole seismic surveys are conducted infrequently, they typically are performed in conjunction with reflective surveys.

Radiometric: The most commonly used radiometric tool is the borehole gamma-ray logger (Zapecza, 1989). The tool consists of a detector that responds to gamma rays. Gamma rays are emitted more frequently from clay than from quartz sand; therefore, gamma-ray logs are frequently used in combination with electric logs to delineate lithology. Surface gamma-ray tools are most commonly used for mineral exploration or for regional mapping.

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WORKSHOP M

CONVERTING A NEW JERSEY ROAD MAP TO A GEOLOGIC PROVINCE MAP

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Activity: Converting a New Jersey Road Map To a Geologic Province

Purpose: To indicate on a road map of New Jersey the boundaries of the geologic regions and gain some insights of the attributes of each region.

Materials: Road map of New Jersey, Geologic map of New Jersey, pencil, felt-tip markers in black, brown, blue, red, and green.

Part I

New Jersey is geologically divided into 4 different natural regions trending in a northeast-southwest direction. Each region has its own particular rocks, geologic structures, and geologic history, thereby giving each region its own characteristic topography (relief) which is different from that of an adjacent area. Each of these characteristic areas of New Jersey is part of a much larger region of similar topography found in adjacent states where there is a similar sequence of rock types, geologic structures and commonality of geologic history. Each such area in its entirety is known as a physiographic province.

A. Ridge and Valley Province

1. Locate and with a pencil, mark a small x on the following locations in northern New Jersey. The towns form a line in a northeast-southwest direction.

   Owens, McAfee, Hamburg, Hardistonville, Monroe, Lafayette, Andover, Tranquility, Allamuchy, Vienna, Buttzville, Roxburg, Brainards

2. Join the marks with a pencil line.

3. With a black marker, draw over the pencil line.

4. The region above the line is the Ridge and Valley Province of New Jersey. This province represents five percent of our State's surface area. Label it just outside the region in Pennsylvania. Leave the interior free for further information.

B. Highlands Province

1. Follow procedures A-1, 2, and 3 in marking the following towns on the map.

   Mahwah, Oakland, Pompton Lakes, Boonton, Morristown, Bernardsville, Peapack, Lebanon, Clinton, Jutland, Riegelsville

2. The region above this line and below the A-3 line is the Highlands Province of New Jersey. This province represents fifteen percent of New Jersey's surface area. Label it on the map, leaving the interior free for information.

C. Piedmont Province

1. Follow procedures A-1, 2, and 3 in marking the following towns on the map.

   Bayonne, Carteret, Woodbridge, Metuchen, Highland Park, Monmouth Junction, Plainsboro, Trenton

2. The region above this line and below the B-2 line is the Piedmont Province of New Jersey. This province represents twenty percent of our State's surface area. Label it on the map.

D. Coastal Plain Province

1. Follow procedures A-1, 2, and 3 in marking the following towns on the map. Join the towns with a broken (dashed) line instead of a solid line.

   Monmouth Beach, Eatontown, Colts Neck, Freehold, Smithburg, Perrineville, Cream Ridge, Juliustown, Evesboro, Somerdale, Blackwood, Mullica Hill, Sharptown, Salem, Oakwood Beach.

2. Above the broken line and below the C-2 line is the Inner Coastal Plain. Follow procedure A-4 and label.

3. Below the broken line is the Outer Coastal Plain. Label it following procedure A-4.

   The inner and outer Coastal Plain contain sixty percent of our State's total area. Together they represent the Coastal Plain Province of New Jersey.

E. Refer to the Geologic Map of New Jersey

1. In each province on the road map write the age (period) of the rock types in the area where each is found.

If the rock is igneous write the age in red, if sedimentary write in blue, and if metamorphic use green.

Part II

About 80,000 years ago, the last of four great Pleistocene ice sheets advanced south towards New Jersey. The spread of this continental ice mass is called the Wisconsin Glacial Stage. It is estimated that as recently as 18,000 years before the present, the glacier reached its maximum extent and blanketed northern New Jersey with up to a 2,000 foot thick mass of ice. As it advanced, the ice scraped, gouged, and plucked thousands of tons of rock debris which became frozen in the mass. The glacier, like a giant conveyor belt transported this heterogeneous mix of clay, sand, gravel, and huge boulders. Rapid melting 12-10,000 years ago left deposits of this debris called till covering much of northern New Jersey. Some of this till accumulated as a mound marking the furthest advance of the ice. This mound of till is called the terminal moraine. The terminal moraine in New Jersey varies in height from tens of feet to over 300 feet thick and extend east-west across New Jersey as a low ridge averaging about a mile wide.

Wisconsin Glacial Terminal Moraine

1. On the road map, find the following locations and pencil mark with an x.

   Perth Amboy, Metuchen, Oak Tree, Scotch Plains, Chatham, Morristown, Littleton, Mountain Lakes, Rockaway, Netcong, Vienna, Bridgeville, Foul Rift

2. Join the marks with a pencil line.
3. With a brown marker, draw over the pencil line.
4. Label this line as the terminal moraine at a suitable spot.

Part III

Some Additional Activities

1. Plan a legend (key) for your geologic province map and put it on the map.
2. Draw in the boundaries and label the Palisades Sill.
3. Show and label the locations of the three Watchung Lava Flows.
4. Draw the shoreline of Glacial Lake Passaic, and label and show its extent.
5. Calculate the number of square miles represented by each province and write it in an appropriate place on the map.

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FIELD TRIP ROAD LOG

GEOLOGICAL ASSOCIATION OF NEW JERSEY

7th ANNUAL CONFERENCE

ASPECTS OF GROUNDWATER IN NEW JERSEY

Compiled by

Mr. James O. Brown, Langan Environmental Services
Dr. Donald B. Krall and Dr. Richard L. Kroll
Department of Geology and Meteorology
Kean College of New Jersey

ASPECTS OF THE GEOMORPHOLOGY OF CENTRAL NEW JERSEY

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Union, N.J. 07083

GLACIAL LAKE PASSAIC

During the maximum extent of the Wisconsinan Ice Sheet, a proglacial lake existed in the upper Passaic River Valley. This lake has been named Glacial Lake Passaic (Salisbury,1893; Kummel, 1895; and Salisbury, 1902). The waters of the lake were impounded on the south and southeast by the basalts of Second Watchung Mountain, on the northeast by the gneissic Highlands and on the northeast by the ice sheet. At its maximum extent, the lake was approximately 48 km (30 miles) long, 13 km (8 miles) to 16.2 km (10 miles) wide, and up to 73 meters (240 feet) deep (Kummel, 1895).

The two main stages of Glacial Lake Passaic are illustrated in Figure 1 and Figure 2. The earlier stage occurred when the ice was at its terminal position within the Passaic Valley. This was approximately along what is now Route 24 between Chatham and Morristown. The outlet of the lake was at Moggy Hollow, 11.2 km north of Somerville,N.J. Interstate 287 now crosses the head of the outlet and somewhat obscures the original characteristics of the channel. As the ice melted back from its terminal position, the lake expanded, reaching its maximum extent just prior to the opening of the outlet at Little Falls. Thus during the earlier stage (Figure 1), the lake existed only in the southern portion of the Passaic Valley, whereas during the later stage (Figure 2), the lake occupied the Valley both to the south and to the north of the terminal moraine.

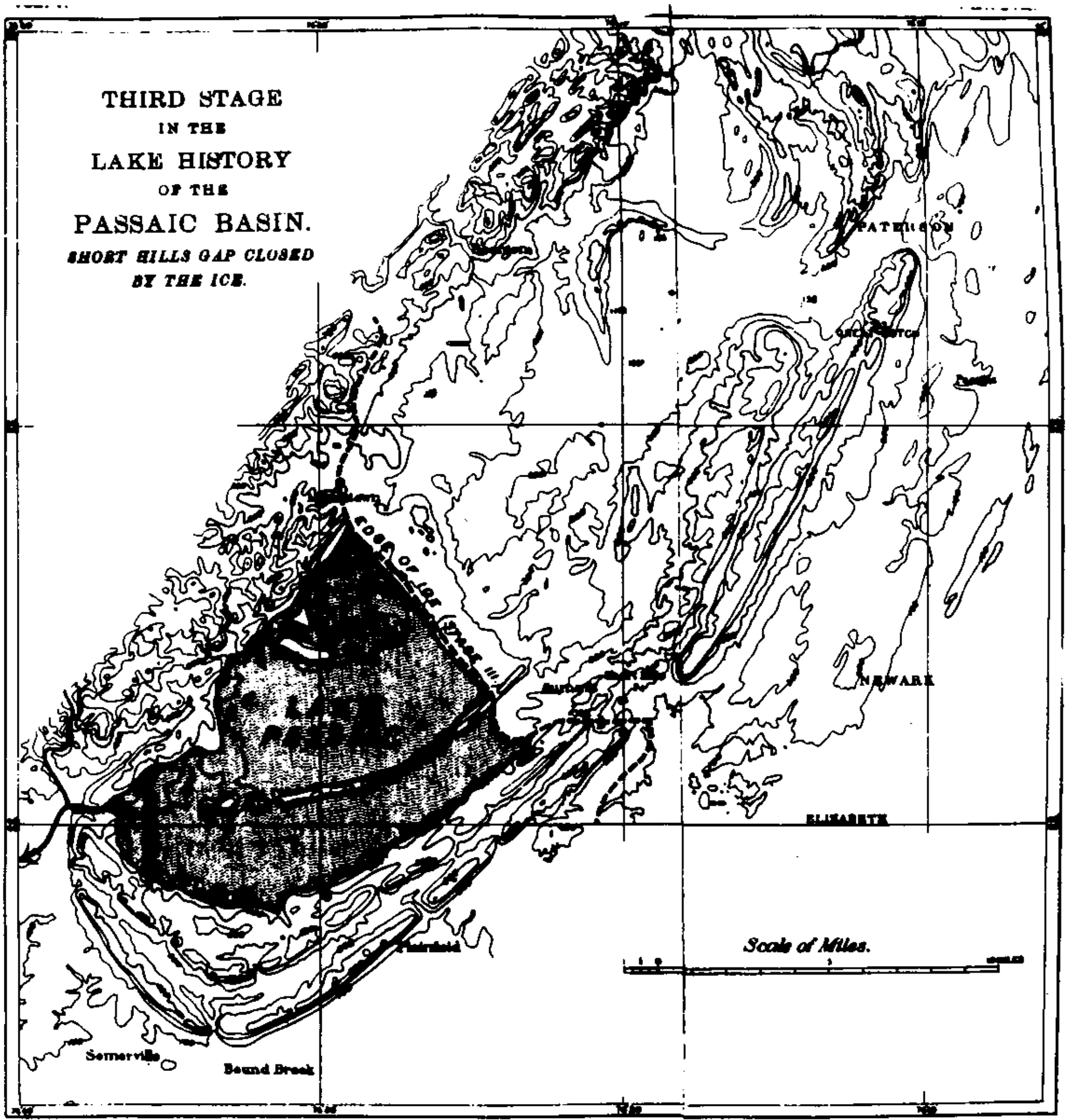

Figure 1. Glacial Lake Passaic when ice was at the terminal moraine. From Salisbury (1902).

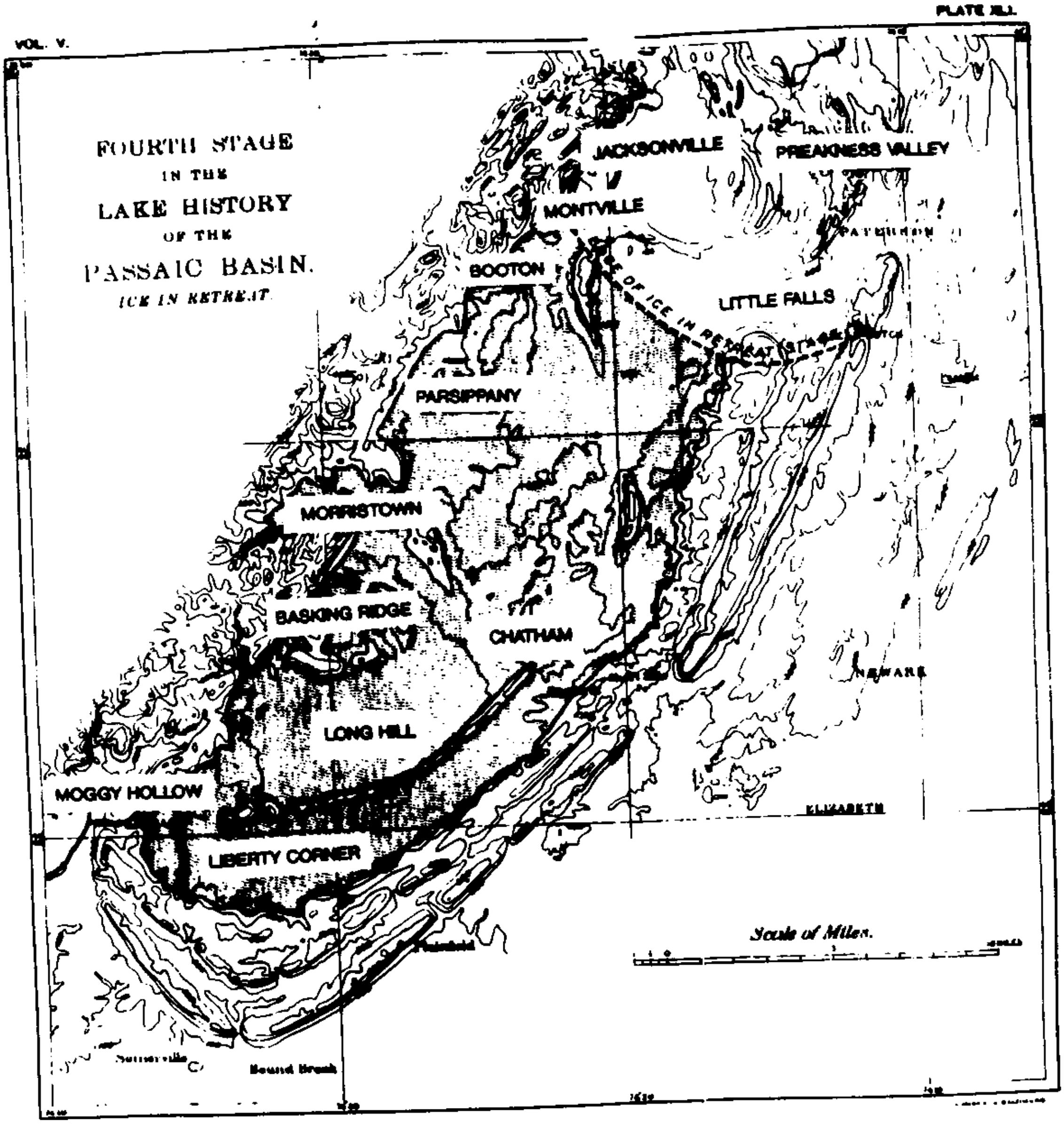

Figure 2. Glacial Lake Passaic just prior to maximum extent. From Salisbury (1902).

The outlet at Moggy Hollow has been cut to a present-day elevation of 101 meters (331 feet). Kummel (1895) estimated lake level at this point to be about 109 meters (356 feet). Wave cut terraces, spits, sandbars, kame deltas, and wave built terraces delineate the shoreline of the lake at different locations throughout the Valley. South of the moraine where the lake existed for a longer time, erosional features are better developed. North of the moraine where abundant sediments were being shed off the ice sheet, kame deltas predominate. Some of the more prominent wave cut terraces are located near the Moggy Hollow outlet, along the northwest side of Long Hill, and near Morristown. Prominent constructional features include spits and wave built terraces extending along the southeastern side of Long Hill. Additional wave built terraces are found east of Basking Ridge and on the outer portion of the moraine between Chatham and Morristown. The most prominent kame deltas are found at the extreme northern part of the lake. Examples include kame deltas located 1) between Booton and Montville, 2) at Jacksonville, 3) in the Upper Preakness Valley, and 4) 1.6 km north of Parsippany.

The shoreline features increase in elevation from 105 meters (345 feet) 2.4 km south of Liberty Corner to 126 meters (412 feet) at the extreme northwestern end of the lake, indicating post-lake deformation of 0.44 meters/km (2.6 feet/mile) (Kummel, 1895). The tilt of the shoreline is attributable to glacial rebound over the last 18,000 years as the heavy load of the last continental ice sheet was removed from the land.

For further details of the lake features and a more complete history of Glacial Lake Passaic, see the references cited above as well as Salisbury and Kummel (1895), Kummel (1940) and Wolfe (1977).

Mileage	Log begins at the Kean College of New Jersey entrance/exit gate on Morris Ave. (Rt. 82).
0.0	Leave campus and turn left (north) on Morris Ave.
1.8	Right turn to Rt. 22 entrance. Bear right, then left to Rt. 22 westbound.
5.8	Crossing the Wisconsin Glaciation Terminal Moraine, marked by small rise in road. First Watchung Mountain to west and northwest.
6.4	Off Terminal Moraine; it runs parallel to Rt. 22 on south side of road.
7.8	Terminal Moraine veers to southwest.
10.5	Scotch Plains Exit for I-78; onto Bonnie Burn Road. Proceed up hill, rising through First Watchung Basalt (Orange Mountain Basalts).
11.4	Intersection with County Road 527. Continue straight onto County Road 641. Leaving First Watchung Basalt.
12.1	Pass under I-78 and through Second Watchung Basalt (Preakness Formation).
12.4	Left turn toward I-78 westbound.
12.6	Bear right to I-78 westbound ramp, join I-78.
13.2	Green Brook in woods drains southward into Raritan River Drainage System. Query? Why is the drainage divide between the Passaic and Raritan drainage basins located north of the First and Second Watchung ridges?
14.7	Outcrop of Second Watchung Basalt.
14.8	Cross drainage divide into Passaic Basin.
16.6	Basalt outcrop.
20.8	View north across floor of ancient glacial Lake Passaic.
21.7	Sign for Scenic Overlook.
22.4	Exit for Scenic Overlook.
22.7	Parking area for Scenic overlook. Proceed to southeast end of parking area. View to west.

STOP 1

STOP 1.

LEADER - Dr. Donald B. Krall, Kean College of New Jersey

OVERLOOK FROM SECOND WATCHUNG MOUNTAIN

INTERSTATE ROUTE 78, MILEPOST 33

Peneplain, Peneplains,
How many can there be?
Is there none?
Only one?
Or maybe two or three!

BACKGROUND

Davis (1889) noticed a concordant of summit elevations in New Jersey and throughout the Appalachians. He suggested that these summits are remnants of a large, nearly flat, erosional surface that had formed near sea level. He coined the term peneplain to describe such surfaces. This particular peneplain was subsequently warped during uplift and later dissected by a second period of stream erosion. He named this surface the Schooley peneplain after Schooley Mountain, a flat topped mountain in the New Jersey Highlands, 6.4 km south of Hackettstown and 20.9 km northwest of this overlook. Schooley was an ideal choice because the flat top of Schooley Mountain represents one of the largest remnants of this erosional surface. Campbell (1903) introduced the term Harrisburg for an erosional surface below the Schooley peneplain located on the higher areas of the Great Valley underlain by the Martinsburg shale. Davis and Wood (1890) suggested the name Somerville for an even lower, rather local erosional surface on the Brunswick shale extending from Raritan Bay southwestward to Salem, N.J. It reaches its widest point near New Brunswick where it extends in a northwesterly direction past Somerville. Each of these three surfaces supposedly represents successively younger cycles of uplift and erosion. Other writers correlated erosional surfaces throughout the Appalachians to these surfaces. Thus they all became known as peneplains because of their wide extent. Bascom (1921) recognized an additional five erosional surfaces within the Piedmont province of Pennsylvania.

In contrast to this proliferation of peneplains, Ashley (1935) maintained that all the erosional surfaces were the products of only one uplifted and dissected peneplain. The various levels were merely caused by different rates of erosion due to rocks of varying resistances. Hack (1960) denied the basic tenant of the Davisian model of a cyclical pattern of rapid uplift followed by long periods of crustal stability and erosion. He introduced the idea of dynamic equilibrium which implies that landscapes quickly adjust to changes in diastrophism or climate. He stressed the importance of differences in bedrock and processes in landform development. According to this concept, no matter what the characteristics of the original surface, different topographic levels would rapidly form and be maintained because of the differential erosional rate on various lithologies. Therefore, no original peneplain need to have existed.

DESCRIPTION OF THE OVERLOOK

Peneplain, Peneplains,
How many can you see?
Is there none?
Maybe one?
But never two or three!

This overlook is located on the western flank of Second Watchung Mountain. The view is toward the southwest across the northwestern portion of the Piedmont Lowlands. The topography is directly related to the resistance of the underlying bedrock. In the near foreground is First Watchung Mountain (Figure 3). Both First and Second

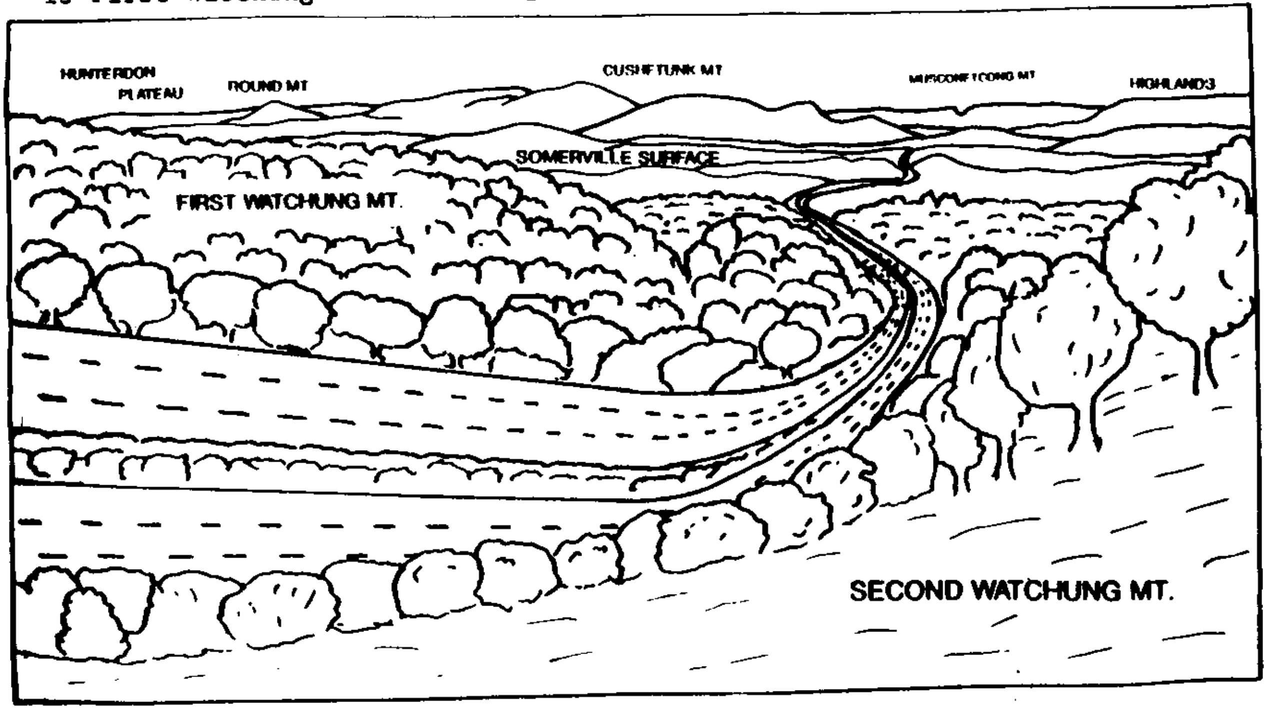

Figure 3. Overlook From Second Watchung Mountain along Interstate Route 78 at milepost 33. View is toward the southwest. Brunswick shale underlies area labeled Somerville surface (see text).

Watchungs are composed of basalt. Forming the skyline from S 55° W to N 65° W is the Hunterdon County Plateau, Round Mountain, Cushetunk Mountain, and the southeastern edge of the New Jersey Highlands. On a very clear day, Musconetcong Mountain, another Highland ridge, can be seen due west. The Hunterdon County Plateau is formed on Lockatong argillites. Round Mountain and Cushetunk Mountain are underlain by diabase and the Highlands are composed of Precambrian gneisses. The valley between First and Second Watchung Mountains as well as the broad lowland in the middle distance is underlain by Brunswick shale.

The highest elevations represent the remnants of the Schooley peneplain (surface?). These include First Watchung (500 feet), Second Watchung (600 feet), the Highlands (840 feet in this view, 1,000 feet on Musconetcong Mountain, and up to 1140 feet on Schooley Mountain), Cushetunk Mountain (840 feet), Round Mountain (620 feet), and the Hunterdon County Plateau (800 feet). The Hunterdon County Plateau slopes off to the southeast at about 4.2 to 5.0 meters/km (25 to 30 feet/mile) matching the warped surface of the Schooley peneplain in the Valley and Ridge and The New Jersey Highlands Province (Wolfe, 1977). In the broad lowland in the middle distance the low flat divides are at an elevation of about 300 feet and represent the type area of the Somerville peneplain (Kummel, 1940). Within this local area, remnants of the Harrisburg peneplain were completely eroded during the cycle forming the Somerville peneplain (Wolfe, 1977).

Can the surfaces on the skyline literally represent the resistant remnants of an erosional surface uplifted in middle Tertiary time?

Erosional rates have been estimated based on the thickness of sediments on the continental margins and the total load of rivers. Menard (1961) estimated an erosional rate of 6.2 cm/1,000 years over the last 125 million years based on the thickness of post-Jurassic sediments. Mathews (1975), using seismic profiles of Emery and others (1970) estimated an erosional rate equivalent to 3.1 cm/1,000 years over the last 65 million years. The difference between these rates involves the problem of dissolved load. Mathews, allowing for porosity and some non-clastic marine deposition, decreased the values for sediment thickness to 40 percent to relate the thickness of the sediments to the thickness of the rocks from which they were derived. He made no adjustment for dissolved load. Menard assumed porosity of the sediments would approximately equal dissolved load and therefore made no reduction in total thickness. Judson and Ritter (1964) estimated a rate of 4.9 cm/1,000 years based on both dissolved and suspended stream load averaged from seven major rivers flowing out of the Appalachians into the Atlantic Ocean.

If the Schooley surface is middle Miocene (Kummel, 1940) and assuming uniform erosion rates over time, this would produce from 460 to 920 meters (1,500 to 3,000 feet) of surface lowering throughout the Appalachians over the last 15 million years. Mathews (1975) estimated that the soft rocks have been eroded to a mean depth of 0.25 km (820 feet) below the Schooley surface. This would imply a lowering of the Schooley surface on the resistant rocks to be between 207 to 665 meters (680 to 2,180 feet). The other alternative would be that the Schooley peneplain is much younger than previously thought.

Peneplain, Peneplains,
How many can there be?
Perhaps there's none.
But if there's one,
Then why not two or three?

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Leave Scenic Overlook

23.0	Rejoin I-78 westbound.
24.5	I-287 overpass. At base of Watchung Mts.
28.0	Cross Lamington River.
31.9	Jersey Till underlies homes in valley to north.
33.2	Round Valley to south.
34.3	Take Exit 20-B for Cokesbury.
34.5	Join County Road 639 (Cokesbury Road). Head north toward Cokesbury.
35.5	Onto Precambrian bedrock.
37.1	Cokesbury Methodist Church on right.
37.2	Bear left over stone bridge following County Road 639.
37.3	Bear left toward High Bridge following County Road 639.
39.3	Bear straight ahead onto narrow road as County Road 639 bears sharply left.
39.4	Stop at bridge to disembark. Cross bridge over South Branch of Raritan River. Walk up hill toward railroad overpass and turn left onto private driveway immediately before railroad. This is private property. Please do not leave driveway. This area is not open to the public without owners permission. Walk 1000 feet to Camp Dill.

STOP 2

STOP 2. SCOUT CAMP AT LAKE SOLITUDE - GEOLOGY

LEADER - RICHARD A. VOLKERT, New Jersey Geological Survey.

This stop is located within the Raritan River drainage basin. The South Branch of the Raritan River, seen directly to our immediate east, originates at Budd Lake on Schooleys Mountain. It flows southeastward, incising resistant bedrock of Middle Proterozoic age on the eastern flank of Schooleys Mountain, until it reaches the valley which is underlain by less resistant dolomite of the Leithsville Formation of Cambrian age. Here, the stream makes almost a right-angle bend and turns southwest, following structurally weakened rocks along the Longwood Valley Fault. Southwest of Califon, the stream has deeply incised the Proterozoic bedrock, creating scenic Ken Lockwood Gorge. The stream gradient steepens considerably as the South Branch descends approximately 240 feet in elevation between Califon and High Bridge (Bayley and others, 1914). Damming of the South Branch, to our south, has created Lake Solitude. Many of the tributary streams joining South Branch are likewise structurally controlled; they follow the dominant joint/fracture trend in the underlying bedrock. Other streams cut through the less resistant veneer of saprolite and show no control by bedrock structure.

The Proterozoic rock exposed at this stop is a medium-grained, buff, locally rusty weathering, light-gray biotite-quartz-oligoclase gneiss containing minor graphite and pyrite ($FeS2$). Oxidation of the thin, sulfide-rich layers results in the rusty weathering of the gneiss. Some conformably interlayered, dark-gray, biotite-bearing amphibolite occurs at the western end of the outcrop. The likely protolith for this gneiss is a graywacke sandstone. The graphitic phases represent locally interbedded carbonaceous material.

The alignment of quartz grains and plates of biotite define a foliation that trends about N36E and dips 55SE. Mapping in this area (Markewicz, unpublished data; Volkert, unpublished data) and to the immediate east (Volkert, 1989) suggests that these rocks are folded into southeast-plunging antiforms and synforms that were refolded by a subsequent phase of northeast-plunging folds.

In terms of aquifer characteristics, the Middle Proterozoic rocks are often critically limited in their ability to store and transmit groundwater because of their tightly interlocking texture. The few pores present are small and poorly connected. Consequently, the water-bearing capacity of these rocks is largely controlled by secondary porosity and permeability resulting from fracturing and weathering of the rock. Secondary porosity is markedly higher in the saprolite overlying fresh bedrock. Beneath the saprolite, the storage and movement of much groundwater occurs in joints and fractures. Groundwater yields, therefore, depend largely on fracture density, width, spacing, extent of interconnection, degree of mineralization, and continuity. Also, a thick overburden enhances recharge rates to the bedrock. Although well yields depend on several factors, it is probably safe to say that the average yield of typical domestic wells penetrating Proterozoic rock is about 10 gallons per minute. For a more extensive treatment of the occurrence of ground-water in the Highlands, see Volkert (1987).

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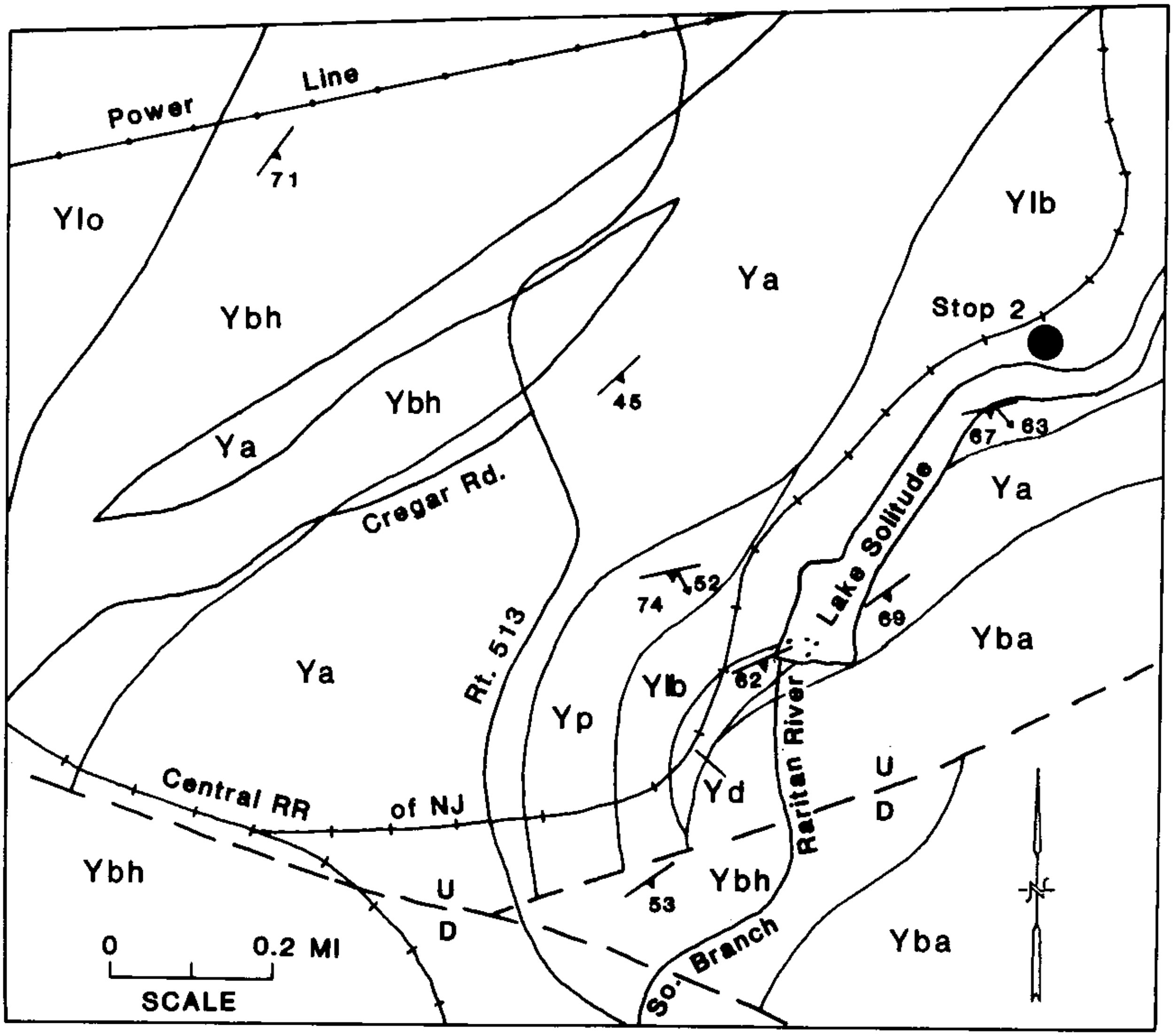
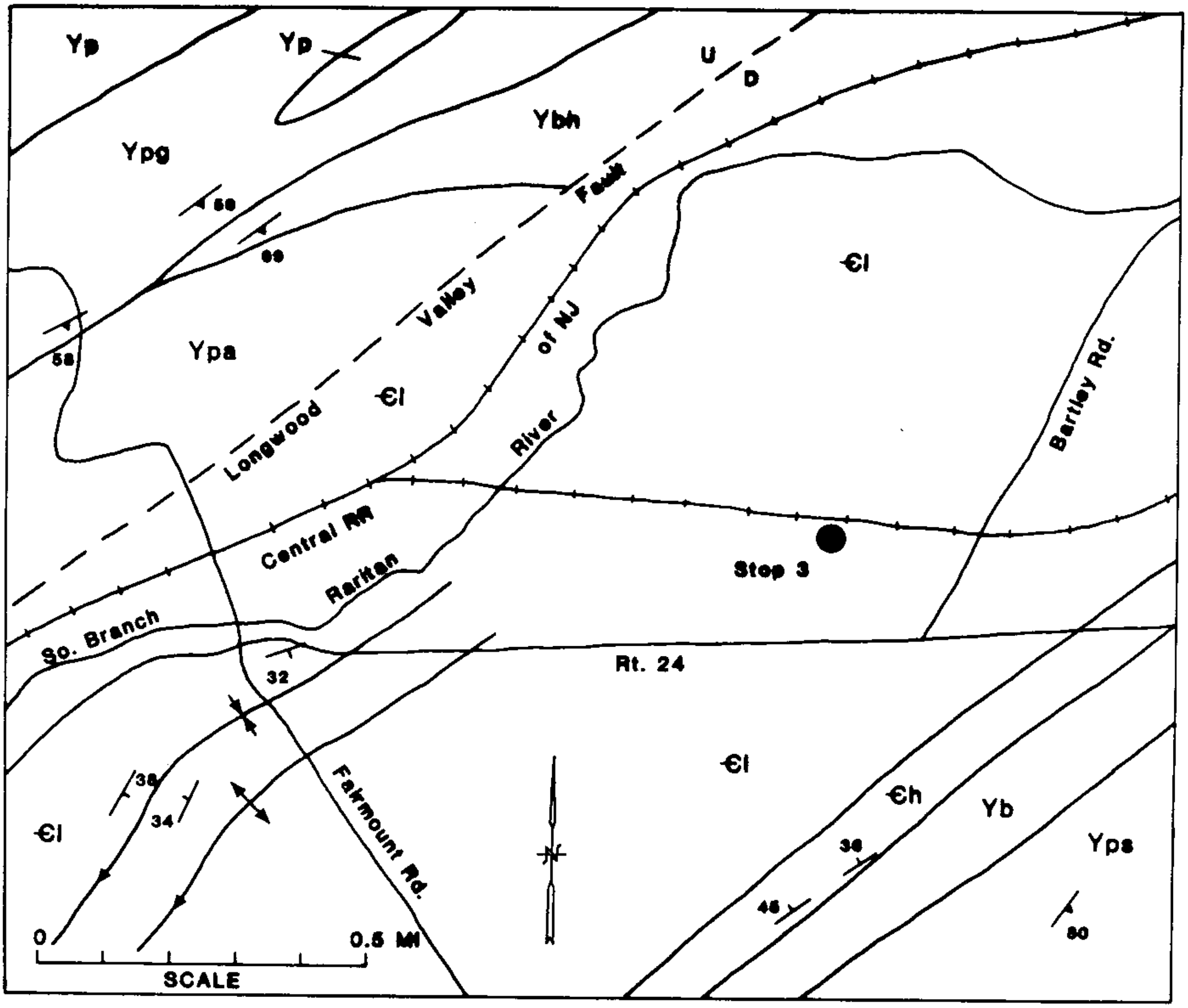


Geologic map of the Lake Solitude area, High Bridge quadrangle (Markewicz, unpublished data; Volkert, unpublished data). Map unit and symbol explanations shown on adjacent page are for stops 2 and 5.

EXPLANATION OF MAP UNITS AND SYMBOLS

JTru	Undifferentiated Mesozoic rocks	Jurassic and Triassic
Cl	Leithsville Formation	Cambrian
Ch	Hardyston Quartzite	
Ybh	Hornblende granite	Middle Proterozoic
Yba	Microperthite alaskite	
Ya	Amphibolite	
Yb	Biotite-quartz-feldspar gneiss	
Yp	Pyroxene gneiss	
Ylo	Quartz-oligoclase gneiss	
Ylb	Biotite-quartz-oligoclase gneiss	
Yd	Diorite	

——— ••	Contact - Dotted where concealed
	Faults - Dotted where concealed
— $\frac{U}{D}$ — ••	Normal - U, upthrown side; D, downthrown side
▲ ▲ ▲	Inclined thrust - Sawteeth on upper plate
34 ⊥	Crystallization foliation in Proterozoic rocks
→ 7	Mineral lineation bearing & plunge in Proterozoic rocks
15 ⊥	Inclined bedding in Paleozoic rocks
●	Field trip stop location



Geologic map of the Long Valley area, Hackettstown quadrangle. Data from Volkert, R.A., Monteverde, D.H., and Drake, A.A., Jr., Bedrock geologic map of the Hackettstown quadrangle, Morris, Warren, and Hunterdon counties, New Jersey: New Jersey Geological Survey, Geologic Map Series, in press, scale 1:24,000.

STOP 2. SCOUT CAMP AT LAKE SOLITUDE: WELL INSTALLATION

By JAMES O. BROWN, Langan Environmental Services, Inc. and
GERARD MALACK, Empire Soils Investigations, Inc.

The installation of a water supply well will be the main feature of Stop 2. Empire Soils Investigations, Inc. of Edison, New Jersey will be installing the well.

If all has proceeded according to schedule, EMPIRE will have mobilized the drill rig and begun drilling on the previous day. By the time GANJ has arrived, drilling operations completed should include the setting and grouting of well casing into competent bedrock. Depending on the arrival time of GANJ, either the drilling through the casing or development of the well will be in process.

A presentation of the drilling equipment and proceedures will be given by an EMPIRE representative. Although this is a water supply well, EMPIRE typically installs ground water monitoring wells. Information about EMPIRE is attached.

* **Edison,**
New Jersey: 201-287-2224
Featuring seventeen drill rigs and crews all geared to assuring you complete satisfaction in every possible way.

* **Morgantown,**
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Empire's latest location with the finest drillers and equipment this trade can offer.

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The Edison and Morgantown offices are strategically located to perform virtually any type of exploratory drilling and soil/rock sampling.

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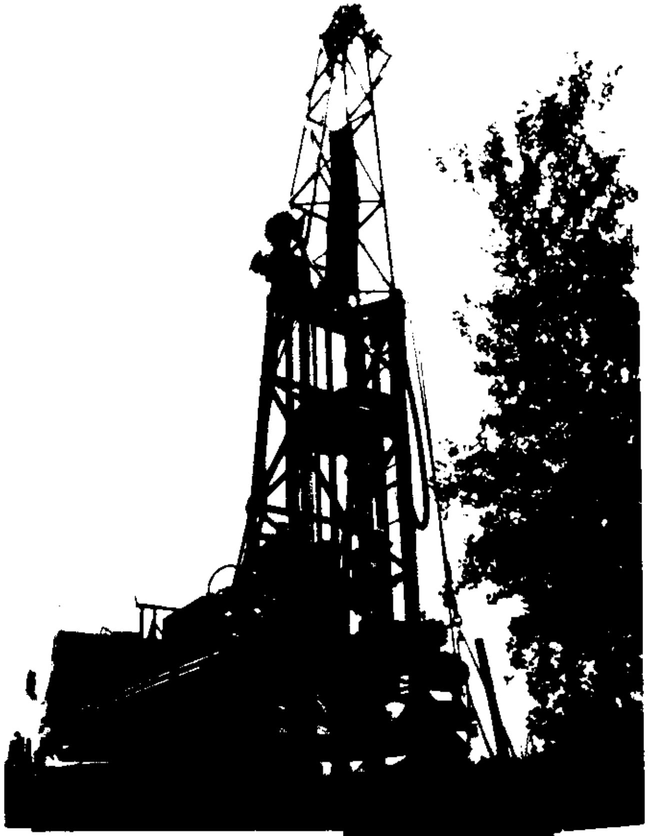
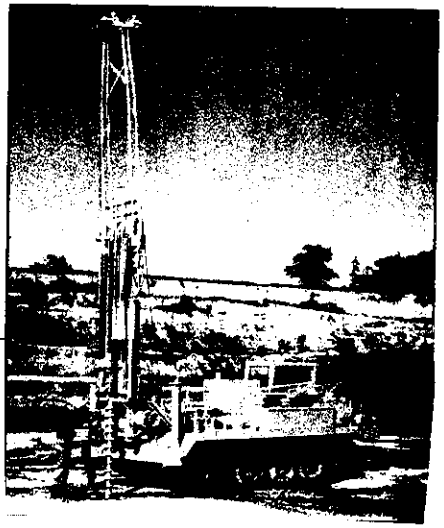


Fifty years of commitment to exploratory drilling has given Empire a reputation for expert drilling, accurate monitoring and unsurpassed service.

We have become the first choice for drilling and our professional knowledge ensures solutions to any difficult problems.



EXPERIENCED WORKFORCE

Fully licensed and OSHA certified drillers are the backbone of our operation. Whether it's a large or small project we guarantee the same commitment, concern and overall performance.

Supervisory project managers provide an important communication link between the site and the office. This coordinating link means all personnel are informed on every aspect of the project therefore saving time and eliminating costly mistakes.

EXTENSIVE SAFETY REGULATIONS

We are proud of our excellent health and safety programs which meet all the OSHA requirements for hazardous waste sites.

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- Failing F-10 Rigs
- Acker AD II Rigs
- Drilltechs / Tripods
- Bull Dozer
- Air Compressors
- Schramm Air Rotary Rigs
- Mobile B-61 Rigs
- Midway Air/Mud Rotary Rigs
- CME - 55, 45B, 45C, 75 Rigs
- Pump Trucks
- Variety of Tender Trucks, Flatbeds, Stake Racks, Water Tanks & more.

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We have the technology and expertise which is unequalled by any other ground investigations network. Our vast selection of customized drilling systems means your project receives the most suitable system required for job completion.

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- Auger Drilling
- Insitu Testing
- Core Drilling
- Down Hole Hammer
- Split Spoon Sampling
- Shelby Tube Sampling
- Falling Head Tests
- Tubex Method Drilling
- Packer Testing
- Pump Testing
- Well Sealing

COMPREHENSIVE MAINTENANCE PROGRAM

Our maintenance crew is a crucial support system to our field crews, equipment and overall operation. We specialize in on-time performance so the importance of our preventative maintenance program cannot be underestimated.

39.4	Leave from bridge, returning along County Road 639 eastbound.
40.4	Turn left onto Mt. Grove Road.
41.4	Turn left onto Hoffman's Crossing Road.
41.9	Scenic View of Long Valley and Schooley Mtn.
42.3	Turn right, before bridge, onto Raritan River Road and parallel the river.
43.9	Turn left on Main Street, cross the bridge, then uphill.
44.4	Intersection with County Road 513. Turn right onto County Road 513 northbound.
46.0	Cross river.
50.0	Rt. 513 joins Rt. 24 East.
51.0	Turn left onto County Road 625 (Bartley Road).
51.2	Turn left onto gravel road.
51.4	Disembark at Drew University farm.
	STOP 3

STOP 3

PROGRESS IN THE EVALUATION OF A CARBONATE-ROCK AQUIFER NEAR LONG VALLEY IN THE NEW JERSEY HIGHLANDS

ROBERT S. NICHOLSON

U.S. GEOLOGICAL SURVEY
810 BEAR TAVERN ROAD
WEST TRENTON, NJ 08628

In 1987, the U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, began a comprehensive study of the aquifers of the unconsolidated valley-fill sediments and the underlying carbonate rock in the New Jersey Highlands near Long Valley (fig. 1). The study will include a hydrologic assessment, a baseline water-quality assessment, and predictive computer simulations of ground-water-flow conditions. Results of the study will be useful to New Jersey's water-resources managers for planning purposes in an area that is experiencing increases in residential and commercial growth and in the demand for ground water.

The purpose of this report is to present some of the preliminary results of this study, focusing on the preliminary hydrogeologic characterization of an area in Long Valley near a farm property owned by Drew University. This farm property is the site of a scheduled stop on a field trip sponsored by the Geological Association of New Jersey to be held on October 27, 1990 . The preliminary hydrogeologic characterization includes discussion of (1) the hydrogeologic framework, (2) ground-water-flow directions, (3) ground-water-level fluctuations, and (4) aquifer characteristics. Discussion is limited to the carbonate-rock aquifer of the Cambrian-age Leithsville Formation.

The carbonate-rock aquifer underlies most of the valleys in the study area (fig. 2). It is overlain by unconsolidated valley-fill sediments of glacial and post-glacial origin and is underlain by the Hardyston Quartzite of Cambrian age, which is in turn underlain by gneiss or granitoid gneiss of Precambrian age (fig. 3). The structure of the carbonate-rock aquifer is being determined in detail by means of outcrop interpretations, geophysical methods, test drilling, and existing well records. The hydrologic function of the underlying Cambrian- and Precambrian-age rocks also is being investigated.

Ground-water-flow directions in the carbonate-rock aquifer are being determined from water levels measured synoptically in more than 100 wells during September, 1988, and April 1989. As shown in figure 4, preliminary data collected in September, 1988 indicate that north of Kenvil ground-water flows toward the Rockaway River. In the central part of the study area, ground water appears to flow toward pumping centers at Flanders and Ironia. South of Flanders, flow is generally to the southwest and locally toward the South Branch Raritan River, roughly following surface-drainage directions. The South Branch Raritan River appears to have a strong influence on ground-water flow south of Flanders, and aquifer drainage to the river here is significant.

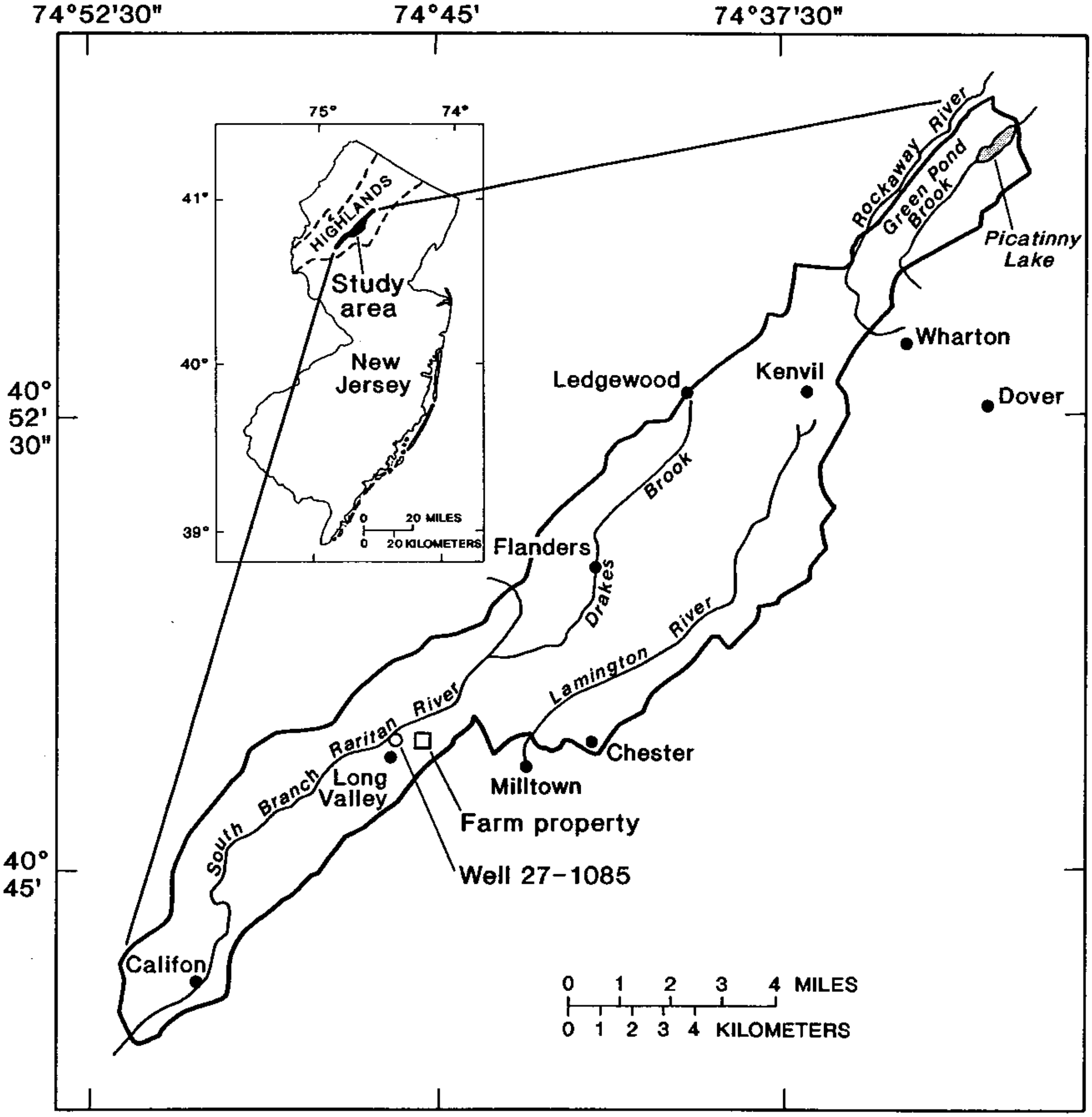


Figure 1.--Location of study area, farm property owned by Drew University, and well 27-1085.

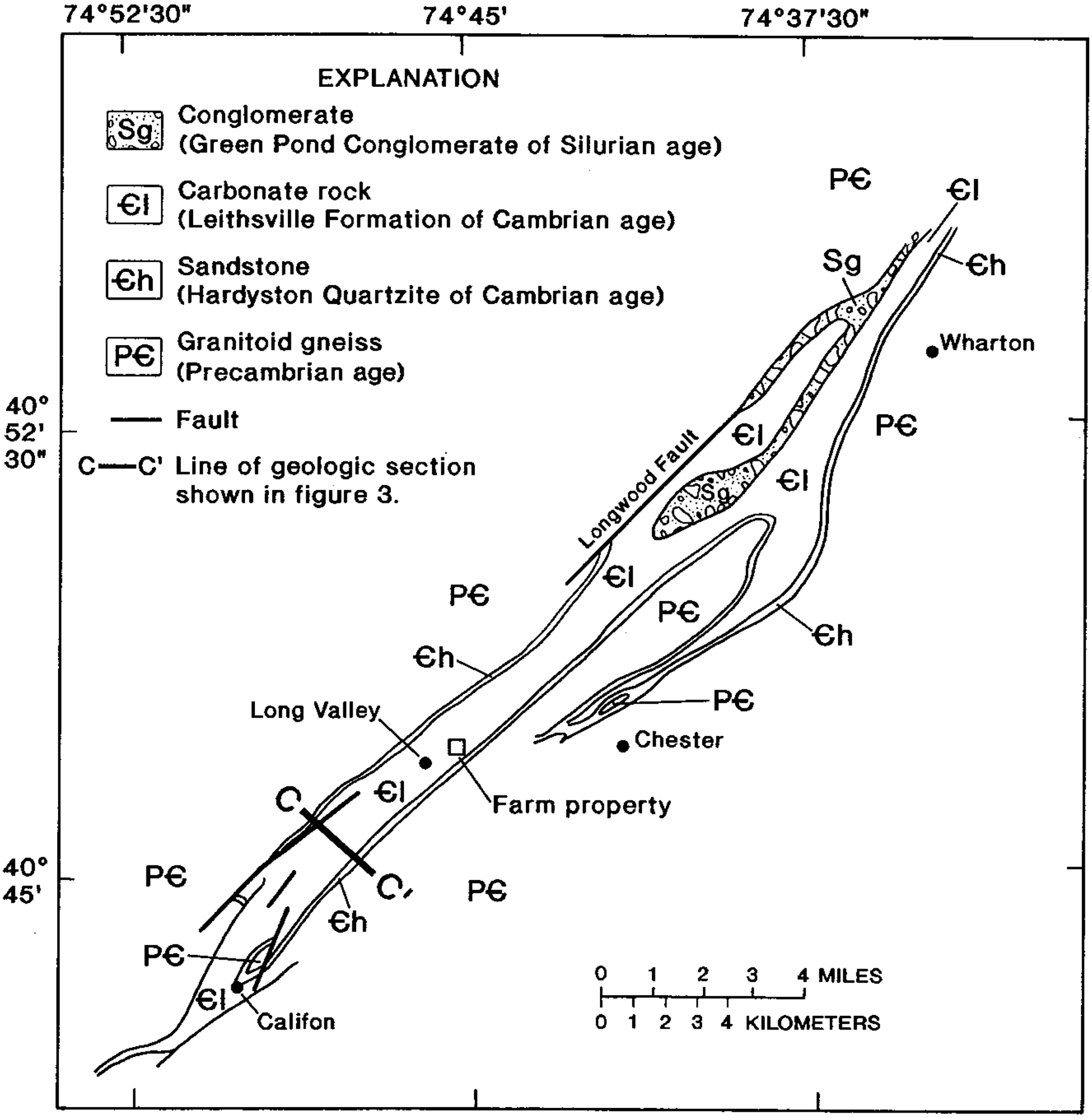
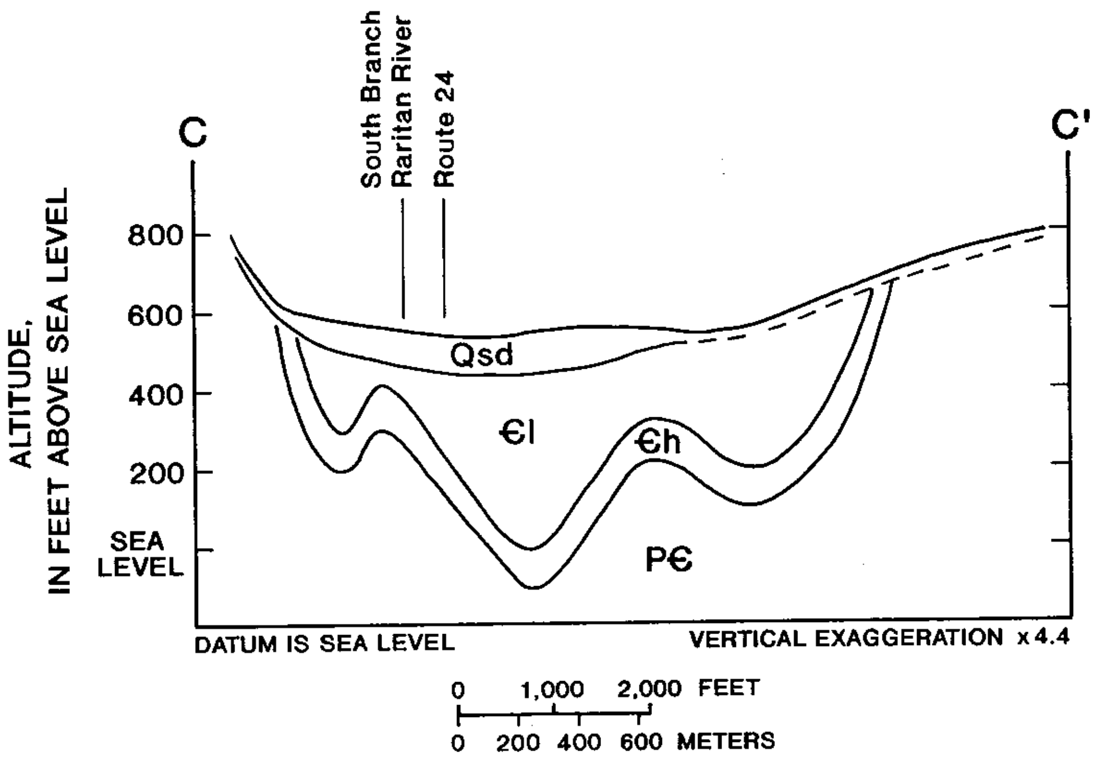


Figure 2.--Geohydrologic rock units in the study area. (From James Mitchell, New Jersey Geological Survey, written communication, 1988)



EXPLANATION

Qsd Stratified drift, dashed where approximately located. (Quaternary age)

Ꞓl Carbonate rock (Leithsville Formation of Cambrian age)

Ꞓh Sandstone (Hardyston Quartzite of Cambrian age)

PꞒ Granitoid gneiss (Precambrian age)

Figure 3.--Generalized geologic section C-C'. (Location of section shown in fig. 2) (From James Mitchell, New Jersey Geological Survey, written communication, 1988)

Long-term water-level fluctuations are being determined from water levels measured in several wells instrumented with automatic water-level recorders. Water levels in several additional wells are measured monthly. Ground-water fluctuations are the result of changes in storage of water in the aquifer, which can result from pumpage, injection, recharge from precipitation, and aquifer interactions with surface water.

The hydrograph in figure 5A shows water levels measured in 1989 in an observation well owned by the Washington Township Municipal Utilities Authority (well 27-1085). The well is 290 feet deep, cased to a depth of 117 feet, and open to the carbonate-rock aquifer. The well is located about 0.5 mile west of the farm property owned by Drew University, 200 feet south of the South Branch Raritan River in Long Valley (fig. 1). During the period of measurement in 1989 the water level fluctuated between about 9 and 12 feet below land surface. The pattern of rise and fall is characteristic of the aquifer response to recharge from precipitation and drainage to the nearby river, and can be used to determine aquifer hydraulic properties. Examination of a 4-day segment of the hydrograph (fig. 5B) shows that the water level rose and fell rapidly, indicating an increase in bank storage as river water entered the aquifer when a flood wave passed the stream reach adjacent to the well. This rapid response in the aquifer is another indication of a good hydraulic connection between the South Branch Raritan River and the carbonate-rock aquifer at Long Valley.

Hydraulic characteristics of the carbonate-rock aquifer also are being determined from aquifer tests conducted at a number of locations in the study area. Analysis of test data indicates that aquifer transmissivity is heterogeneous, which could be the result of spatial variability in aquifer thickness, fracture density, degree of weathering, and extent of solution channelling. One of these aquifer tests was conducted at the farm property (fig. 1) in April 1990. A 6-inch test well was drilled by the New Jersey Geological Survey to a depth of 225 feet. Carbonate rock was encountered at 68 feet and casing was set to a depth of 98 feet. A void was encountered between 113 and 116 feet. The well was pumped at a rate of 100 gallons per minute for 24 hours. The drawdown in the pumped well was only 1.0 foot at the end of pumping, indicating a high aquifer transmissivity at the site, probably resulting from extensive weathering and solution channelling.

The evaluation of all the aquifers considered as part of this study will include the components discussed above as well as determinations of stream base flow, ground-water-withdrawal summaries, in-situ geochemical-tracer analyses, a baseline ground-water-quality assessment, and a water budget. On the basis of the hydrologic assessment, a ground-water-flow model will be developed, calibrated, and used to simulate ground-water-flow conditions under a variety of water-use scenarios. Results of these simulations then can be used to evaluate water-management alternatives.

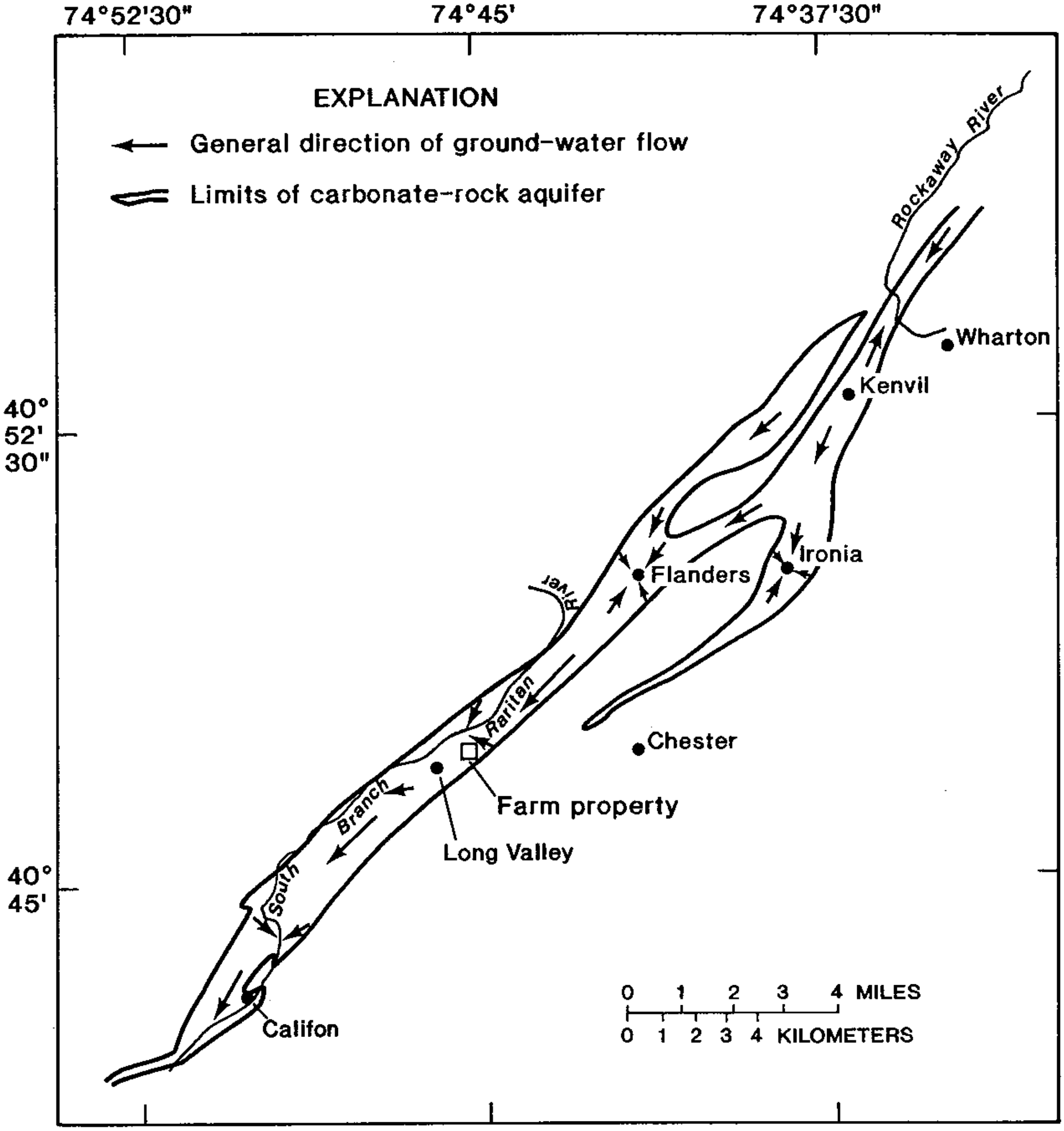


Figure 4.--Preliminary ground-water-flow directions in the carbonate-rock aquifer, September, 1988.

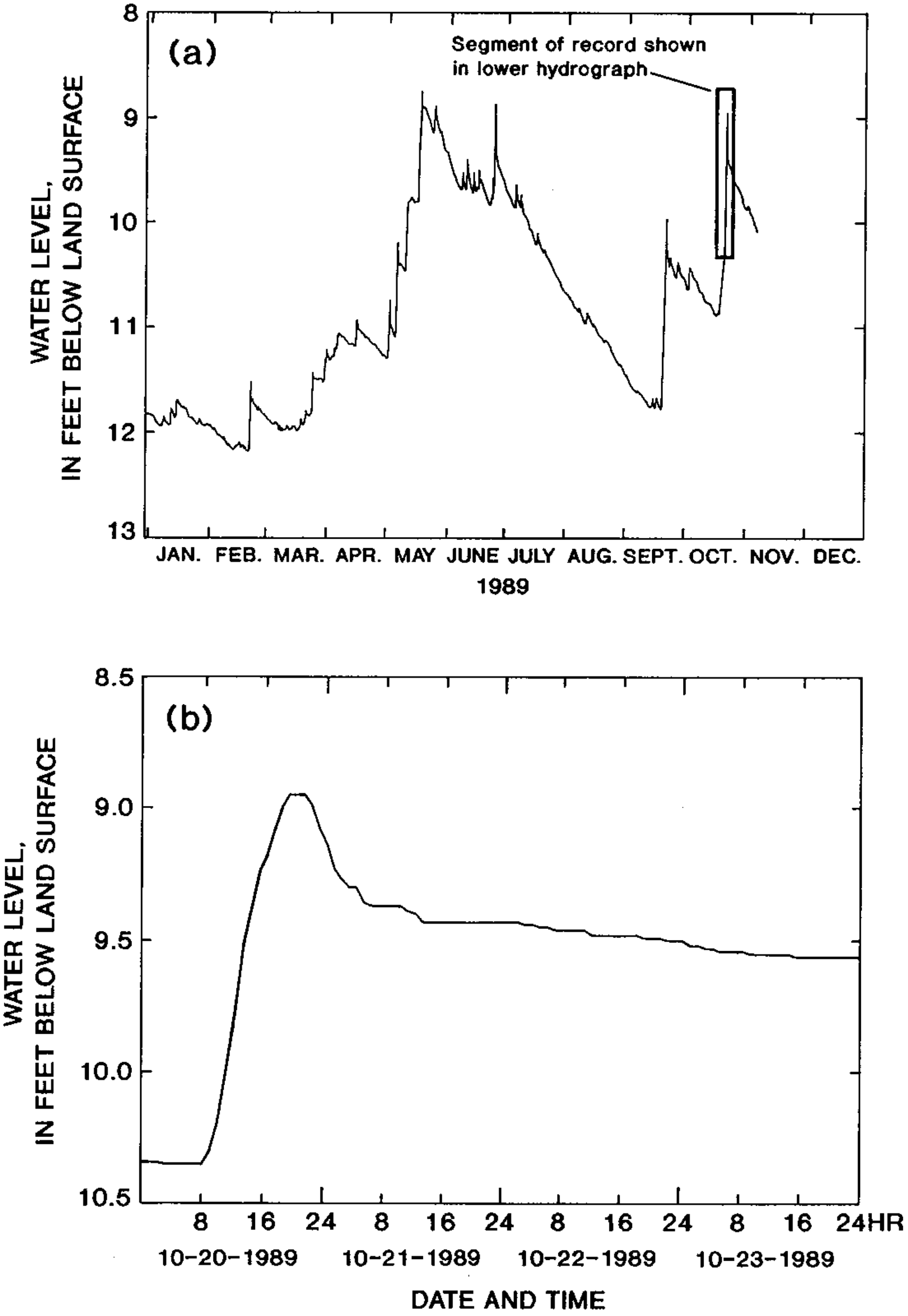


Figure 5.--Hydrographs of water level in well 27-1085 during 1989.

51.4	Leave farm along gravel road.
51.6	Turn right onto Rt. 24 westbound and Rt. 513 southbound.
52.5	Turn left onto County Road 517.
60.4	Onto Mesozoic redbeds
61.4	Town of Oldwick.
61.8	Join County 523 southbound.
62.1	Jersey Till in roadcut (covered by vegetation).
62.8	Turn right onto I-78 westbound.
67.1	Take exit 20-A for Lebanon.
67.6	Turn right onto Rt. 22 westbound.
68.1	Take exit for Round Valley Recreation Area.
68.4	Cross Rt. 22 toward Recreation Area.
69.9	Pass Entrance to Recreation area.
70.6	Left turn onto N.J. Water Authority access road.
	Stop mileage. This road is accessible only with permission of the Water Authority.
	Proceed to south dam.
	Lunch.
	STOP 4.

STOP 4

SPRUCE RUN/ROUND VALLEY RESERVOIR SYSTEM
INFORMATION AND DATA

by

Edward Buss, P.E.

New Jersey Water Supply Authority
P.O. Box 5196
Clinton, N.J. 08809

I. SYNOPSIS

The Spruce Run/Round Valley Reservoir System in Hunterdon County, N.J. was constructed by the State of New Jersey as an initial step in the long-range water conservation and development program authorized by the 1958 Water Supply Law and its companion Water Bond Act.

The 11 billion gallon (bg) (33,800 acre-feet) on-stream Spruce Run Reservoir, which was placed into operation in 1963, includes a 6,000 foot long earthen dam and two earthen dikes.

The 55 billion gallon (168,800 acre-feet) Round Valley Reservoir, which became operational in 1965, was formed by construction of two dams and a dike, closing off gaps in a natural horseshoe rim-shaped valley.

The two reservoirs make available 160 million gallons per day (mgd) for sale from the Raritan River at Bound Brook based on the 1960's drought by augmenting streamflow during periods of low natural flow. Additionally, a minimum statutory flow of 90 mgd must be maintained in the Raritan River at the Bound Brook stream gauge.

This paper summarizes the salient features and the operational characteristics of the Spruce Run/Round Valley Reservoir System.

II. INTRODUCTION

The New Jersey Water Supply Law of 1958 and its companion Water Bond Act empowered the State through the then Department of Conservation and Economic Development and its Division of Water Policy and Supply to "plan, design, develop, acquire, construct, operate and maintain a reservoir system known as the Spruce Run/Round Valley (SR/RV) Reservoir System".

Today, the SR/RV Reservoir System and the Delaware & Raritan Canal Water Transmission Complex are operated by the New Jersey Water Supply Authority on a self-supporting basis. They provide the basic source of water to a number of public and private water utilities serving over 1,200,000 people in Central New Jersey.

III. SYSTEM DETAILS

The SR/RV Reservoir System is located in the foothills of Hunterdon County within the Raritan Valley watershed about 30 miles north of Trenton and 35 miles west of Newark. The two reservoirs are only four miles apart and obtain their water from the South Branch Raritan River and its tributaries.

The Reservoir System includes two large reservoirs having a combined storage capacity of 66 billion gallons (202,600 acre-feet); a pumping station in the vicinity of Hamden with a 350 mgd capacity; a 108 inch diameter 3.2 mile pipeline between the pumping station and Round Valley Reservoir; and a 3.6 mile 108 inch diameter pipeline between Round Valley Reservoir and the Whitehouse Station Release Structure.

Spruce Run Reservoir is filled by natural stream flow whereas Round Valley Reservoir must be filled by pumping.

These two reservoirs provide for a safe yield of 160 mgd at the Bound Brook gauge on the Raritan River based on the 1960's drought, in addition to sustaining statutory minimum flows of 40 mgd at the Stanton gauge on the South Branch Raritan River, 70 mgd at the Manville gauge on the Raritan River and 90 mgd at the Bound Brook gauge on the Raritan River. The drainage area of the Raritan River Basin at the Bound Brook gauge is 785 square miles.

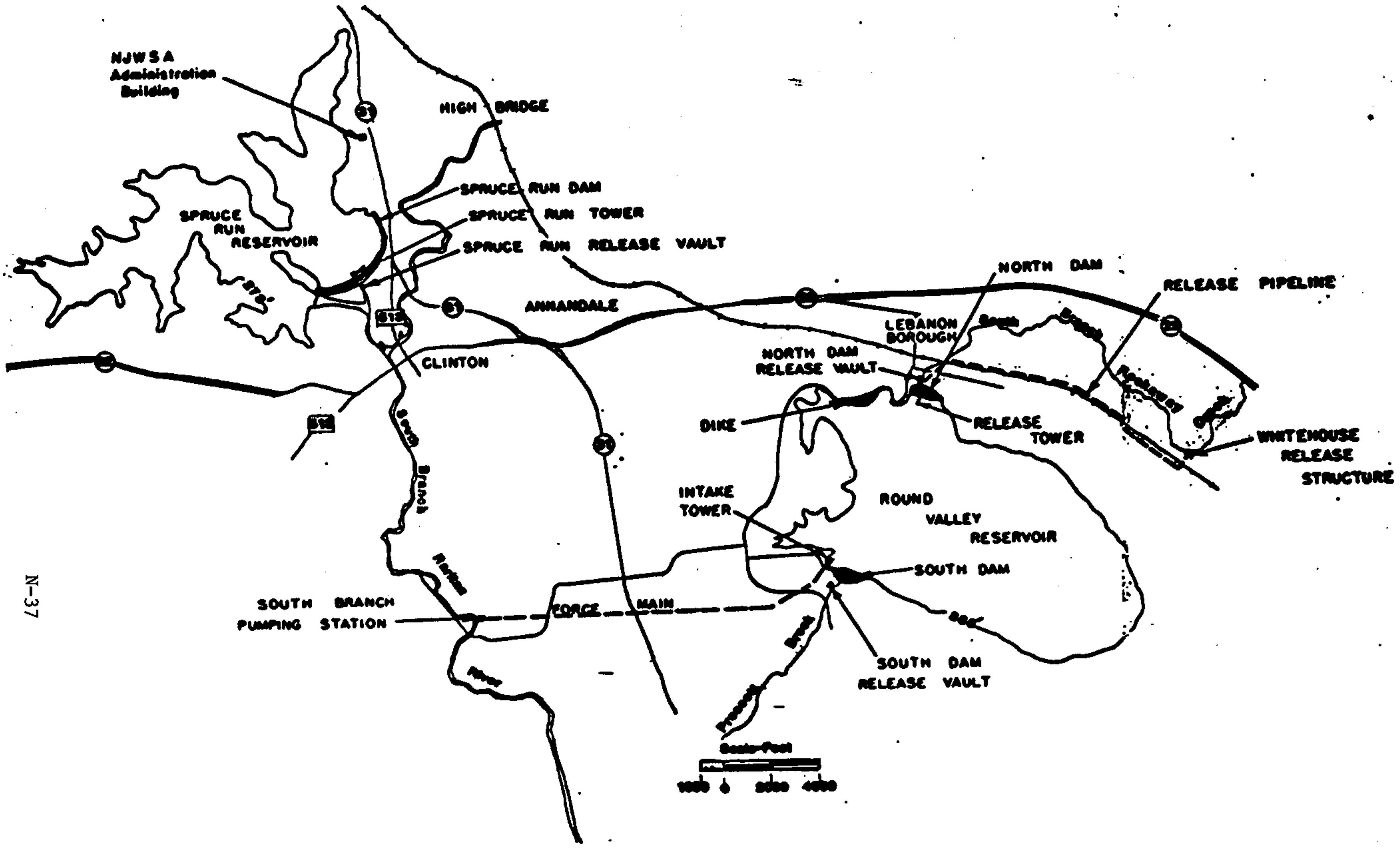
Figure 1 shows the location of the Spruce Run/Round Valley Reservoir System.

Spruce Run Reservoir

Spruce Run Reservoir is located in Hunterdon County approximately one mile north of the Town of Clinton. The reservoir is impounded by the Spruce Run Dam and Dikes A & B.

Spruce Run Dam is a zoned earth embankment constructed at the confluence of Spruce Run Creek and Mulhockaway Creek with a length of 6,000 feet and a maximum height of 93 feet. A 550 foot long service spillway is located at the right abutment of the dam (looking downstream) with a crest elevation at the normal operating pool level of Elevation 273 (top of dam is Elevation 283). Dikes A & B are earth embankments constructed across natural swales in the topography to retain reservoir levels above normal operating pool.

Outflows from the reservoir are conveyed through the base of the dam by twin seven foot diameter conduits which reduce to 30 inch diameter pipes at the downstream outlet control vault. Flow is controlled by conical-shaped discharge valves near the outlet of the pipes.



FIGUIRE 1

NEW JERSEY WATER SUPPLY AUTHORIT

RESERVOIRS FACILITIES MAP

Although the area surrounding the dam site, including parts of the reservoir basin, is underlain by gneiss and shale, the valley in the vicinity of the dam is underlain by cavernous limestone. The main body of the reservoir is underlain and bounded by Kittatinny limestone which is covered by a highly variable alluvial and glacial overburden. The overburden in most instances is clay and silt, except where the limestone is exposed, and serves as an excellent seal against reservoir leakage.

About 2,000 feet of the Spruce Run Dam is underlain by limestone. The limestone at the dam site was known to be susceptible to solutioning and ranges from tight and intact to blocky, seamy and cavernous. The rock surfaces vary from smooth and tight to pinnacled, and solution channels were found at depths of 5 to 100 feet. The designers of the dam were aware of the limestone defects and called for an extensive investigation and grouting program to provide a suitable foundation for the dam. The geological investigation included more than 300 core borings with an average depth of approximately 100 feet. The grouting program for the dam foundation consisted of deep centerline grouting along the length of the dam and blanket grouting under the upstream and downstream shells where required by the rock conditions. There was a total of 1,938 curtain line holes with an average depth of 80 feet, into which 272,000 cubic feet of grout was injected. There were 736 blanket holes with an average depth of 55 feet; 325,000 cubic feet of grout was injected into these holes.

The grouting program was successful as the dam has been performing satisfactorily during its almost 30 year lifespan.

Figure 2 shows a typical dam section at Spruce Run Reservoir.

Round Valley Reservoir

Round Valley Reservoir is located in the foothills of Hunterdon County, approximately one mile south of Lebanon, N.J. The reservoir is impounded by the Round Valley North Dam, South Dam and Dike.

The North Dam, which was constructed across a tributary of the South Branch Rockaway Creek, is a zoned earth embankment with a length of 1,500 feet and a maximum height of 135 feet. The South Dam was constructed across Prescott Brook and consists of a 1,400 foot long zoned earth embankment with a maximum height of 185 feet. The dike is a zoned earth embankment with length of 2,350 feet and maximum height of nearly 80 feet, constructed across a natural swale which drains toward the South Branch Rockaway Creek.

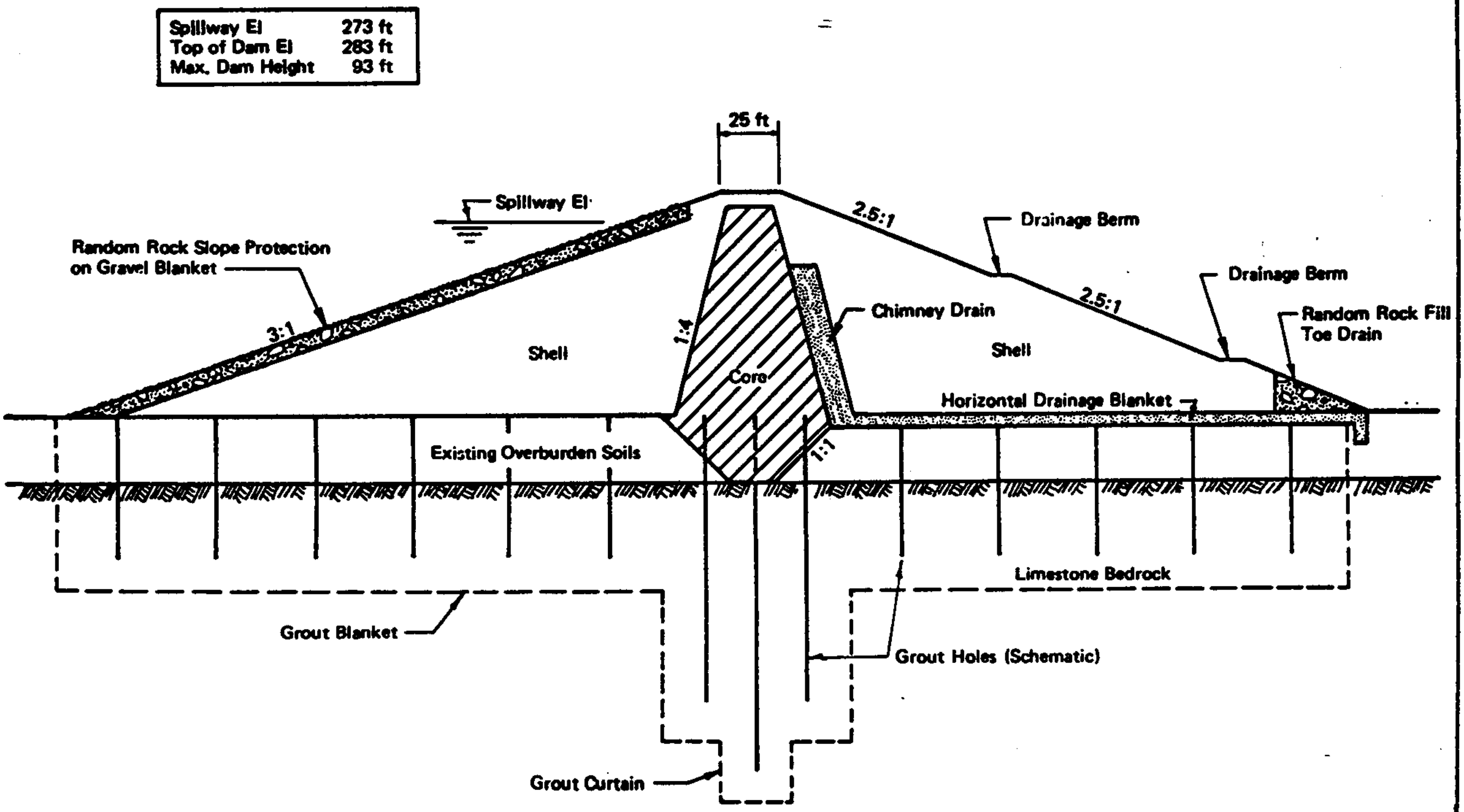


FIGURE 2

SPRUCE RUN DAM

The reservoir is filled by pumping South Branch Raritan River water through a 3.2 mile, 108 inch diameter conduit to a concrete intake tower located at the upstream toe of the South Dam. Recently, this pipeline has been retrofitted with valving at the pumping station so it can be used to discharge up to 125 mgd from the reservoir back into the South Branch Raritan River.

Outflows from the reservoir are conveyed through the base of the North Dam by twin six foot diameter pipes which converge into a single 108 inch diameter 3.6 mile pipeline which extends to the Whitehouse Station Release Structure. Four conical shaped valves at the Release Structure control rates of discharge up to 450 mgd.

The normal operating pool level of Round Valley Reservoir is Elevation 385 and the top of the embankments is Elevation 395. This 10 feet of freeboard is to guard against overtopping during a cloudburst over the reservoir and wave runup.

Reservoir storage can be increased to 75 bg (230,200 acre-feet) in the future by raising the dams and dike 25 feet without interrupting the use of the reservoir.

The Round Valley Reservoir is in an unusual geological formation, being horseshoe shaped, about 2-1/2 miles average length and 1-1/2 miles average width. Over 90% of the reservoir rim is surrounded by high mountains and less than 10% of the circumference is closed-off with a man-made embankment.

The east abutment of the South Dam, both abutments of the North Dam and the east abutment of the Dike are underlain by diabase. The west abutment of the south Dam is underlain by gneiss and the west abutment of the Dike is underlain by quartzite. Limestone was detected in bedrock at a small section of the Dike and was determined to be in good condition as it has been protected by the overlying shale.

The dams and dike were constructed from the soils in the area using an impervious earth core to limit seepage.

Figure 3 shows a typical dam section at Round Valley.

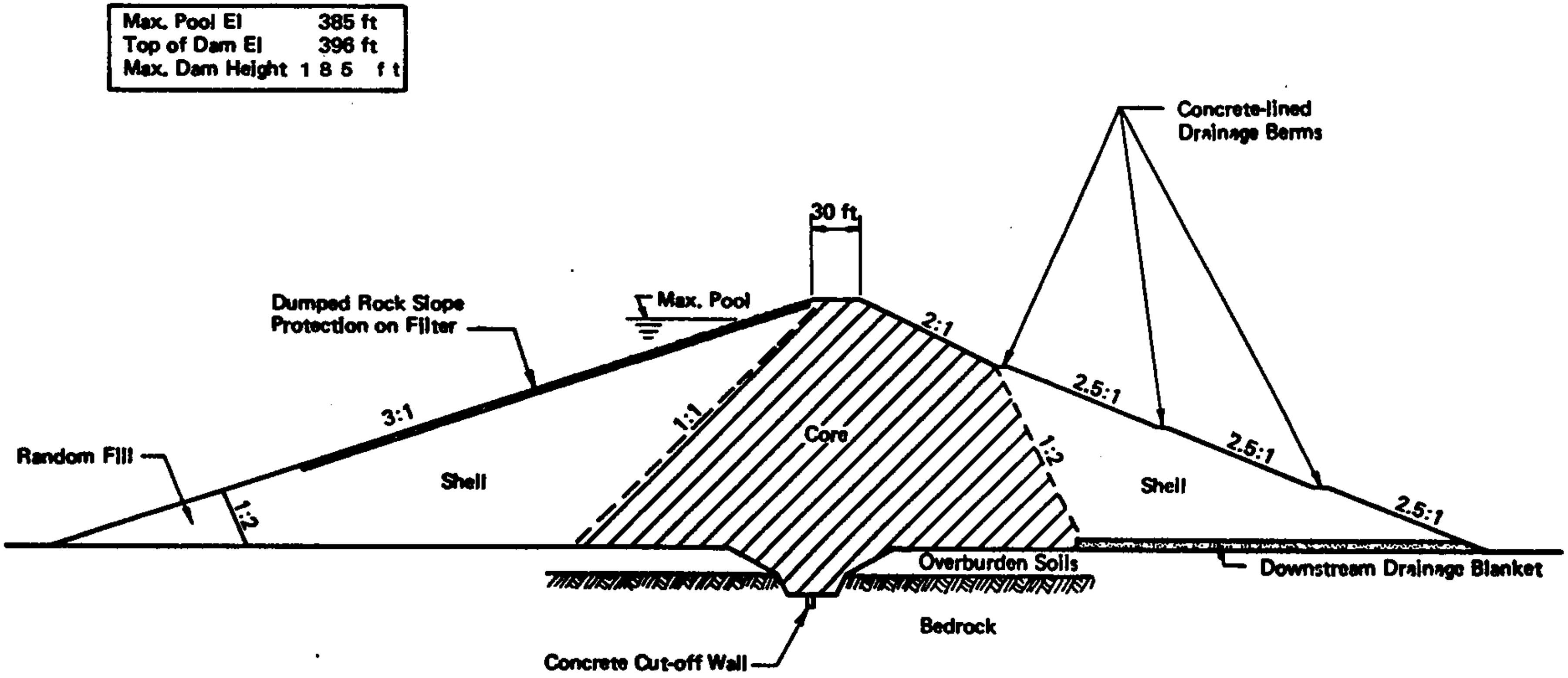


FIGURE 3

ROUND VALLEY

]

NEW JERSEY WATER SUPPLY AUTHORITY
RESERVOIR DATA

		SPRUCE RUN RESERVOIR	ROUND VALLEY RESERVOIR
Construction	Year	1963	1965
Capacity	Billion Gallons	11	55
	Acre-Feet	33,800	168,800
Yield at Reservoir	Annual Average MGD *	20	70
Flow Line Elevation	Feet above Sea Level	273	385
Water Surface	Acres	1,290	2,350
Property Acquisition	Acres	2,100	4,000
	Cost	$2,777,625	$2,956,830
Watershed Area	Square Miles	41	5.7
North Dam	Length, Feet		1,500
	Maximum Height, Feet		135
South Dam	Length, Feet		1,400
	Maximum Height, Feet		185
Dike	Length, Feet		2,350
	Maximum Height, Feet		80
Spruce Run Dam	Length, Feet	6,000	
	Maximum Height, Feet	93	
Force Main	Diameter, Inches		108
	Length, Miles		3.2
Release Pipeline	Diameter, Inches		108
	Length, Miles		3.6
Pumping Station	Capacity, MGD		350
	Elevation, Feet above Sea Level		160
	Net Drainage Area, Acres		99
Shoreline Length	Miles	15	10
Total Construction Cost		$13,819,369	$37,139,912 **

* Based on the 1960's drought, yield at Bound Brook 160 mgd

** Includes Round Valley Release Pipeline constructed in the mid-1970's

71.1	Leave dam and turn right onto County Road 629 northbound (Stanton-Lebanon Road).
71.6	Turn left onto Valley Crest Road.
71.9	Turn left onto Allerton Road.
73.2	Intersection with Rt. 31. Turn left onto Rt. 31 southbound.
73.5	Take exit for jughandle to Molasses Hill Road.
73.6	Cross Rt. 31.
74.8	Disembark and walk along access road.
	STOP 5.

STOP 5. LEIGH CAVE

LEADERS - RICHARD F. DALTON and RICHARD A. VOLKERT,
New Jersey Geological Survey

This locality affords trip participants the opportunity to examine the effects of ground-water flow on a carbonate rock over a protracted period of time. Also, this is a relatively rare exposure in New Jersey enabling participants to place their hand on a thrust fault which has emplaced Middle Proterozoic rock over Cambrian dolomite.

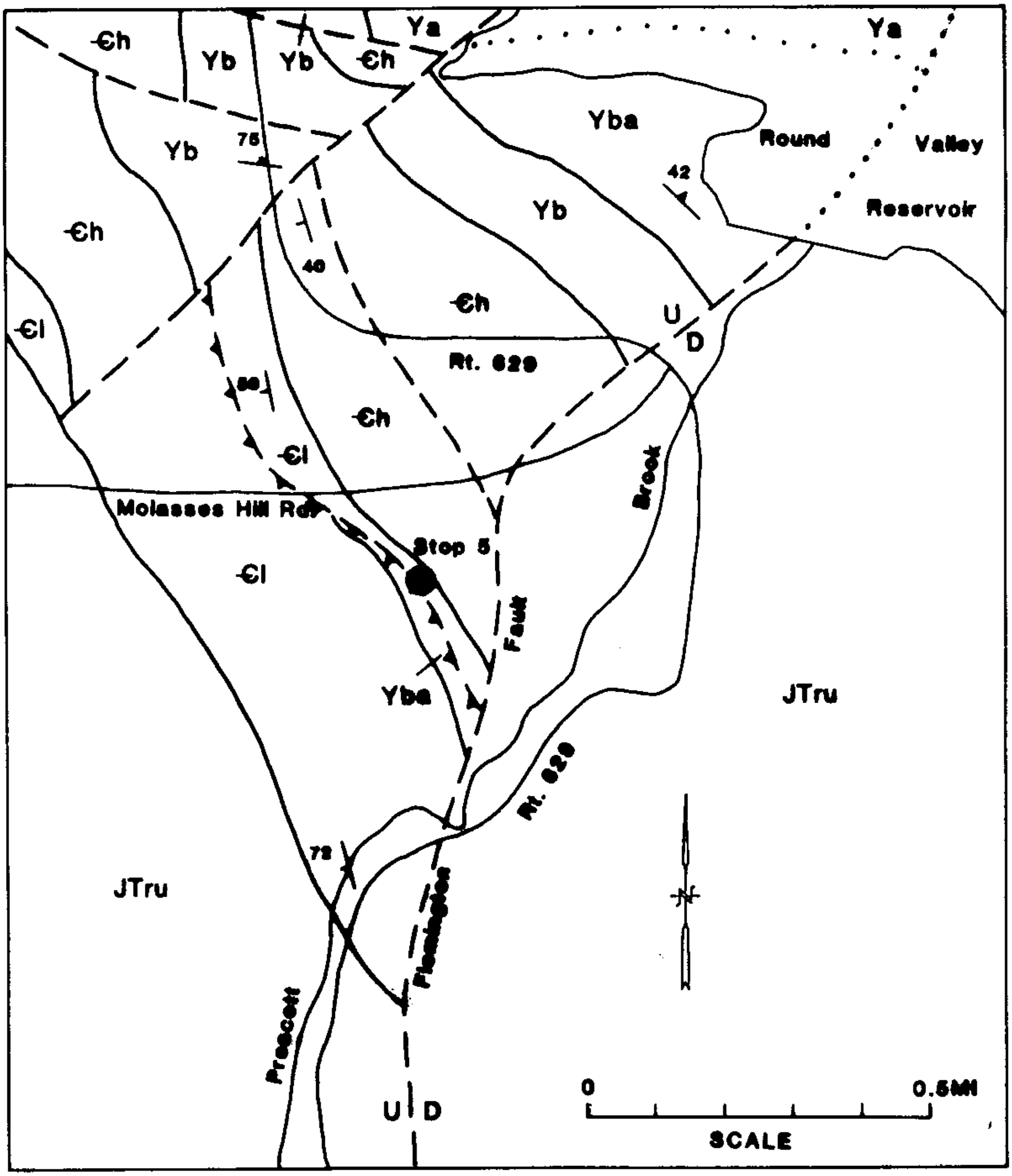
The Leigh cave is probably the largest cave in New Jersey in terms of total underground volume. It is second or third largest in total length, containing more than 800 feet of subterranean passages (Dalton, 1976). Its date of discovery is unknown. The Leigh cave was surveyed in detail in 1960 by members of the Kittatinny Grotto and the Northern New Jersey Grotto. The overall plan of the cave suggests that it formed at a level below the water table. It was subsequently modified by subaerial processes when the cave was above the water table. A series of pits and depressions on the bedrock floor are aligned with intersecting sets of fractures in the cave roof and appear to be forming from water dripping from the fracture sets. Growths of stalactites, stalagmites, and flowstone are lacking in the Leigh cave because little of the roof rock is carbonate.

The orientation of the cave passages is clearly structurally controlled. They follow the trend of bedding in the dolomite, the general trend of the thrust fault, and many of the dominant fracture zones (Dalton, 1976). The floor and walls of the cave consist of dolomite of the Leithsville Formation; the roof is a microperthite alaskite. Both rock types are highly brittly deformed and recrystallized. The trend of the Leigh cave thrust fault varies, but it generally strikes northwest and dips southwest. The thrust relations seen here have been recognized for some time and are mentioned briefly in Bayley and others (1914).

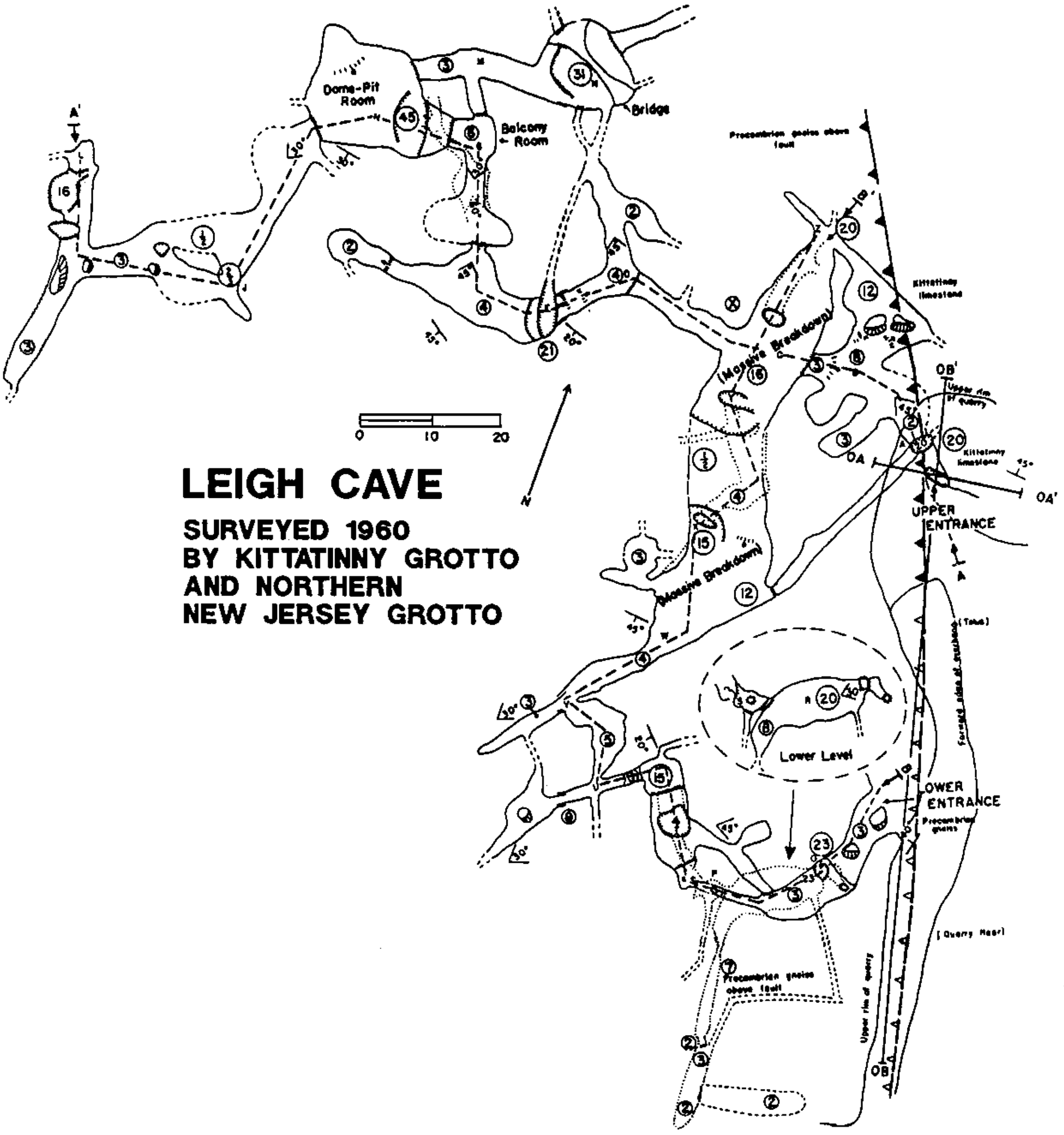
STOP 5 REFERENCES

Bayley, W.S., Salisbury, R.D., and Kummel, H.B., 1914, Raritan Folio, New Jersey: U.S. Geological Survey Geologic Atlas Folio 191, 32p.

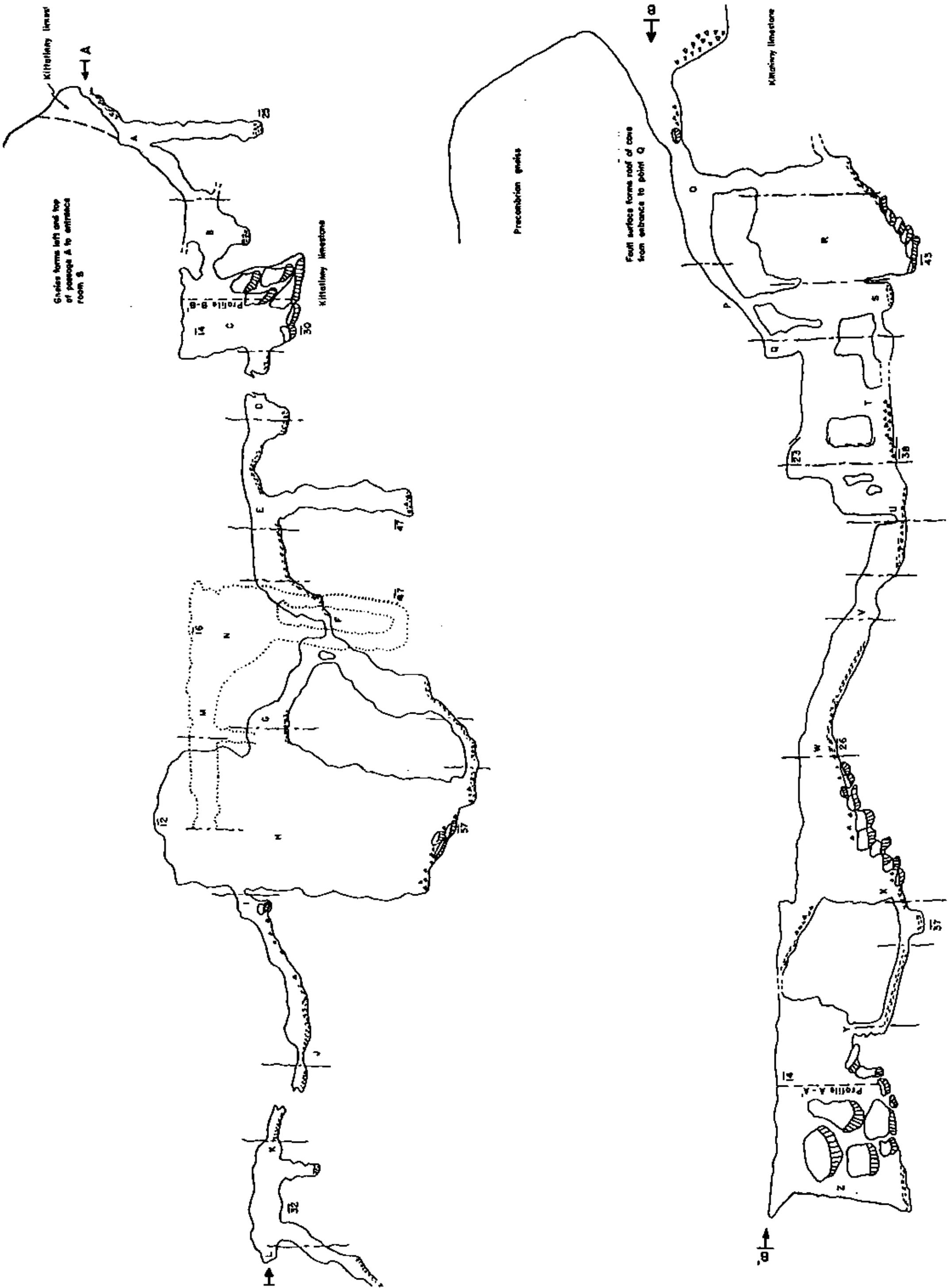
Dalton, R.F., 1976, Caves of New Jersey: New Jersey Geological Survey, Bulletin 70, 51p.



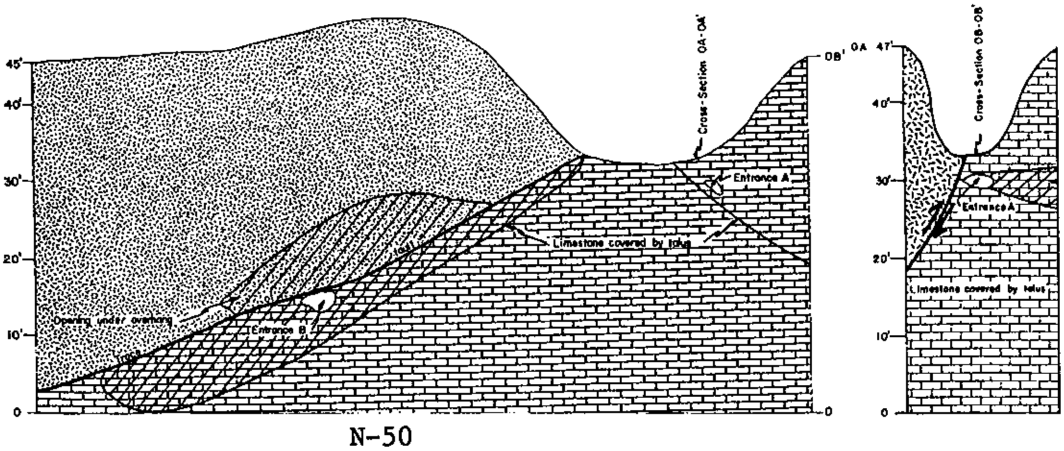
Geologic map of the Leigh cave area, Flemington quadrangle (Volkert, unpublished data). Map symbols are shown after stop 2.



Plan view (this page) and section profiles (facing page) of the Leigh cave. Figure is plate 2 from Dalton (1976).



Kittatinny limest
A
Gneiss forms left and top of passage A to entrance room B
Kittatinny limestone
Profile B-B'
A'
B
Kittatinny limestone
Precambrian gneiss
Fault surface forms roof of cave from entrance to point Q
Profile A-A'
B'



45'
40'
30'
20'
10'
0
Cross-Section OA-OA'
OB'
Entrance A
Limestone covered by talus
Opening under overhang
Entrance B
0
OA 47'
40'
30'
20'
10'
0
Cross-Section OB-OB'
Entrance A
Limestone covered by talus

74.8 Leave Stop 5.

75.1 Turn left onto road 629 (Stanton-Lebanon Road).

78.2 Intersection with Rt. 22. Turn left onto Rt. 22 westbound.

79.6 Join I-78 westbound.

80.0 Exit onto Rt. 31.

80.7 Follow Rt. 31 northbound.

81.7 Turn left at intersection of County Road 513 and bear left again immediately.

81.9 Right turn onto access road.

82.2 Public parking lot.

Stop mileage.

Proceed to Spruce Run Dam spillway.
This access road is accessible only with permission of the Water Authority.

STOP 6

STOP 6 SPRUCE RUN RESERVOIR

LEADER: Don Monteverde
New Jersey Geological Survey

This stop is located on the Spruce Run reservoir dam, just north of the overflow spillway (fig. 6.1). As previously indicated, this reservoir is part of the Spruce Run-Round Valley reservoir system. The Spruce Run area was studied in the late fifties and early sixties to ascertain whether its geological and engineering characteristics were suitable for the construction of water storage facilities. The Spruce Run site, underlain chiefly by carbonate bedrock, is geologically more complex and required more underground exploration than Round Valley (report 15), which is downstream several miles to the southeast.

Spruce Run reservoir lies on the hinterland side of the the New Jersey Highlands, just north of the Newark Basin of Mesozoic age. To the north and east, Proterozoic gneisses and granites, such as those seen at STOP 2, crop out. The Lower Cambrian Hardyston Quartzite unconformably overlies the Proterozoic rocks. The Hardyston ranges from an arkose to nearly pure quartz in composition. The grain size varies from siltstone, through sandstone to a cobble conglomerate. Conformably overlying the Hardyston and underlying the eastern two thirds of the reservoir is the Cambrian and Ordovician Kittatinny Supergroup (Drake and Lyttle, 1980). The supergroup contains, in ascending order, the Leithsville Formation, Allentown Dolomite and the Beekmantown Group. It consists largely of platform margin dolomite and minor interbedded limestone, shale and quartz sandstone. The Jacksonburg Limestone rests unconformably on the Kittatinny. The western third of the reservoir rests on the Jutland sequence. The Jutland is structurally above the Kittatinny and Jacksonburg and contains siltstone and shale with lesser interbedded sandstone and limestone. To the south, resting unconformably on all the other previously described units is the conglomerate, sandstone and shale of the Newark Basin. The Kittatinny Supergroup and the Jutland Sequence have undergone three episodes of deformation, thereby forming folds, faults and related fractures. In the Kittatinny, these deformational features, combined with the ready solubility of the largely carbonate rocks resulted in many solution channels at the reservoir site.

Dolomite and to a greater extent, limestone, will dissolve in a weak acid. The dissolution of the carbonate, as outlined by Fetter (1988), follows the following general pathway. Rainwater in contact with carbon dioxide in the atmosphere and the soil, dissolves carbon dioxide equal to the partial pressure. This solution reacts to form a weak acid, carbonic acid. When this enters the ground water and comes in contact with carbonate rock, it dissolves the rock. This continues until the ground water is saturated with respect to dolomite or calcite. With continued infiltration of rainwater, more dissolution of carbonate occurrs. In this process, ground water traverses the most permeable route which is where the most solution has previously taken place. In this way water traveling through many smaller openings tends to coalesce into fewer, larger conduits.

Test drilling to locate the best site for the main dam encountered both open and sediment filled voids. The openings persisted to a depth of as much as 200 feet. Solution channels were more abundant near the major north-south fault. The openings in the core paralleled the bedding surfaces and fracture planes. Figure 6.2 depicts subsurface conditions of the bedrock at the site (Anonymous, unpublished notes on file at New Jersey Geological Survey). The predominance of bedding and fractures planes as the main ground water pathway is related to the intensity of breakage and the lithology of the individual carbonate bed. Regional studies suggest that the coarser the grain size in the dolomite beds, the more susceptible they are to solution (Markewicz and Dalton, 1977). The quantity of insoluble material in individual dolomite beds would also affect the probability of solution. In general, the higher the insoluble content, the lower the solution potential. In less soluble beds, the fracture planes could be the dominent pathway for the ground water. For example, ground water, traveling the most permeable route, could traverse a less soluble bed through fractures to a more soluble bed which has been greatly enlarged by solution. Fractures dominate in some beds where as closely spaced bedding predominates in others. Both contribute significantly to the enlarged solution openings that form the major conduits for the ground water.

The spillway offers the best opportunity to see both the lithologic variation of the Kittatinny Supergroup and the degree of fracturing. The dominent trends of the carbonates are: bedding N.40° W.36° SW., jointing N.45° E.79-90° NW., fault planes

N.30°E.90° and N.74°E.86°NW. Both recemented and slightly open fractures can be seen.

References

Anonymous, unpublished field notes, on file at the New Jersey Geological Survey, Trenton, New Jersey.

Drake,A.A.,Jr., and Lyttle,P.T., 1980, Alleghanian thrust faults in the Kittatinny Valley, New Jersey: in Manspeiser, Warren, ed., Field studies of New Jersey geology and guide to field trips, Newark, New Jersey, Rutgers University Press, p.92-114.

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Markewicz,F.J., and Dalton,Richard, 1977, Stratigraphy and applied geology of the Lower Paleozoic carbonates in northwestern New Jersey: in 42nd Annual Field Conference of Pennsylvania Geologists, Bureau of Topographic and Geologic Survey, Department of Environmental Resources, Harrisburg, Pennsylvania, 55p.

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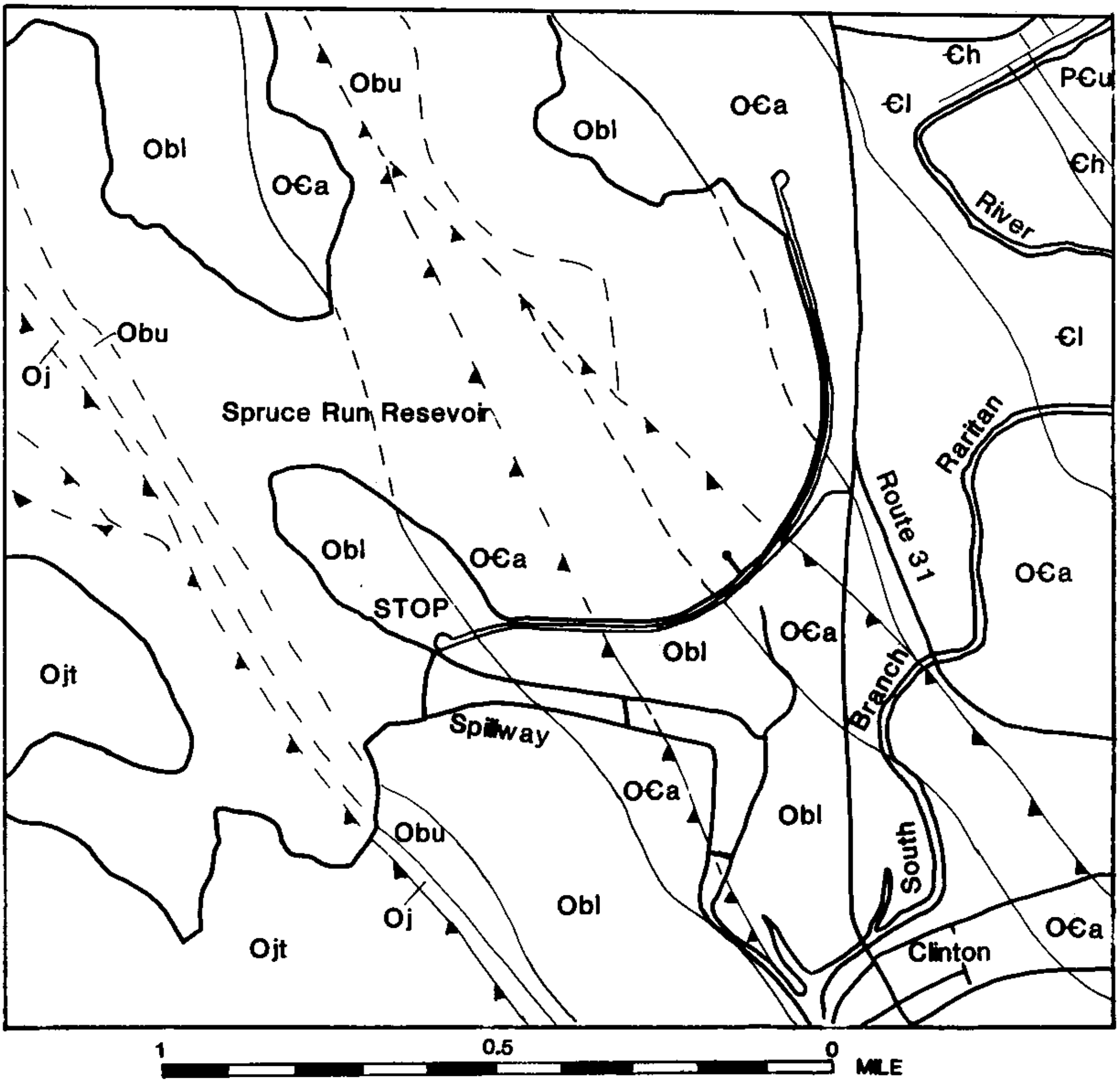

Figure 6.1 Showing bedrock geology of the Spruce Run reservoir area. Lithologic abbreviations are: PꞒu- Proterozoic gneisses and granites, undivided, Ꞓh-Hardyston Quartzite, Ꞓl-Leithsville Formation, OꞒa-Allentown Dolomite, Obl-Beekmantown Group, lower part, Obu-Beekmantown Group, upper part, Oj-Jacksonburg Limestone, Ojt-Jutland sequence. Major faults are thrusts; sawteeth on the upper plate. Smaller faults are not shown. Lines are dashed where underwater. (Geology by D. Monteverde)

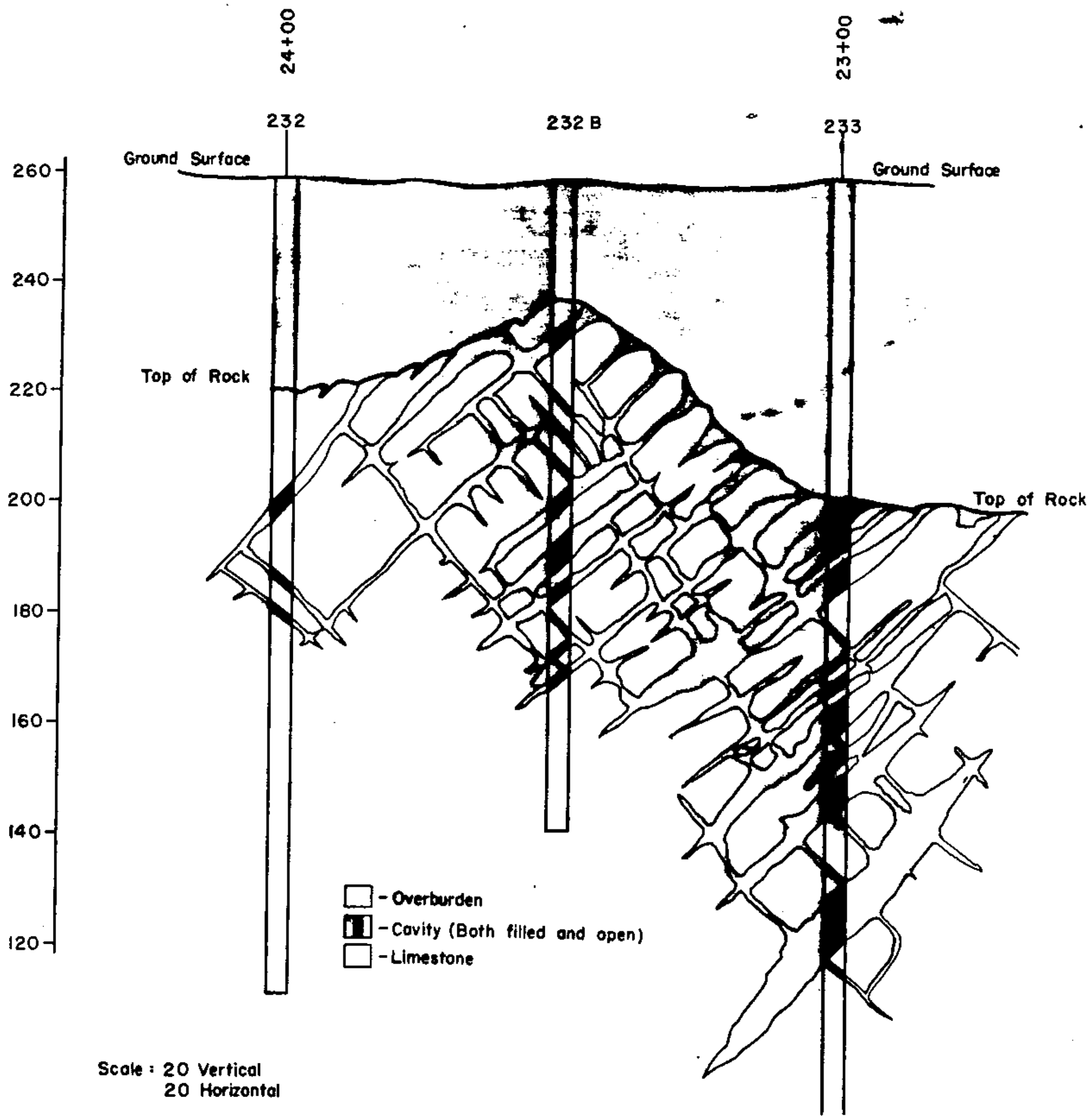

Figure 6.2 Section facing north-north west showing cavites intercepted during drilling of the Kittatinny Supergroup. Except where intercepted by drilling, bedrock solution channels in the bedrock is inferred. Beds dip southwest, fractures dip northeast and southeast. (Figure modified from anonymous source on file at New Jersey Geological Survey, Trenton, New Jersey.)

	Leave Spruce Run parking lot. Turn left, then right onto Rt. 31 south.
83.5	Bear left onto Rt. 78 eastbound.
118.5	Exit onto Garden State Parkway South.
120.4	Exit for Rt. 22.
120.7	Right turn exit for Rt. 82 (Morris Ave.).
120.8	Right turn onto Rt. 82 East (Morris Ave.).
123.0	Entrance to Kean College.

SIMULATED HYDROLOGIC EFFECTS OF CLIMATIC CHANGE IN THE DELAWARE RIVER BASIN

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ABSTRACT: Projections of climatic change indicate uncertainty regarding future availability of water in the Delaware River basin. Simulations of the effects of atmospheric warming on runoff indicate that a decrease in snow accumulation in the northern part of the basin and an increase in evapotranspiration throughout the basin could change the temporal distribution of runoff and reduce total annual streamflow by as much as 25 percent given current precipitation patterns. An increase in precipitation of about 3 percent would be needed to counteract decreases in runoff that would result from each degree Celsius warming. Simulations indicate that without more reliable estimates of regional precipitation and warming patterns, the future direction and magnitude of basin streamflow changes cannot be determined precisely.

INTRODUCTION

Changes in climate resulting from increasing concentrations of atmospheric carbon dioxide (CO2) may alter the characteristics of precipitation and temperature in the Delaware River basin and, therefore, will affect evapotranspiration, streamflow, and ground-water recharge. A rise in sea level may accompany global warming and could alter the salinity of the Delaware Estuary and increase the intrusion of saltwater into adjacent aquifer systems. In view of the uncertainty of climatic-change projections, and because the potential effects of climatic change on basin hydrology are poorly understood, a study was initiated to define the basic relations of water-resource systems to current climate and the effects of simple assumptions of climatic change on the sensitivity of these systems (Moss and Lins, 1988; Ayers and Leavesley, 1988). This paper describes some of the results of that study.

MODELS AND PRELIMINARY RESULTS

Climate Models

Two regional climate models have been developed to simulate temporal sequences of daily temperature and precipitation over the Delaware River basin and to develop scenarios of climatic change for the basin. One model stochastically predicts consecutive wet and dry periods and precipitation intensities for the wet periods (Wolock and others, 1989) and is linked directly to a watershed model that simulates daily streamflow. The second model stochastically predicts the daily weather pattern over the basin (McCabe and others, 1989). A weather pattern characterizes the weather conditions for the day, such as a high-pressure system, a cold-frontal passage, or a warm-frontal passage (McCabe, 1990). The model assigns values of temperature and precipitation to each weather pattern based on observed relations between the variables and weather patterns in historical records. Both models replicate the statistics of historical climate records.

The weather-pattern climate model also is used to disaggregate temperature and precipitation data from coarse-gridded general circulation models (GCMs) to define spatially detailed climatic-change scenarios for the basin. Initial analyses indicate that the monthly frequencies of regional weather patterns produced by the GCMs for present climatic conditions are similar to the frequency of observed weather patterns for the basin. The frequencies for conditions of doubled CO2 do not change significantly; rather, the characteristics of the weather patterns (mean temperature, precipitation intensity, and probability of producing rainfall) change instead. This infomation will be used to define temperature- and precipitation-change scenarios for the basin.

Moisture Index Analyses

The Thornthwaite moisture index (Thornthwaite and Mather, 1955) is an indicator of the supply of water (precipitation) in an area relative to the climatic demand for water (potential evapotranspiration). Mean annual temperature and precipitation were adjusted to doubled-CO2 conditions with percentage and absolute changes derived from three GCMs: the Goddard Institute for Space Studies (GISS) model, the Oregon State University (OSU) model, and the Geophysical Fluid Dynamics Laboratory (GFDL) model. These change scenarios were used to simulate changes in the moisture index for steady-state doubled-CO2 conditions and for gradual changes from present to doubled-CO2 conditions.

Mean annual moisture indices for current conditions were compared with indices derived from steady-state GCM projections of doubled-CO2 conditions (table 1). The GISS and GFDL GCMs indicate decreases in the mean annual moisture index, which are attributable principally to the projected increases in temperature and the absence of an offsetting increase in precipitation. The magnitudes of the changes projected by these two GCMs were large in comparison with natural year-to-year variability. The OSU GCM did not produce significant changes in the mean annual moisture index because of a projected increase in precipitation that offsets the temperature increase.

Table 1. Comparison of current (1950-83) mean annual moisture indices at three study sites with indices derived from projections of doubled-CO2 conditions from three General Circulation Models. [GISS, Goddard Institute for Space Studies; GFDL, Geophysical Fluid Dynamics Laboratory; OSU, Oregon State University]

Site	Current CO2	Doubled CO2 GISS	Doubled CO2 GFDL	Doubled CO2 OSU
Salisbury, Maryland	39	13 *	12 *	40
Philadelphia, Pennsylvania	40	11 *	10 *	38
Scranton, Pennsylvania	45	10 *	8 *	38

* Significantly different from current at alpha less than 0.001

Differences among GCMs also are evident in the results of the gradual climatic-change scenarios. The number of years required to reach 50- and 100-percent probability levels of detecting a statistically significant trend in the moisture index was calculated (table 2) assuming doubled-CO2 conditions in 100 years. The GISS or GFDL model projections yield a 50-percent probability of detecting a trend in the moisture index in 45 to 55 years. With the OSU projection, the 50-percent probability is not reached for at least 145 years. The site-to-site differences in trend detectability are caused principally by differences in precipitation variability.

Table 2. Number of years until the likelihood of detecting significant (alpha equals 0.05) trends in annual moisture index is 50 and 100 percent. [GISS, Goddard Institute for Space Studies; GFDL, Geophysical Fluid Dynamics Laboratory; OSU, Oregon State University]

	Years until likelihood equals 50 percent or (100 percent)		
Model	Salisbury	Philadelphia	Scranton
GISS	75 (125)	55 (105)	55 (95)
GFDL	65 (125)	55 (105)	55 (95)
OSU	>200 (>200)	185 (>200)	145 (>200)

Results indicate that temperature and precipitation under doubled-CO2 conditions yield lower Thornthwaite moisture indices, implying drier conditions in the basin. The amount of decrease depends on the GCM data used; the precipitation projections of the GCM are especially important.

Watershed Models

Models of monthly streamflow (with and without reservoirs) and daily streamflow (without reservoirs) have been developed to analyze the effects of climatic change on streamflow in the basin. Several sensitivity analyses have been completed.

Monthly Flow Analyses

Analyses of the sensitivity of monthly streamflow to changes in climate using a monthly water-balance model without reservoirs (McCabe and Ayers, 1989) indicate that warming would cause an increase in the proportion of winter precipitation that falls as rain in the northern part of the basin. This effect would reduce snow accumulation, increase winter runoff, and reduce spring and summer runoff. Basin-wide estimates of total annual runoff (table 3) indicate that a warming of 2 to 4 °C (degrees Celsius), without corresponding precipitation increases, would cause a 9- to 25-percent decrease in total annual runoff as a result of increased evapotranspiration. An increase in precipitation of about 3 percent would be needed to counteract decreases in runoff that would result from each °C warming. Scenarios derived from the three GCMs resulted in changes in annual runoff ranging from -39 to +9 percent.

Table 3. Annual volume of and percent change in runoff resulting from prescribed temperature and precipitation scenarios at two sites [P, monthly precipitation; P±x, P plus or minus x percent]

Scenario	Montrose		Trenton	
	millimeters	percent change	millimeters	percent change
Current				
P	486	--	381	--
+2 degrees C				
P+20	632	+ 30	501	+ 31
P+10	532	+ 9	411	+ 8
P	441	- 9	329	- 14
P-10	351	- 28	258	- 32
P-20	268	- 45	188	- 51
+4 degrees C				
P+20	571	+ 17	431	+ 13
P+10	476	- 2	359	- 6
P	389	- 20	286	- 25
P-10	306	- 37	221	- 42
P-20	231	- 52	157	- 59

Decreases in snow accumulation in the northern part of the basin and increases in evapotranspiration throughout the basin could change the timing of runoff and significantly reduce total annual streamflow, without a concurrent increase in precipitation. The northern part of the basin is more sensitive in winter than in summer to the range of values tested.

Sensitivity analyses of monthly streamflow to changes in climate using a stochastic monthly flow model with reservoirs show that the risk of drought is significantly greater for scenarios in which precipitation does not increase sufficiently to offset the CO2 induced warming (Gary Tasker, U.S. Geological Survey, written commun., 1989). Assuming 1986 water-use levels, the results of these simulations indicate a significant increase in the percent of time the Delaware River basin would be in a drought warning or emergency condition.

The probability of entering a drought condition in the basin currently is 9.5 percent, based on a 1,000-year simulation (table 4). With a warming of 2 and 4 °C, the probability of drought in the basin increases by 1.9 and 2.9 times, respectively. When the two warming scenarios are accompanied by a 10-percent decrease in average precipitation, the probability of drought increases to 4.8 and 6.4 times the probability under current conditions, respectively. A 10-percent increase in average precipitation with a warming of 2 °C actually causes a decrease in the probability of drought. A simulated range in the amount of time the basin would experience drought from a 60-percent decrease to a 540-percent increase is the uncertainty associated with the current knowledge of potential climatic change in the basin.

Table 4. Simulated percent of the time in which the Delaware River basin is in a drought warning or emergency condition for prescribed temperature and precipitation scenarios

Change in temperature *	Change in precipitation *		
	No change	-10 percent	+10 percent
1986 water use			
No change	9.5		
+ 2 degrees C	17.7	45.8	5.6
+ 4 degrees C	27.2	61.1	10.3
2040 water use			
No change	9.6		
+ 2 degrees C	17.8	46.0	5.7
+ 4 degrees C	29.3	61.3	10.4

* Change from current conditions.

Simulation results (table 4) indicate that virtually no change in the probability of drought will result from the projected growth in consumptive water use in the basin. A drought currently is defined only by the contents of the New York City reservoirs, however, the magnitude of consumptive water use in the upper part of the basin has a small effect on reservoir contents relative to the diversions to New York City and to the increased evapotranspiration that would accompany the warming. Analyses of the sensitivity of drought probability to changes in diversions and reduced water use in other parts of the basin will be addressed in the study.

Daily Flow Analyses

A topographically based hydrologic model (TOPMODEL) was developed and linked with the wet/dry climate model for the sensitivity analysis of daily streamflow (Wolock and others, 1989; Wolock and Hornberger, 1990). The sensitivity of streamflow in non-urban watersheds in the Delaware River basin to climatic change was evaluated using this daily flow model. The model stochastically generates time series of temperature and precipitation and uses estimates of parameters derived from watershed topography (Price and others, 1989) and soil hydraulic properties to generate a time series of streamflow.

Fifty 60-year simulations, each representing a different possible future realization of the same climatic change projection (a warming of 3 °C with current precipitation characteristics) was performed. Annual and monthly maximum daily streamflow and Kendall's tau statistics then were calculated for each of the 60-year streamflow time series to detect trends in streamflow.

These simulations (table 5) illustrate two important characteristics about the sensitivity of basin watersheds to climatic change. First, seasonal differences in the expected effects of global warming on streamflow are observed. Maximum daily streamflows increase with time (more positive than negative trends) in mid-winter months, decrease in spring and summer, and change little in fall and early winter. These seasonal differences in trend primarily reflect changes in snowfall accumulation and snowmelt. With warming, more winter precipitation falls as rain than as snow, and snowmelt occurs earlier.

Table 5. Number and type of trends in maximum daily streamflow for the 50 simulations and 6 streamflow records in the Delaware River basin [positive (+) or negative (-) trend at alpha equals 0.05; 0, no trend]

				Trends in observed streamflow records					
	Simulated trends			Latitude greater than 40.8 degrees				Latitude less than 40.8 degrees	
Month	+	-	0						
January	12	2	86	0	0	0	0	0	0
February	34	8	58	+	+	+	+	0	0
March	4	22	74	0	0	0	0	0	0
April	0	42	58	0	+	0	0	0	0
May	0	20	80	0	+	0	+	0	0
June	0	14	86	0	0	0	+	0	+
July	0	14	86	-	0	0	0	0	0
August	0	14	86	-	0	0	0	0	0
September	0	8	92	-	0	0	0	0	0
October	0	8	92	0	0	0	0	0	0
November	0	8	92	0	0	0	0	0	0
December	4	8	88	0	0	0	0	+	+
Annual	0	16	84						

The warming effect is strongest in the northern part of the basin where snow accumulation currently is significant. Second, natural variability in precipitation masks the effects of increasing temperature. The percentage of simulations that do not show a significant increase or decrease is greater than 58 percent in any month and averages 84 percent.

Six U.S. Geological Survey streamflow records in the basin were identified as having at least 75 years of record and little effects from diversions, reservoirs, or urbanization. Comparing monthly trends in table 5, the observed data show an increase in February maximum daily streamflow over the past 75 years for the more northern watersheds, similar to the simulated results.

Results of the simulations using the daily watershed model (without reservoirs) indicate that, overall, warming alone would cause a decrease in daily streamflow, specifically the maximum and average daily flow and 7-day low flow. Most of this decrease would occur in the warmer months. Where snow accumulation currently is significant (in the northern part of the basin), however, the warming would result in an increase in the February average and maximum daily flow, regardless of precipitation changes. In general, watershed runoff was found to be more sensitive to changes in daily precipitation amounts than to changes in daily temperature or precipitation duration. Detectibility of runoff changes was masked by the underlying variability in precipitation.

Estuary Models

A rise in sea level is likely to accompany global warming and would alter estuarine salinity. A global warming of about 4.5 °C for conditions of doubled CO2 could result in an estimated sea-level rise of about 4.5 ft (feet). A two-dimensional salinity model is being developed to assess the effects of sea-level rise on salinity dynamics in the Delaware Estuary. Results of an existing one-dimensional salinity model of the Estuary indicate that a rise of 2.4 ft would cause the saltwater front to move about 8 miles upstream (Hull and others, 1986) and could have serious implications for the continued availabilty of fresh surface and ground water in the area of upstream movement.

Ground-Water-Flow Models

Calibration of three ground-water-flow models to assess the potential effects of sea-level rise and resulting changes in salinity dynamics on ground-water availability is near completion. A model of the aquifer system near New Castle, Delaware was used for sensitivity analyses. Model results indicate that this aquifer system, which is semi-confined, is sensitive to the inundation that would result from a rise in estuary levels (William Werkheiser, U.S. Geological Survey, written commun., 1989). Because of the presence of a confining unit directly under the estuary, a sea-level rise of 5 ft alone would not result in a significant change in recharge of saline estuary water into the aquifer system. A combination of inundation and a sea-level rise of 5 ft, however, would triple the amount of saline water that recharges to the aquifer system, because the inundation would extend beyond the confining unit.

SUMMARY AND CONCLUSIONS

Results of analyses of the potential effects of climatic change on water resources in the Delaware River basin suggest serious implications for future availability of water-related resources, if precipitation amounts and variability do not change significantly. Given current precipitation patterns, decreases in snow accumulation in the northern part of the basin and increases in evapotranspiration throughout the basin could change the temporal distribution of runoff and reduce total annual streamflow. Ground-water recharge of saline estuary water in one aquifer near New Castle, Delaware could triple with a sea-level rise of 5 ft.

Several novel approaches are being developed in this study that use stochastic climate models in conjunction with deterministic models to study the effects of climatic change on water resources. Additional analyses are needed to refine the models and scenarios to better quantify the effects and associated risk of potential changes in streamflow and sea level. Analyses to date, however, indicate that without more reliable estimates of regional precipitation and warming patterns, the future direction of basin streamflow changes cannot be determined precisely.

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