New Jersey Geological Survey
Geological Survey Report GSR 40

HYDROSTRATIGRAPHY OF THE KIRKWOOD AND COHANSEY FORMATIONS OF MIOCENE AGE IN ATLANTIC COUNTY AND VICINITY, NEW JERSEY

N.J. Department of Environmental Protection - Division of Science, Research and Technology

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Cover illustration: Drilling at the Atlantic City Coast Guard Station by the U.S. Geological Survey Eastern Region Branch truck-mounted drilling rig in June, 1993. The site is located adjacent to Absecon Inlet and the Farley State Marina. Results from this site are shown in figure 3 of the report. This borehole was part of the New Jersey Coastal Plain Drilling Project (Leg 150X) and funded by the National Science Foundation.

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Hydrostratigraphy of the Kirkwood and Cohansey Formations of Miocene Age in Atlantic County and Vicinity, New Jersey

by

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ABSTRACT

Borehole geophysical logs were used to produce cross sections, equal thickness maps, and structure contour maps of aquifers and confining units of the Kirkwood and Cohansey Formations in Atlantic, and parts of Ocean, Burlington, Cape May and Cumberland Counties. Two observation wells offshore from Atlantic City allowed interpretations to be extended beneath the Atlantic Ocean. Aquifers mapped with their associated confining units are, from oldest to youngest, the composite confining unit, Atlantic City 800-foot sand, the Wildwood-Belleplain confining unit (named in this report) which commonly contains the Rio Grande water-bearing zone, and the Kirkwood-Cohansey aquifer system.

Where confined, the Atlantic City 800-foot sand contains a lower sand from the unnamed lower member of the Kirkwood Formation and an upper sand from the Shiloh Marl Member of the Kirkwood Formation. A clay-silt at the base of the Shiloh Marl Member may act in places as a leaky confining unit separating the two sands. The confining bed overlying the Atlantic City 800-foot sand, the Wildwood-Belleplain confining unit, can exceed 400 feet in thickness (in Cape May County), and is correlative with the Wildwood Member of the Kirkwood Formation and, in places, the lower part of the Belleplain Member of the Kirkwood Formation. Where the Wildwood-Belleplain confining unit is not present, the Atlantic City 800-foot sand and Kirkwood-Cohansey aquifer system may be connected and unconfined.

INTRODUCTION

Rapid population growth in and around Atlantic City (fig. 1) since the 1970's has increased demands on ground-water supply and renewed longstanding concern about water availability and water quality in the region, including the threat of salt water intrusion. Past efforts to manage the region's ground water resources have been hampered by incomplete knowledge of the hydrogeologic framework. Because of this, the New Jersey Statewide Water Supply Master Plan of 1981 designated the Atlantic City region as one of several areas in the State needing additional hydrostratigraphic investigation to resolve major questions concerning the Kirkwood aquifer. To delineate the Atlantic City 800-foot sand, the extent of the confining unit overlying it required identification. In areas to the northwest where this confining unit is absent, the Atlantic City 800-foot sand is coarser, and distinguishing it from the Kirkwood-Cohansey aquifer system is extremely difficult. The ability to differentiate between the two is essential because where the two aquifers are interconnected, recharge to the confined part of the Atlantic City 800-foot sand is from this unconfined aquifer system to the west. In addition, the updip extent of the confining unit overlying the Atlantic City 800-foot sand required delineation because it defines both the extent of the Kirkwood-Cohansey aquifer system and the Atlantic City 800-foot sand.

This report represents part of a cooperative program between the N.J. Geological Survey and the U.S. Geological Survey Water Resources Division. The primary responsibility of the N.J. Geological Survey was to show the extent and thickness of the major confining unit overlying the Atlantic City 800-foot sand (named the Wildwood-Belleplain confining unit in this report), and to map the extent and thickness of Miocene aquifers, principally in Atlantic County. These aquifers supply most of the ground water used by the New Jersey shore communities from southern Ocean County to Cape May, and inland to the western limit of the Pinelands.

Acknowledgments

An extensive database prepared by Lloyd Mullikin over many years was used in the preparation of this report. That unpublished data contributed significantly in the report's completion, and is available for examination at the N.J. Geological Survey. Otto Zapecza of the U.S. Geological Survey generously reviewed the report and offered many valuable suggestions. The author is also grateful to Richard Dalton, Jeffrey Waldner and Robert Canace for their expert reviews. Borehole geophysical information supplied by well-drilling contractors was also useful and appreciated.

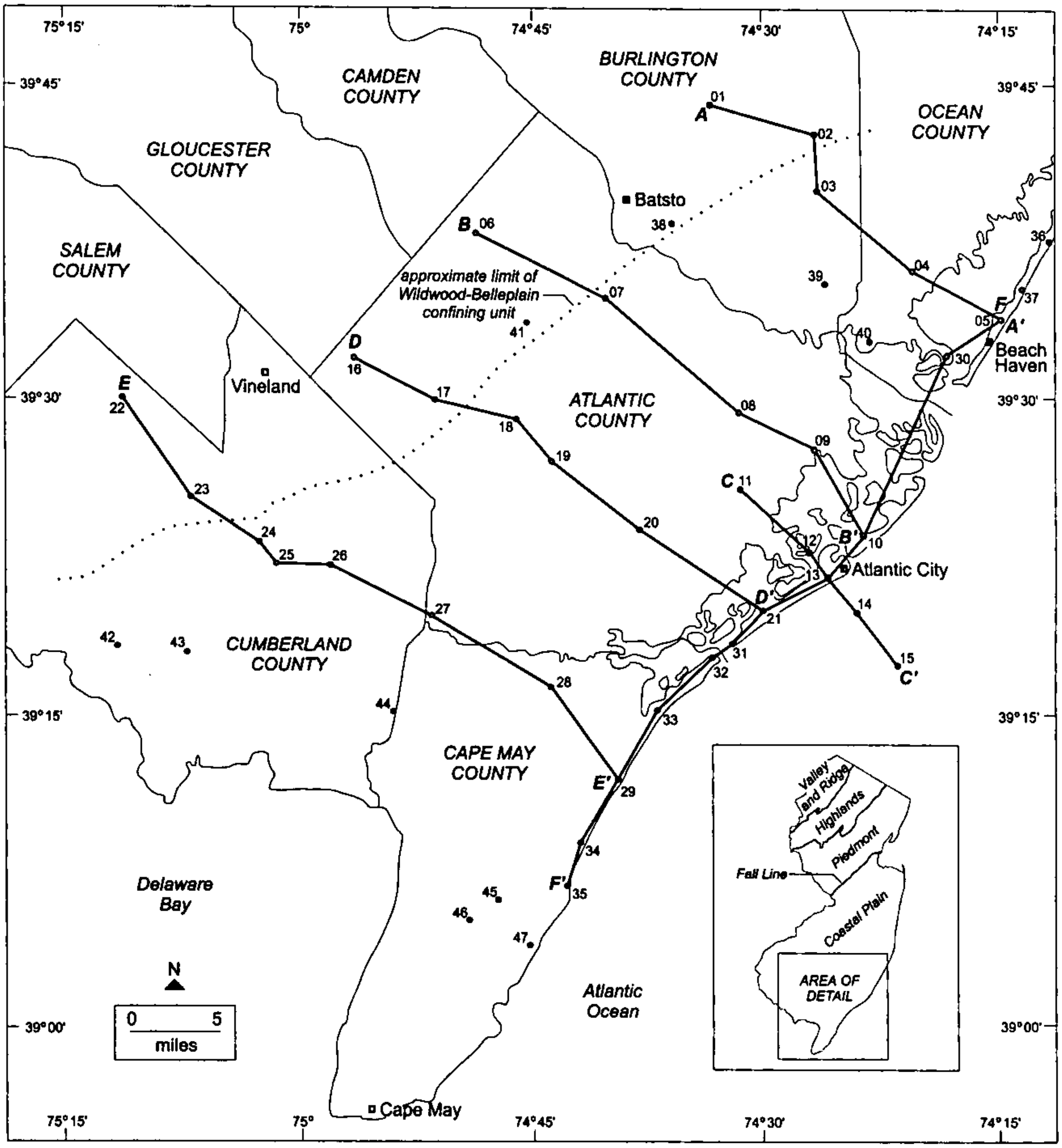

Figure 1.-- Location of study area in southern New Jersey, distribution of wells, and location of cross sections. The dotted line indicates the approximate updip limit of the Wildwood-Belleplain confining unit. Table 2 provides information on the wells.

PREVIOUS HYDROGEOLOGIC INVESTIGATIONS

The earliest descriptions of the Kirkwood Formation came from field reconnaissance mapping (Knapp, 1904), clay mining (Ries and others, 1904), and water supply investigations (for example, Woolman, 1891, 1894). The Kirkwood was drilled for water supply at Atlantic City and southward on the beaches, and described as a series of permeable sands separated by impervious diatom-rich clays (Woolman, 1891, 1894, fig. 2). Knapp (1904) recognized a major Tertiary subdivision of the New Jersey Coastal Plain - the outer Coastal Plain - which included the Kirkwood (Miocene) and the Cohansey (Pliocene?) Formations. Ries and others (1904) described the outcropping Kirkwood Formation, including the Asbury Clay to the northeast, the "Fluffy Sand" in the central and southern New Jersey Coastal Plain, and the Alloway Clay and Shiloh marl (containing Miocene fossils) in the southwest.

Woolman (1894, fig. 2) subdivided the Kirkwood at Wildwood into about 300 feet of lower Miocene clays and sands (including a major water horizon) infrequently containing the diatom *Actinophytcus heliopelta*, a thick middle "Great Diatom Bed" of about 400 feet (previously termed the "diatomaceous clay-bed") correlative with the Chesapeake Group, and an upper St. Mary's bed of about 80 feet (fig. 2).

Four water bearing units were typically penetrated in artesian wells along the coast of Atlantic and Cape May Counties. These included the 800-foot Atlantic City horizon and the Atlantic City 950-foot horizon, the 700-foot Atlantic City horizon occurring just below the base of the "Great Diatom Bed," and 550-foot horizon occurring 125 feet below the top of the "Great Diatom Bed" at Atlantic City (fig. 2). Woolman (1894) also identified several minor water horizons above the "Great Diatom Bed."

Richards and Harbison (1942) suggested a subdivision of the Kirkwood Formation similar to that of Woolman (fig. 2), based in part on correlations with the Chesapeake Group of Maryland and Virginia. They subdivided the Kirkwood into a thick lower Calvert Phase, which consisted of: Basal Greensand Marl, the Lesser Diatom Bed, the 800-foot Sand, and the Great Diatom Bed. The Calvert was also correlative with the Shiloh Marl. In effect, Richards and Harbison (1942) lumped the 700- and 800-foot sand units of Woolman (1896) into a single water bearing zone. Above the Calvert Phase, Richards and Harbison identified a thin upper St. Mary's Phase in the Kirkwood.

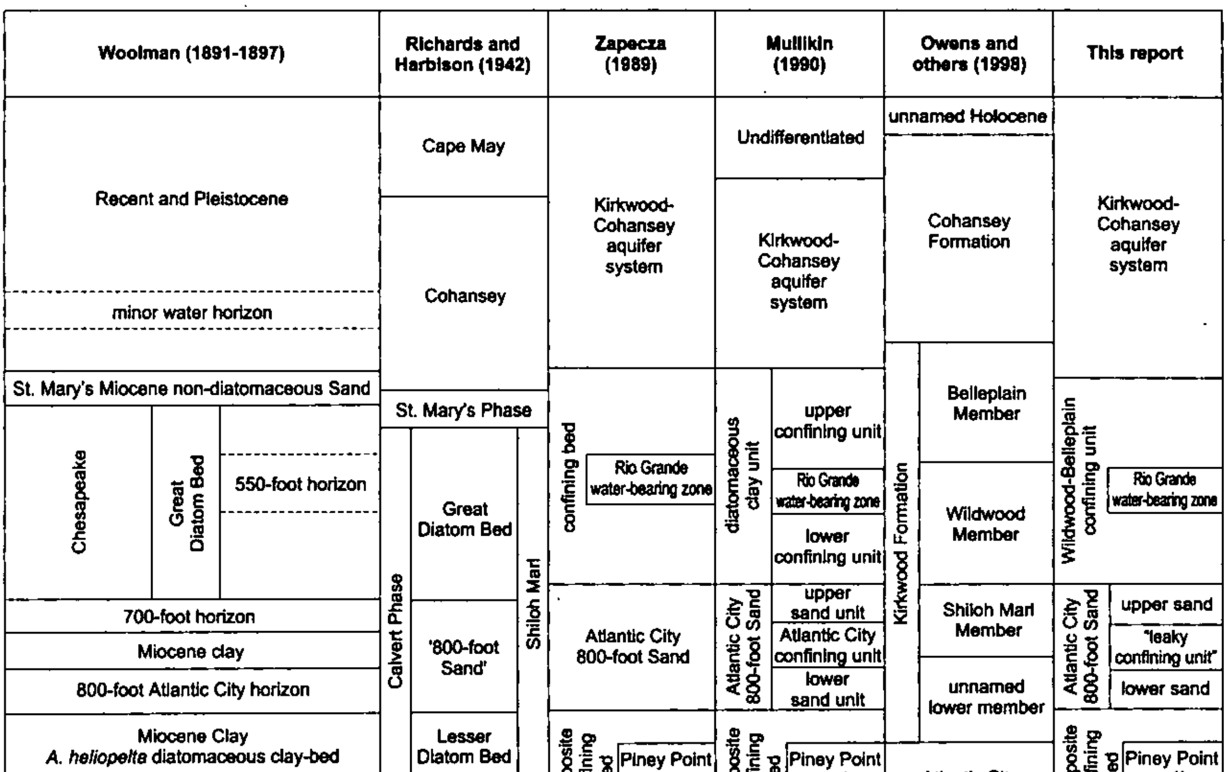

Figure 2.-- Correlation chart of nomenclature of hydrostratigraphic and geologic units developed in the Atlantic City area over the past century.

Isphording (1970) reexamined the outcropping relationships of the Kirkwood, and defined three members: (1) Asbury Park, (2) Grenloch and (3) Alloway Clay. These members were distinct facies interpreted predominantly as shelf deposits, but could not be recognized downdip in the subsurface along the coast of southern New Jersey.

In the 1980's modern hydrogeologic and geologic frameworks were developed for the New Jersey Coastal Plain, including the Miocene age Kirkwood and Cohansey Formations. Zapecza (1989) developed a hydrogeologic framework based on more than 1,000 geophysical logs, and mapped two major aquifers and two major confining beds (fig. 2). These include: (1) the composite confining bed, a complex series of geologic units ranging in age from late Cretaceous through lower Miocene, (2) the Atlantic City 800-foot sand, a major water bearing unit at the base of the Kirkwood Formation whose thickness ranges from 40 to 150 feet, and contains a thin (10-30 feet) clay bed in the middle of the aquifer, (3) a major confining bed overlying the 800-foot sand consisting of a massive clay bed, whose thickness ranges from 100 to 450 feet, and is correlative with the "Great Diatom Bed" of Woolman (1896). In the middle of this confining bed, from Ocean to Cape May County, is a thin, generally 40 feet thick, confined water bearing zone termed the Rio Grande (the Atlantic City 550-foot horizon of Woolman, 1891), and (4) the Kirkwood-Cohansey aquifer system, a water-table aquifer that includes the upper Kirkwood Formation, the Cohansey Formation, and parts of surficial sand and gravel units including the Bridgeton and Cape May Formations. Mullikin (1990) presented a slightly modified version of Zapecza's 1989 hydrostratigraphic subdivision, identifying a thin Atlantic City confining unit which separates an upper and lower sand unit within the Atlantic City 800-foot sand, and separated the Great Diatom Bed into an upper and lower confining unit (fig. 2).

In 1984 the first continuous corehole in the New Jersey Coastal Plain was drilled near Mays Landing to a depth of 945 ft. Designated ACGS-4 (Owens and others, 1988), this marked the beginning of modern integrated stratigraphic studies of the Kirkwood Formation. The Kirkwood was shown to consist of three major unconformity-bounded stratigraphic sequences correlative with Andrews' (1988) East Coast Diatom Zones 1, 2, and 6 (Owens and others, 1988; Andrews, 1988; Sugarman and others, 1993). Andrews (1988) established East Coast Diatom Zone 1 as lower Miocene, with an estimated age range 19.1-18.9 Ma; East Coast Diatom Zone 2 as upper lower to lower middle Miocene, with an age range of 17.4-15.6 Ma; and East Coast Diatom Zone 6 as middle Miocene, with an estimated age range of 13.8-12.8 Ma.

Using shell material recovered from boreholes, strontium-isotope (Sr-isotope) stratigraphy was applied to correlate the Kirkwood sequences to the geomagnetic polarity time scale (Sugarman and others, 1993), a chronology based on reversals of the Earth's magnetic field. This technique provides a better framework for estimating the age and duration of these units: three unconformity-bounded Kirkwood sequences were confirmed (below) and a fourth inferred.

Sequence Stratigraphy

Kirkwood Sequences	Sr-isotope age estimates (Millions of years ago)	Age Error (Millions of Years)
Upper	13.6 to 12.2	+/- 0.9
← Hiatus →		
Middle	17.4 to 15.5	+/- 0.6
← Hiatus →		
Lower	22.6 to 19.2	+/- 0.6

During 1993-1994, three boreholes were drilled at Island Beach, Atlantic City, and Cape May (Miller and others, 1994). Hydrogeologic and geologic units at the Atlantic City site were identified, along with corresponding Sr-isotope age estimates (fig. 3). Sugarman and Miller (1997) used sequence stratigraphic information developed from these boreholes to develop predictive hydrostratigraphic models for Miocene aquifers.

Based on abundant new data from subsurface cores from the Kirkwood Formation, Owens and others (1998) subdivided the Kirkwood Formation into an unnamed lower member, the Shiloh Marl Member, the Wildwood Member, and the Belleplain Member (figs. 2, 3). The lower Kirkwood Member is the oldest (about 24-21 Ma), followed by the Shiloh Marl (about 20.5-20 Ma), Wildwood (about 18-15.6 Ma), and Belleplain (about 13.6-12 Ma) Members. Detailed descriptions of these formations can be found in Owens and others (1998).

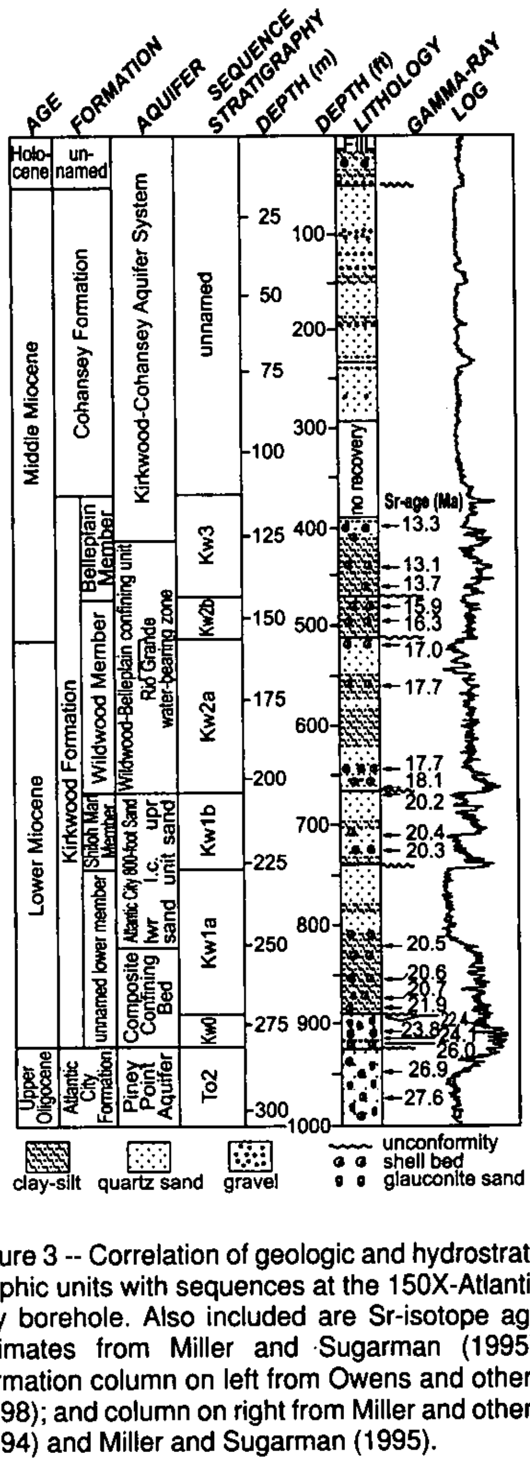

Figure 3 -- Correlation of geologic and hydrostratigraphic units with sequences at the 150X-Atlantic City borehole. Also included are Sr-isotope age estimates from Miller and Sugarman (1995). Formation column on left from Owens and others (1998); and column on right from Miller and others (1994) and Miller and Sugarman (1995).

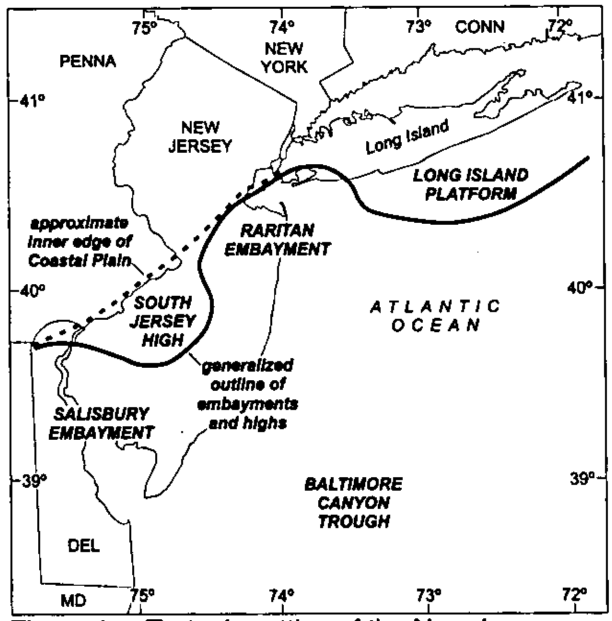

Figure 4.-- Tectonic setting of the New Jersey Coastal Plain.

GEOLOGIC SETTING

The New Jersey Coastal Plain is underlain by a wedge of unconsolidated Cretaceous to Recent sediments (table 1) which thickens from a feather edge along the Fall Line (fig. 1) to more than 6,000 feet beneath southern Cape May County (Zapecza, 1989). New Jersey Coastal Plain sediments occupy two major structural basins: the Raritan Embayment in the north, and the larger Salisbury Embayment in the south (Owens and others, 1988; fig. 4). Distribution of the aquifers and confining units described in this report was controlled in large part by the structural behavior of the Salisbury Embayment, a landward extension of the Baltimore Canyon Trough. The Salisbury Embayment has undergone differential movement through time. It appears to have downwarped progressively to the north during the early Cretaceous and into the Paleogene, but the direction of migration shifted to the south in the Neogene. Consequently, in Miocene time the basin accumulated a thick marine section which includes the major water bearing sands and confining units discussed in this report. The Cohansey Formation marks the end of marine deposition in the middle Miocene, and may represent uplift in the Salisbury Esmbayment.

SYSTEM	SERIES	GEOLOGIC UNIT	LITHOLOGY	HYDROGEOLOGIC UNIT	HYDROGEOLOGIC CHARACTERISTICS
QUATERNARY	Holocene (Recent)	Alluvial deposits	Sand; silt; 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. May be included in Kirkwood-Cohansey aquifer system.
		Beach sand and gravel	Sand, medium to coarse, light-colored, quartz, pebbly.		
	Pleistocene	Cape May Formation	Sand, heterogeneous, light-colored, quartz, clayey, pebbly.		
TERTIARY / NEOGENE	Miocene	Pennsauken Formation			
		Bridgeton Formation			
		Beacon Hill Gravel	Gravel, light-colored, quartz, sandy.	Kirkwood-Cohansey aquifer system	Ground-water occurs generally under water-table conditions. In Cape May County, the Cohansey Sand is under confined conditions.
		Cohansey Formation	Sand, medium to coarse, light-colored, quartz, pebbly; local clay beds.		
		Kirkwood Formation: Belleplain Member	Members are typically clay-silt at the base and sand at top.		
		Kirkwood Formation: Wildwood Member	Belleplain Member- Silty clay and micaceous fine sand with occasional shell hash grading upward to shelly, laminated clay-silt, silt, and fine sand. Wildwood Member- Micaceous, shelly laminated clay-silt to very fine sand.	Wildwood-Belleplain confining unit; Rio Grande water-bearing zone	Thick clay-silt unit occurs along coast and for a short distance inland. A thin water-bearing sand occurs within the middle of this unit in Cape May, Cumberland, and parts of Atlantic County.
		Kirkwood Formation: Shiloh Marl Member	Shiloh Marl Member- Clayey-sands with shells, interbedded shelly silt and very-fine sand, with overlying interbedded sand and lignitic silt and pebbly sand.	Atlantic City 800-foot sand	A major aquifer along the coast. A relatively thin clay bed within the aquifer separates an upper and lower sand, and may act as a leaky confining unit.
		Kirkwood Formation: unnamed Lower Member	Unnamed Lower Member- Shelly glauconite sand, silty sand, and sandy silt underlying quartz sands with interbedded clay and silt.	Composite confining unit	Poorly permeable sediments.
TERTIARY / PALEOGENE	Oligocene	Atlantic City Formation	Sand, fine to coarse, quartz; glauconite.	Piney Point aquifer	Yields moderate quantities of water locally.
		Sewell Point Formation			
	Eocene	Absecon Inlet Formation	Clay, silty and sandy, glauconitic; fine quartz sand.		
		Shark River Formation			Poorly permeable sediments.
		Manasquan Formation			
	Paleocene	Vincentown Formation	Sand, fine to coarse, quartz, glauconitic; clayey, fossiliferous.	Vincentown aquifer	Yields small to moderate quantities of water in and near its outcrop area.
		Hornerstown Formation	Sand, glauconitic.		Poorly permeable sediments.
CRETACEOUS	Upper Cretaceous	Tinton Formation	Sand, fine to coarse, quartz, glauconitic, silty, micaceous.		
		Red Bank Formation		Red Bank sand	Yields small to moderate quantities of water in and near its outcrop area.
		Navesink Formation	Sand, clayey, glauconitic.		Poorly permeable sediments.

Figure 5.-- Geologic and hydrostratigraphic units of the New Jersey Coastal Plain discussed in this report (modified from Zapecza, 1989).

Tertiary confining units and aquifers generally consist of unconformity-bounded, shallowing upward, silica-rich cycles of sedimentation. They typically include a thin lower glauconite sand (transgressive), a thicker clay-silt, and an upper coarse quartz sand (regressive). These deposits reflect a transition from marine-shelf to near-shore marine and non-marine sedimentation. Confining units typically correspond to the lower clay-silt and glauconite sands, whereas the aquifers consist of the upper quartz sands (Sugarman and Miller, 1997). The upper confining unit is commonly the clay-silt at the base of the next sequence. Miocene and Cretaceous sequences are generally similar, except that the glauconite sand at the base of the Miocene deposits, if present, is usually thinner than glauconite found at the base of Cretaceous sequences.

The lower member of the Kirkwood Formation (fig. 3) is a good example of these cycles of sedimentation. It consists of lower, fine-grained marine shelf sediments (glauconite sand, silty sands and sandy silt) and upper, coarser deltaic and nearshore marine sediments (quartz sands with interbedded silt and clay).

The Shiloh Marl Member is another example of an unconformity-bounded coarsening upward cycle of sedimentation (fig. 3). Its base consists of interbedded silt and very fine sand, containing mica, finely dispersed carbonaceous material, and occasional broken shells (Owens and others, 1988). These grade upward at Atlantic City into massive clayey sands with shells, interbedded sands and lignitic silts, and pebbly sands. At ACGS-4, the sand typically consists of olive-gray, medium to coarse quartz grains with thick shell beds (Owens and others, 1988).

The Shiloh Marl Member of the Kirkwood Formation is unconformably overlain by the Wildwood Member, and a major hiatus of about 2 m.y. exists between the two (20.2-18.1 Ma; Miller and Sugarman, 1995). The Wildwood is a fine grained unit consisting of laminated clay-silt to fine-sand which is frequently micaceous and sometimes shelly, with thin interbeds of clay and sand. Less typical is a massive, burrowed silt deposit. Sr-isotope age estimates date the Wildwood to about 18.1-16.3 Ma. Sugarman and others (1993) termed this sequence the Kirkwood (Kw)2 and, using Sr-isotopes, identified a hiatus of about 1 m.y. within it. Miller and Sugarman (1995) then divided Kw2 into Kw2a and Kw2b (fig. 3), with a 0.7 m.y. hiatus (17-16.3 Ma) separating them. An upper quartz sand is typically present in the Kw2a sequence. At Atlantic City, a 25 foot section at the top of Kw2a, and in the middle of the Wildwood Member, contains interbedded sands and carbonaceous silts.

The Wildwood Member is overlain by the Belleplain Member. A major hiatus of 2.6 m.y. at Atlantic City separates the two and, typically, a thin gravel layer composed primarily of quartz and phosphatized bone material is present between them (Owens and others, 1998). The Belleplain has a relatively limited distribution compared with the lower Kirkwood, Shiloh Marl, and Wildwood Members (Sugarman and others, 1993). The upper contact of the Belleplain is inferred from the gamma log because core was unrecovered in this interval; it is about 100 ft thick at Atlantic City. Sr-isotope age estimates are 13.7-13.1 Ma, but at the Belleplain State Forest borehole the estimates are as young as 12.2 Ma (Miller and Sugarman, 1995; Sugarman and others, 1993).

The Belleplain also coarsens upward where well preserved. Middle (?) to inner neritic shelf sediments consisting of burrowed silty clay and micaceous fine sand (each containing occasional shell hash) grade

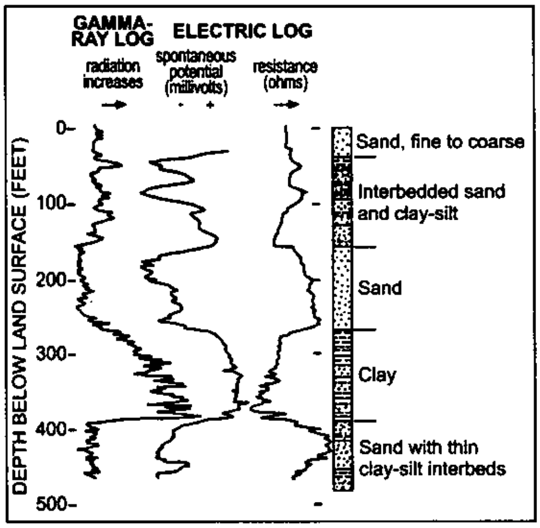

Figure 6.– Idealized borehole geophysical responses to lithology.

upwards into laminated clay-silt, silt and fine sand which is sometimes shelly and often contains mica and carbonaceous material. Interpreted as tidal flat deposits, the clay-silt and fine sand lamina grade upward into interbedded fine sand and silt.

The Cohansey Formation, unconformably overlying the Kirkwood, consists of interfingering marginal marine, barrier island, tidal flat, and lagoonal sediments (Carter, 1978). The Cohansey rarely contains fine-grained marine shelf sediments characterizing regional confining units of the Kirkwood Formation. Instead, interfingering fine and coarse sediments near shore make up a complex, locally variable aquifer system.

Unconformably overlying the Cohansey Formation are flat-lying, late Miocene (?) to Holocene (Recent) fluvial sands and gravels. These are mostly thin and permeable, and act as water-table aquifers or recharge areas. They are included in the Kirkwood-Cohansey aquifer system. Near the coast and southward into Cape May County, the fluvial deposits interfinger with estuarine and marginal marine deposits containing less permeable materials and form confining units. In Cape May County, the post-Cohansey confining units are of substantial extent.

METHODS OF INVESTIGATION

Borehole Geophysical Logs

Distinctive signatures or patterns on electric and gamma-ray logs mark boundaries between aquifers and confining units more reliably than descriptions of cuttings of New Jersey Coastal Plain sediments obtained from water well drilling (Zapecza, 1989). Geophysical logs are the primary means of correlation used in this report. Forty-seven wells with geophysical logs were used in this study (Table 2). Selected logs are shown in cross sections in figures 7-12.

Gamma-ray logs show the rate at which gamma-rays are emitted by the formations penetrated in a borehole. On the gamma-ray log, radiation increases to the right (fig. 6). In general, silt-and clay-rich sediments show higher rates of gamma radiation than sandy sediments (fig. 6). Quartz sands and gravel (permeable sediments) exhibit little natural radiation and show as deflections to the left. Consequently, aquifers and confining unit materials are usually easy to differentiate on the gamma-ray log.

Single-point resistance logs show electrical resistance of formations. Typically, silt- and clay-rich layers have lower resistance and show on logs as deflections to the left (fig. 6). The gamma-ray log (G), if available, is shown on the cross sections. If unavailable, a single point resistance log is shown (E).

Lithologic Logs

Cores and cuttings collected during drilling provide direct information on the depth and composition of hydrogeologic units. However, information from cuttings may be inaccurate because drillers' logs are not recorded with any standard method, and travel time of drill cuttings up the borehole is rarely calculated. Without this calculation, assumptions must be made concerning the depth from which logged sediments were drilled. Drilling difficulties, such as borehole cave-ins, may result in a higher proportion of material from above a given zone than estimated, introducing additional misinformation.

HYDROSTRATIGRAPHY

Hydrostratigraphic-section interpretation

Cross sections and maps in this report show hydrostratigraphic units based on correlations related to the lithologic composition of materials. Permeabilities are inferred from lithologic identification and geophysical interpretation. The hydrostratigraphic framework of the study area is shown in a series of six cross sections (figs. 7-12), five of which are dip sections (figs. 7-11), and one a strike section (fig. 12). In addition, five maps illustrate the elevation and thickness of the key horizons studied (figs. 13-17). These are: (1) the elevation of the top (fig. 13) and base (fig. 14) and the thickness (fig. 15) of the Wildwood-Belleplain confining unit; (2) the thickness of the Atlantic City 800-foot sand (fig. 16) where confined by the Wildwood-Belleplain confining unit ; and (3) the elevation of the top of the composite confining unit (fig. 17). The data used to construct these maps are given in Table 3. These cross-sections and maps provide the information necessary for water resource studies and planning. They also illustrate changes in the updip configuration of the Wildwood-Belleplain confining unit, a major goal of the study.

Composite Confining Unit

The composite confining unit consists of Late Cretaceous to Miocene deposits overlying the Wenonah-Mount Laurel aquifer and underlying the Atlantic City 800-foot sand. The top of this unit is described as the brown to greenish-gray, micaceous clay-silt known as the Basal clay or the Alloway clay member (Nemickas and Carswell, 1976). Although the top of the composite confining unit consists predominantly of clay-silts and silty and clayey glauconitic quartz sands of low to moderate permeability, it may incorporate fairly permeable sands which form the Red Bank, Vincentown, and Piney Point aquifers. In this study area it correlates

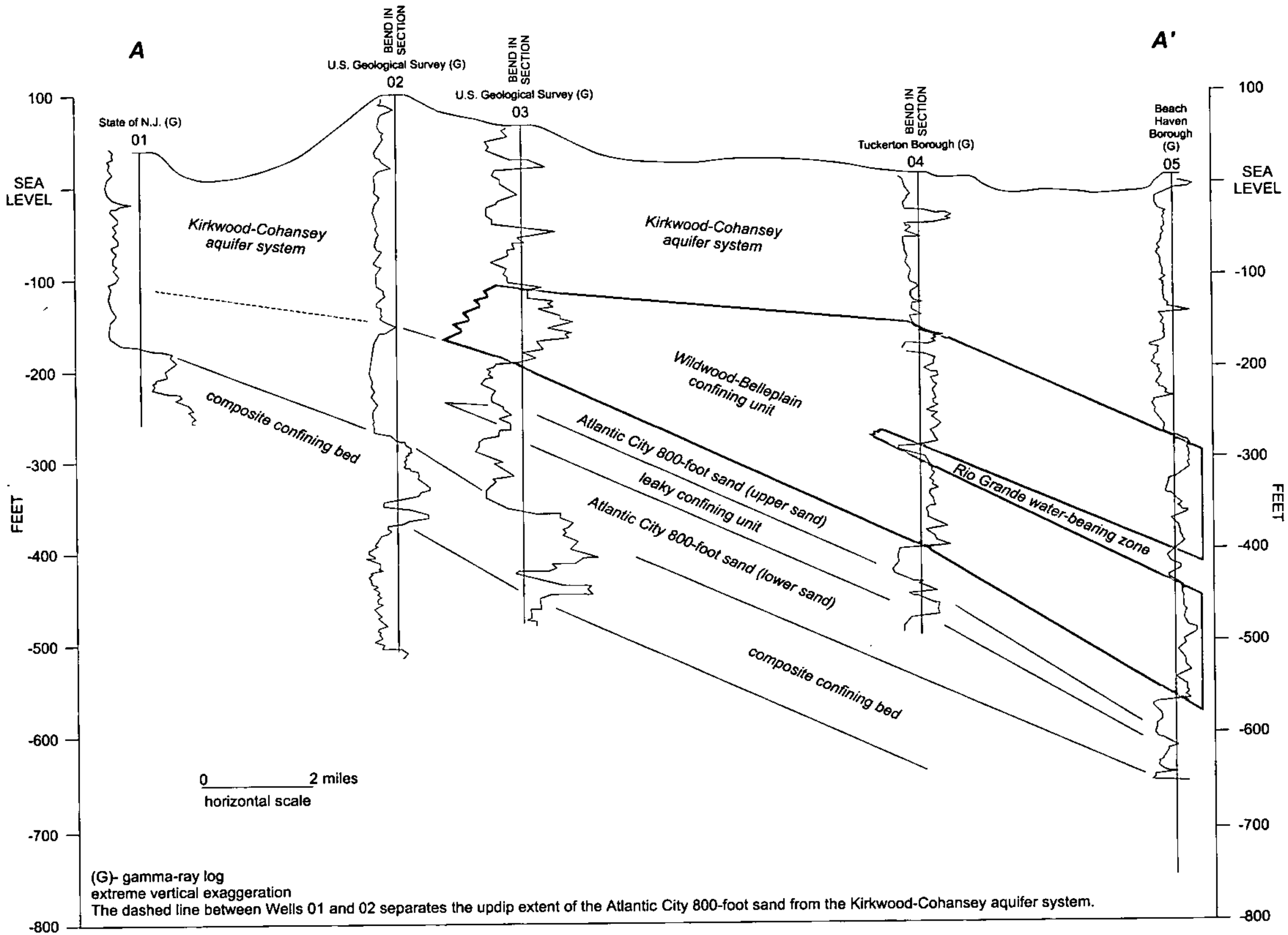

Figure 7.-- Cross-section A-A'.

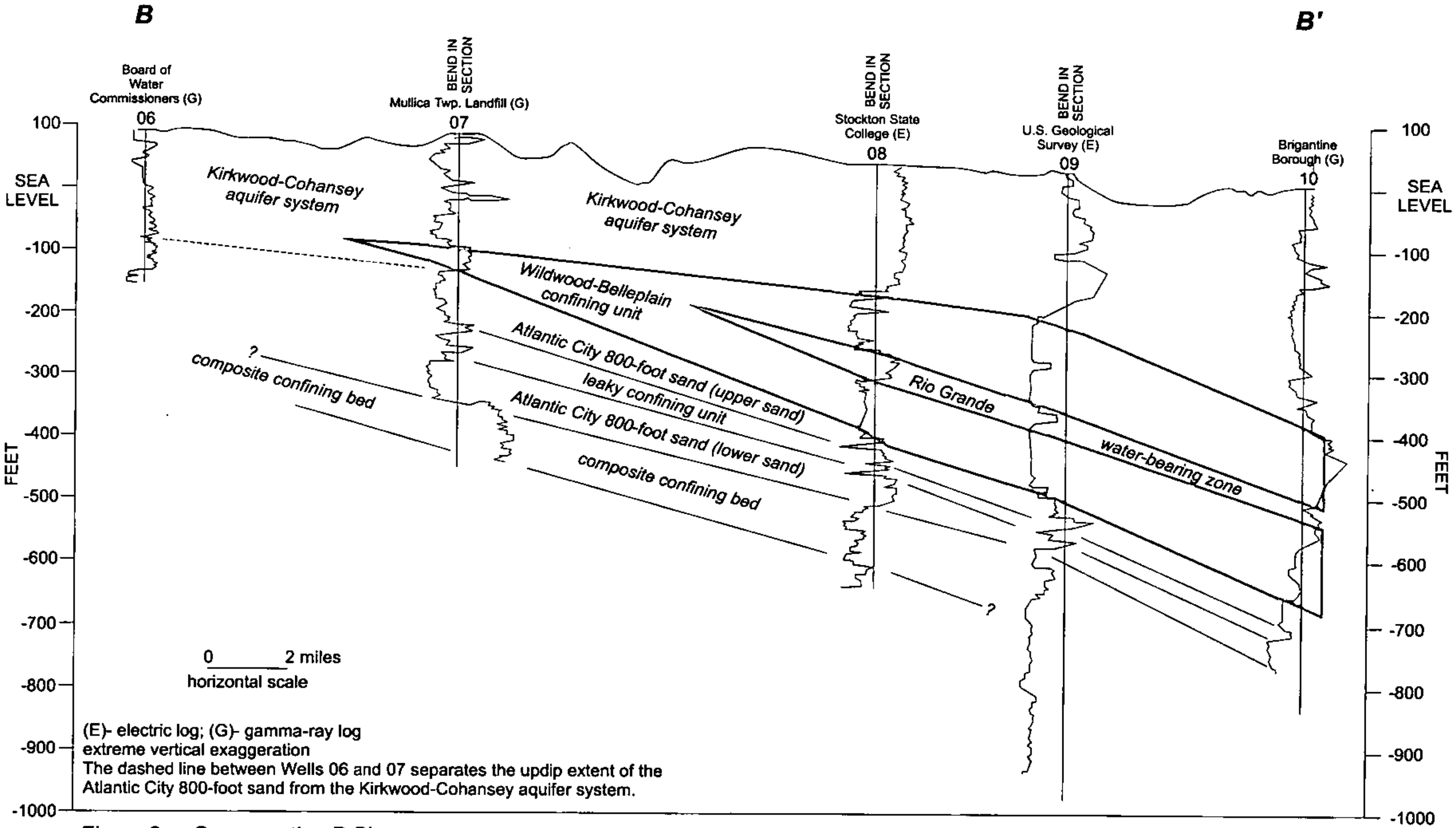

Figure 8.-- Cross-section B-B'.

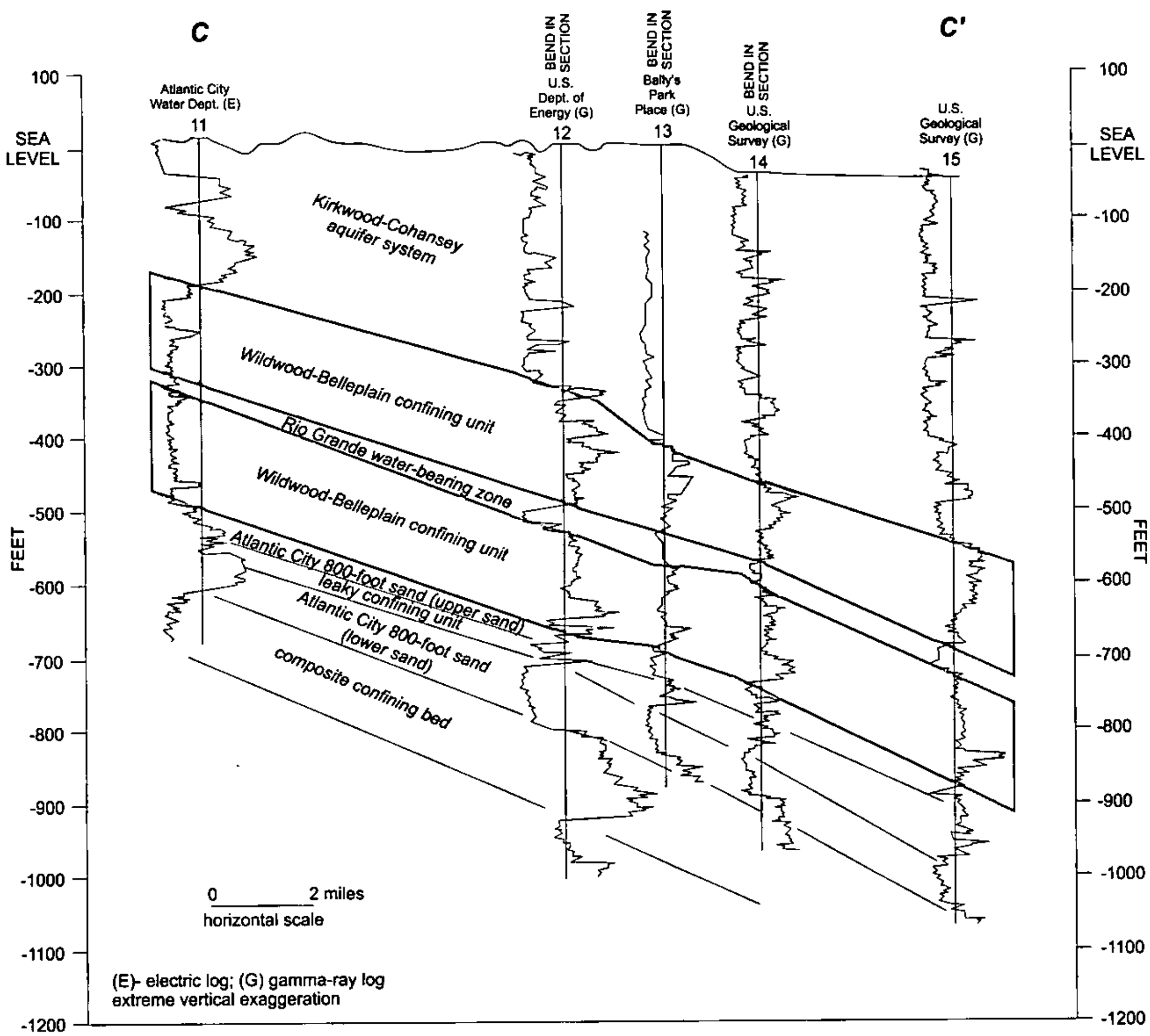

Figure 9.-- Cross-section C-C'.

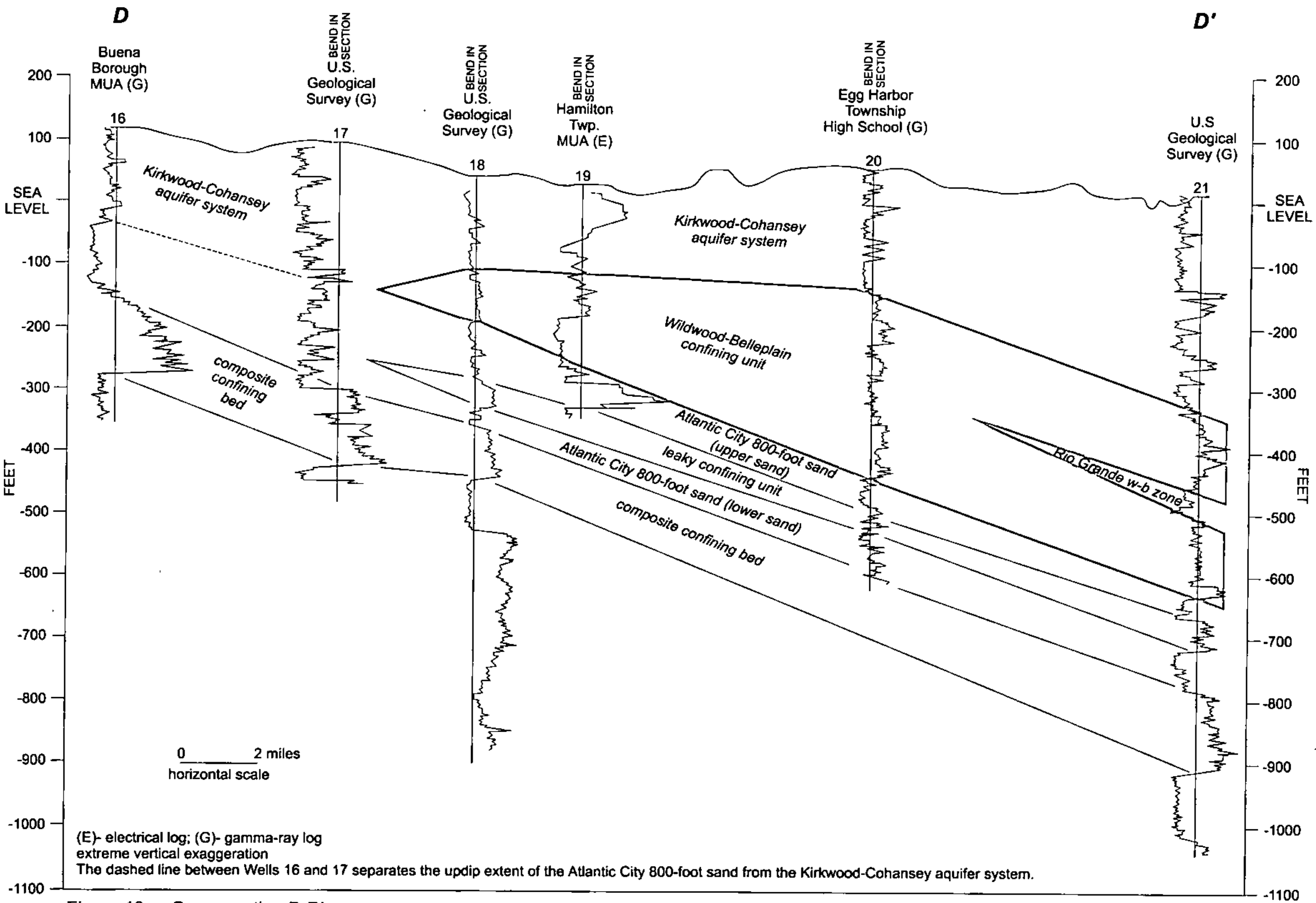

Figure 10.-- Cross-section D-D'.

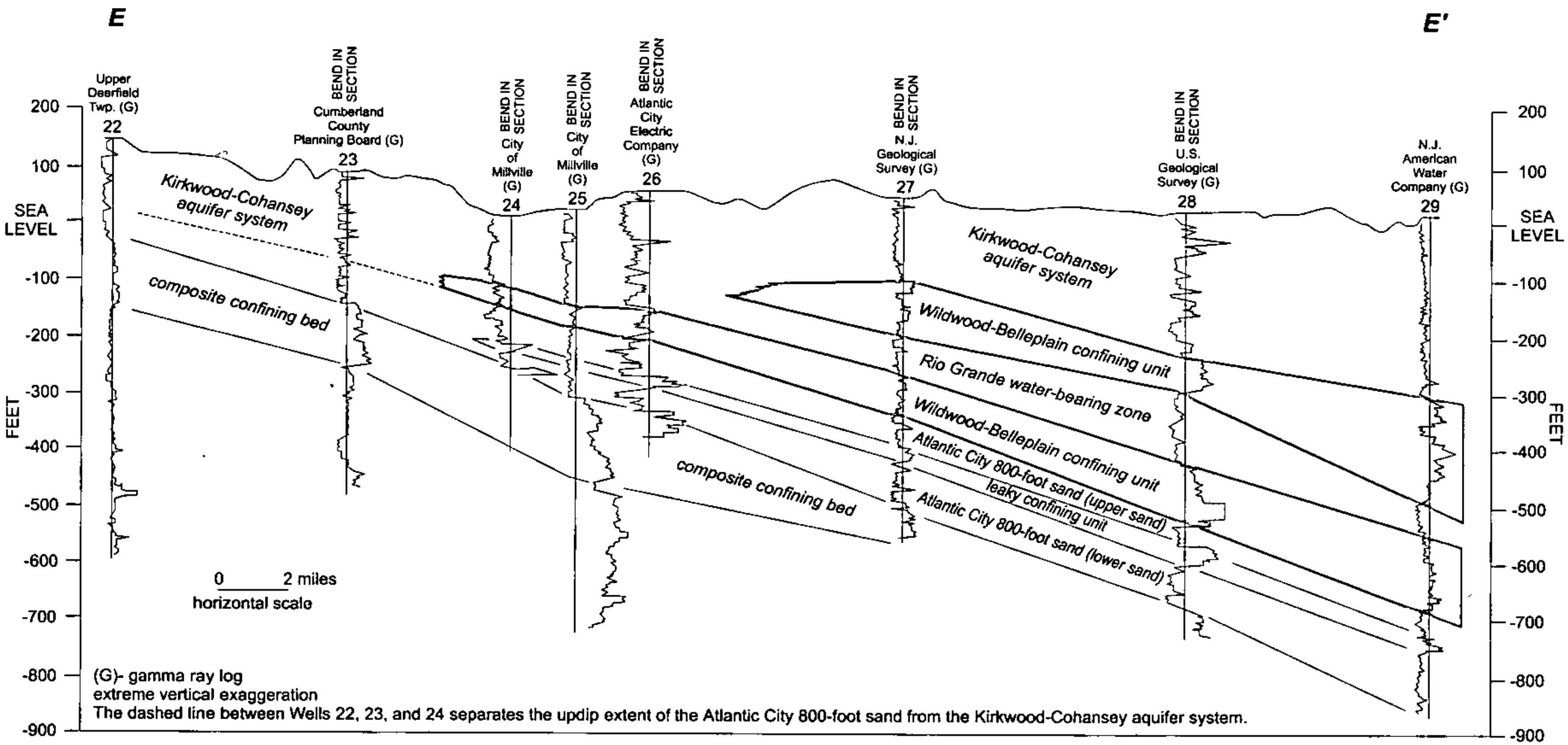

Figure 11.-- Cross-section E-E'.

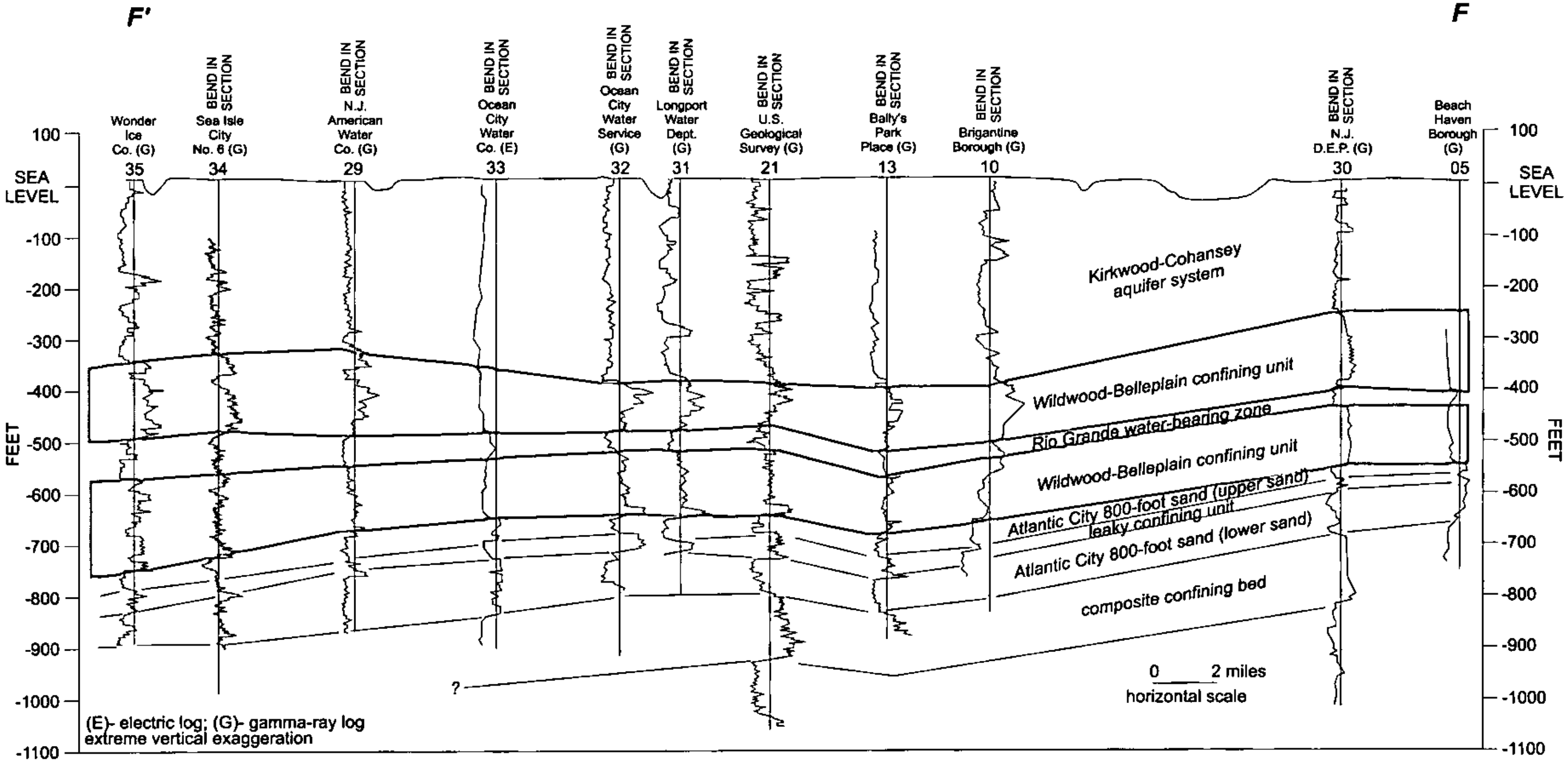

Figure 12.-- Cross-section F'-F.

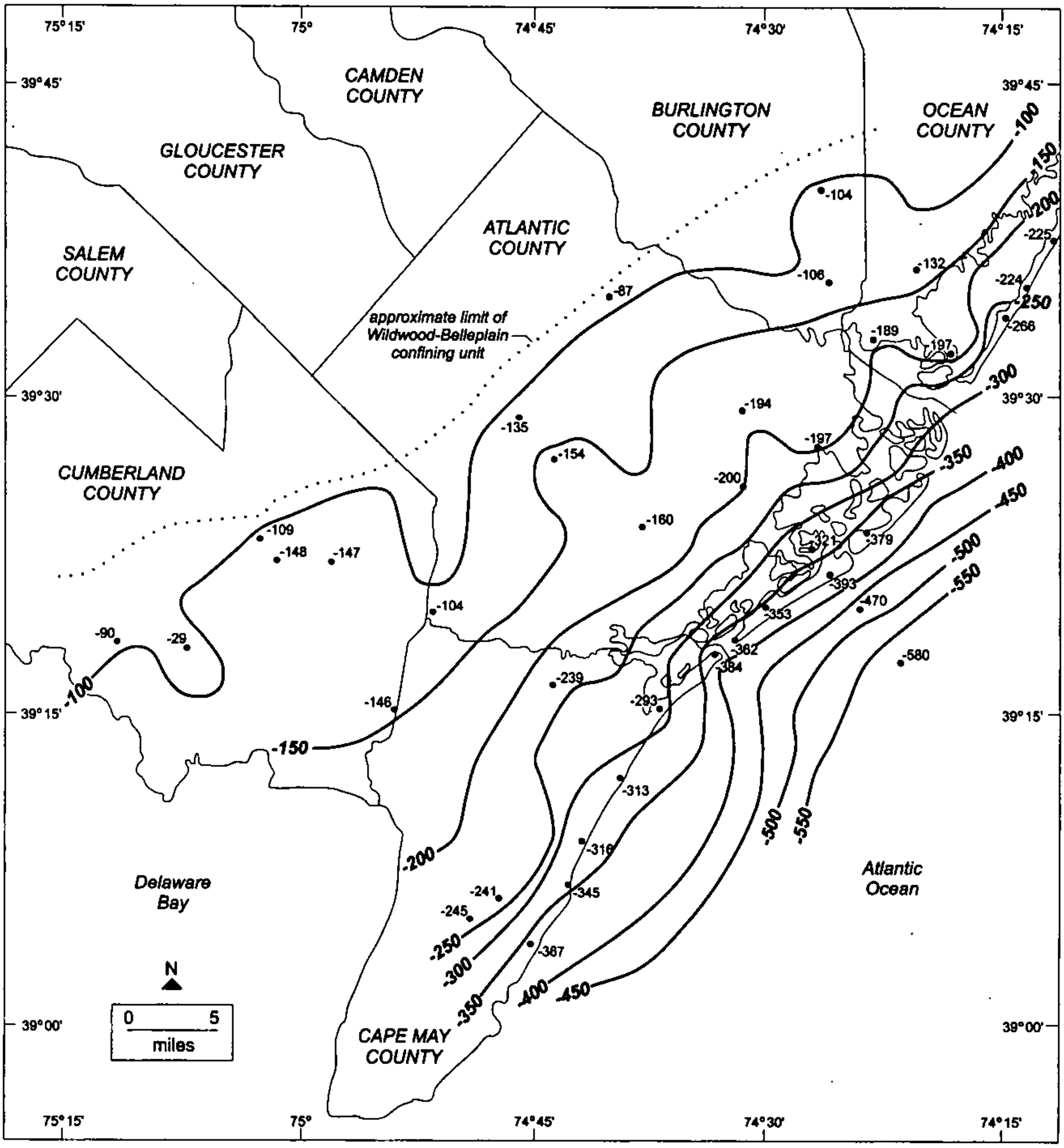

Figure 13.-- Elevation of top of Wildwood-Belleplain confining unit, in feet below sea level. Contour interval 50 feet.

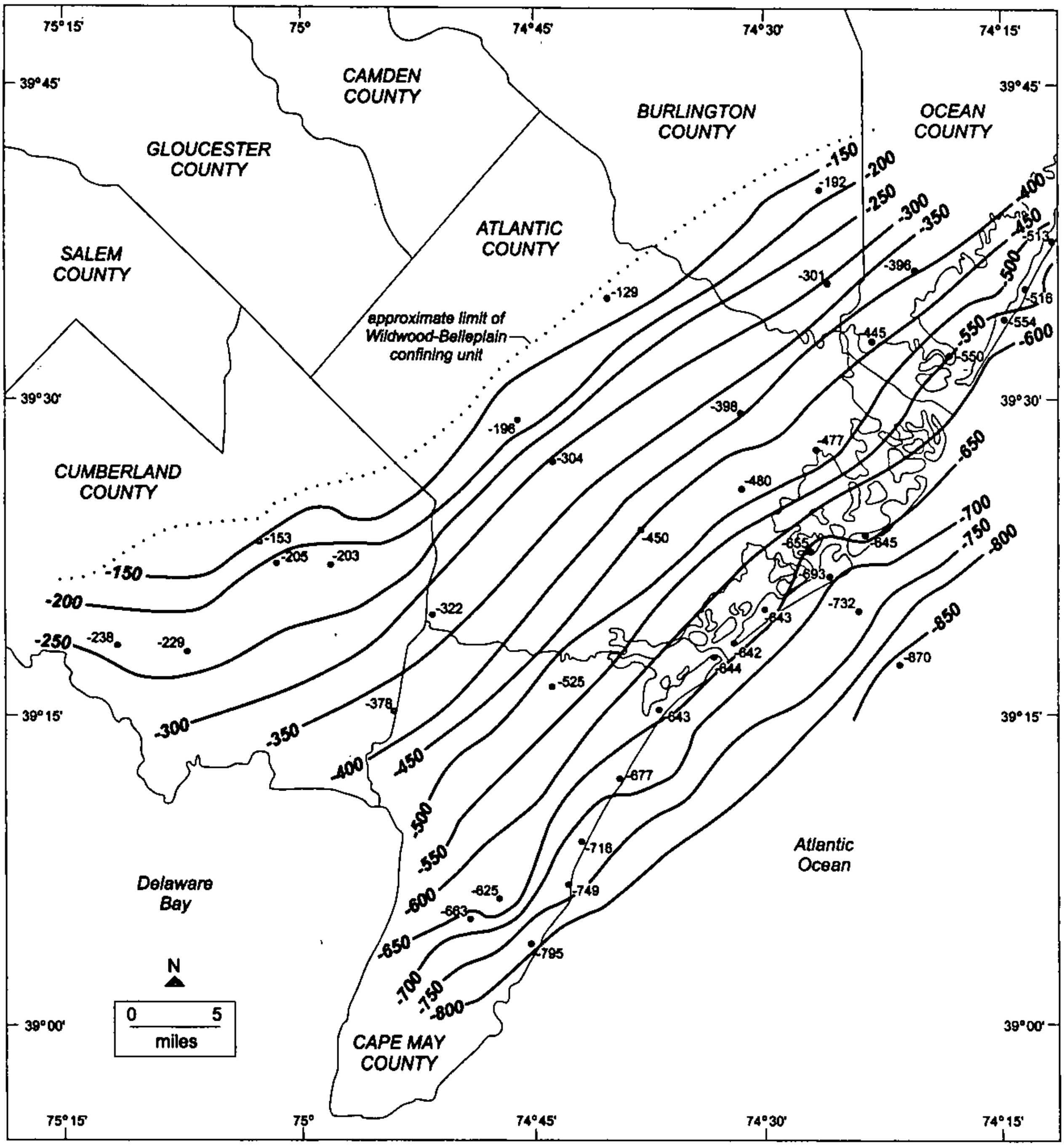

Figure 14.-- Elevation of base of Wildwood-Belleplain confining unit, in feet below sea level. Contour interval 50 feet.

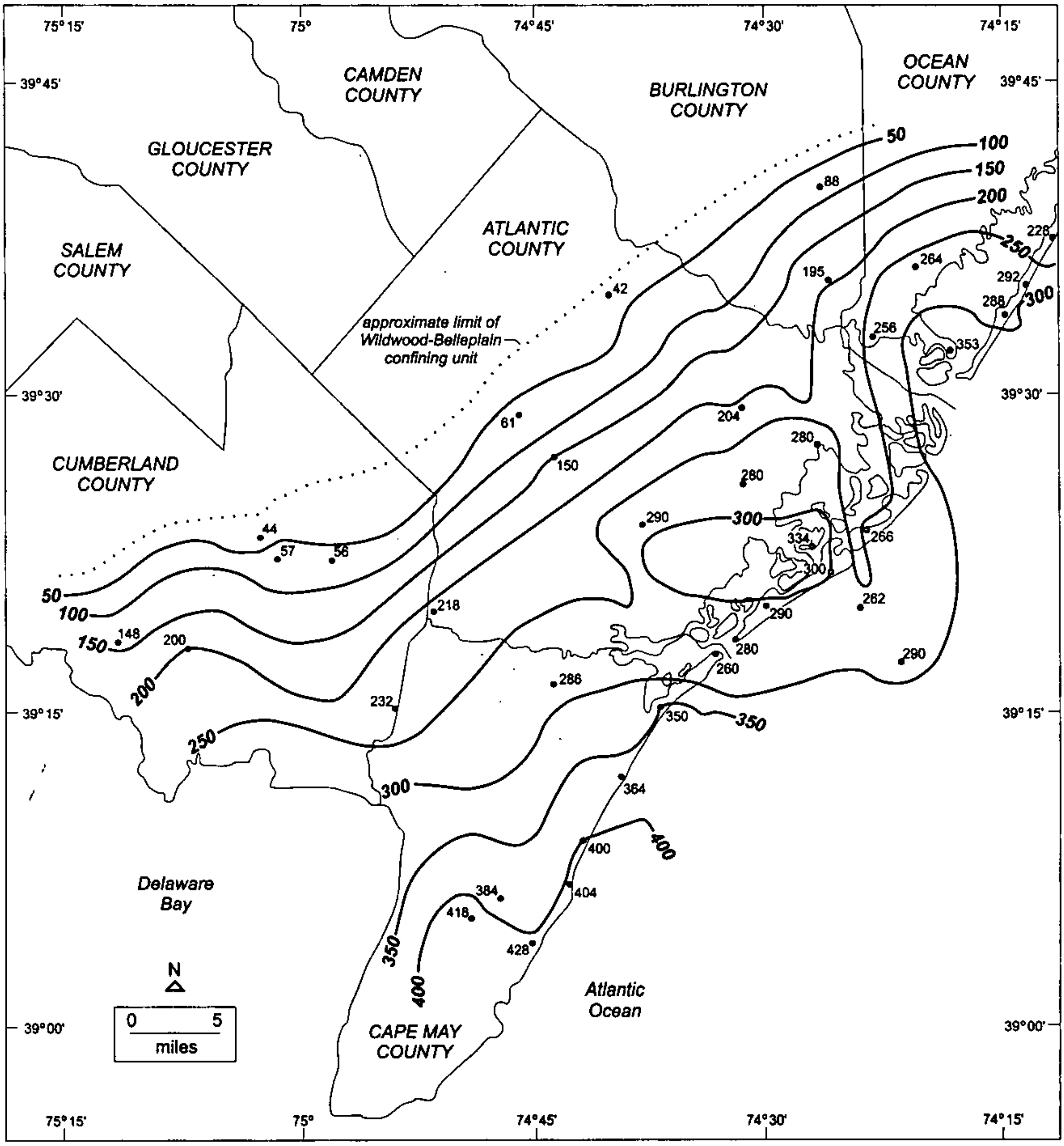

Figure 15.– Thickness of the Wildwood-Belleplain confining unit, in feet. Contour interval 50 feet.

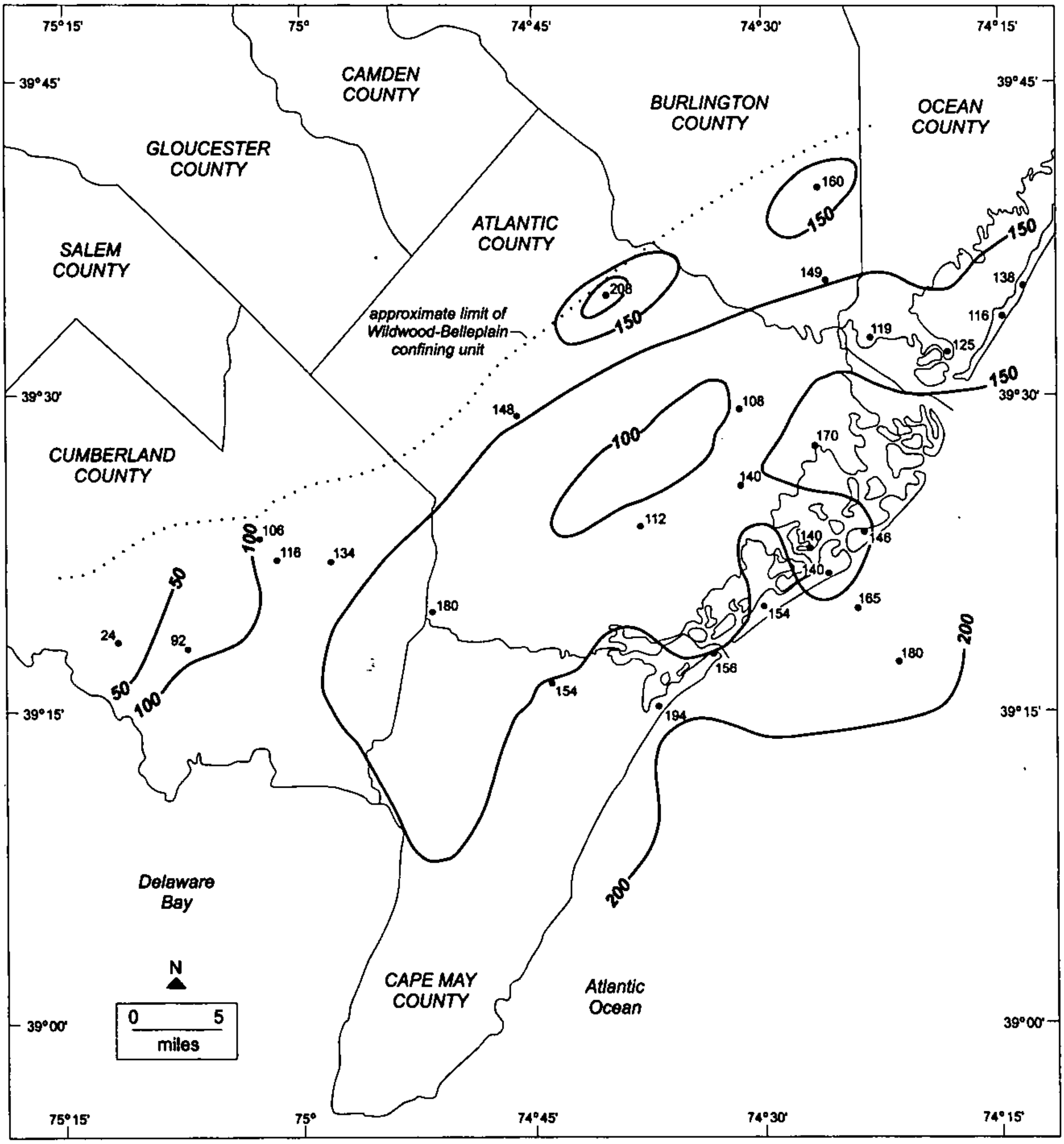

Figure 16.– Thickness of Atlantic City 800-foot sand, where confined by Wildwood-Belleplain confining unit, in feet. Contour interval 50 feet.

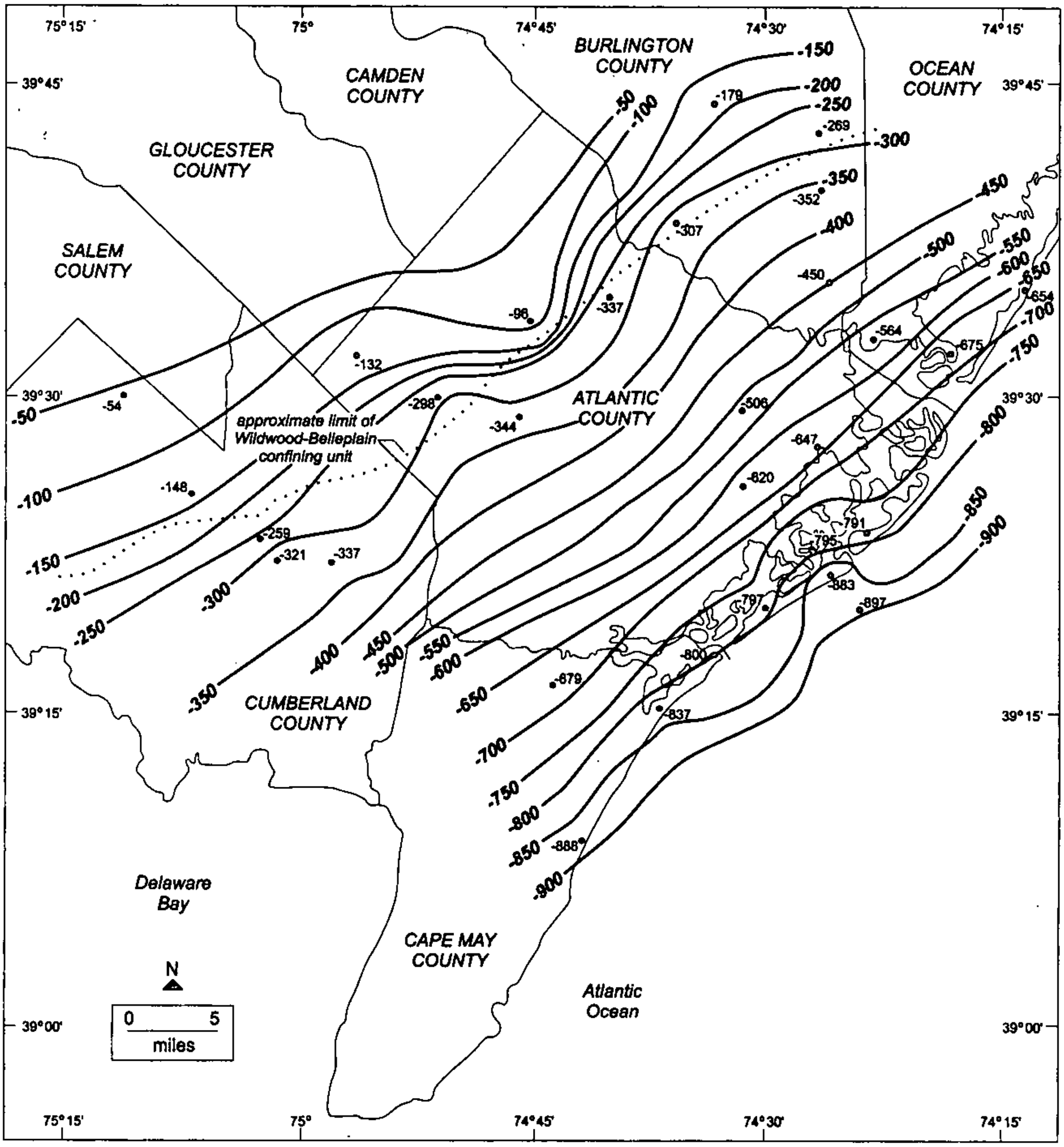

Figure 17.-- Elevation of top of composite confining bed, in feet below sea level. Contour interval 50 feet.

with the lower clay-silts and glauconitic sands of the lower member of the Kirkwood Formation which unconformably overlies glauconitic sand, silt-clay, and glauconitic quartz sand deposits of Eocene to Oligocene age.

The composite confining unit is as much as 100 feet thick and includes local sandy layers. At Atlantic City, it is 73 feet thick (Miller and others, 1994); about 20 miles updip, at the ACGS-4 borehole near Mays Landing, it is about the same thickness. It dips fairly uniformly to the south east at about 25 ft/mi. Along the coastline in Atlantic County, the top is about 850 feet below sea level (fig. 16).

Atlantic City 800-foot Sand

The Atlantic City 800-foot sand is the principal confined aquifer supplying water to Atlantic City, and points north along the barrier islands to Harvey Cedars (Ocean County), as well as south to Stone Harbor (Cape May County) (Zapecza, 1989). It consists of sands from the lower Kirkwood and Shiloh Marl members, and is informally subdivided in this report into: (1) a lower sand, (2) a leaky, relatively thin confining unit and (3) an upper sand. The lower sand overlies the composite confining unit, and corresponds to the upper quartz sand of the lower member of the Kirkwood Formation (or Kw1a sequence of Miller and Sugarman, 1995). The confining unit and the upper sand correspond to the Shiloh Marl Member of the Kirkwood Formation and the Kirkwood Kw1b sequence (fig. 3). Mullikin (1990) called it the Atlantic City confining unit. Aquifer testing in Atlantic City showed that it is leaky (Johnson, 1980). Zapecza (1989) cited unpublished evidence that significant amounts of water can pass from the upper to the lower sand.

The Atlantic City 800-foot sand is about 150 feet thick along the barrier islands in Atlantic County. At Atlantic City (fig. 3) the aquifer is about 140 feet thick and consists of a lower sand (808-741 feet below land surface) and an upper sand (733-666 feet below surface) separated by a thin bed of clay-silt (741-733 feet below land surface) which is probably too thin at this site to act as a leaky confining unit. The upper sand unit of the Atlantic City 800-foot sand ranges in thickness from 10 to 105 feet, and generally contains finer sand and more interbedded clay and silt than does the lower sand unit. Most of the production wells along the Atlantic County coast withdraw water from the lower sand unit; in Ocean County the production wells are typically in the upper sand. At Atlantic City the lower sand is generally a gray massive medium to coarse quartz sand, with some laminated layers of fine to medium sand at the base, and occasional thin interbeds of clay. The upper sand unit at Atlantic City is more variable; it includes massive clayey sand with shell hash, pebbly coarse sand, and micaceous fine to medium sand interbedded with silty clay.

Approximately 5 miles offshore of Atlantic City at the U. S. Geological Survey marine observation well 2 (well number 15, table 2), the Atlantic City 800-foot sand is 180 ft thick (figs. 9, 16; table 2). The lower sand is much thicker here.

Updip, at the ACGS-4 borehole (well number 18), the Atlantic City 800-foot sand consists primarily of the upper sand (90 feet) of the Shiloh Marl Member, and about 24 feet of the upper part of the lower Kirkwood member (fig. 10). The lower clay-silt of the Shiloh Marl member, which forms the leaky confining unit, is about 40 feet thick at the ACGS-4 borehole, significantly thicker than at Atlantic City.

Wildwood-Belleplain Confining Unit

Between the Atlantic City 800-foot sand and the Kirkwood-Cohansey aquifer system is a massive clay-silt bed that is typically rich in diatoms. Referred to by Woolman (1892, 1895) as the "Great Diatom Bed," it is also the confining bed of Zapecza (1989), composed largely of the Wildwood Member of the Kirkwood Formation. The bed is here called the Wildwood-Belleplain confining unit because the lower part of the Belleplain Member of the Kirkwood Formation forms the upper part of this unit (fig. 3) in southeastern Atlantic and Cumberland counties (Sugarman and others, 1993).

Midway within the Wildwood-Belleplain confining unit at Atlantic City is the Rio Grande water-bearing zone (fig. 3). This was first recognized in Atlantic City as a 554-foot-deep water-bearing sand (Woolman, 1889, p. 90), but is now used for water supply only in southern Cape May County (Zapecza, 1989). It typically is a gray sand with some interbedded silt and clay, and ranges in thickness from 10 to 105 feet. Throughout the coastal areas of Atlantic and Ocean Counties it is generally less than 40 feet thick. Its silt content increases north and west of Atlantic City. The Rio Grande water-bearing zone is thickest at well 28 in Upper Township, Cape May County, where it is 105 feet. As depicted in cross section E-E′ (fig. 11), where the Rio Grande water-bearing zone is thick, it effectively divides the Wildwood-Belleplain confining unit into an upper and lower unit.

The lithology of the confining unit is similar above and below the Rio Grande water-bearing zone. It is a dark-colored, diatomaceous clay-silt. Thin interbeds of sand occur throughout the unit (Andrews, 1987), but are especially common in the Cape May area (Zapecza, 1989). The thickness of the confining bed increases downdip from 61 feet in the vicinity of Mays Landing to about 260 feet near Atlantic City (Miller and others, 1994). At the ACGS-4 borehole near Mays Landing, the Wildwood-Belleplain confining bed is an olive-gray to dusky-yellowish-brown clayey silt and fine sand, laminated to massively bedded, containing diatoms, small pieces of wood, and mica (Owens and others, 1988). At Atlantic City, the lower part of the confining unit below the Rio Grande water-bearing zone is a dark gray, micaceous clay-silt and fine sand, with scattered intervals of shells. Above the Rio Grande, the upper confining unit is a massive bioturbated to laminated clay-silt, commonly with shells (Miller and others, 1994).

Elevations of the top and base of the Wildwood-Belleplain confining unit are shown in figures 13 and 14, and given in table 2. In the study area, the top of the Wildwood-Belleplain confining unit updip is about -100 feet (relative to sea level); along the shoreline, downdip, the top of the unit is approximately -390 feet. Correspondingly, the base of the Wildwood-Belleplain confining unit at wells located updip in the area is at about -130 to -160 feet, whereas downdip along the coast the base is at -650 feet.

The thickness of the Wildwood-Belleplain confining unit (including the Rio Grande water-bearing zone) is shown in figure 15. In general, the unit thickens toward the southeast. Along the coast of Atlantic County, its thickness is fairly constant at about 270 feet. It is over 400 feet thick in northern Cape May. The updip limit of the Wildwood-Belleplain confining unit is shown in figure 1; this areal representation is based on interpretations shown on figures 7-11. The termination of this confining unit is based on lithologic mapping and correlation, and requires hydrologic testing to verify. Where the Wildwood-Belleplain confining unit is not present, the Kirkwood-Cohansey aquifer system may also contain lithologic equivalents of the Atlantic City 800-foot sand (figs. 7, 8, 10 and 11). On section A-A' (fig. 7), the Wildwood-Belleplain confining unit loses its competency between wells 2 and 3 in Bass River Township, resulting in a thick Kirkwood-Cohansey aquifer system at the U.S.G.S. Oswego Lake observation well 1. On section D-D' (fig 9) through southern Atlantic County, the Wildwood-Belleplain confining unit is thickest (290 feet) at the Egg Harbor Township High School. A little more than 10 miles updip at the U.S. Geological Survey ACGS-4 well, the confining unit is 61 feet thick, and is interpreted to pinch out just updip from this site. At well 17 in Hamilton Township, the Kirkwood-Cohansey Aquifer system is 390 feet thick, this increased thickness due to the termination of the confining unit, and the interconnection of the Kirkwood-Cohansey and Atlantic City 800-foot sand.

Kirkwood-Cohansey aquifer system

The Kirkwood-Cohansey aquifer system is predominantly unconfined and consists of the upper part of the Belleplain Member of the Kirkwood and all of the Cohansey Formation. Where the Wildwood-Belleplain confining unit is absent, this aquifer system also includes the lower Kirkwood and Shiloh Marl Members of the Kirkwood Formation. The Kirkwood-Cohansey aquifer system can also include the Beacon Hill, Bridgeton, and Cape May Formations (Rhodehamel, 1973). It is confined beneath fine-grained, post-Cohansey, estuarine deposits throughout much of Cape May County (Gill, 1962) and locally along the coast, as at Leeds Point, Atlantic County, and Barnegat, Ocean County. Along the coast and for several miles inland, the base of the Kirkwood-Cohansey aquifer system overlies the top of the Wildwood-Belleplain confining unit (for example, figs. 8 and 11). The Kirkwood-Cohansey aquifer system typically contains sandy beds at the top of the Belleplain Member and coarser quartz sand in the Cohansey Formation. Within the Cohansey Formation local clay beds, some of them reaching several tens of feet thick, create perched water tables and semi-confined conditions (Rhodehamel, 1973).

In the western part of the study area, confining units within and above the Atlantic City 800-foot sand pinch out, become sandy, or are truncated at the unconformity at the base of the Cohansey Formation. West of this, the Kirkwood-Cohansey aquifer system extends downward to the top of the composite confining unit (figs. 7, 8, 10 and 11).

SUMMARY AND CONCLUSIONS

The Kirkwood Formation of the New Jersey Coastal Plain consists of four major hydrostratigraphic units based on lithologic composition and permeability. From bottom to top these are: (1) the composite confining unit, which is predominantly the lower part of the lower member of the Kirkwood Formation in this study, (2) the Atlantic City 800-foot sand, which informally consists of a lower sand, a middle leaky confining unit, and an upper sand, (3) the Wildwood-Belleplain confining unit overlying the Atlantic City 800-foot sand, which includes the Rio Grande water-bearing zone, used for water supply in parts of Cape May and Cumberland Counties and, 4) The Kirkwood-Cohansey aquifer system, which includes several overlying post-Miocene fluvial formations within the study area. The Kirkwood-Cohansey aquifer system is predominantly under water-table conditions, but locally includes perched and semiconfined zones.

The confining unit overlying the Atlantic City 800-foot sand may pinch out to the west or be truncated at the unconformity between the Kirkwood and Cohansey Formations. Because of this, the Kirkwood-Cohansey aquifer system extends to the top of the composite confining unit in the western part of the study area.

Table 1.-- Well records used in study.

Well	Municipality, County	Well Permit No.	Location		Name/Owner	Elevation (ft)	Depth (ft)	Log Type[1]
			Latitude	Longitude				
01	Washington Township, Burlington County	--	39°43'05"N	74°33'57"W	State of New Jersey (Mullica 13D)	41	302	G
02	Bass River Township, Burlington County	32-436	39°42'08"N	74°26'45"W	U.S. Geological Survey (Oswego Lake Obs. Well 1)	97	600	G
03	Bass River Township, Burlington County	32-10890	39°40'07"N	74°26'30"W	U.S. Geological Survey	68	540	G
04	Tuckerton Borough, Ocean County	32-22508	39°36'10"N	74°20'31"W	Tuckerton Borough	10	503	G
05	Beach Haven Borough, Ocean County	53-31	39°33'43"N	74°14'30"W	Beach Haven Borough	6	656	G
06	Hammonton Town, Atlantic County	51-140	39°37'59"N	74°48'24"W	Board of Water Commissoners	90	245	G
07	Mullica Township, Atlantic County	32-10935	39°35'07"N	74°40'40"W	Mullica Township Landfill	95	540	G
08	Galloway Township, Atlantic County	36-4982	39°29'33"N	74°31'30"W	Stockton State College	40	680	E
09	Galloway Township, Atlantic County	36-294	39°27'53"N	74°27'01"W	U.S. Geological Survey	27	1002	E
10	Brigantine City, Atlantic County	56-12	39°23'30"N	74°23'48"W	Brigantine Borough	9	840	G
11	Egg Harbor Township, Atlantic County	36-454	39°26'22"N	74°32'12"W	Atlantic City Water Department	20	691	E
12	Atlantic City, Atlantic County	56-65	39°22'47"N	74°27'13"W	U.S. Department of Energy	5	1004	G
13	Atlantic City, Atlantic County	36-1084	39°21'25"N	74°26'04"W	Bally's Park Place	7	884	G
14	Atlantic City, Atlantic County	36-5615	39°19'55"N	74°25'07"W	U.S. Geological Survey (Marine Obs. Well 1)	-32	931	G
15	Atlantic City, Atlantic County	36-5972	39°17'26"N	74°22'21"W	U.S. Geological Survey (Marine Obs. Well 2)	-43	1025	G
16	Buena Borough, Atlantic County	35-4559	39°31'48"N	74°56'17"W	Buena Borough MUA	118	474	G
17	Hamilton Township, Atlantic County	35-4656	39°29'02"N	74°50'51"W	U.S. Geological Survey	92	577	G
18	Hamilton Township, Atlantic County	35-4274	39°29'33"N	74°46'04"W	U.S. Geolgical Survey (ACGS-4)	40	945	G
19	Hamilton Township, Atlantic County	36-391	39°27'09"N	74°44'39"W	Hamilton Township MUA	92	577	E
20	Egg Harbor Township, Atlantic County	36-5091	39°23'44"N	74°37'49"W	Egg Harbor Township High School	50	678	G
21	Margate City, Atlantic County	36-10548	39°20'17"N	74°30'02"W	U.S. Geological Survey	5	1055	G
22	Upper Deerfield Township, Cumberland County	35-4055	39°30'05"N	75°10'57"W	Upper Deerfield Township	110	730	G
23	Millville City, Cumberland County	35-1196	39°25'26"N	75°06'43"W	Cumberland County Planning Board	80	560	G
24	Millville City, Cumberland County	35-841	39°23'31"N	75°02'25"W	City of Millville	7	280	G
25	Millville City, Cumberland County	35-842	39°22'20"N	75°01'12"W	City of Millville	20	738	G
26	Millville City, Cumberland County	35-2569	39°22'16"N	74°58'28"W	Atlantic City Electric Company	49	460	G
27	Estell Manor City, Atlantic County	35-4903	39°19'46"N	74°51'25"W	N.J. Geological Survey	40	600	G
28	Upper Township, Cape May County	37-01340	39°16'21"N	74°43'35"W	U.S. Geological Survey	15	740	G
29	Upper Township, Cape May County	36-13154	39°11'51"N	74°39'28"W	N.J. American Water Company	5	870	G
30	Little Egg Harbor Township, Ocean County	36-05251	39°31'15"N	74°19'10"W	N.J. Department of Environmental Protection	5	1012	G
31	Longport Borough, Atlantic County	56-80	39°18'21"N	74°32'08"W	Longport Water Department	6	803	G
32	Ocean City, Cape May County	36-314	39°17'26"N	74°33'52"W	Ocean City Water Service	10	922	G
33	Ocean City, Cape May County	36-412	39°15'00"N	74°36'45"W	Ocean City Water Company	7	902	E
34	Sea Isle City, Cape May County	36-10378	39°07'33"N	74°42'31"W	Sea Isle City No. 6	10	921	G
35	Avalon Borough, Cape May County	56-93	39°06'42"N	74°42'48"W	Wonder Ice Company	5	898	G
36	Long Beach Township, Ocean County	33-13836	39°37'24"N	74°11'50"W	Long Beach Water System	5	616	G
37	Long Beach Township, Ocean County	33-1275	39°35'10"N	74°13'27"W	Long Beach Water Company	8	697	G
38	Washington Township, Burlington County	32-1525-12D	39°38'32"N	74°36'08"W	State of New Jersey	51	370	G
39	Bass River Township, Burlington County	32-21761	39°36'42"N	74°26'12"W	State of New Jersey (Bass River)	28	1936	G
40	Little Egg Harbor Township, Atlantic County	32-609	39°32'53"N	74°23'08"W	Mystic Island Water Company	5	607	G
41	Hamilton Township, Atlantic County	32-00173	39°33'33"N	74°44'26"W	Scholler Brothers Chemical Company	90	238	G
42	Lawrence Township, Cumberland County	34-852	39°18'29"N	75°12'08"W	Cumberland County Planning Board	10	570	G
43	Downe Township, Cumberland County	35-849	39°18'26"N	75°06'58"W	Pennsylvania Glass Sand Company	55	413	G
44	Maurice River Township, Cumberland County	35-4640	39°15'18"N	74°53'55"W	Belleplain State Forest	40	600	G
45	Middle Township, Cape May County	55-81	39°07'04"N	74°47'50"W	Eastern Shore Nursing Home	15	654	G
46	Middle Township, Cape May County	37-236	39°05'25"N	74°48'51"W	Neptunus Water Company	17	807	G
47	Avalon Borough, Cape May County	37-280	39°04'20"N	74°44'35"W	Avalon Water Company	5	905	G

[1] L- lithologic log; G- gamma-ray log; E- electric log

Table 2.-- Altitude of top and base, and thickness of hydrostratigraphic units (in feet above or below sea level).

Well	Kirkwood-Cohansey Aquifer System			Wildwood-Belleplain Confining Unit			Atlantic City 800-foot Sand			Composite Confining Unit		
	Top	Base	Thickness	Top	Base	Thickness	Top	Base	Thickness	Top	Base	Thickness
01	41	-179	220	--	--	--	--	--	--	-179	--	--
02	97	-269	366	--	--	--	--	--	--	-269	-369	100
03	68	-104	172	-104	-192	88	-192	-352	160	-352	-444	92
04	10	-132	142	-132	-396	264	-396	>-494	>100	--	--	--
05	6	-266	272	-266	-554	288	-554	~-670	116	--	--	--
06	90	-128	218	--	--	--	--	--	--	--	--	--
07	95	-87	182	-87	-129	42	-129	-337	208	-337	--	--
08	40	-194	234	-194	-398	204	-398	-506	108	-506	--	--
09	27	-197	224	-197	-477	280	-477	-647	170	-647	--	--
10	9	-379	388	-379	-645	266	-645	-791	146	-791	--	--
11	20	-200	220	-200	-480	280	-480	-620	140	-620	--	--
12	5	-321	326	-321	-655	334	-655	-795	140	-795	-915	120
13	7	-393	400	-393	-693	300	-693	-833	140	-833	--	--
14	-32	-470	438	-470	-732	262	-732	-897	165	-897	--	--
15	-43	-580	537	-580	-870	290	-870	-1050	180	--	--	--
16	118	-132	250	--	--	--	--	--	--	-132	-272	140
17	92	-298	390	--	--	--	--	--	--	-298	-428	130
18	40	-135	175	-135	-196	61	-196	-344	148	-344	-442	120
19	20	-154	174	-154	-304	150	-304	--	--	--	--	--
20	50	-160	210	-160	-450	290	-450	-562	112	--	--	--
21	5	-353	358	-353	-643	290	-643	-797	154	-797	-919	122
22	110	-54	164	--	--	--	--	--	--	-54	-170	116
23	80	-148	228	--	--	--	--	--	--	-148	-258	110
24	7	-109	116	-109	-153	44	-153	-259	106	-259	--	--
25	20	-148	168	-148	-205	57	-205	-321	116	-321	-677	356
26	49	-147	196	-147	-203	56	-203	-337	134	-337	--	--
27	40	-104	144	-104	-322	218	-322	-502	180	--	--	--
28	15	-239	254	-239	-525	286	-525	-679	154	-679	--	--
29	5	-313	318	-313	-677	364	-677	>-857	>174	--	--	--
30	5	-197	202	-197	-550	353	-550	-675	125	-675	-803	128
31	6	-362	368	-362	-642	280	-642	--	--	--	--	--
32	10	-384	394	-384	-644	260	-644	-800	156	-800	--	--
33	7	-293	300	-293	-643	350	-643	-837	194	-837	--	--
34	10	-316	326	-316	-716	400	-716	~-888	~172	~-888	--	--
35	5	-345	350	-345	-749	404	-749	--	--	--	--	--
36	5	-225	230	-225	-513	288	-513	--	--	--	--	--
37	8	-224	232	-224	-516	292	-516	-654	138	-654	--	--
38	51	-307	358	--	--	--	--	--	--	-307	--	--
39	28	-106	134	-106	-301	195	-301	-450	149	-450	--	--
40	5	-189	194	-189	-445	256	-445	-564	119	-564	--	--
41	90	-96	186	--	--	--	--	--	--	-96	--	--
42	10	-90	100	-90	-238	148	-238	-262	24	-262	-340	78
43	55	-29	84	-29	-229	200	-229	-321?	92?	-321?	--	--
44	40	-146	186	-146	-378	232	-378	--	--	--	--	--
45	15	-241	256	-241	-625?	384?	--	--	--	--	--	--
46	17	-245	262	-245	-663	418	-663	--	>120	--	--	--
47	5	-367	372	-367	-795	428	-795	--	--	--	--	--

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