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GROUND-WATER HYDROLOGY OF THE RARITAN BAY AREA, NEW JERSEY: HYDROGEOLOGIC FRAMEWORK AND SIMULATION OF THE FRESHWATER/SALTWATER INTERFACE UNDER PREDEVELOPMENT CONDITIONS

by
Eric P. Declercq

A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science

in
Geological Sciences

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1986

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

Data from 64 wells was used to construct 9 hydrogeologic sections onshore in the Raritan Bay area, Middlesex and Monmouth counties, New Jersey. In conjunction with these data approximately 7.5 miles (12.1 km) of single-channel and 2.0 miles (3.2 km) of multi-channel marine seismic-reflection data were used to construct structure-contour maps extending the hydrogeologic framework out into Raritan Bay. Saltwater has intruded into the Potomac-Raritan-Magothy aquifer system at several localities south of the Bay. A two-dimensional finite-difference model was developed to simulate the predevelopment flow system; a "trimming" technique was adapted to the simulation to estimate the position of the freshwater-saltwater interface in the upper aquifer of the system. The interface-locating technique is used to test the sensitivity of the interface location to proposed hydrologic concepts including hydrogeologic framework, leakage, and historical water-table conditions.

Five major hydrogeologic units of the Potomac-Raritan-Magothy aquifer system are found in the Raritan Bay area: a lower confining unit, a middle aquifer, a confining unit between the middle and upper aquifers, an upper aquifer, and the Woodbury-Merchantville confining unit. Interpretation of marine seismic data concludes that these units are continuous under the Bay. The lower confining unit, middle aquifer, and middle confining unit are evident across the Bay on Staten Island, New York; however, the upper aquifer and Woodbury-Merchantville confining unit crop out under the bay suggesting a possible cause for saltwater intrusion.

Results of the cross-sectional model developed along a flow line in the predevelopment flow system suggests the presence of saltwater in the upper aquifer. Leakance between the aquifer and confining unit is the major factor regarding the position of the interface. The interface is also sensitive to water-table gradient; however, this factor is not as critical as leakance. Boundary conditions are tested, including use of the general-head boundary package. Results using this package prove to be the most reasonable and further research should concentrate on simulations of this design.

HYDROGEOLOGIC INVESTIGATION OF THE RARITAN BAY AREA, MIDDLESEX-MONMOUTH COUNTIES, NEW JERSEY

by

Eric P. Declercq

INTRODUCTION

Saltwater has intruded into the Potomac-Raritan-Magothy (PRM) aquifer system at several localities south of Raritan Bay in northern Middlesex and Monmouth Counties, New Jersey (Schaefer and Walker, 1981, p. 1; and Schaefer, 1983, p. 4). Increased ground-water withdrawals in these areas in recent years have caused the heads in the aquifer system to decline, and have resulted in a reversal of the ground-water flow direction. This reversal has allowed saltwater to encroach upon pumping centers in the area (Schaefer and Walker, 1981, p. 8). The U. S. Geological Survey (USGS), in cooperation with the New Jersey Department of Environmental Protection, is undertaking a comprehensive study of the area. One of the objectives of this study is to develop a ground-water flow and solute transport model. Models of these type require accurate representation of boundary and initial conditions. To properly represent these conditions, it is necessary to define the hydrogeologic framework of the area. Therefore, a comprehensive definition of the areal distribution of aquifers and confining units is necessary for more detailed modeling efforts.

Purpose and Scope

The purpose of this study is (1) to define the thickness and extent of the principal hydrogeologic units; and (2) to estimate the position of the freshwater-saltwater interface in the PRM aquifer system under predevelopment conditions.

A series of cross sections and structure-contour maps are used to illustrate the hydrogeologic framework in the area. The results are based primarily on the interpretation of 7.5 miles (12.1 km) of single-channel and 2.0 mi (miles) (3.2 km) of multi-channel marine seismic-reflection data, in conjunction with 66 borehole geophysical and lithologic logs. A computer model and a "trimming" technique are used to define possible locations of the saltwater interface under prepumping conditions. The interface-locating technique is used to test the sensitivity of the interface to proposed hydrologic concepts including hydrogeologic framework, leakage and historic water-table conditions.

Location of Study Area

The principal area of study covers approximately 320 mi^2 (828.8 km^2) in parts of Middlesex and Monmouth Counties (fig. 1). A large part of the study area lies beneath Raritan

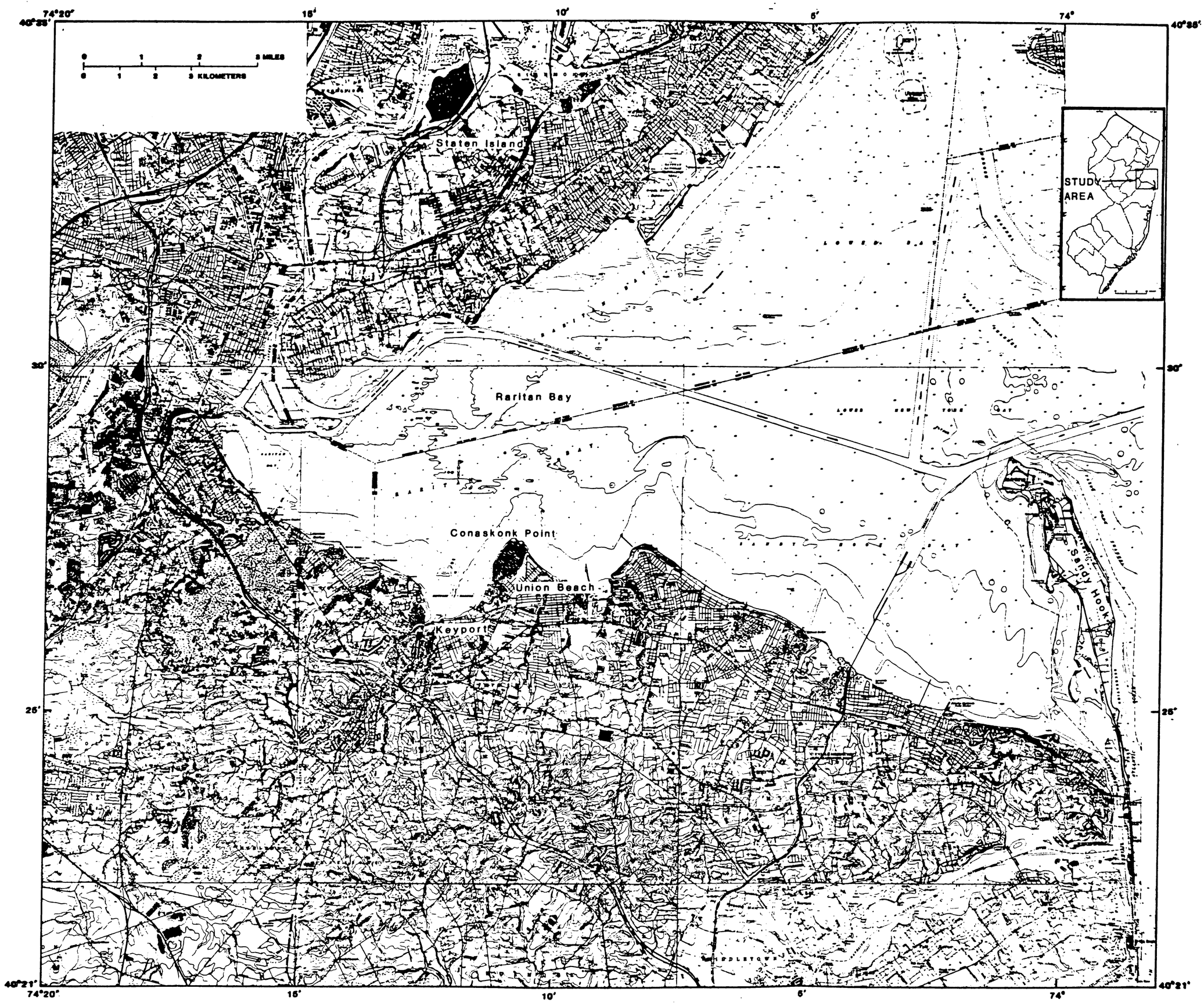


Figure 1.--Study area (Base from U.S. Geological Survey topographic quadrangle sheets. Topographic contour interval is 20 ft)

Bay. Water depths in the Bay are generally shallow (1-10 ft (feet)(0.3-3.0 meters)), and depths rarely exceed 20 ft (6.1 meters) in the channels. The remainder of the study area lies in the coastal plain where elevations seldom exceed 100 ft (30.5 meters) except in the southern part of the area and on Staten Island, New York.

Previous Investigations

Several studies have described the hydrogeologic framework of the Raritan Bay area. Barksdale and others (1943) discussed the principal aquifers in Middlesex County . Jablonski (1968) discussed the major aquifers in Monmouth County. Minard (1969) utilized several borings to describe the subsurface geology of the Sandy Hook, New Jersey 7 1/2 minute quadrangle. Gill and Farlekas (1976) present maps of structure-contours on the bedrock surface, the Potomac-Raritan-Magothy aquifer system, and the overlying confining unit. Farlekas (1979) presented a digital simulation of flow in the middle aquifer. Zapecza (1984) discusses the hydrogeologic framework of the entire New Jersey Coastal Plain. However, due to the general lack of data, only one attempt has been made previously to interpret the geologic framework of the area under Raritan Bay. C. P. Berkey (1955) utilized several borings in the Bay in an attempt to extend the Coastal Plain stratigraphy into the Bay.

Well-Numbering System

The wells cited in this report are numbered according to the system used by the U. S. Geological Survey in New Jersey. Each well has a unique identification number that consists of a two-digit county code followed by a sequence number. The New Jersey county codes used in this report are 23 for Middlesex County, New Jersey, 25 for Monmouth County, New Jersey, and 85 for Staten Island, New York.

HYDROGEOLOGY

Geologic Framework

The New Jersey Coastal Plain consists of a seaward-dipping wedge of unconsolidated Cretaceous to Holocene sediments. Layers of gravel, sand, silt and clay lie unconformably upon Precambrian and early Paleozoic bedrock (Schaefer, 1983, p. 8). These sediments strike from northeast to southwest and dip the southeast from 10 to 60 ft/mi (1.9 to 11.4 meters/kilometer). The sediments of the Coastal Plain were deposited under marine, estuarine, fluvial, and fluvial-deltaic conditions (Farlekas, 1979, p. 5). Quaternary deposits are uncommon and, where present, are generally flat-lying (Schaefer, 1983, p. 8).

The major geologic units and their relation to hydrogeologic units in the study area are shown in table 1.

Table 1.--Geologic and hydrogeologic units in the study area.

System	Geologic units	Hydrogeologic units	
Quaternary	Alluvial deposits	Undifferentiated	
Tertiary	Pensauken Formation Bridgeton Formation Beacon Hill Gravel	Undifferentiated	
	Cohansey Sand	Kirkwood-Cohansey aquifer system	
	Kirkwood Formation		
	Vincentown Formation	Vincentown aquifer	
	Hornerstown Sand	Composite confining bed	
Cretaceous	Tinton Sand		
	Red Bank Sand	Red Bank aquifer	
	Navesink Formation		
	Mount Laurel Sand	Wenonah-Mount Laurel aquifer	
	Wenonah Formation		
	Marshalltown Formation	Marshalltown-Wenonah confining bed	
	Englishtown Formation	Englishtown aquifer	
	Woodbury Clay	Merchantville-Woodbury confining bed	
	Merchantville Formation		
	Formation: Cliffwood beds		
	Morgan beds		
	Magothy formation: Amboy Stoneware clay member		
	Old Bridge sand member	Upper aquifer	Potomac-Raritan-Magothy aquifer system 2
	Raritan formation: South Amboy Fire clay member		
	Sayreville sand member		
	Woodbridge clay member	Confining unit	
	Farrington sand member	Middle aquifer	
	Fire clay member	Confining unit	
	Potomac Group		
Jurassic and Triassic	Newark Supergroup and diabase intrusives		
Lower Paleozoic and Precambrian	Igneous and metamorphic rocks		

1 Modified after Zapecza, 1984, table 2.
2 In order to maintain consistent terminology, the aquifer-system name commonly used throughout New Jersey is used in this report. However, the lower aquifer in not mapable within the study area.

The Potomac Group rests on a basement complex composed of sedimentary and igneous rocks of pre-Paleozoic age (Farlekas, 1979, p. 5). The Potomac Group sediments are considered to be chiefly non-marine, composed of meandering-stream deposits and large amounts of interfluvial silt and clay along with stacked braided-stream deposits (Perry and others, 1975, p. 1543). No consistent upper and lower boundaries of individual formations within the Potomac Group can be established (Owens and others, 1977, p.7).

In ascending order the Raritan Formation includes five members: the Raritan Fire Clay, the Farrington Sand Member, the Woodbridge Clay , the Sayreville Sand Member and the South Amboy Fire Clay . The Raritan Formation is considered to be chiefly of marine origin in coastal parts of New Jersey, except in the Raritan Bay area where non-marine characteristics are dominant (Perry and others, 1975, p. 1535).

The Raritan Fire Clay and South Amboy Fire Clay Members generally consists of light blue to black sandy clay and contain occasional layers of white or red clay.

The Farrington Sand Member consists of clean, angular quartz sand with traces of lignite and pyrite (Berkey, 1955, p. 5) and may contain local clay stringers (Barksdale and others, 1943, p. 105). Perry and others (1975, p. 1543) noted the occurrence of foraminifera, ostracods, bivalves, and gastropod fragments, and inferred that these sands were

deposited in a subaqueous deltaic environment near the outcrop area and in a more marine environment farther downdip.

The Woodbridge Clay Member consists of thick, dark gray, micaceous clay and silt with lignite and pyrite. The basal units are comprised of a hard, tough, "fire clay" (Barksdale and others, 1943, p. 103). The member is massive, yet locally is laminated with light sand and dark clayey silt. Kaolinite-illite is the dominant clay mineral assemblage (Owens and others, 1977, p. 16). This unit is believed to be of estuarine or shallow marine origin (Perry and others, 1975, p.1543). Pollen studies indicate that the Woodbridge Clay member is present as far north as the northern shores of Long Island, New York (Farlekas, 1979, p. 6). Pollen data on sediments from Long Island and on clay from the Sayreville area are also correlative, indicating a continuous unit (Wolfe and Pakiser, 1971, p. B38). The Sayreville Sand Member consists of medium- to fine-grained sand with local thicknesses of 35 to 40 feet (10.7 to 12.2 meters) (Farlekas, 1979, p. 8). These sands generally are light colored and cross-stratified and may be interstratified with thin to thick beds of light to dark clay. The unit consists principally of quartz sand with trace amounts of mica and feldspar (Owens and others, 1977, p. 16).

The Magothy Formation includes the Old Bridge Sand Member, the Amboy Stoneware Clay and the Morgan and Cliffwood Beds. The Magothy Formation is composed of coarse-grained beach sand and associated marine and lagoonal sediments; these

sediments unconformably overlie the Raritan Formation. These units thicken to the north, and they are nearly 980 feet (300 meters) thick under Long Island, New York (Perry and others, 1975, p. 1535).

The Old Bridge Sand Member consists chiefly of a light-colored medium- grained sand which contains interbeds of light- to dark-colored clayey silt and lenses of coarse sand. The member varies in texture, composition, and thickness within short distances. Its deposition is attributed to a high- energy environment, and possibly represents channel and bar deposits (Owens and Sohl, 1969, p. 239). The Old Bridge contains lenses of loose, clean quartz sand which are generally angular and coarse-grained (Berkey, 1955, p. 5). Locally micaceous with traces of lignite, the Old Bridge is often cross-stratified (Owens and others, 1977, p. 20).

The Amboy Stoneware Clay Member is a black, more or less sandy clay with some lignite and pyrite. Locally, it may be light blue to white with lenses of fine-grained quartz sand and specks of pyrite (Berkey, C. P. , 1955, p. 5). The Morgan and Cliffwood Beds consist generally of interstratified light- to dark-gray, thin clay layers, and massive to poorly cross-stratified light-colored sand and silt. The clay mineral assemblage is predominantly kaolinite-illite and permeabilities are considered to be quite low (Owens and others, 1977, pp. 22-25; Zapecza, 1984, p. 19). The Morgan beds are thin bedded, intercalated clay and silt and light-

colored sand that grade laterally into light-colored cross-stratified carbonaceous sand, typical of overbank deposits . The Cliffwood beds are cross stratified sand with interbedded carbonaceous material. Deposition is attributed to nearshore marine activity (Owens and Sohl, 1969, p. 242).

The Merchantville Formation consists of thin bedded, dark-gray , clayey quartz silt and dark greenish-gray quartz glauconite sand. The lowermost beds commonly contain occasional pebbles and lignite. The clay mineral assemblage is predominantly kaolinite-illite although appreciable quantities of montmorillonite and other expandable clays are often present (Owens and others, 1977, p. 29). The Merchantville is of marine deltaic origin and represents a marine transgression in the Raritan Embayment (Owens and others, 1975, p. 27).

The Woodbury Clay directly overlies the Merchantville Formation. Owens and others (1977, p. 31) propose a gradational contact with the Merchantville Formation, chosen where glauconite sand becomes a minor constituent. The Woodbury is a thick, massive, very clayey silt to silty clay with abundant mica (Zapecza, 1984, p. 19). Kaolinite is the major clay mineral present and montmorillonite and illite are present in
nearly equal amounts (Owens and others, 1977, p. 33). The Woodbury Clay was deposited on the inner shelf and contains a well-preserved calcareous marine fauna (Owens and Sohl, 1969, p. 243).

Major Aquifers and Confining Units

The Potomac-Raritan-Magothy aquifer system is the most important source of ground water in the New Jersey Coastal Plain (Schaefer and Walker, 1981, p. 4). In Middlesex County and Monmouth County withdrawals in 1980 averaged approximately 71.2 million gallons/day (0.77 cubic meters per second) (Vowinkel, 1984, p. 19). Three major aquifers have been delineated within the aquifer system: lower, middle, and upper aquifers (Zapecza, 1984, p. 14). Only the middle and upper aquifers are present in the study area. The middle aquifer consists chiefly of the Farrington Sand Member of the Raritan Formation and the upper aquifer consists chiefly of the Old Bridge Sand Member of the Magothy Formation. In the study area the Sayreville Sand Member and the Old Bridge Sand Member collectively form the upper aquifer. Major confining units separate the middle and upper aquifers.

In the following sections, each of the major aquifers and confining units are discussed in a time-stratigraphic sequence from oldest to youngest. Definition of hydrogeologic units is necessary because often a hydrogeologic unit boundary will not coincide with the recognized stratigraphic boundary. Aquifers often consist of more than one member of a formation, and a member that acts as an aquifer in one area may function as a confining unit bed in another (Zapecza, 1984, p. 9).

Lower Confining Unit

The lower confining unit is generally less than 50 ft 15.2 meters) thick; yet in the study area it may reach a thickness of 86 ft (25.9 meters). The thickness is not uniform due to lensing of sand, clay and silt (Zapecza, 1984, p. 16). Near the Fall Line in Middlesex County the lower confining unit consists of the Raritan Fire Clay and the crystalline basement. The thickness of the clay ranges from 0-35 feet (0-10.7 meters) (Farlekas, 1979, p. 7). The lower confining unit is referred to downdip as the layer of clay immediately below the Farrington Sand Member that is greater than 20 ft (6.1 meters) thick (Farlekas, 1979, p. 7).

Middle Aquifer

The middle aquifer corresponds chiefly to the Farrington Sand Member of the Raritan Formation. The Farrington has been referred to in earlier reports as the #1 sand (Barksdale, 1943, p. 66). In the northwest part of the study area, thick glacial deposits of gravel and sand overlie the Farrington, and are considered to be part of this aquifer (Farlekas, 1979, pp. 8-9). The thickness of the middle aquifer ranges from 50 to 100 ft (15.2 to 30.5 meters) in the study area (Farlekas, 1979, p. 11). Sand content varies from 72 percent near the outcrop area to 80 percent in the Keyport-Union Beach area (fig.1) (Zapecza, 1984, plate 8). The

Farrington Sand crops out in Staten Island, New York, where it is covered by thick accumulations of glacial ground moraine and terminal moraine (Farlekas, 1979, p. 8). The Farrington Sand also crops out in the northwest part of the study area (fig. 9).

Middle Confining Unit

The Woodbridge Clay Member of the Raritan Formation is the principal confining unit between the middle and upper aquifer in the study area. Its thickness ranges from 50 ft (15.2 meters) to 160 ft (48.8 meters) (Zapecza, 1984, plate 9). Locally, the clay facies of the overlying Sayreville Sand Member or South Amboy Fire Clay are included as part of this unit (Farlekas, 1979, p. 22).

Upper Aquifer

The upper aquifer is the most extensive unit of the Potomac-Raritan-Magothy system (Zapecza, 1984, p. 18). For the most part, the Old Bridge Sand Member of the Magothy Formation forms the upper aquifer. Yet, locally, where the South Amboy Fire Clay Member is thin or absent, the Sayreville Sand Member is also included as part of the upper aquifer (Zapecza, 1984, p. 22).

The upper aquifer increases in thickness from 50 feet (15.2 meters) near the outcrop area to 150 feet (45.7 meters) downdip near Sandy Hook, New Jersey (Zapecza, 1984, plate 11).

It has been suggested that near Sandy Hook (fig. 1), the interbedded sand, clay and silt of the Cliffwood and Morgan Beds are included in the upper aquifer (Perry and others, 1975, p. 1543). However, recent studies consider the uppermost limit of the upper aquifer to be the top of the Old Bridge Sand Member of the Magothy Formation (Zapecza, 1984).

Woodbury-Merchantville Confining Unit

The Woodbury-Merchantville confining unit includes both the Merchantville Formation and the Woodbury Clay. This unit is the most areally extensive confining unit in the Potomac-Raritan-Magothy aquifer system, and it separates the upper aquifer from the overlying Englishtown aquifer (Zapecza, 1984, p. 19). The Woodbury-Merchantville confining unit crops out in the Keyport-Union Beach area (fig. 1). Its thickness ranges from approximately 200 ft (61 meters) near the outcrop area to 350 ft (106.7 meters) near Sandy Hook (Zapecza, 1984, p. 12). In the downdip region, the upper most units of the Magothy Formation (i.e. the Amboy Stoneware Clay, and the Morgan and Cliffwood Beds) interfinger with and are considered to be part of the upper confining unit (Perry and others, 1975, p. 1540).

METHOD OF INVESTIGATION

Terrestrial Framework

The subsurface mapping technique on which part of this report is based incorporates lithologic and geophysical data to define the hydrogeologic framework. Limited geophysical data for some sites in the study area necessitated the use of lithologic descriptions of drill cuttings. Where both lithologic and geophysical logs are available, good correlation exists between the two.

Lithologic and geophysical data for 64 sites were reviewed (Appendices 1 and 2). Of these, data on 41 sites are used to construct the hydrogeologic cross sections. All of the well logs are used to construct structure-contour maps of the surfaces of the major aquifers and confining units in the study area. Selection of well records was based on quality of data, depth and particularly location. Fifteen of the wells have electric and natural gamma-ray logs, which are considered more reliable than lithologic logs.

The electric logs are dual-track logs that include a spontaneous potential log and a single-point resistance log. Spontaneous potential logs record changes in potential with depth. The log is essentially a graphic presentation of the differences in voltage that develop at the contacts between the borehole fluid, the formation, and the water in the aquifer. The single-point log is related directly to the

formation water and lithology (Zapecza, 1984, p. 9). Clay and silt are less resistive than gravel and sand. Also, factors such as salinity of the formation water or borehole fluid and diameter of the borehole affect the character of the electric logs and must be considered during interpretation (Zapecza, 1984, p. 11).

The natural-gamma log measures the amount of natural-gamma radiation from the surrounding sediments and is independent of the composition of the borehole fluid. Greater ability for ion exchange in clay and silt tends to concentrate radioisotopes in units with high percentages of these materials. In addition, feldspars and micas (minerals present in clay and silt) contain gamma-emitting potassium-40 and emit particles (Keys and MacCary, 1971, p. 65). Therefore, in the Coastal Plain environment, the most important application of natural-gamma logging is in identifying clayey or silty sediments. Low values of gamma radiation are interpreted to represent sandy units. If substantial thickness and continuity is observed, these sandy units are mapped as aquifers.

Marine Framework

Multi-channel and single-channel continuous marine seismic reflection data are used to determine the hydrogeologic framework under the Raritan Bay. The U.S. Geological Survey, Geologic Division, Branch of Atlantic

Marine Geology, provided 2.0 miles (3.2 km) of multi-channel seismic reflection data. A 15-inch water-gun source and a 12-channel, high-resolution multi-channel streamer was used to collect the data. Navigation was by LORAN C with time delays converted to latitude and longitude with overland propagation delays reported by the U.S. Defense Mapping Agency (1981) and McCullogh and others (1982). Locations determined in this manner are accurate to approximately 150 ft (45.7 meters) (Hutchinson and Grow, 1985, p. 988).

The digital processing for the multi-channel data followed a standard sequence: 1) Demultiplex - to order by channel per shot; 2) Statics - to correct for cyclical firing of the water-gun; 3) Sort - to order by channel (offset)/Common depth point (CDP); 4) Edit - to zero channel 1; 5) Spherical divergence correction - to correct for spherical spreading of the wavefront; 6) Filter - a bandpass from 40/50 Hz - 200/250 Hz; 7) Automatic gain control - a scaling factor (100 msec); 8) Mute - to zero direct arrivals; 9) NMO - a normal moveout correction; 10) Stack - to horizontally sum traces within CDP's; 11) Filter - a bandpass from 40/50 Hz - 150/175 Hz, and finally 12) Display - actual plotting of the data.

Reflection profiles were produced from computer processing of the multi-channel marine seismic data. In conjunction with the data processing, a graph of velocity versus time was generated (fig. 2). The depth to a reflector was calculated by multiplying the arrival time of the

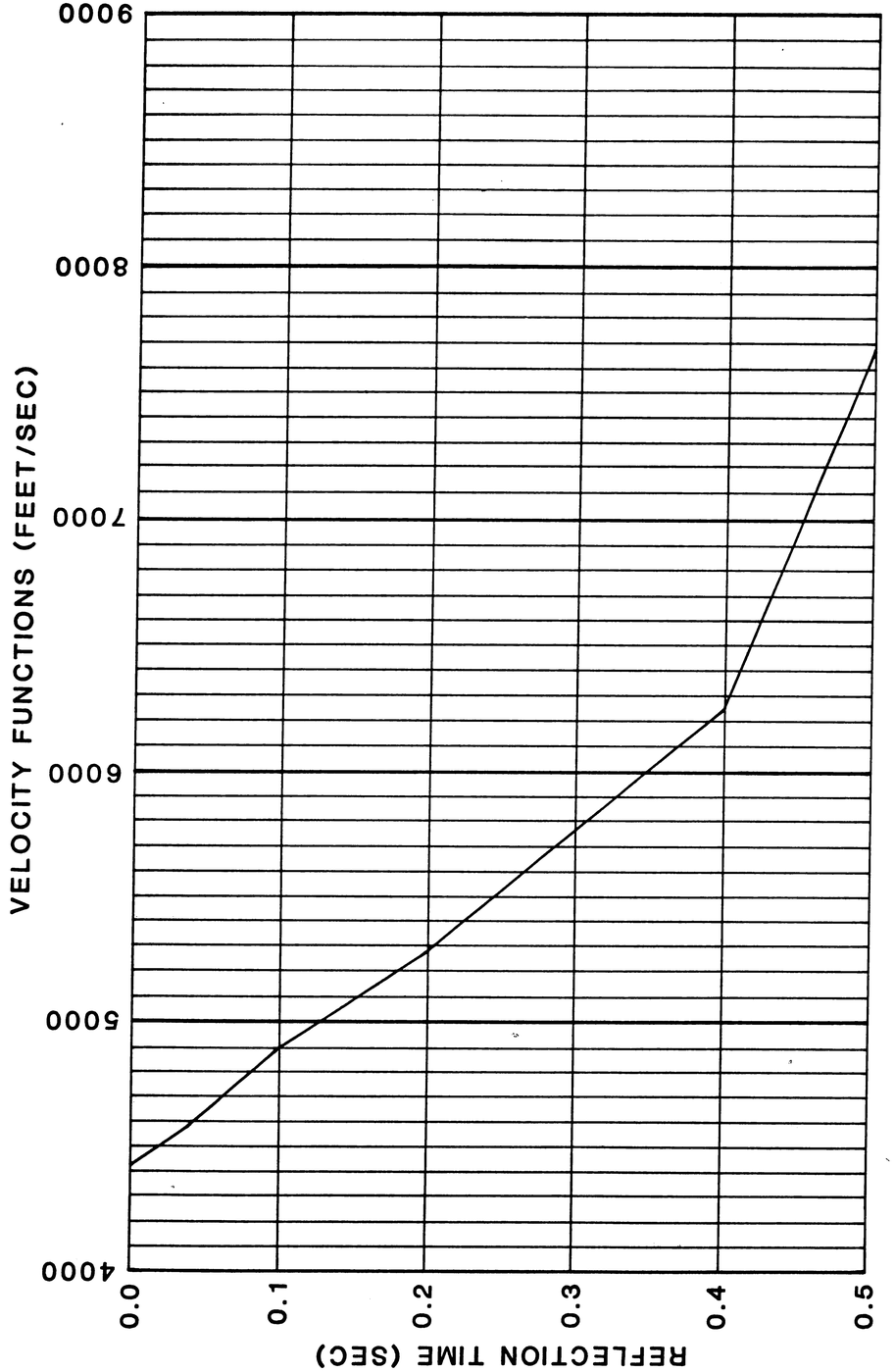
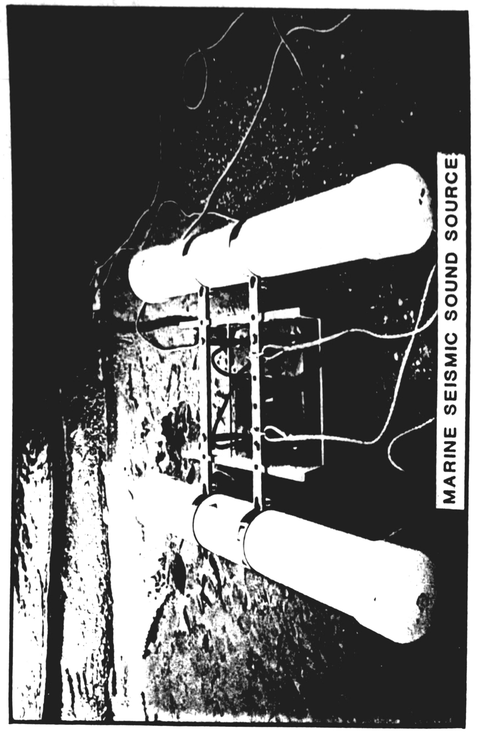


Figure 2.--Graph of reflection time (seconds) versus velocity function (feet/second) used to determine depth to a reflector on the Woods Hole multi-channel seismic-reflection profiles.

reflector by the computed sediment velocity. By selecting a vertical section in several areas of the profiles,a correlation between two-way travel time and depth was developed. This relationship was used to construct a variable depth scale for the profiles. The computer-generated velocity data correlated well with that determined from a seismic check shot at well 25-565. The check shot gave an average velocity of 5300 ft/sec (1615.4 meters/sec) for the upper 500 ft (152.4 meters) of section (Duran, P. B., U.S. Geol. Survey, written commun., 1986).

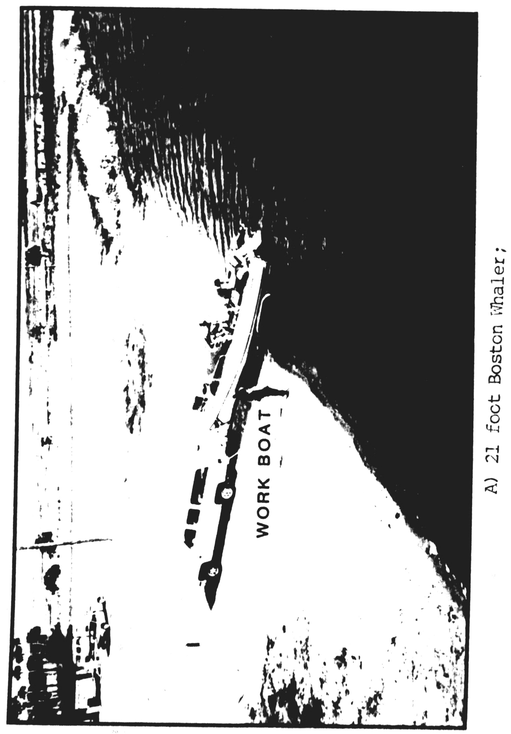
The U.S. Geological Survey/Water Resource Division, West Trenton ,N.J. installed a continuous single-channel seismic profiling system on a small work boat. Navigation was by LORAN C and dead reckoning. The system consists of an acoustic sound source and its power supply, an ORE Geopulse hydrophone, a Bloodworth Geomarine Systems amplifier and filter unit, an EPC Model 1600 graphic recorder and a Honda electric generator for power (fig. 3).

These data were collected using a 350 joule power supply fired at 2 second intervals. The filter setting was 200-800 Hz and was processed at 0.2 second time base as the data was collected. The record obtained is a graph of the arrival times of reflected energy against distance traveled along the profile. The abscissa is the distance axis and the ordinate is the two-way travel time of the reflected signal. The apparent depth of the reflectors was determined using the sediment velocity as with the multichannel data. These

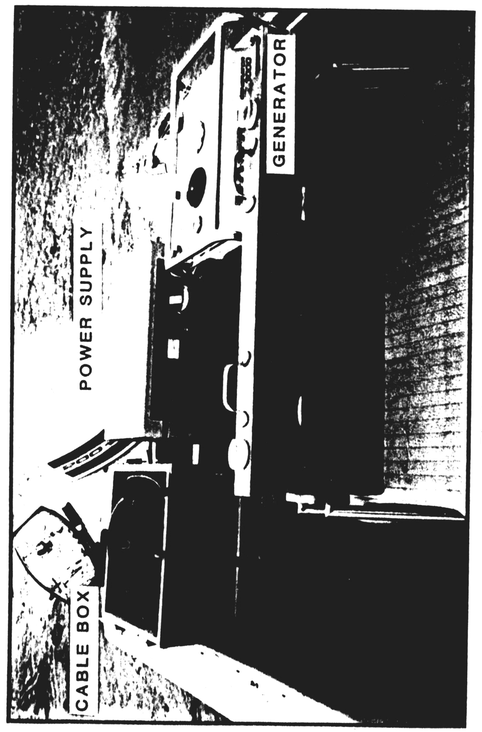


C) Sound source;

D) Recording equipment.



A) 21 foot Boston Whaler;



B) Power supply;

Figure 3.—Boat and equipment used for single-channel continuous seismic-reflection profiling.

profiles were correlated to borehole data in the area and to the multi-channel profiles to develop the hydrogeologic framework under the bay.

A problem encountered while collecting both types of data was the limited penetration of the sound source into the substrate. This is attributed to the presence of naturally produced gas in the underlying sediments (Hampton and Anderson, 1974, p. 258). This problem is unavoidable and is often encountered in shallow marine continuous seismic profiling.

Hydrogeologic Interpretation of the Terrestrial Framework

Lithologic and geophysical well logs were used to prepare the hydrogeologic sections and structure-contour maps. Nine sections were developed (fig. 4); four are oriented approximately in the direction of regional dip (northwest-southeast), and the remainder are oriented along regional strike. The sections are oriented in these directions for several reasons: (1) they present the most informative view of the hydrogeology onshore; (2) they enable correlation between the terrestrial and marine framework; (3) they incorporate the best assemblage of available logs; and (4) the sections emphasize conditions near the outcrop areas.

The sections (fig. 5a-j) correlate well with previously published sections (Barksdale and others, 1958; Zapecza, 1984). The major aquifers and confining units dip gently to

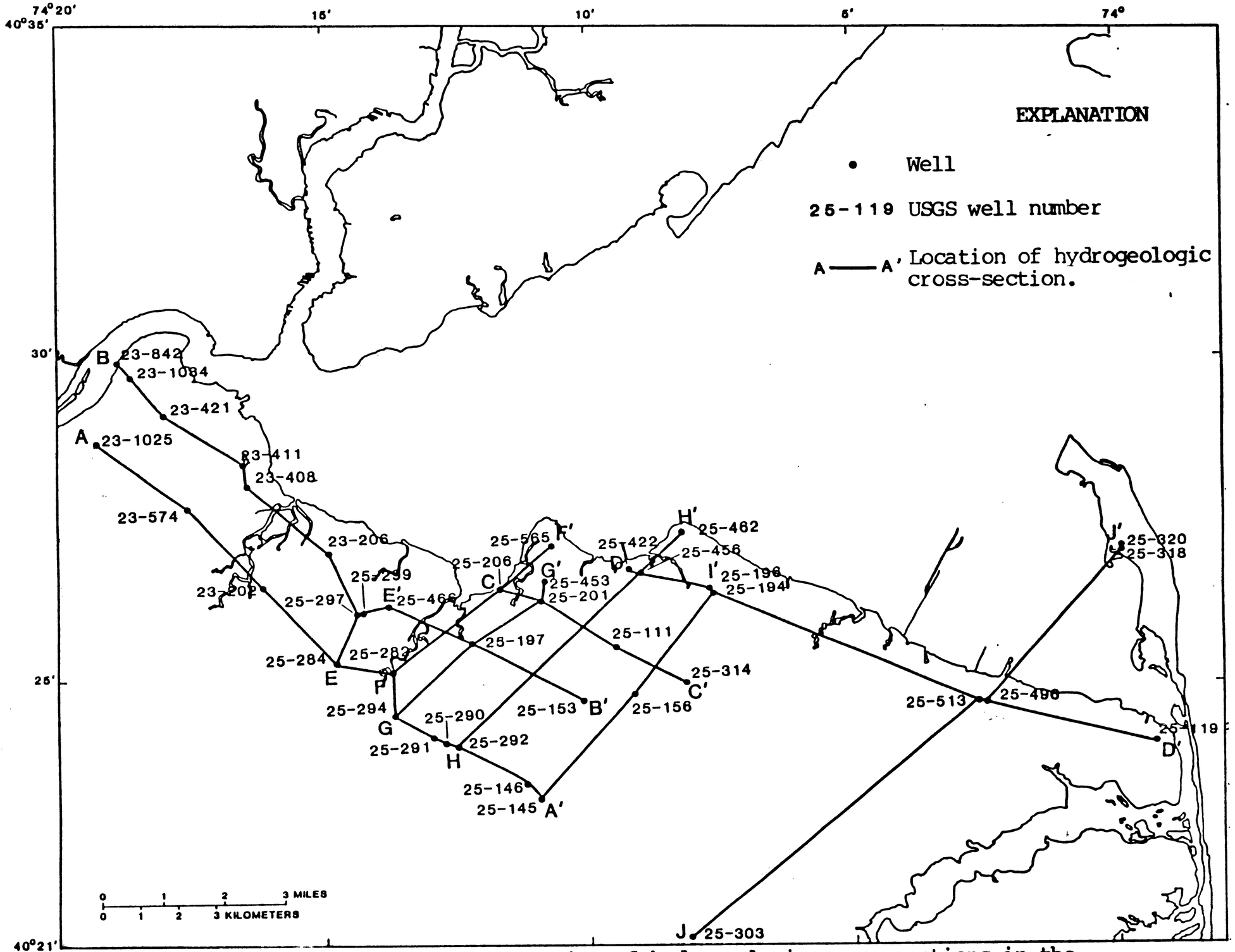


Figure 4.-- Map showing location of hydrogeologic cross sections in the Raritan Bay area.

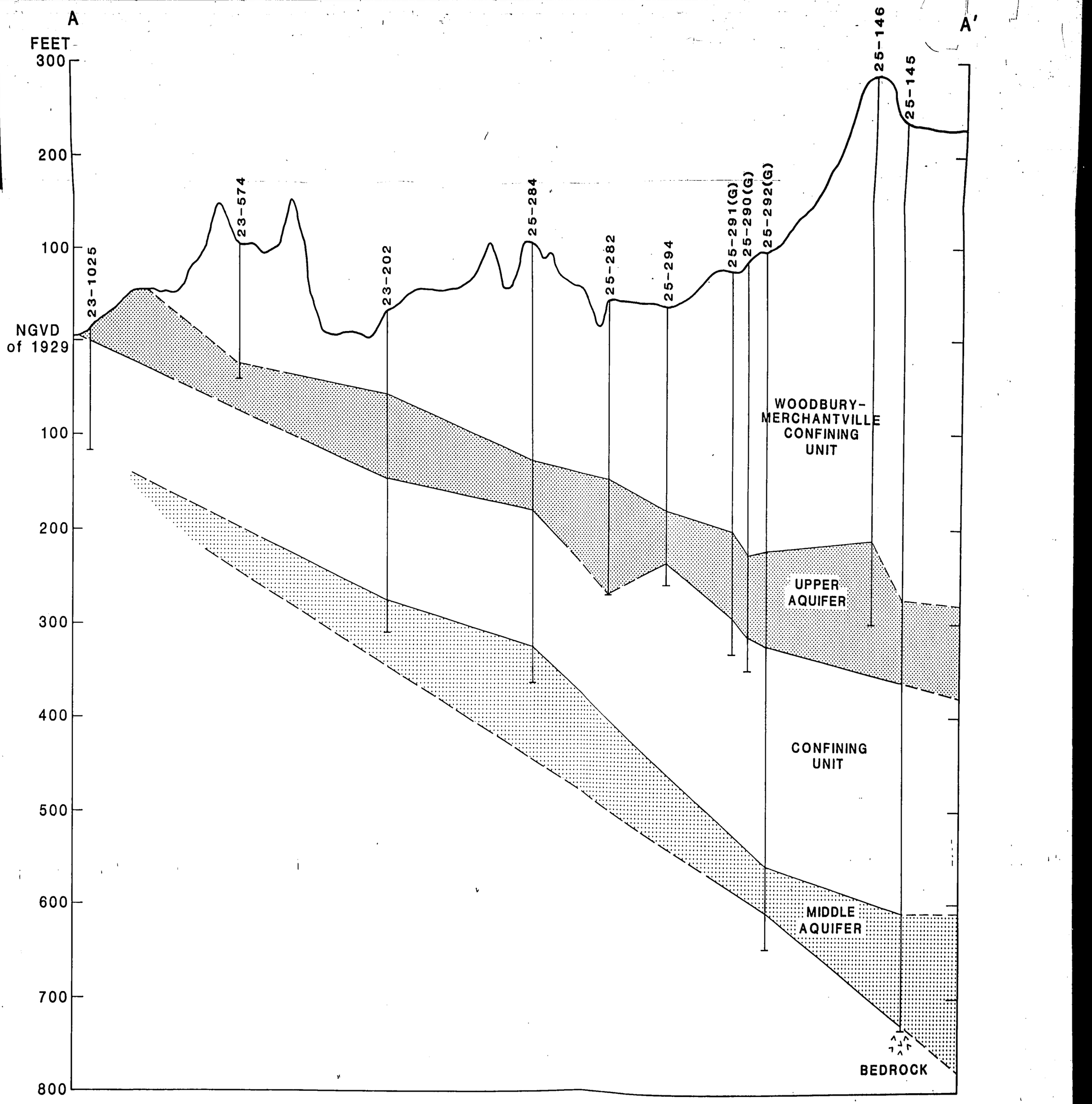


Figure 5a.-- Hydrogeologic cross section in the study area, section A-A'.

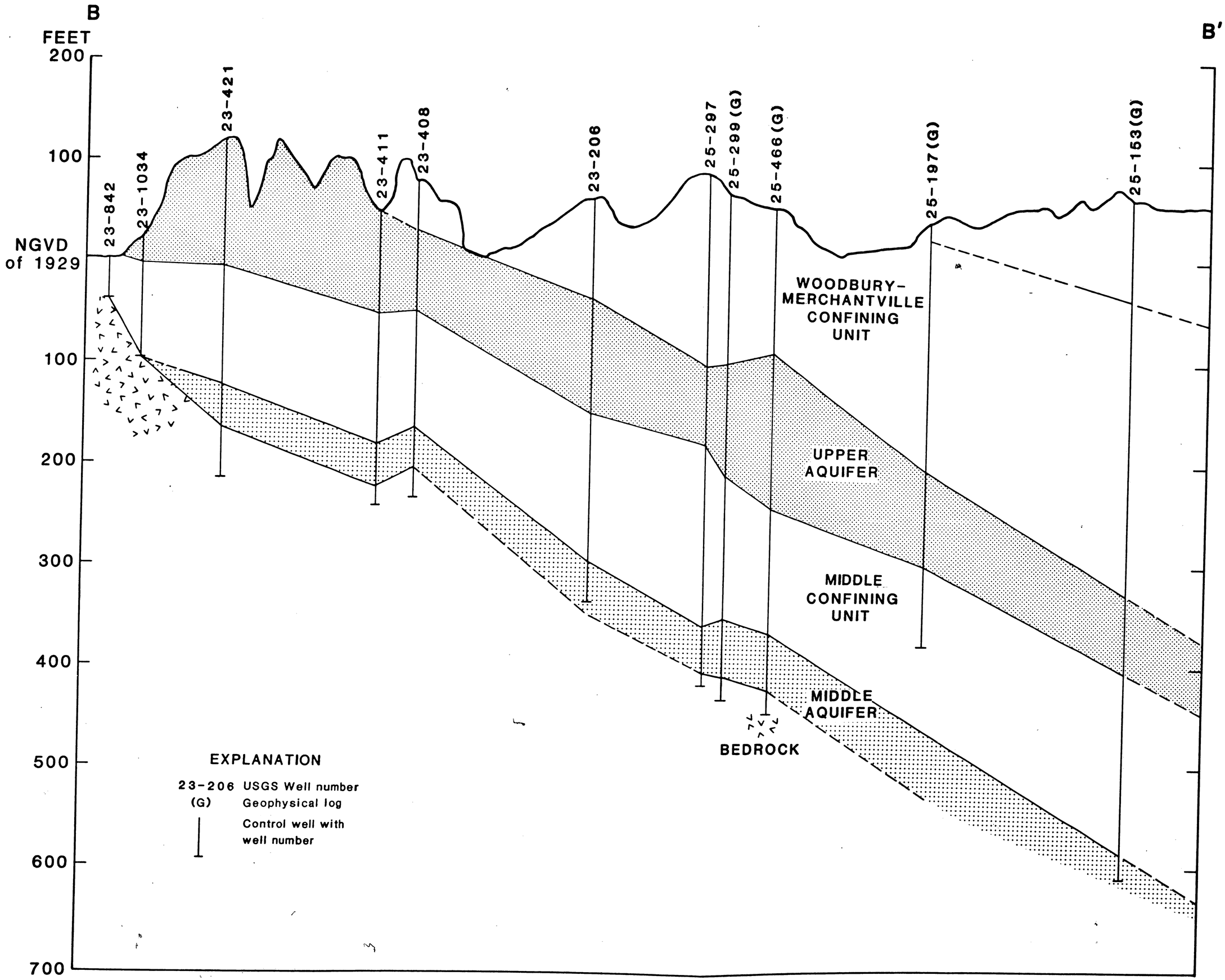


Figure 5b.-- Hydrogeologic cross section in the study area, section B-B'.

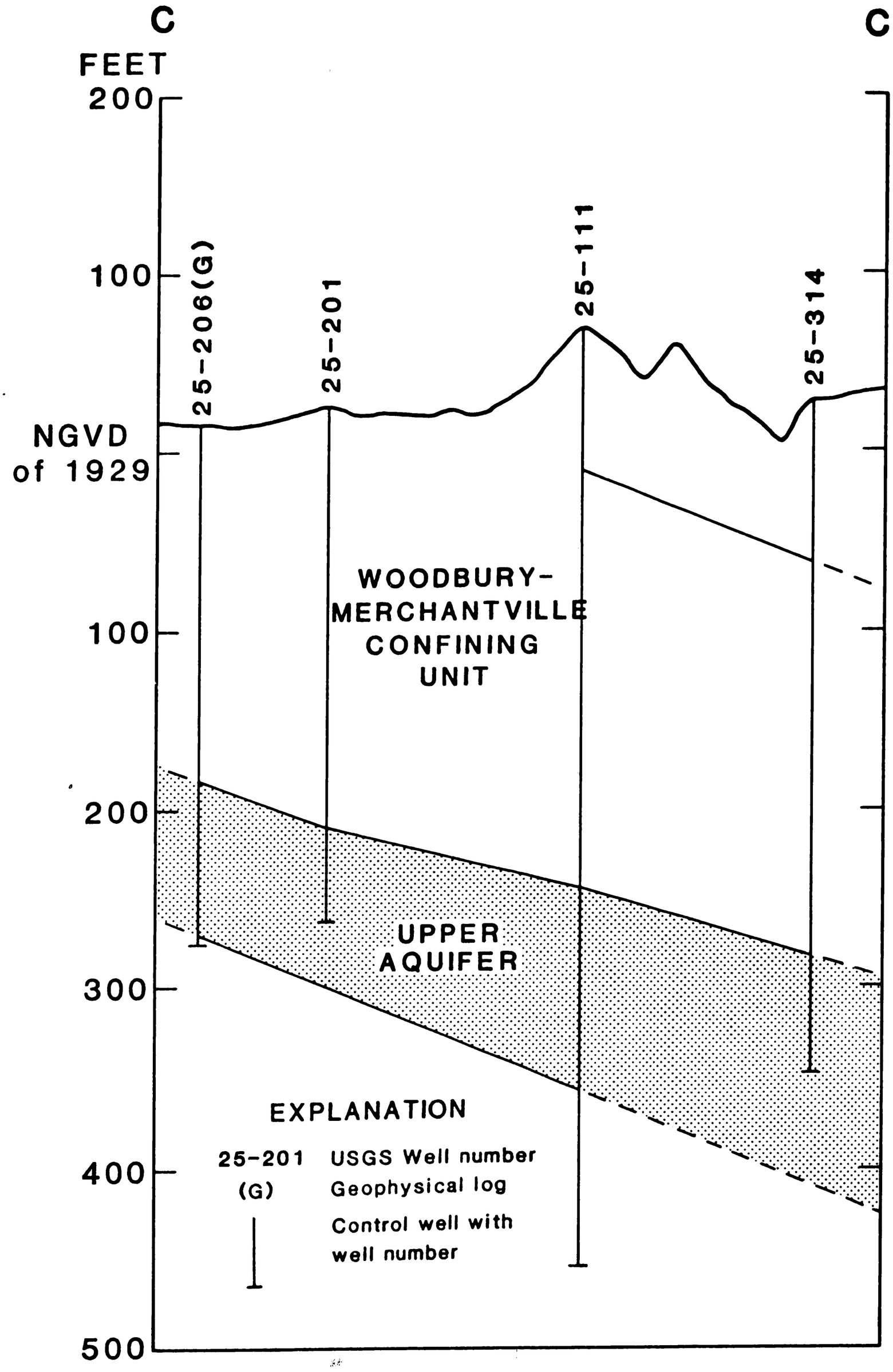


Figure 5c.-- Hydrogeologic cross section in the study area, section C-C'.

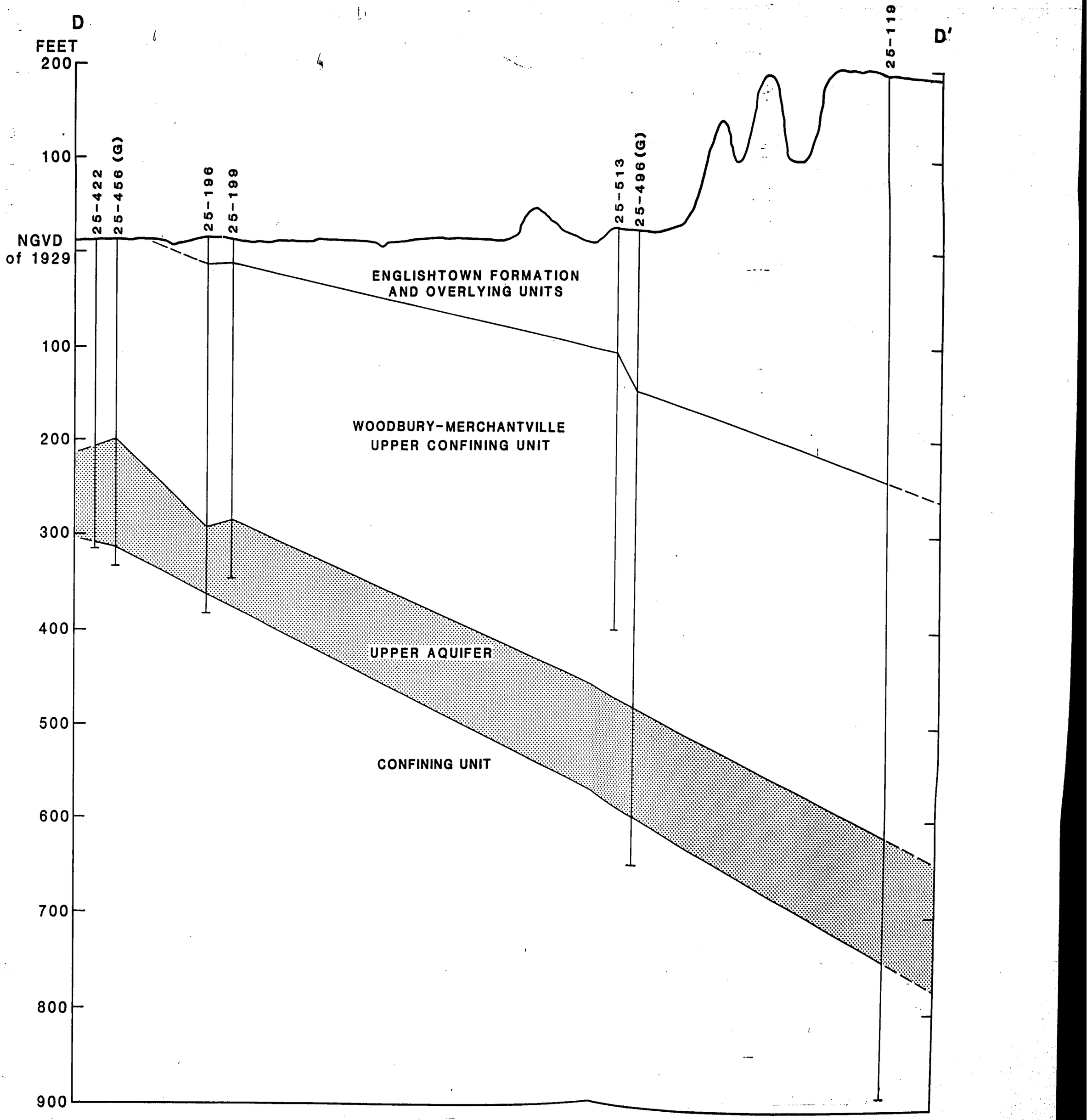


Figure 5d.— Hydrogeologic cross section in the study area, section D-D'.

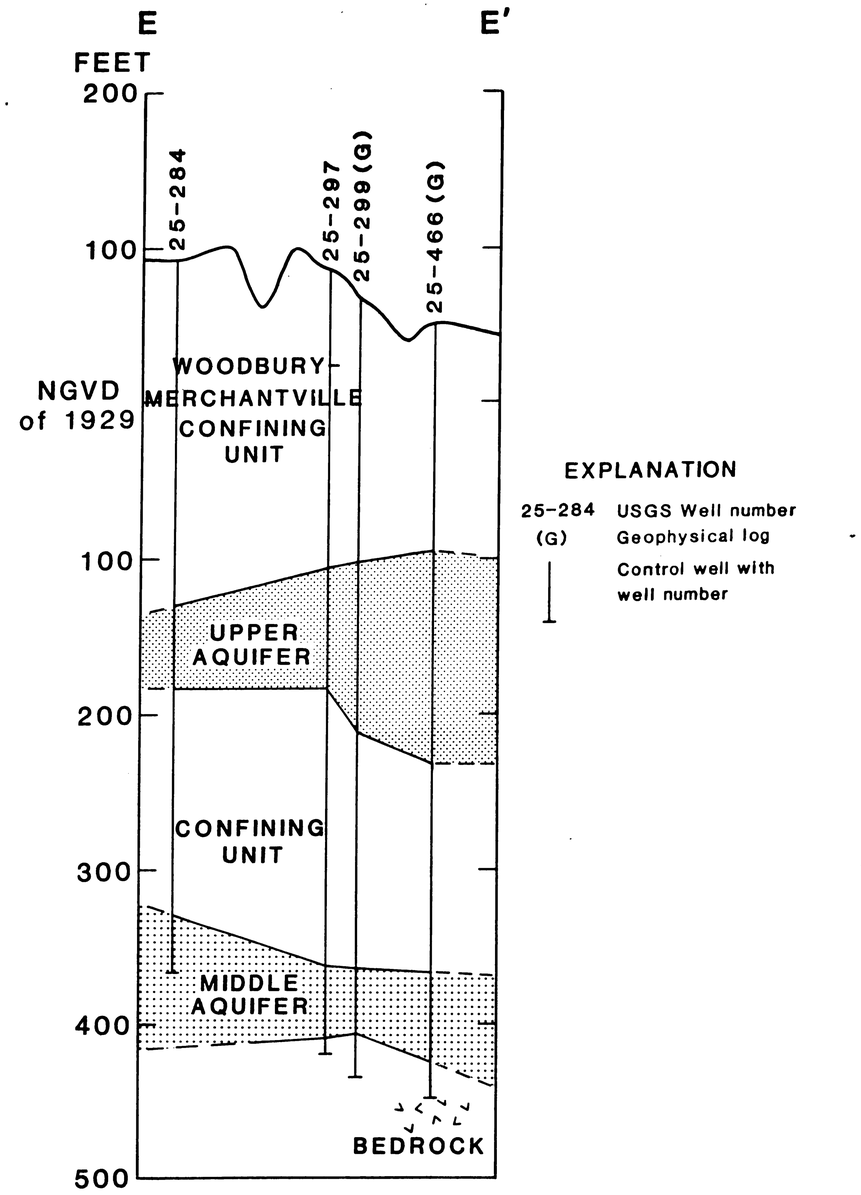


Figure 5e.— Hydrogeologic cross section in the study area, section E-E'.

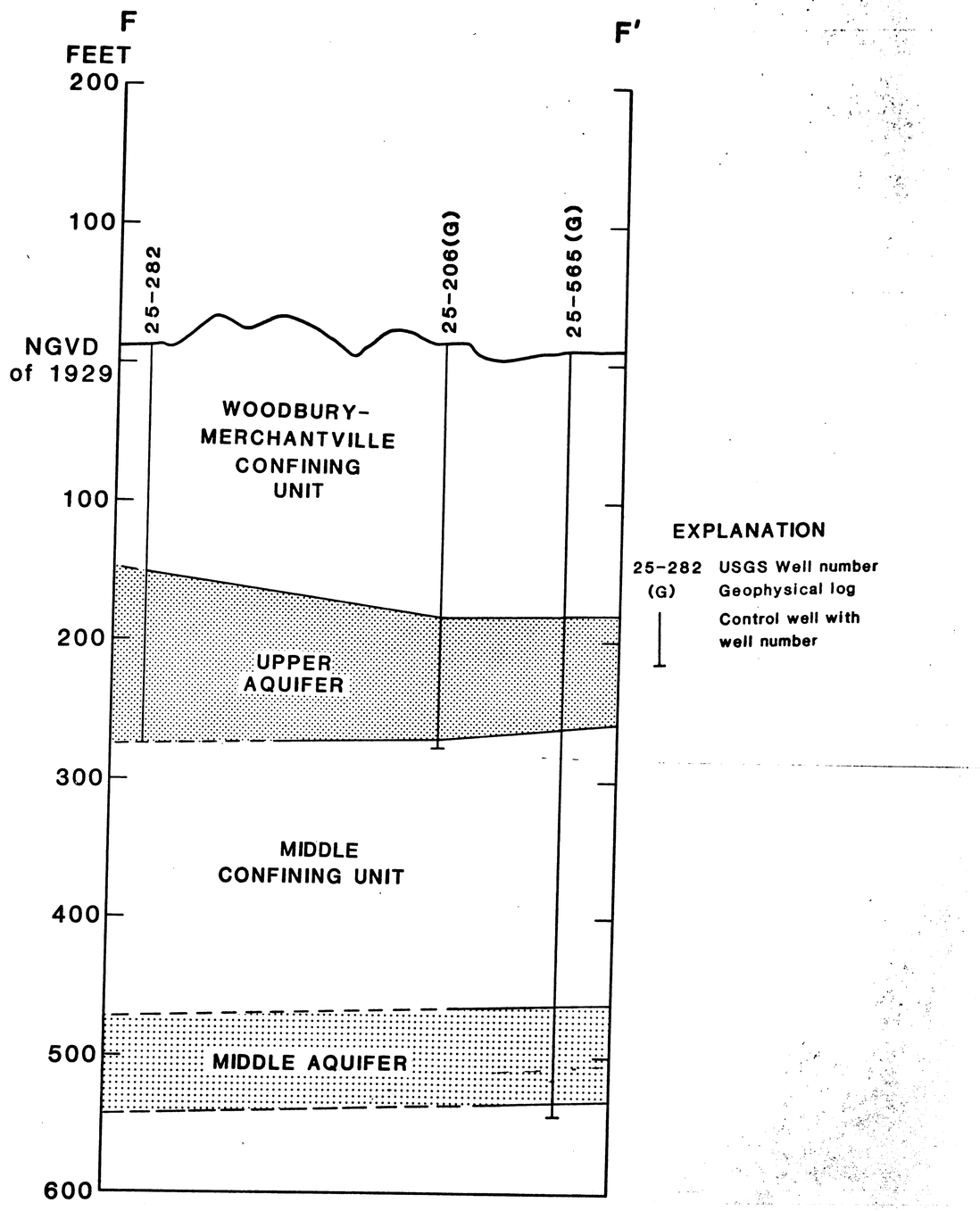


Figure 5f.— Hydrogeologic cross section in the study area, section F-F'.

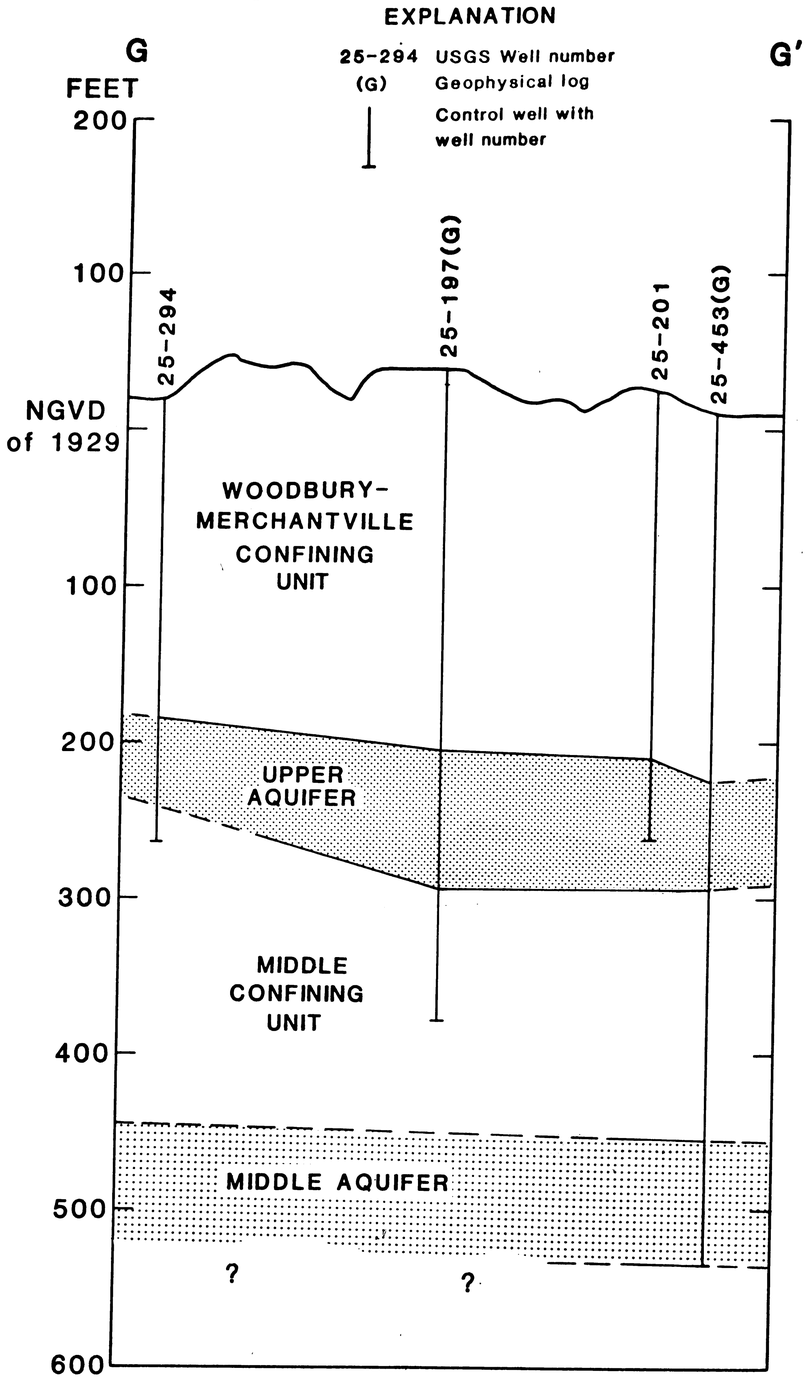


Figure 5g.-- Hydrogeologic cross section in the study area, section G-G'.

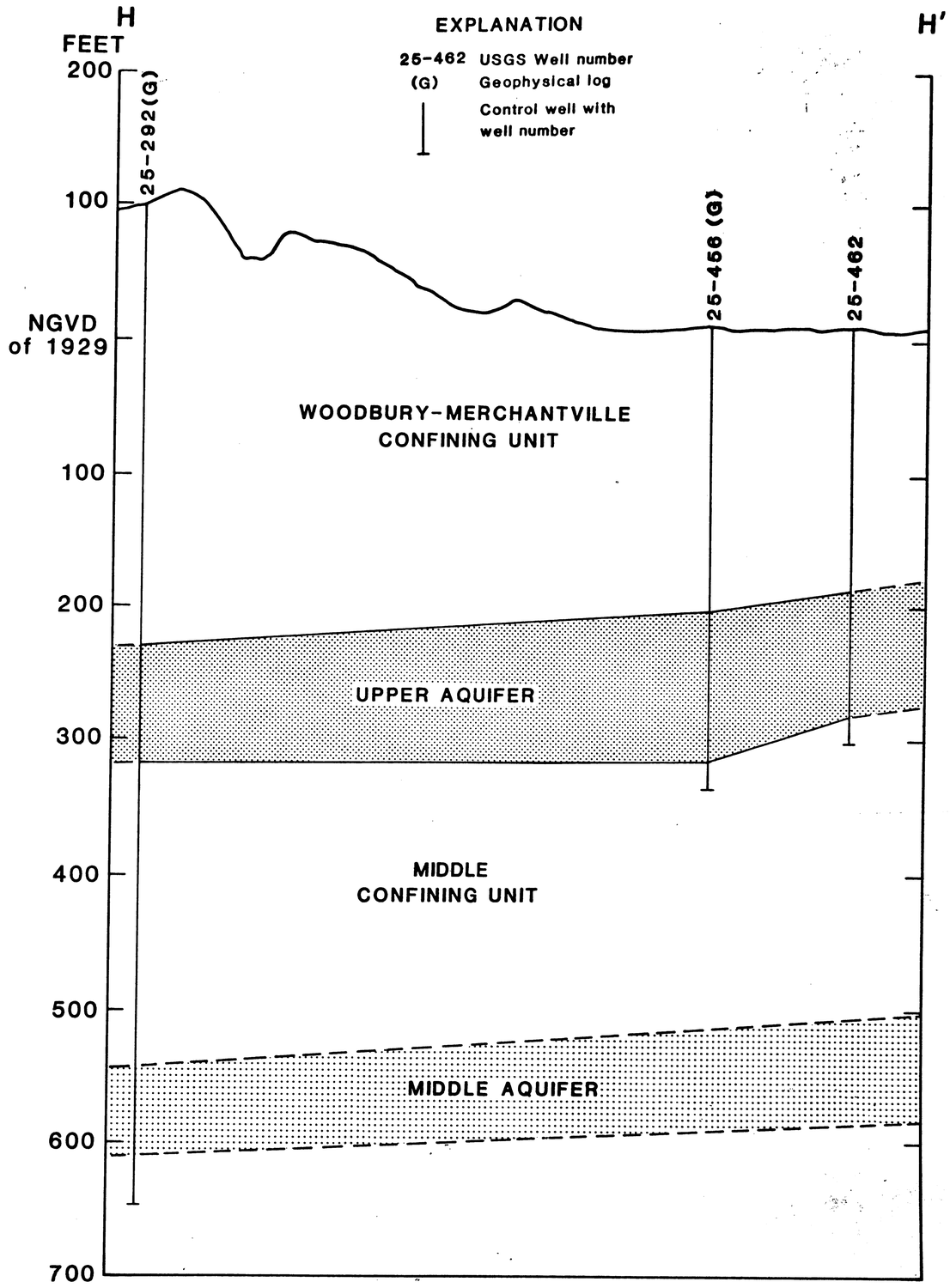


Figure 5h.-- Hydrogeologic cross section in the study area, section H-H'.

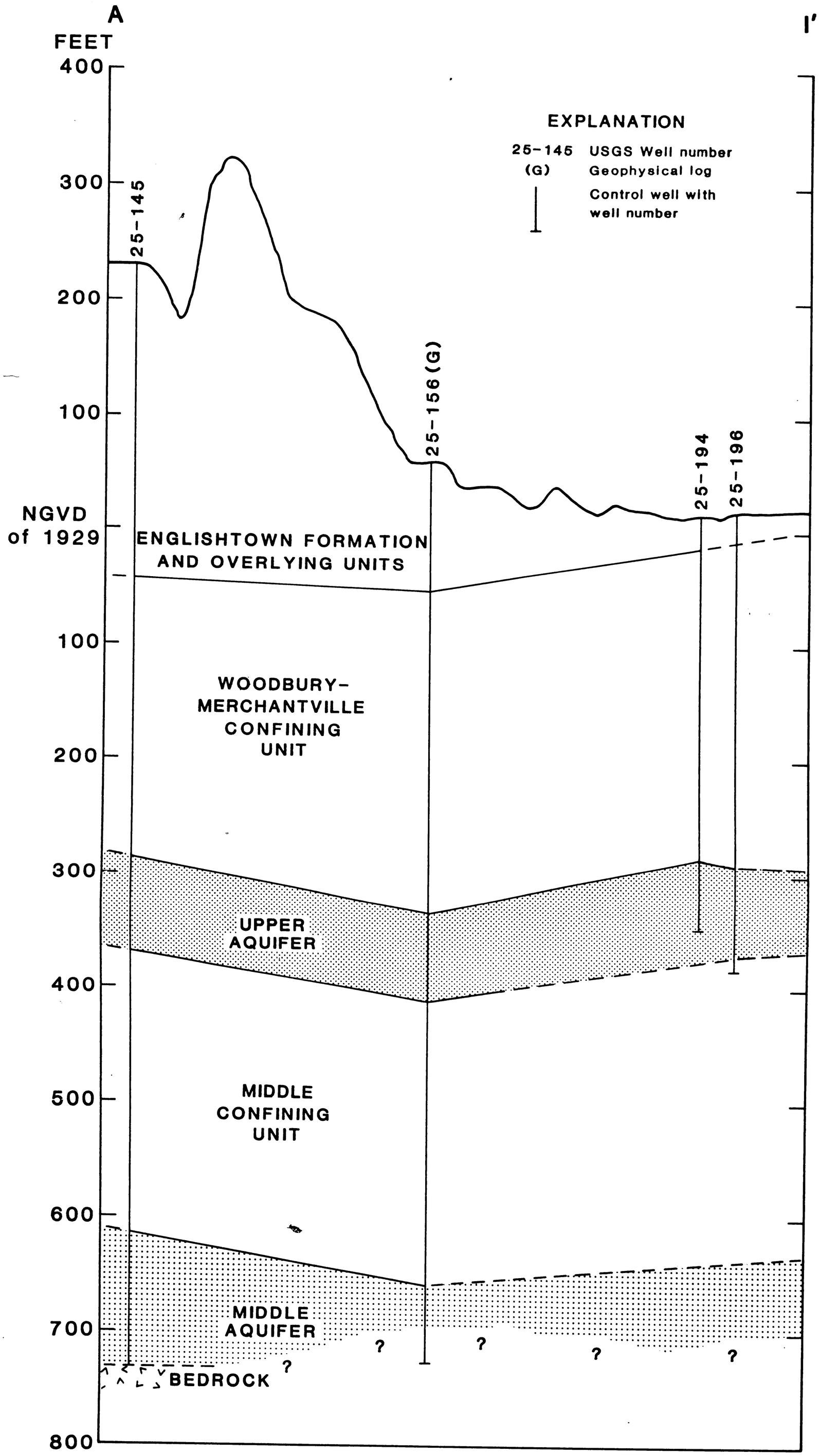


Figure 5i.-- Hydrogeologic cross section in the study area, section A-I'.

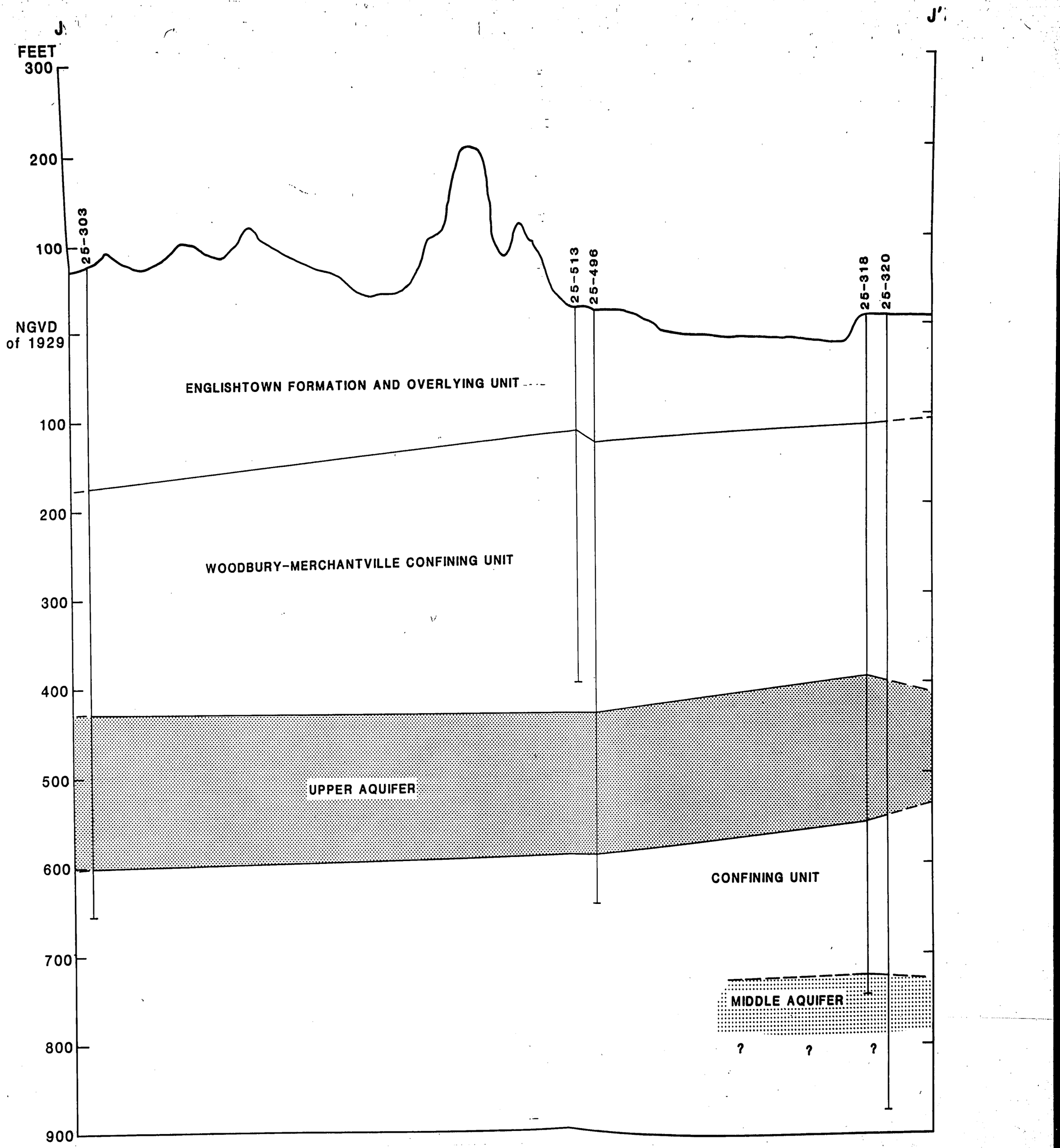


Figure 4j.--Hydrogeologic cross section in the study area, section J-J'.

the southeast at 40-50 ft/mi (7.6-9.5 meters/kilometer), and gradually thicken in that direction. Other units appear in the southeastern corner and are labeled as Englishtown and overlying units. These are not major hydrologic units in the study area but are listed in Table 1. The five major hydrogeologic units consist of a lower confining unit, middle aquifer, confining unit between the middle and upper aquifer (middle confining unit), upper aquifer and upper confining unit .

The sections show that the lower confining unit correlates primarily to basement in the western portion of the study area near the Raritan River. Further downdip a thin clay overlies basement and acts as the lower confining unit.

The middle aquifer directly overlies the lower confining unit in the study area. The middle aquifer crops out in the northwestern corner of the study area in New Jersey. No outcrop is found on Staten Island, New York it is apparently covered by glacial moraine and outwash deposits (Farlekas, 1979, p. 8; Soren, Julian, U.S. Geol. Survey, oral commun., 1986). All sections indicate that the middle aquifer dips to the southeast at 40-50 ft/mi (7.6-9.5 meters/kilometer). The unit is absent near the Raritan River. However, downdip of the river the unit is 40 ft (12.2 meters) thick, and the thickness increases to 130 ft (39.6 meters) in the southeastern part of the study area. Data from boreholes on Staten Island confirm the presence of a water-bearing sand at depths of 100-150 ft (30.5-45.7 meters) (Appendix 1).

A confining unit overlies the middle aquifer and separates it from the upper aquifer. This unit thickens from 90 ft (27.4 meters) to more than 200 ft (61 meters) in the southeastern part of the study area. Thin glacial moraine and outwash deposits overlie the confining unit on Staten Island (Perlmutter and Arnow , 1953, plate 2). This confining unit is apparently continuous and of sufficient thickness to inhibit the flow of water between the two adjacent aquifers.

The upper aquifer crops out to the southeast of the Raritan River in New Jersey. It gradually thickens from a feather edge near the mouth of the Raritan River to 130 ft (39.6 meters) at the southeastern boundary of the study area. The upper aquifer is less uniform in composition than the middle aquifer; and of variable thickness downdip. Lithologic and geophysical logs indicate abundant clay lenses in the upper aquifer. These lenses are usually discontinuous. On Staten Island, however, Soren (U.S. Geol. Survey, written commun., 1986) indicates the absence of anything except glacial debris above the previously discussed clay member. Review of available well logs (Appendix 1) from Staten Island support the conclusion that the upper aquifer is not present on Staten Island. This supposition requires that the upper aquifer crop out directly offshore of Staten Island under Raritan Bay.

The most extensive confining unit in the study area overlies the upper aquifer. The Woodbury-Merchantville confining unit thickens from approximately 100 ft (30.5

meters) northwest of Keyport to greater than 350 ft (106.7 meters) at the southeastern boundary of the study area.

Table 2 presents altitudes for the top of each of the units as determined from all borehole data. These data supplement the hydrogeologic sections and are used to correlate the marine geophysical data to the hydrogeologic units. The data in table 2 were used to prepare the structure-contour maps of the various units.

Hydrogeologic Interpretation of Marine Framework

The interpretation of the marine seismic-reflection data followed the methods of other studies of hydrogeologic framework (Tufekcic, 1978; Sangree and Widmier, 1979; Wolansky et. al., 1982; Haeni, U.S. Geol. Survey, written commun., 1983). Interpretation requires knowledge of the local geology (Zapecza, 1984; Smolansky, D., U.S. Geol. Survey, written commun., 1986; Soren, J., U.S. Geol. Survey, written commun., 1986), proximal lithologic and geophysical logs and estimates of the average seismic velocities of the geologic units (Wolansky and others, 1982, p. 12).

These principles, in conjunction with the framework on the south side of the Bay, preliminary results of a report on the geology of Staten Island (Soren, J., U.S. Geol. Survey, written commun., 1986) and preliminary results of a report dealing with the hydrogeology of Long Island (Buxton,

Table 2.--Altitudes of the top of hydrogeologic units in the Raritan Bay, area.
[In feet above or below sea level]

Well number	Altitude of land surface	Top of Woodbury-Merchantville confining unit	Potomac-Raritan-Magothy aquifer system			
			Top of upper aquifer	Top of middle confining unit	Top of middle aquifer	Top of lower confining unit
230146	80	80	-88	-154	-251	---
230176	45	38	-59	-140	-261	-365
230191	115	---	-75	---	---	---
230201	15	15	-20	-95	-223	---
230202	11	11	-56	-146	-277	---
230206	60	45	-38	-150	-295	---
230369	45	---	---	-55	---	---
230386	102	---	102	-21	-144	-216
230399	90	---	90	-8	-106	-156
230404	23	23	-25	-87	-174	-266
230408	73	73	30	-49	-184	-205
230411	10	---	10	-48	-181	-222
230421	118	---	118	-4	-122	-164
230424	16	---	---	-2	-84	-99
230574	100	79	-23	---	---	---
230576	30	---	---	7	-105	-123
230603	15	---	15	-71	---	---
230783	90	30	-160	---	---	---
230842	0	---	---	-14	---	---
231025	10	---	---	0	---	-116
231034	18	---	---	-3	---	-96
250111	59	-11	-246	-350	---	---
250119	20	-235	-604	-756	---	---
250145	229	-42	-283	-369	-610	-727
250146	280	0	-215	---	---	---
250153	65	-25	-321	-391	-567	-625
250156	60	-52	-330	-410	-652	-676
250194	10	-15	-285	---	---	---
250196	12	-16	-294	-356	---	---
250197	35	25	-205	-290	---	---
250201	20	10	-210	---	---	---
250206	15	-55	-185	-270	---	---
250262	140	-45	-280	-410	-570	-672
250269	111	-3	---	---	-483	---
250272	118	0	-212	-354	-471	---
250282	10	0	-153	---	---	---
250284	90	90	-130	-183	-330	---
250290	71	21	-234	-319	---	---
250291	61	61	-209	-299	---	---
250292	87	37	-223	-323	-563	-613

Table 2.--Altitudes of the top of hydrogeologic units--Continued.
[In feet above or below sea level]

Well number	Altitude of land surface	Top of Woodbury-Merchantville confining unit	Potomac-Raritan-Magothy aquifer system: Top of upper aquifer	Top of middle confining unit	Top of middle aquifer	Top of lower confining unit
250294	20	20	-184	-239	---	---
250297	80	80	-104	-181	-360	-406
250299	60	60	-100	-206	-364	-397
250303	70	---	-426	-602	---	---
250314	20	-60	-280	-348	---	---
250318	8	-112	-388	-552	-707	---
250320	14	-102	-394	-535	-715	-851
250453	10	10	-218	-294	-452	-528
250456	10	---	-203	-312	---	---
250459	80	-210	-470	---	---	---
250462	10	-81	-190	-279	---	---
250466	56	---	-84	-238	-369	-417
250467	70	-25	-313	-400	-580	---
250496	15	-120	-409	-535	---	---
250513	20	-109	-401	-509	---	---
250547	100	20	-150	-165	---	---
250565	10	10	-180	-265	-460	-541
850013	150	---	---	60	26	-210
850014	20	---	---	-33	-157	---
850015	5	---	---	-68	-125	---
850016	10	---	---	-65	-90	-260
850017	15	---	---	-69	---	-338
850018	30	---	---	-40	-94	---
850018	20	---	---	-50	-130	---

Herbert, U.S. Geol. Survey, written commun., 1986), assisted in the determination of the hydrogeology beneath Raritan Bay.

Interpretation of Multi-Channel Seismic-Reflection Data

Correlation of individual reflectors to various clay or sand "horizons" onshore was found to be impossible. Therefore, geometrical form or special seismic characteristics were mapped (Tufekcic, 1978, p. 333). The reflection profiles (fig. 6a-c) consistently showed three principle patterns: (1) discontinuous-reflection zones, with occasional discontinuous horizontal reflectors; (2) layered-reflection zones, characterized by abundant simple layered parallel reflectors and (3) a chaotic-reflection zone, typically composed of a discontinuous, diffracted reflector pattern. The gently-dipping reflector patterns lead to the conclusion that the Coastal Plain sediments present on both sides of the Bay are continuous under the Bay.

The specific reflection patterns are separated into seismic-stratigraphic units by identifying the termination of reflection patterns at the upper and lower unit boundaries (Wolansky and others, 1982, p. 68). Section A-A' (fig. 6b) shows five seismic-stratigraphic units. In ascending order, these units are: (1) zone of chaotic reflection; (2) layered-reflection zone; (3) discontinuous-reflection zone;

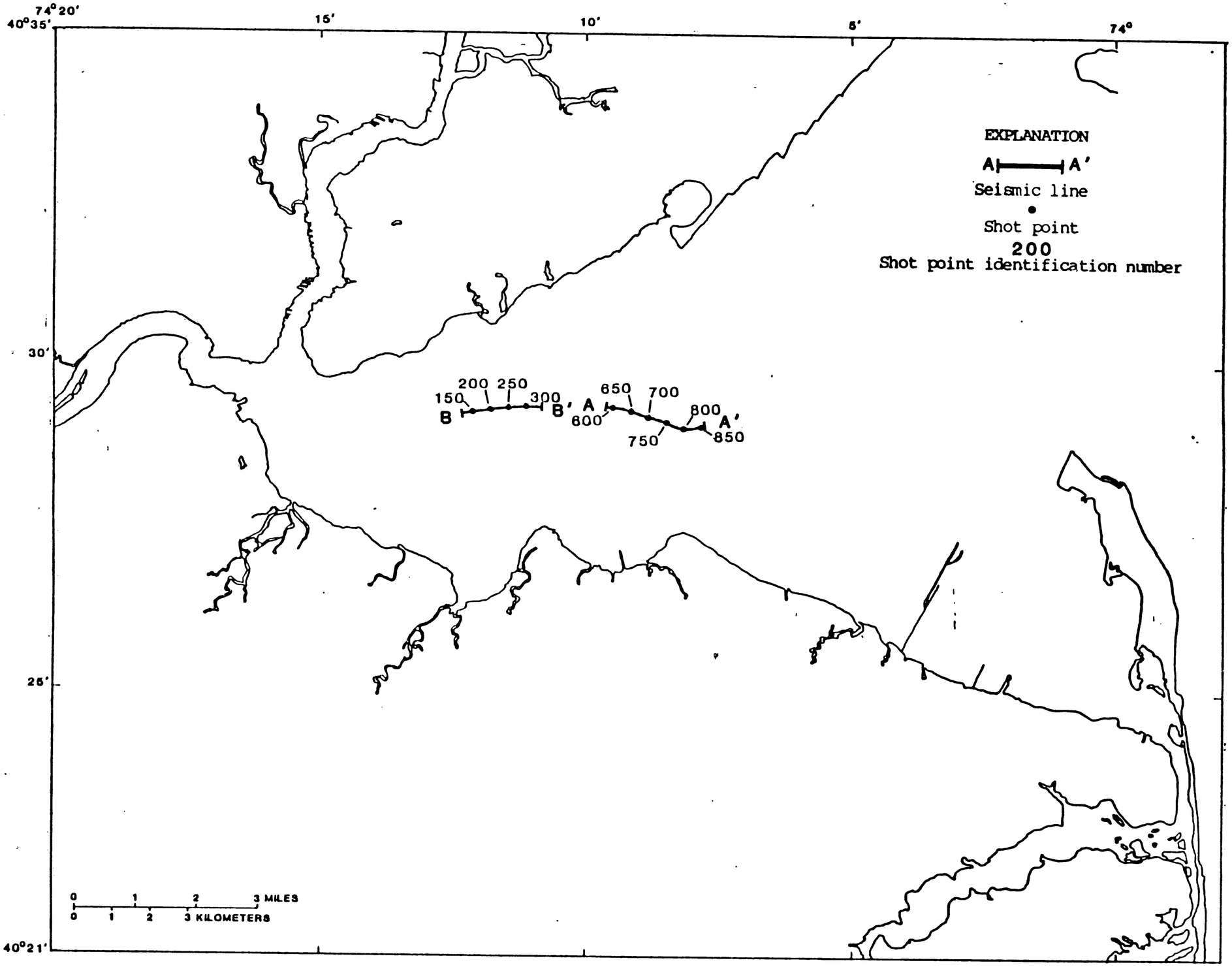


Figure 6a.--Map showing location of seismic lines for Woods Hole multi-channel marine seismic-reflection data.

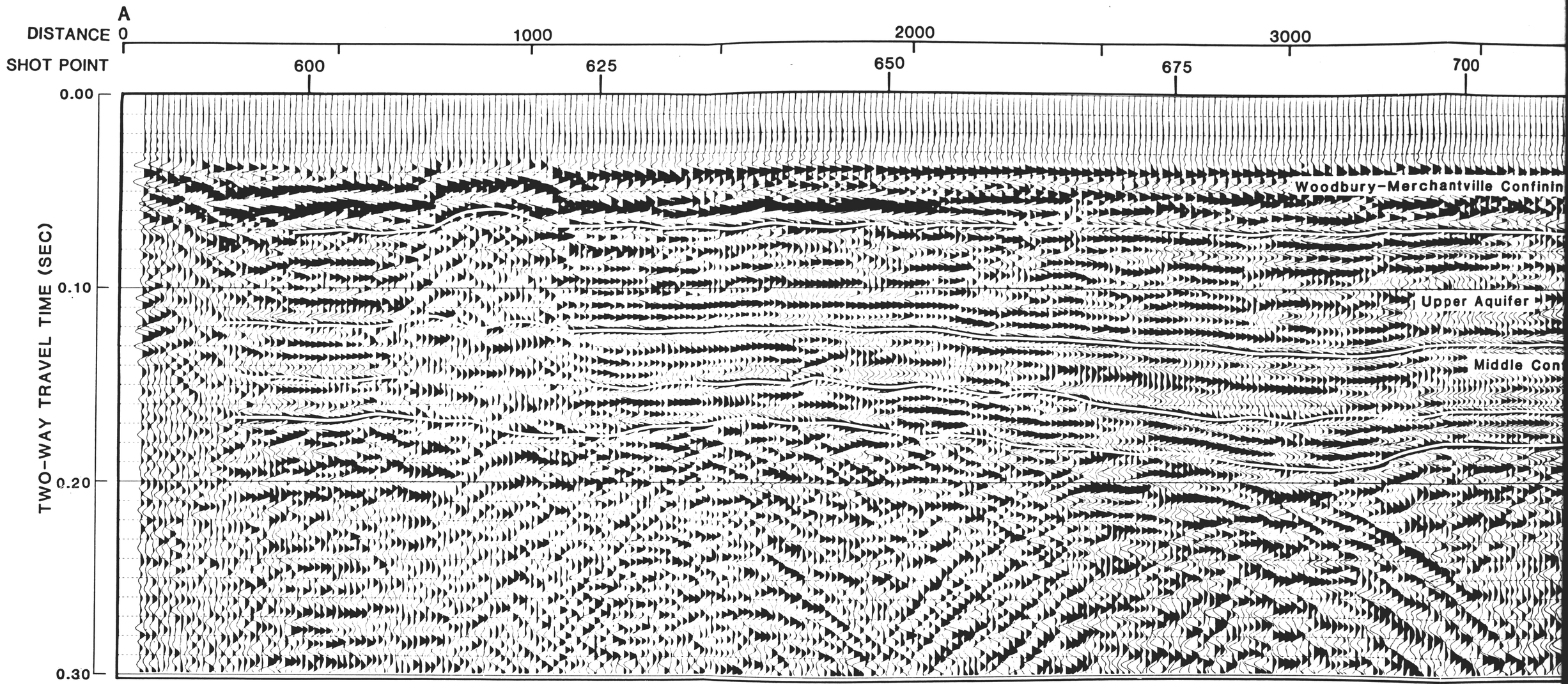
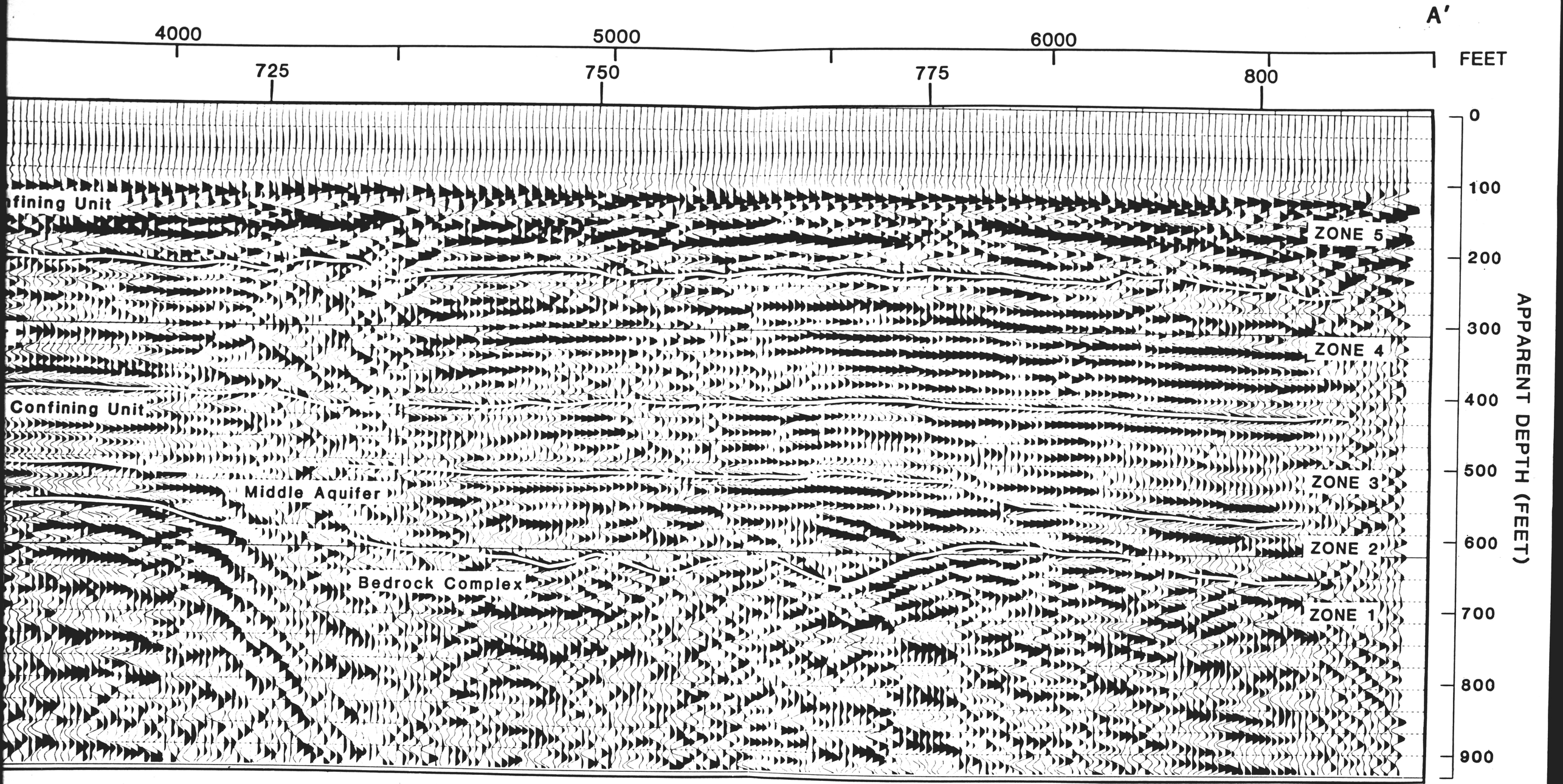


Figure 6b.—Woods Hole multi-channel marine seismic-reflection record and diagramatic presentati



ntation of seismic-stratigrahic units under Raritan Bay, Section A-A'.

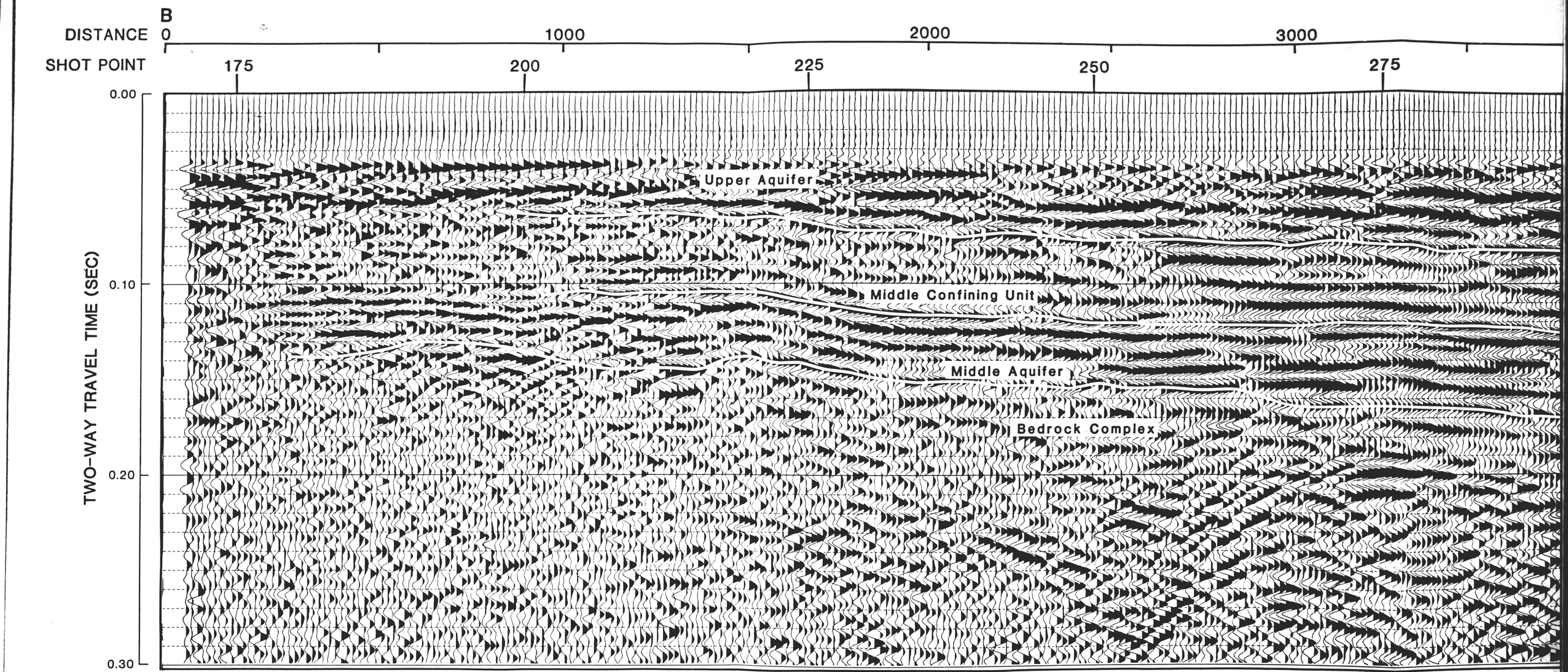
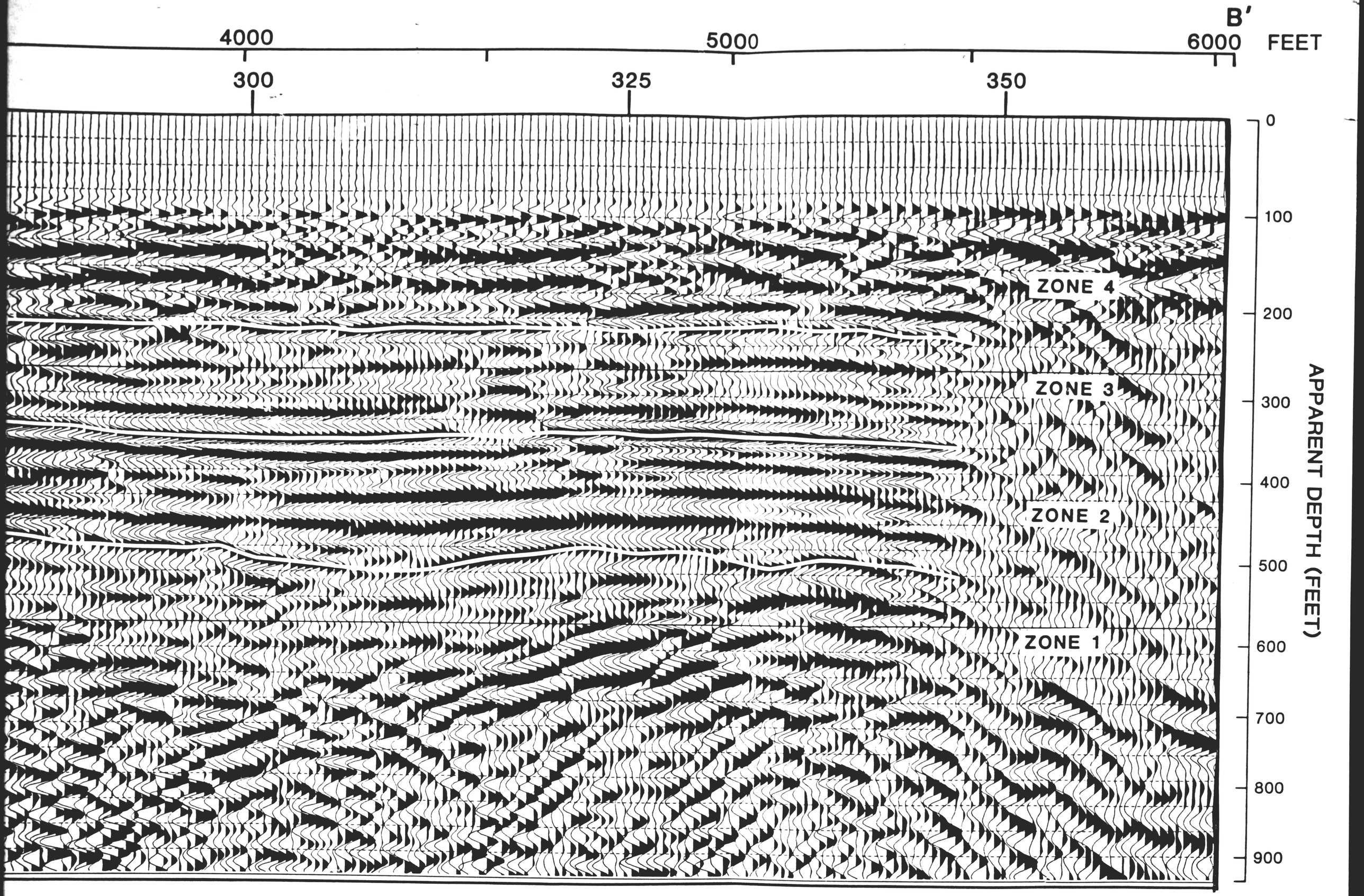


Figure 6c.—Woods Hole multi-channel marine seismic-reflection record and diagramatic presentation of seismic



of seismic-stratigraphic units under Raritan Bay, Section B-B'.

(4) layered-reflection zone; and (5) a distorted layered-reflection zone, characterized by thicker and branching reflectors. Section B-B' (fig. 6c), farther up-dip, shows only four seismic-stratigraphic units identical to the lowermost four units of section A-A'. The seismic-stratigraphic units offshore are correlated with units onshore by isolating each seismic-stratigraphic unit and predicting its lithologic content based on seismic characteristics (Tufekcic, 1978, p. 331).

Irregularities on the surface of the basement rock many times generate a diffraction pattern that gives rise to a series of arcuate reflections. The surface configuration of these arcs can define the topography of basement quite closely. In sections A-A' and B-B' the chaotic reflector zone is typical of the the arcuate pattern of basement (Dobrin, 1976, p. 268). A dipping surface is estimated at the top of the arcs. Depths are then estimated according to the variable-depth scale at the side of each profile. Approximate depths to basement offshore are located at the corresponding shot point along the seismic track. Values for depth to basement, the location of known bedrock points on the both sides of the bay (Table 2) and work done by Soren and Smolansky and others (fig. 7a-b, U.S. Geol. Survey, written commun., 1986) on Staten Island and Long Island, New York respectively, were used to prepare a contour map of the bedrock surface (fig. 8).

A layered-reflection zone overlies the basement surface

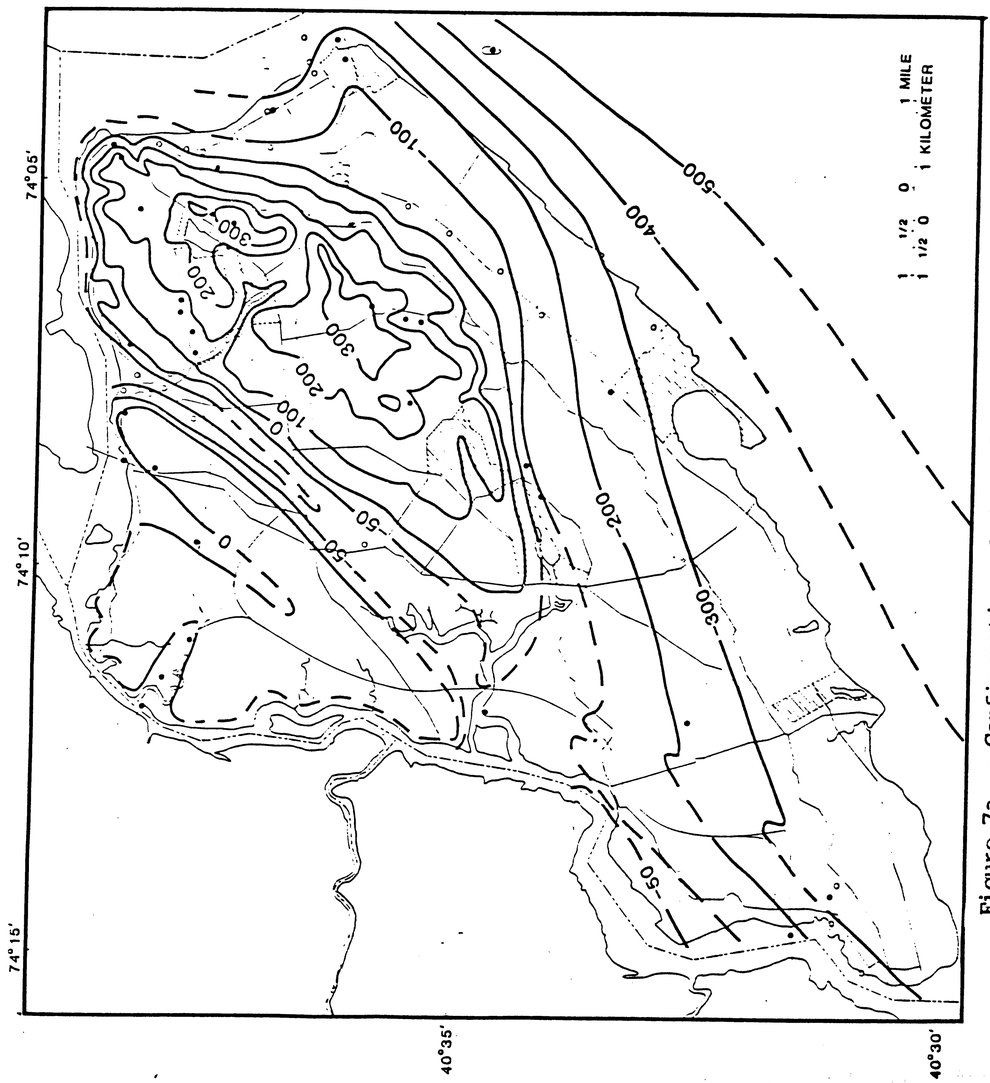


Figure 7a.-- Configuration of the bedrock surface of Staten Island, New York. (Modified from Soren, J., U.S. Geol. Survey, written comm., 1986)

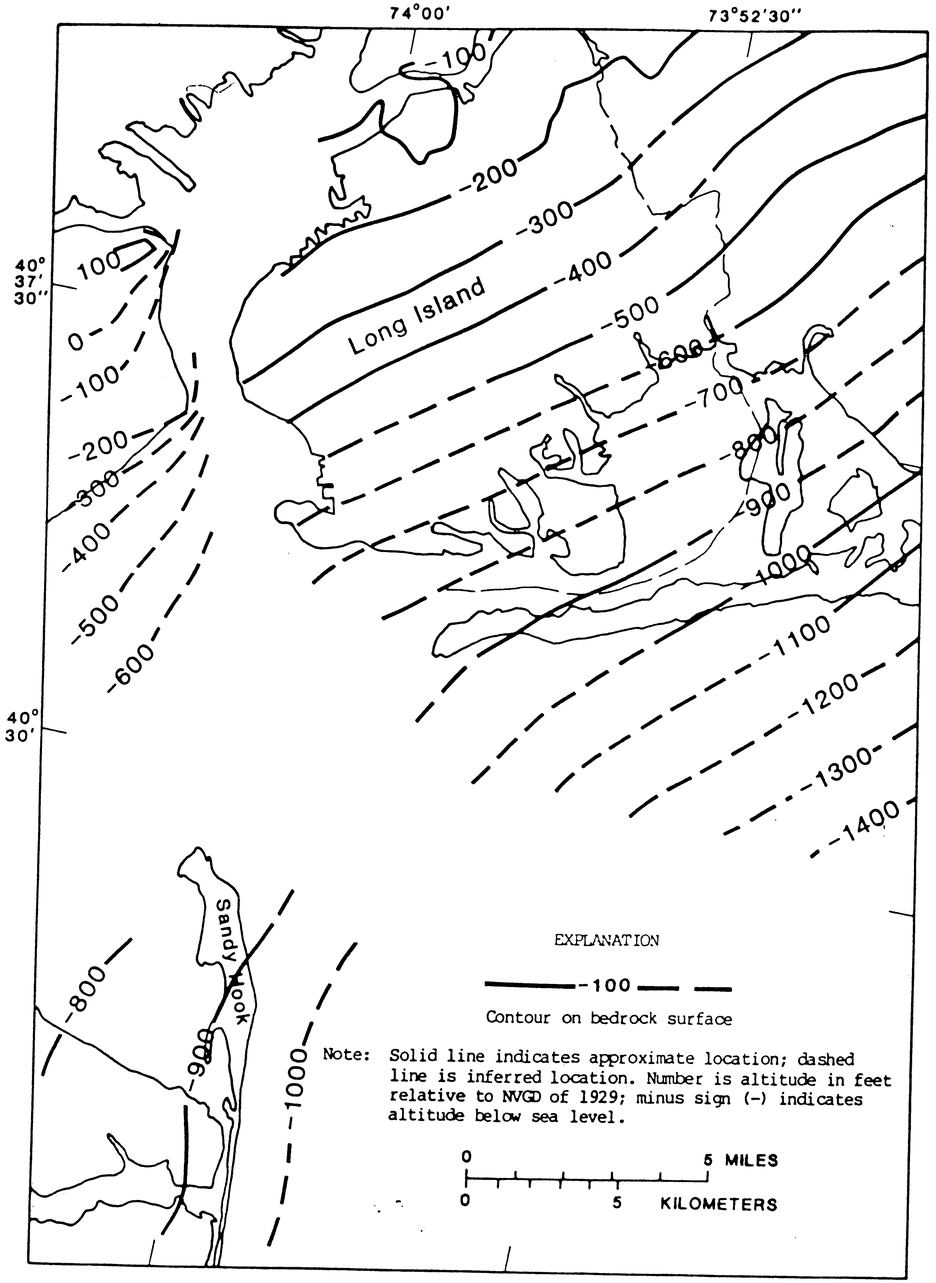


Figure 7b.-- Configuration of the bedrock surface, Long Island, New York. (Modified from Smolansky, D., U.S. Geol. Survey, written comm., 1986)

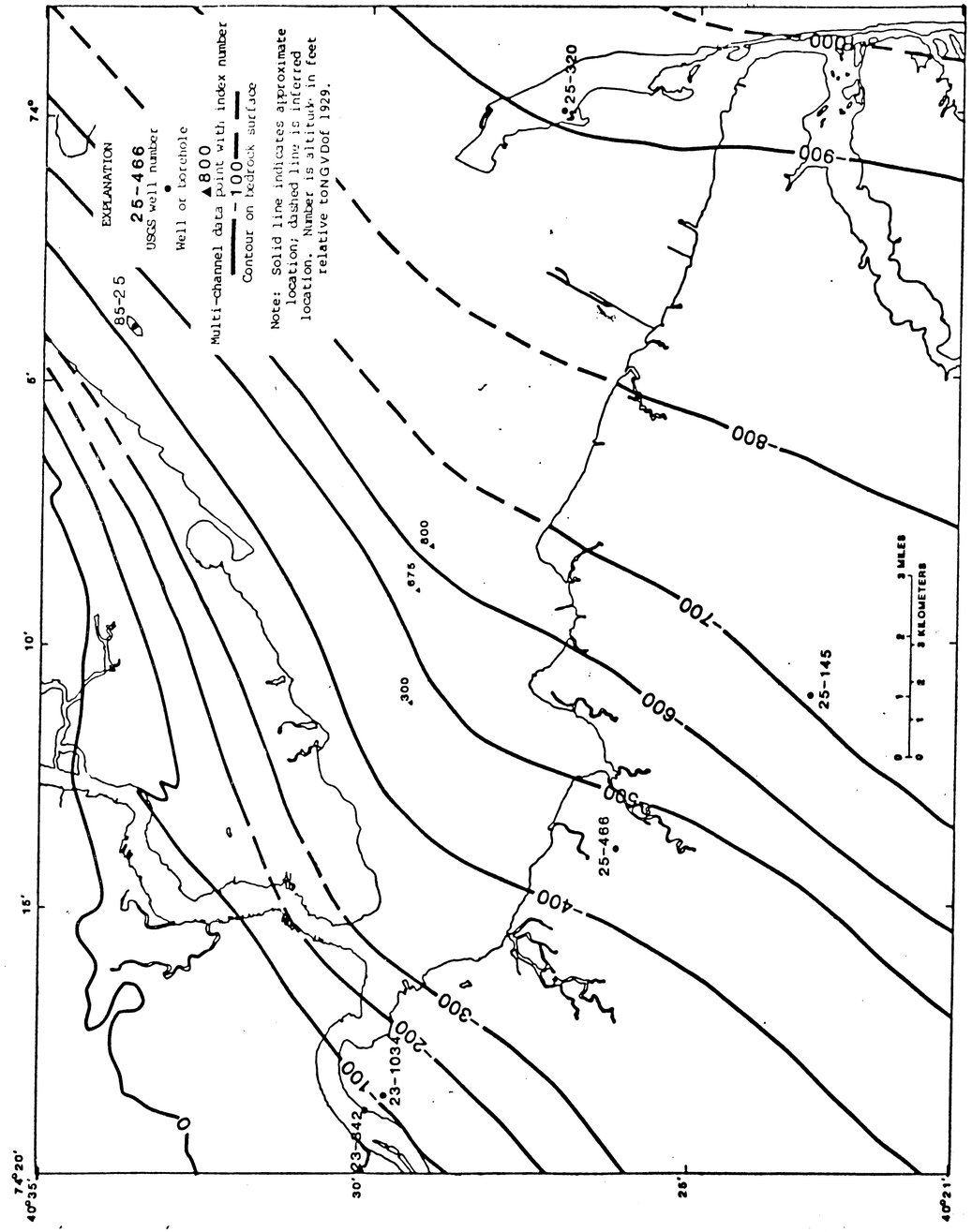


Figure 8.-- Configuration of the bedrock surface in the Raritan Bay area.

on both sections A and B. This simple layered pattern indicates an environment of uniform deposition, generally consisting of a granular material (Wolansky and others, 1982, p. 68). In the Coastal Plain, this pattern of layered reflectors could be produced by acoustic impedence contrast between a predominately sandy material and clay stringers. The depositional history and lithology of the aquifer units favor these criteria. This "seismic facies unit" , defined as a mappable group of reflections (Sangree and Widmier, 1979, p. 138), is separated from a discontinuous-reflection zone above by a strong continuous reflector, which represents the break between materials of contrasting seismic velocities (Missimer and Gardner, 1976, p. 5). This boundary between two seismic-stratigraphic units is interpreted as the boundary between two hydrogeologic units. A structure-contour map of the surface of the middle aquifer (fig. 9) has been prepared from data on this surface along with altitudes (Table 2) for the surface of the middle aquifer on both sides of the bay. The contour lines have been extended in the northeastern corner of the study area in accordance with the results of work presently being conducted by Smolansky and others (U.S Geol. Survey, written commun., 1986) on Long Island (fig. 10).

The discontinuous-reflection zone above the boundary reflector is indicative of a more homogeneous lithology. In clastic settings, this configuration usually represents a homogeneous marine clay (Sangree and Widmier, 1979, p. 138). The middle confining unit composed primarily of the Woodbridge

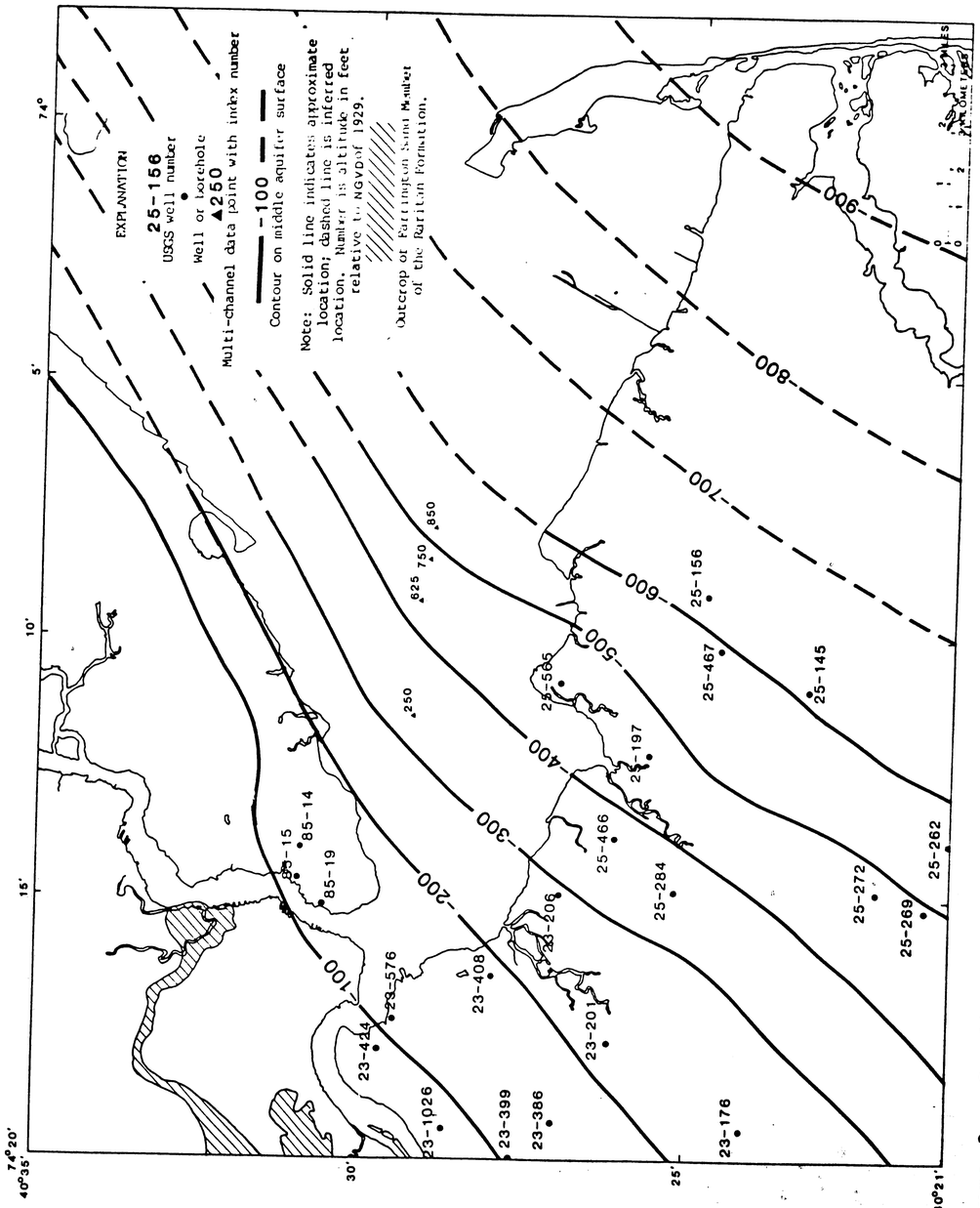


Figure 9.--Configuration of the surface of the middle aquifer in the Raritan Bay area.

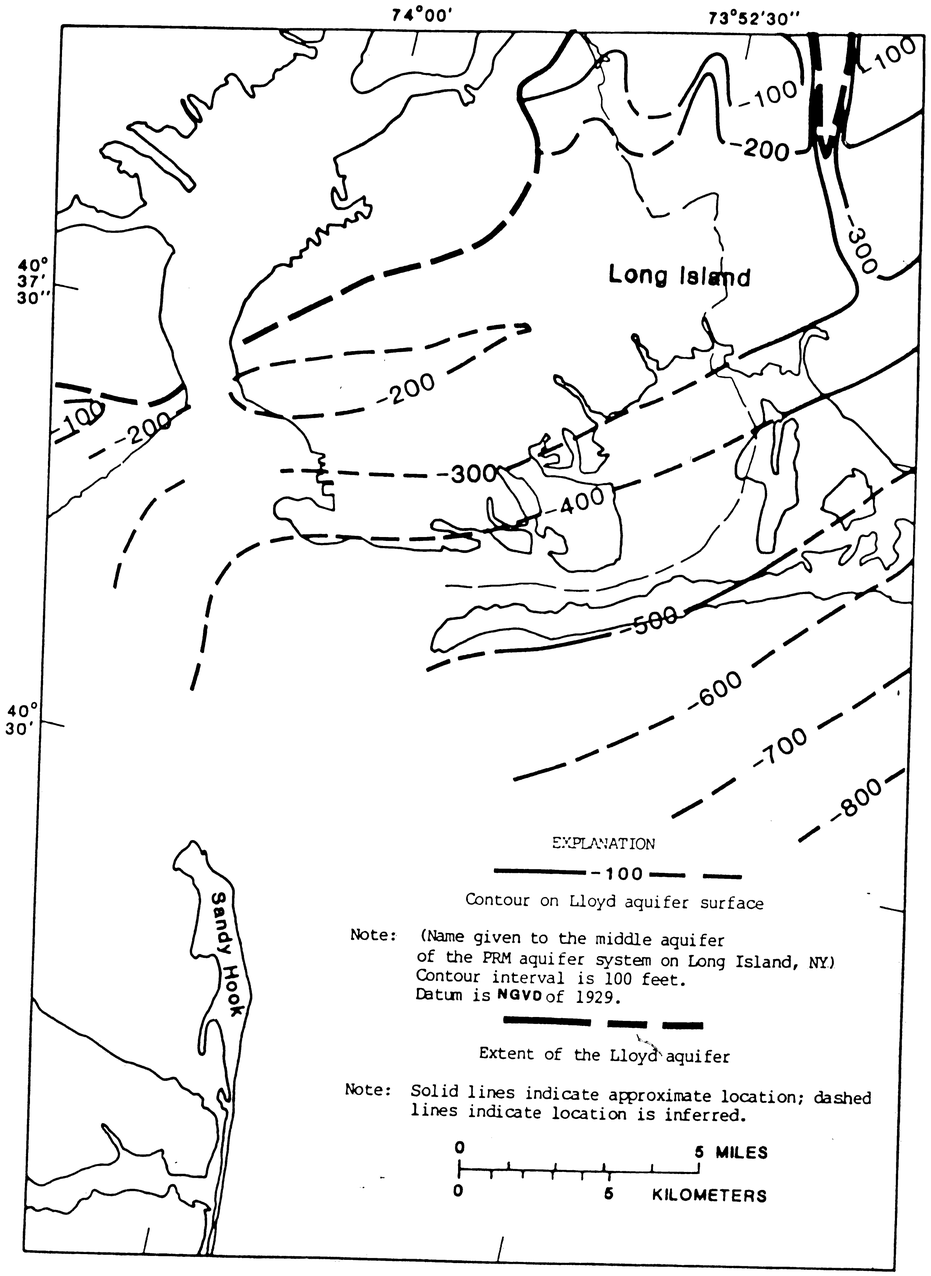


Figure 10.-- Surface altitude of the Lloyd aquifer, Long Island, New York. (Modified from Smolansky, U.S. Geol. Survey, written comm., 1986)

Clay Member conforms to this description. The lithology of the confining unit between the middle and upper aquifer could produce a discontinuous-reflection zone. Occasional discontinuous reflections are attributed to the intermittent sandy stringers present in the Woodbridge Clay. The bounding reflector between this seismic-stratigraphic unit and the overlying layered-reflection zone is interpreted as the surface of the confining unit between the middle and upper aquifer. Figure 11 utilizes the altitudes in table 2, Soren's interpretation of the surface of the clay member at Staten Island (fig. 12a) and reflectors from the shallower single-channel data discussed in the next section. Contour lines in the northeast corner of the study area are extrapolated from work on Long Island (fig. 12b).

The layered-reflection zone above the reflection-free zone in profile A and B is interpreted as aquifer material for reasons similar to those discussed for the middle aquifer. However, the bounding-reflector surface for profile A is not visible due to the processing technique. A muting procedure eliminates data in the upper 100 ft (30.5 meters) to provide a clear picture at depth. As the location of profile B is near the outcrop area of the upper aquifer, the contact between the confining unit and upper aquifer is likely to lie at a depth less than 100 ft (30.5 meters). The bounding-reflector is observed in profile A and correlates well with data on the southern side of the Bay (table 2). Depth to reflectors as determined from the single-channel data correlates well with

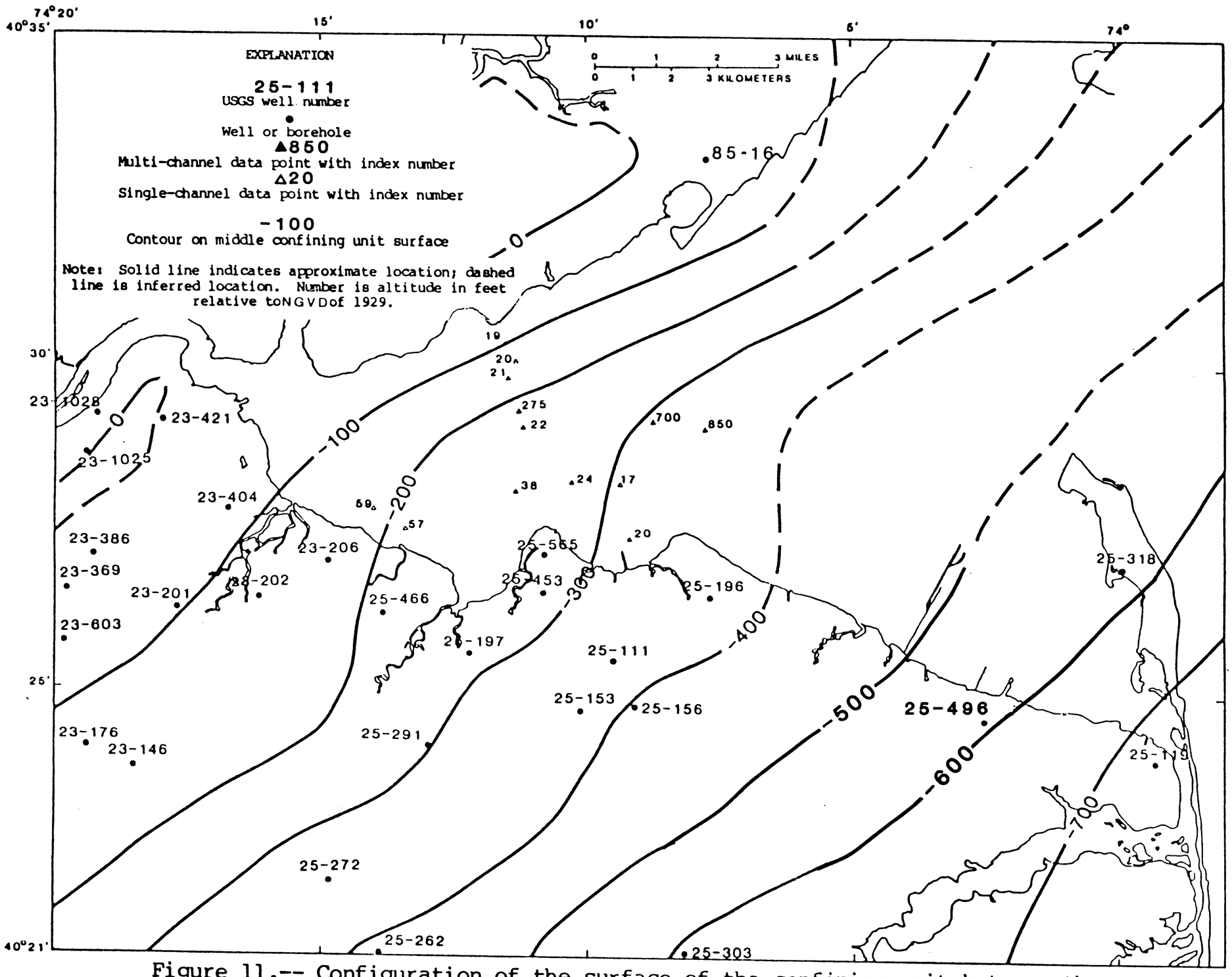


Figure 11.-- Configuration of the surface of the confining unit between the middle and upper aquifers in the Raritan Bay area.

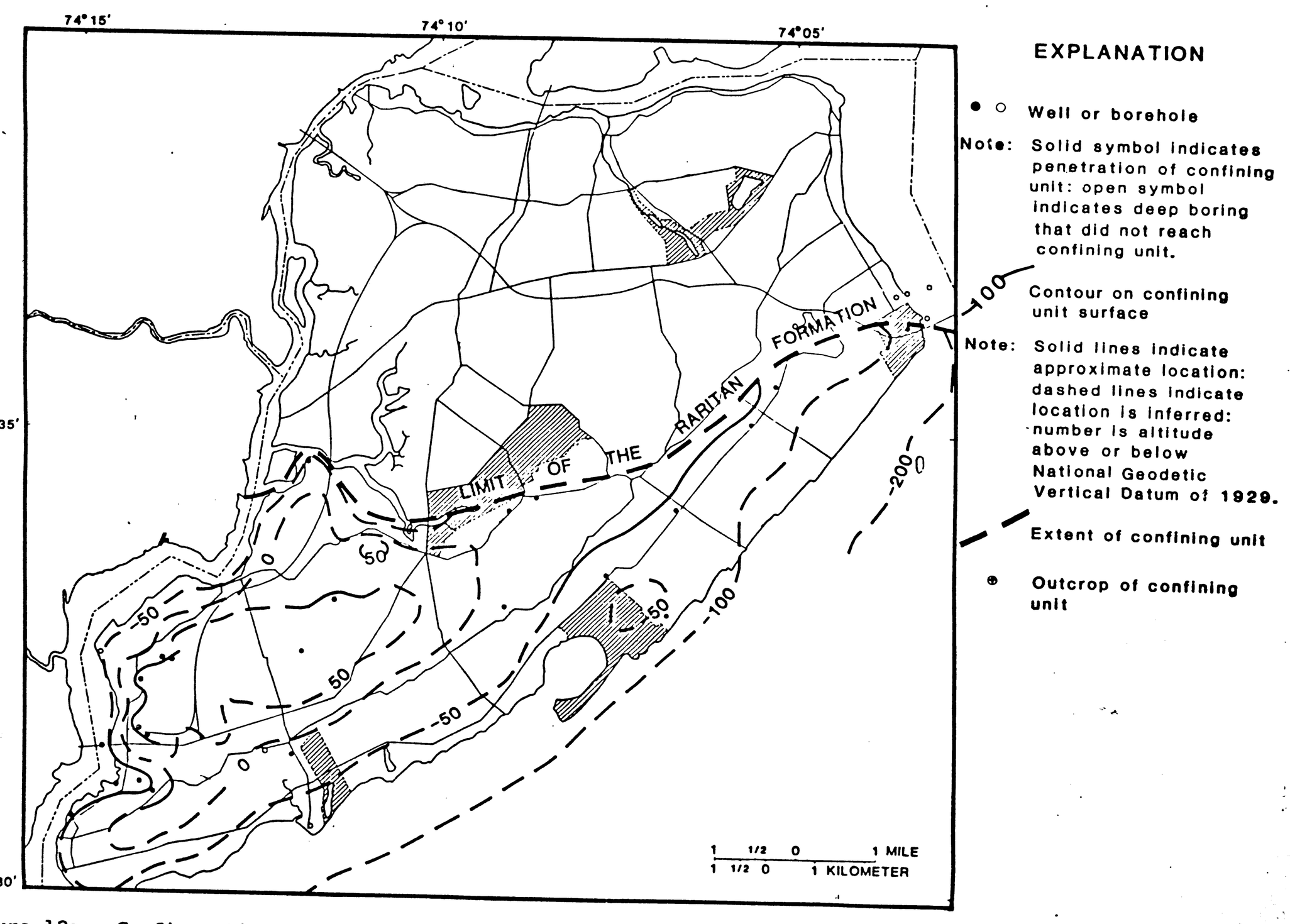


Figure 12a.--Configuration of the surface of the confining unit between the middle and upper aquifer on Staten Island, New York. (Modified from Soren, J., U.S. Geol. Survey, written commun., 1986)

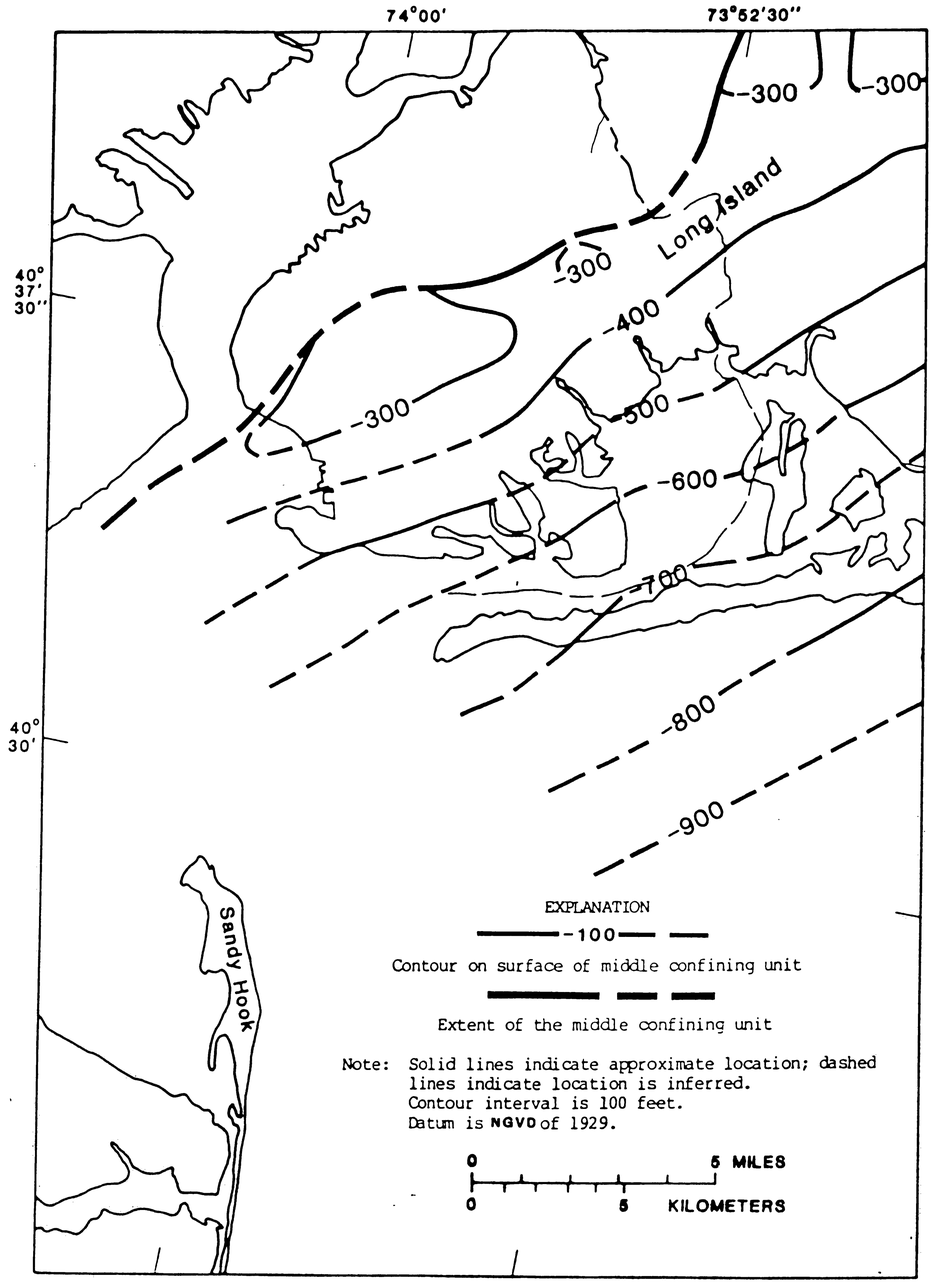


Figure 12b.--Surface altitude of the middle confining unit, Long Island, New York. (Modified from Smolansky, U.S. Geol. Survey, written commun., 1986).

the depth of this boundary reflector. The contour map of the surface of the upper aquifer, presented in figure 13, is based on these data.

The marine seismic data were not useful for locating the surface of the upper confining unit (fig. 14). This map is based only on the altitudes determined from borings and presented in table 2. A somewhat distorted layered-reflection zone is evident above the zone interpreted to be the upper aquifer. The silty clay with abundant fine-grained sand and silt stringers typical of this unit would produce a pattern of this character. It is also possible that proximity to the muted zone may have some effect on the quality of the adjacent data.

Interpretation of USGS Single-Channel Data

Approximately 7.5 miles (12.1 km) of single-channel marine seismic-reflection data are used to supplement the multi-channel reflection data (fig. 15). Unfortunately this single-channel data represents only a part of the data collected. Limited penetration is attributed to gassy sediments of the Bay floor. In Holocene sediments, methane is one end product of anaerobic bacterial decomposition of organic matter (Claypool and Kaplan, 1974, p. 100). Gas bubbles, when present in sediments even in small amounts, dominate the acoustic characteristics of the sediment. For the most part, attenuation due to gas bubbles in sediments has

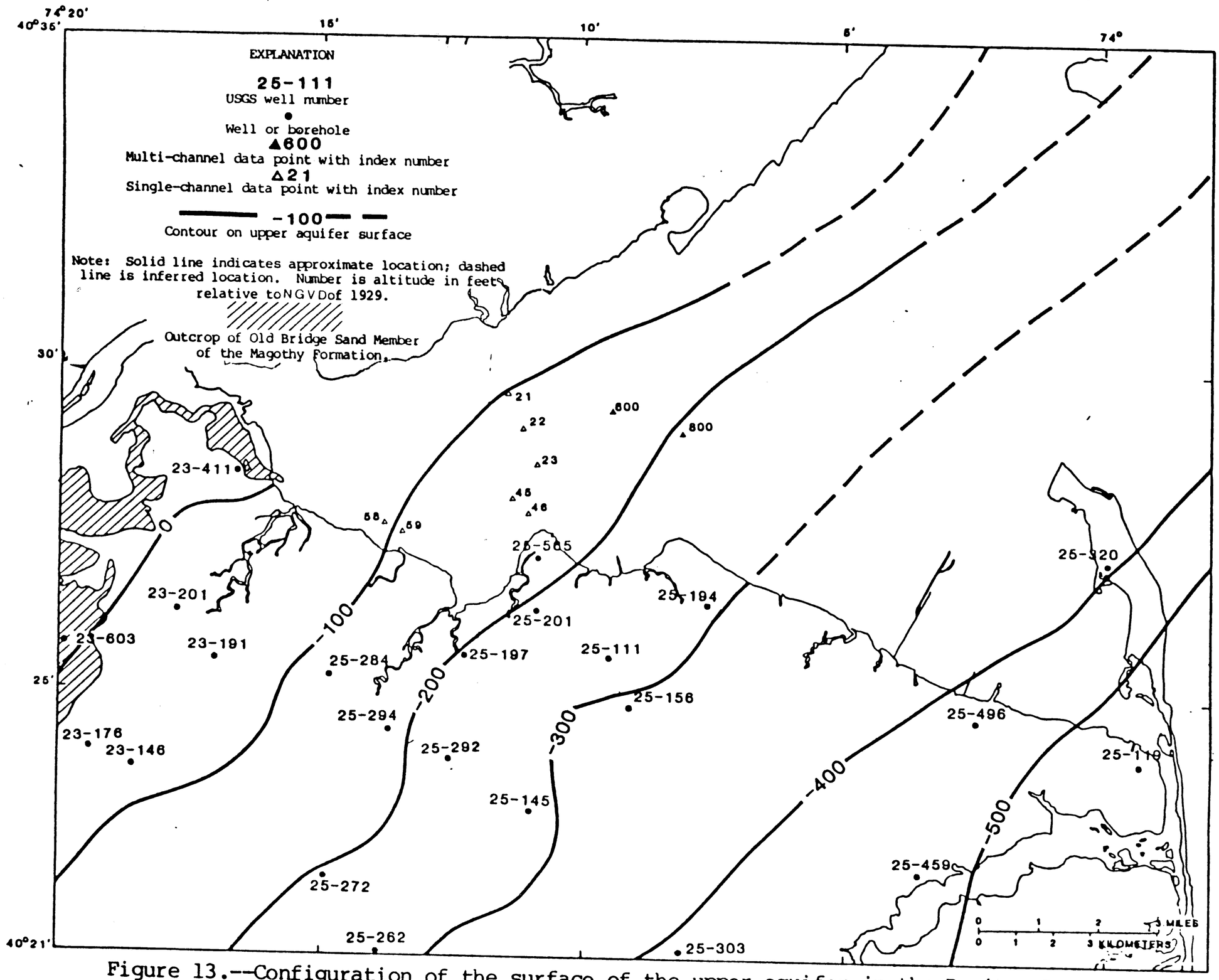


Figure 13.--Configuration of the surface of the upper aquifer in the Raritan Bay area.

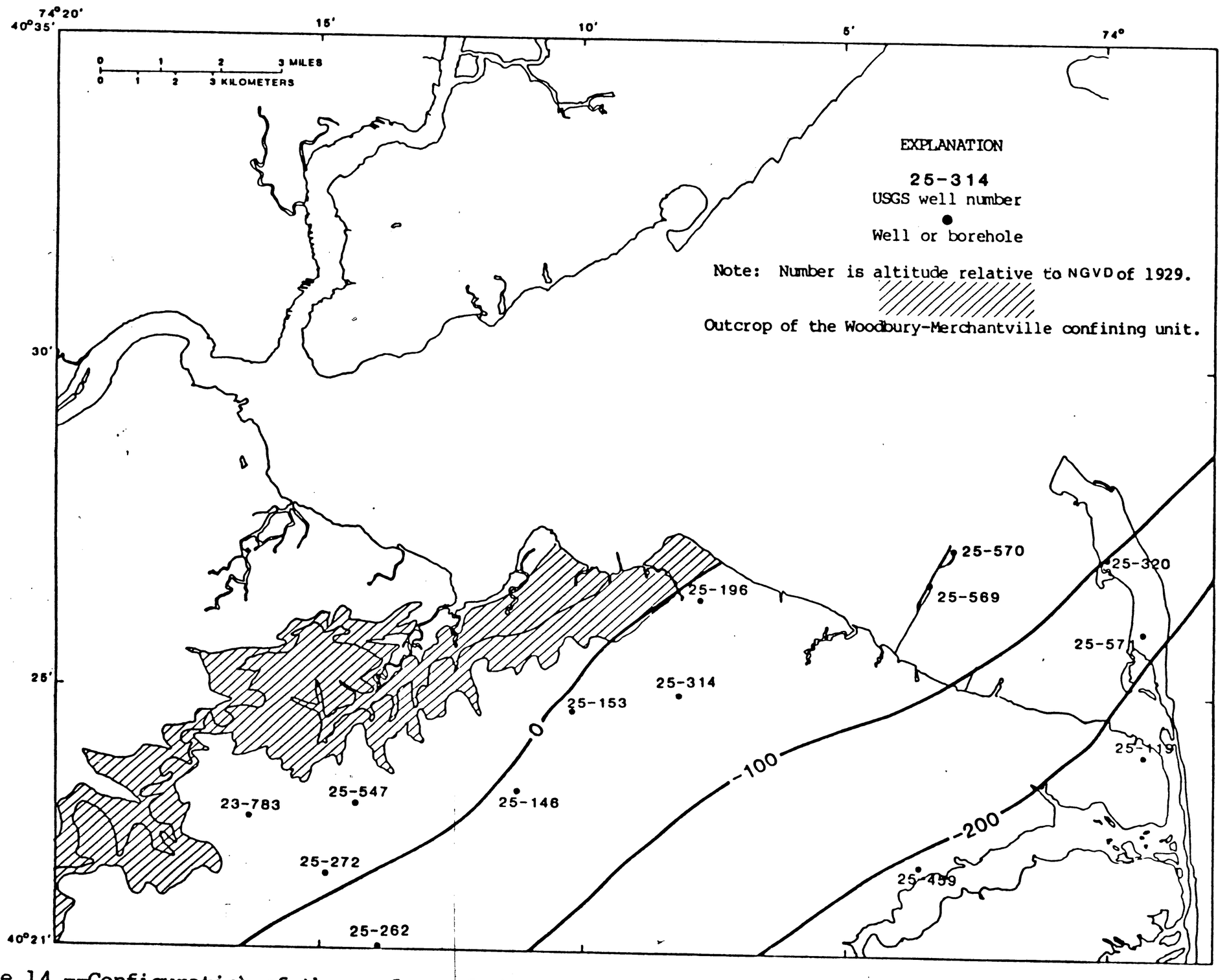


Figure 14.--Configuration of the surface of the Woodbury-Merchantville confining unit in the Raritan Bay area.

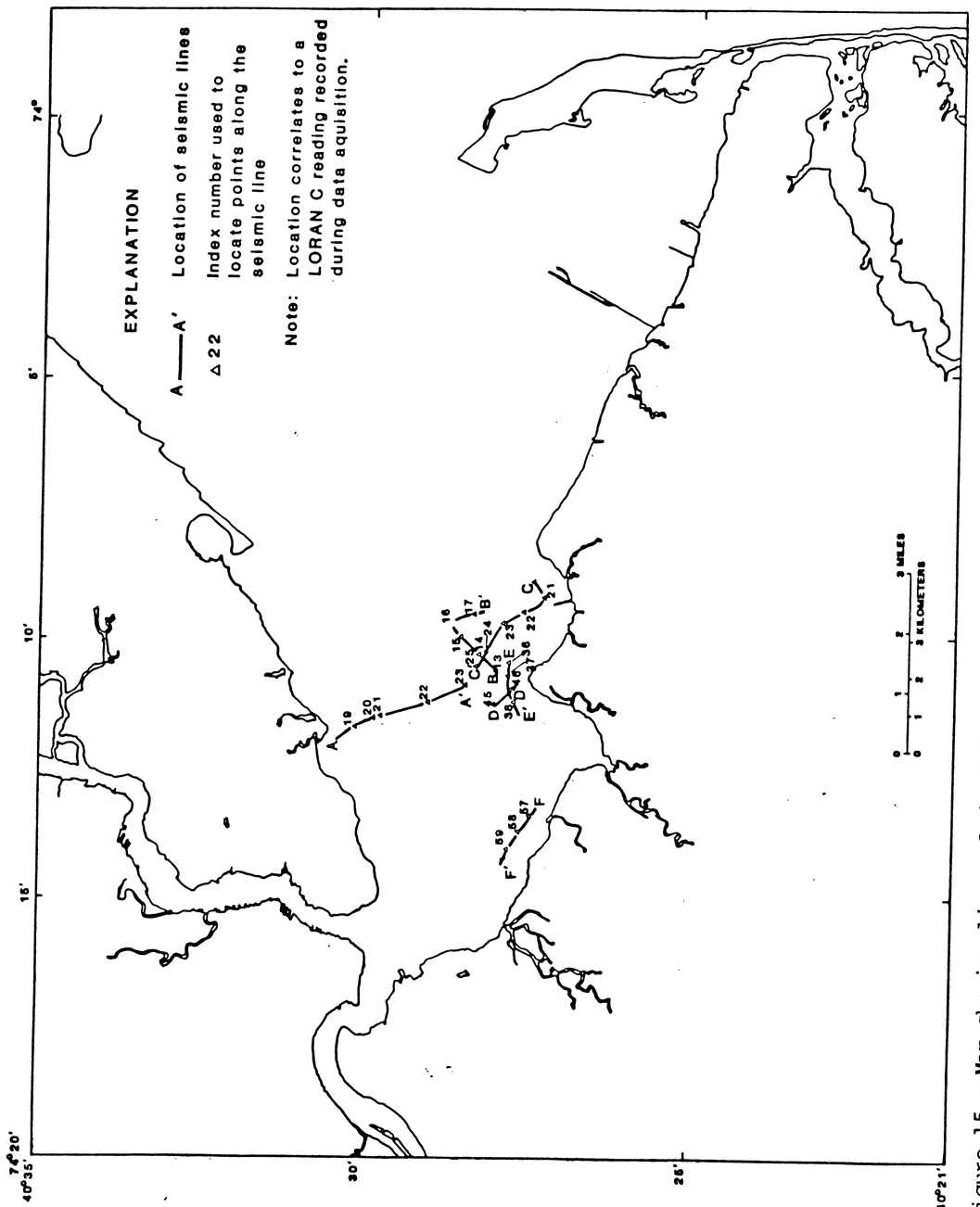


Figure 15.--Map showing lines of the USGS single-channel marine seismic-reflection data in Raritan Bay.

been reported as an interference rather than as a constructive element (Hampton and Anderson, 1974, p. 258).

Figure 16a-f presents the processed data along with the interpretation of reflectors. The sections include an index number used to orient the profiles along the lines illustrated in figure 15. These index numbers correspond to LORAN C measurements made during the data collection. Aside from its limited coverage, the single-channel data are useful and supportive of the other data used in the study.

Of particular interest is seismic section A-A' which provided evidence of two strong reflectors. These reflectors are interpreted to be the top of the middle confining unit and the top of the upper aquifer. The reflectors indicate a gradual dip to the southeast then become almost horizontal. This reflector configuration supports the flattening of the surfaces of the hydrogeologic units shown in figures 11 and 13. Section F-F' also shows strong supporting evidence in an area where little offshore data existed. Two strong reflectors are observed at depths of 95-110 ft (29.0-33.5 meters) and 195-225 ft (59.4-68.6 meters) and correlate well with data onshore directly adjacent to that area. The remainder of the data presented exhibit reflector configurations that supported and assisted preparing the figures in the previous section.

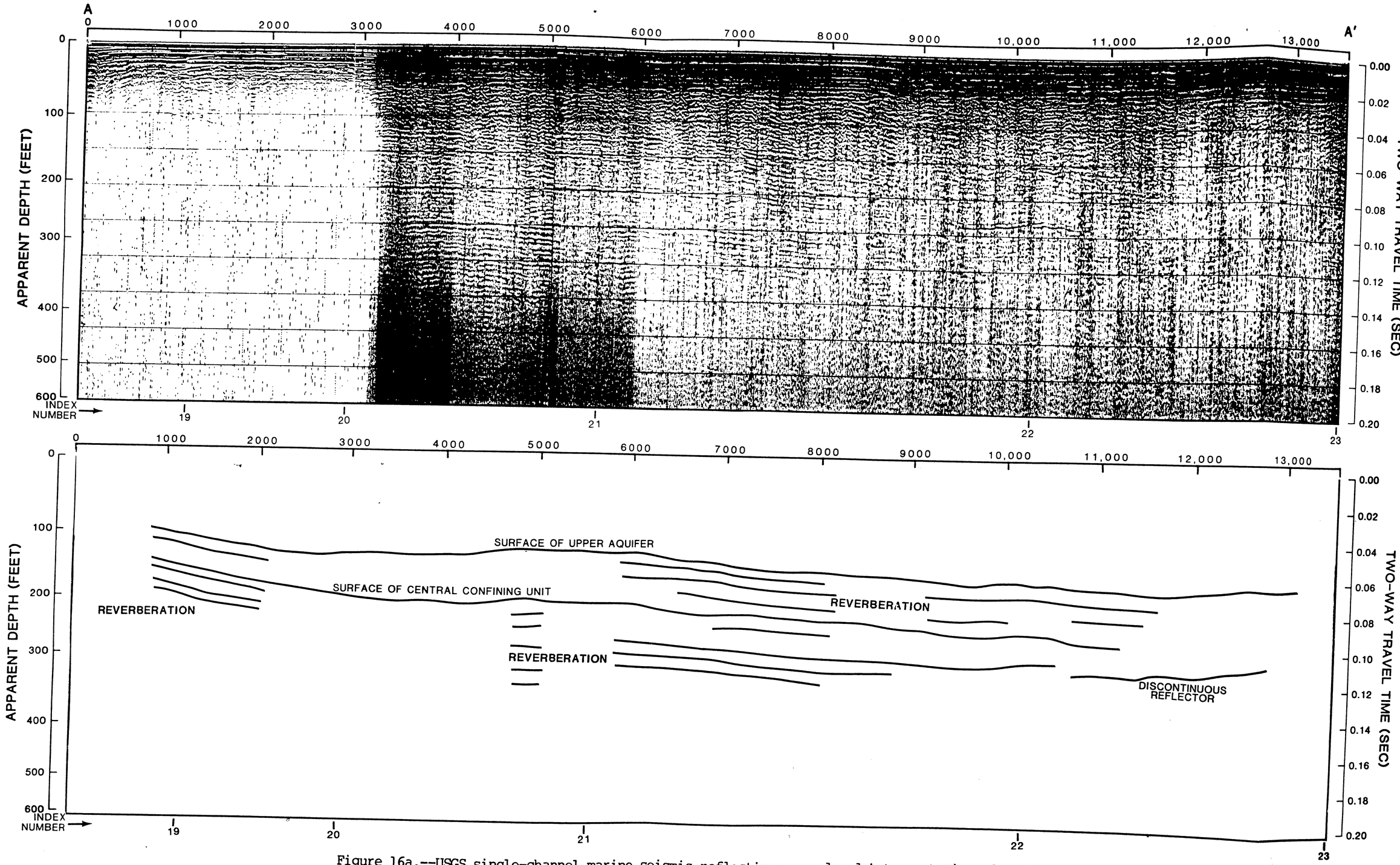


Figure 16a.--USGS single-channel marine seismic-reflection record and interpretation of reflectors under the Raritan Bay, Section A-A'.

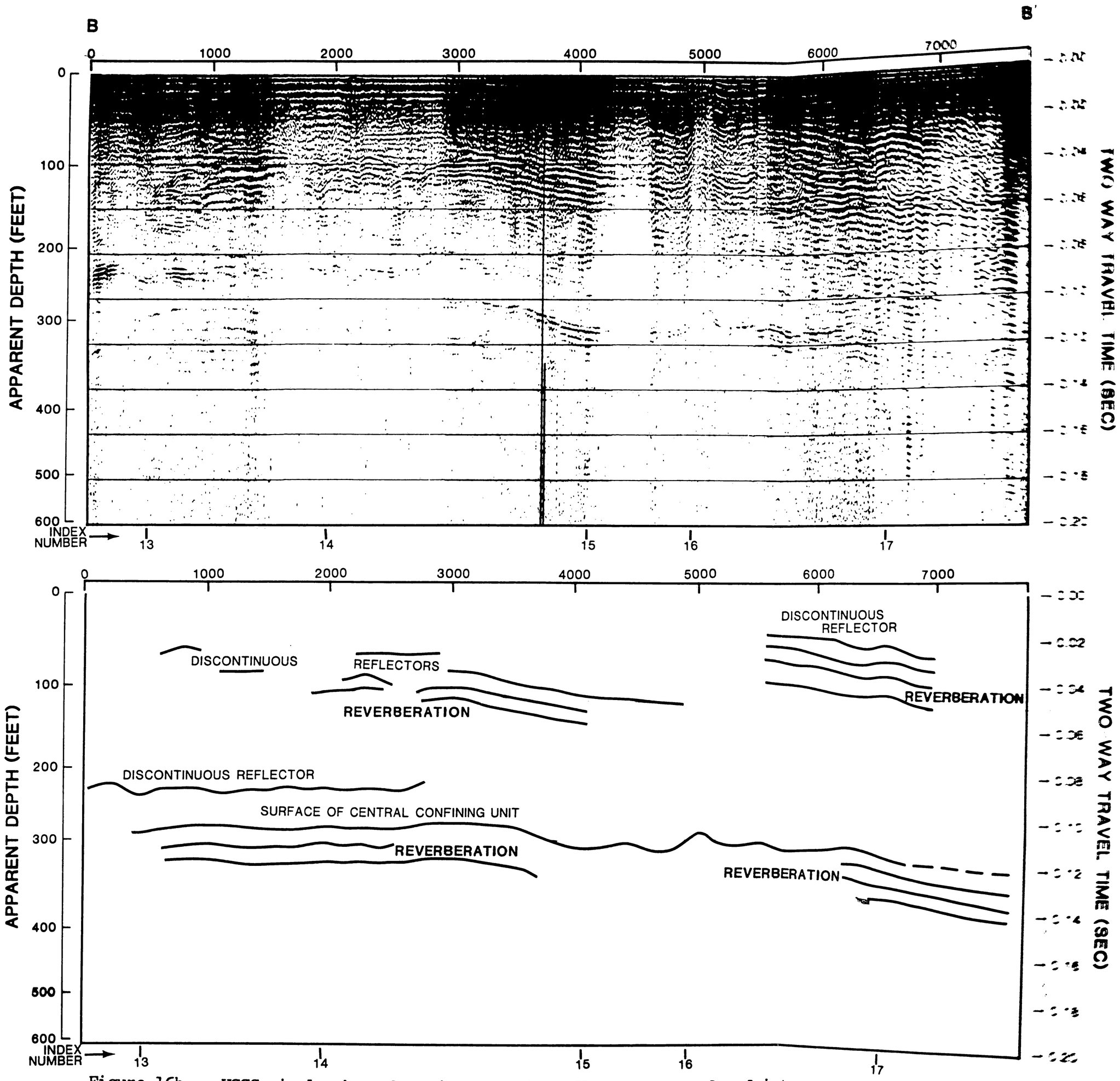


Figure 16b.-- USGS single-channel marine seismic-reflection record and interpretation of reflectors under the Raritan Bay, Section B-B'.

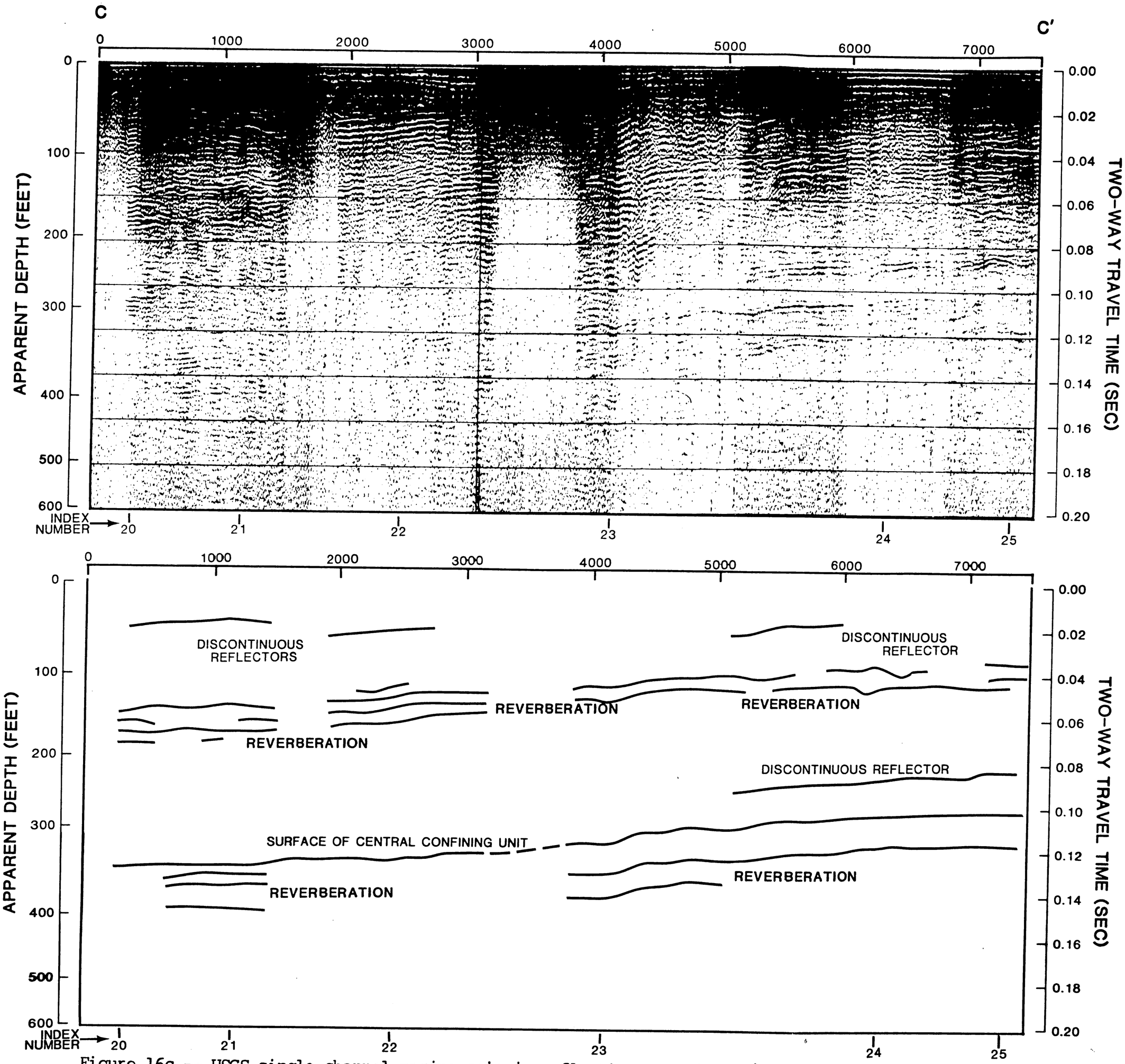


Figure 16c.-- USGS single-channel marine seismic-reflection record and interpretation of reflectors under the Raritan Bay, Section C- C'.

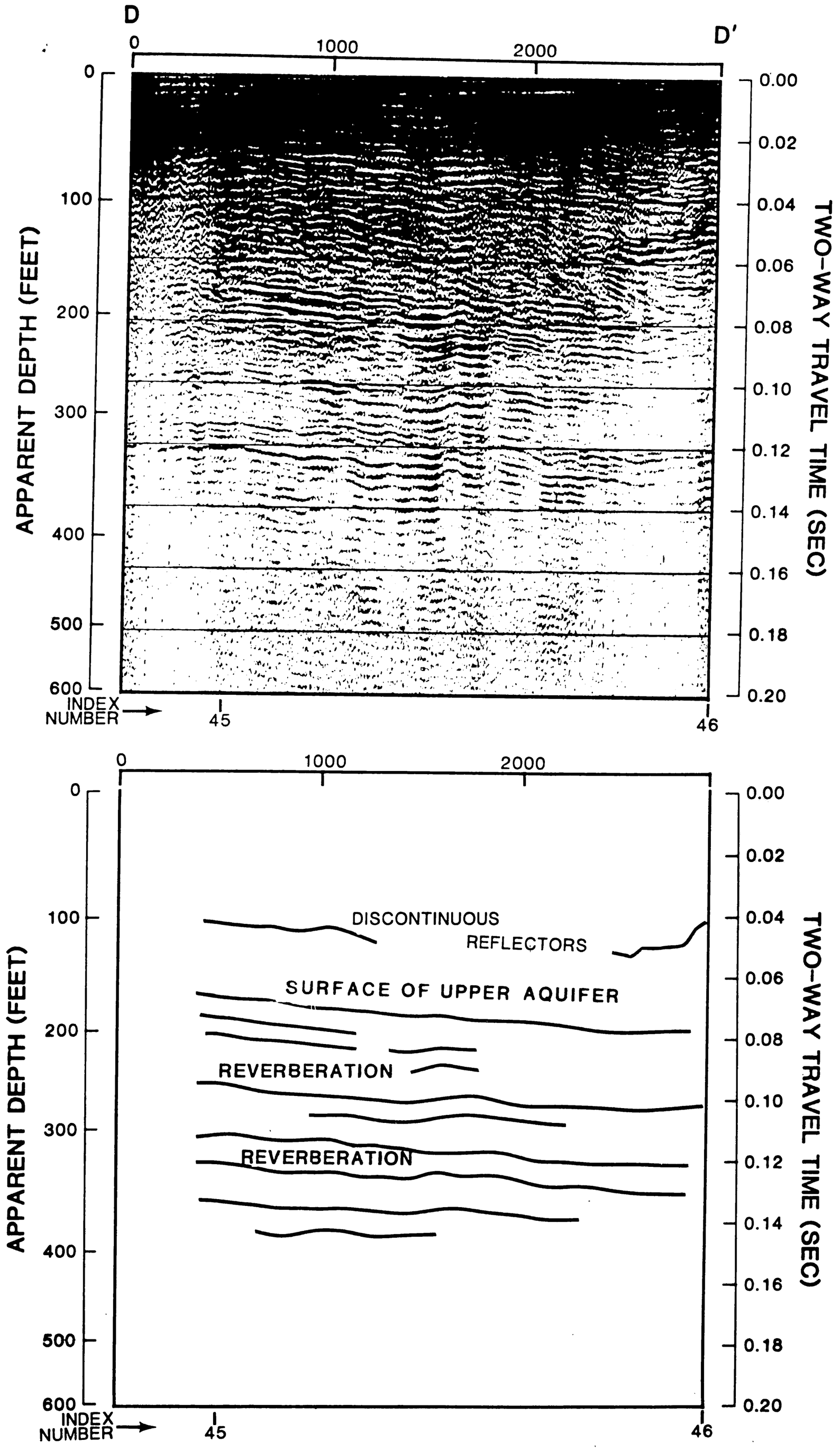


Figure 16d.-- USGS single-channel marine seismic-reflection record and interpretation of reflectors under the Raritan Bay, Section D-D'.

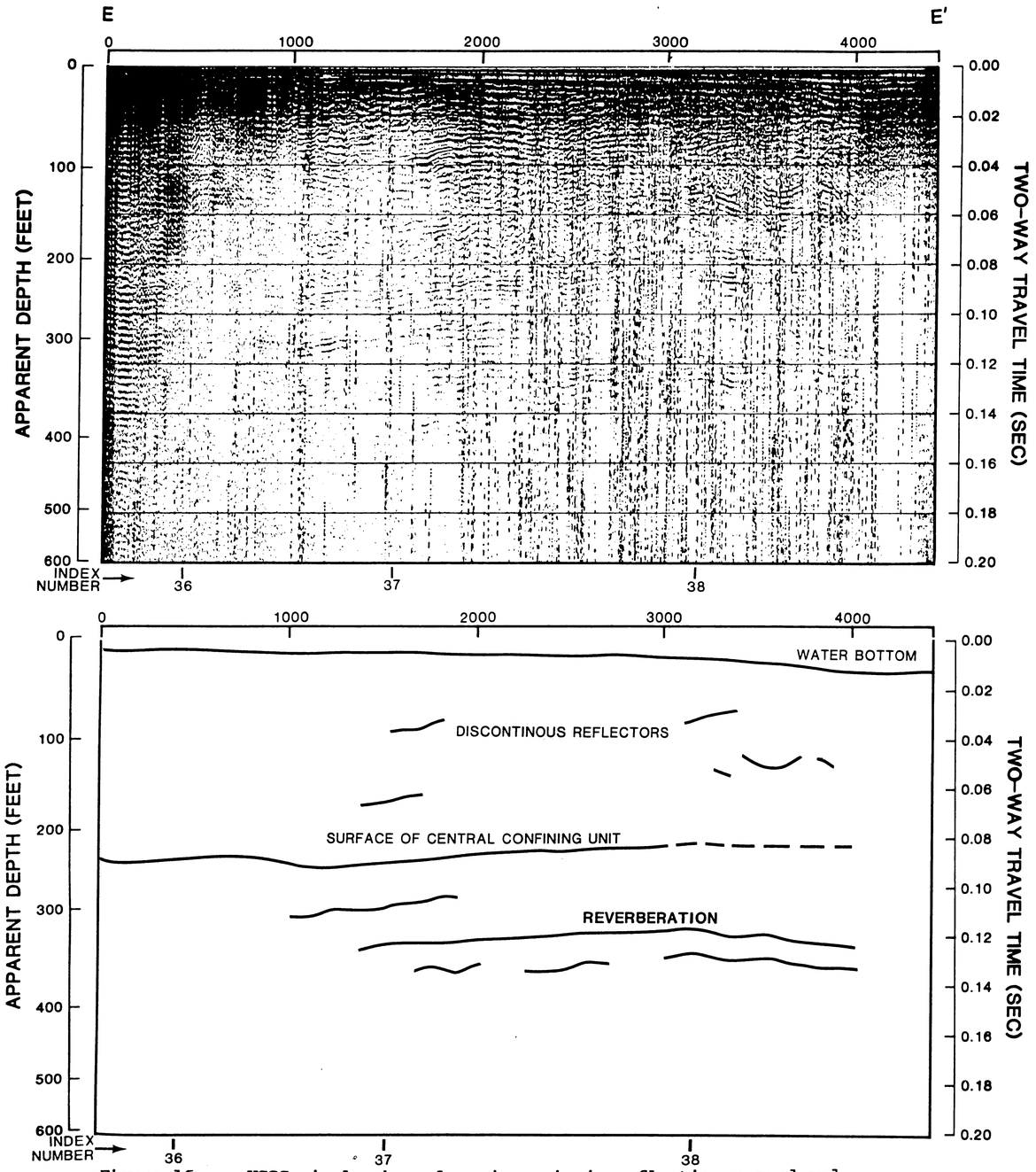


Figure 16e.-- USGS single-channel marine seismic-reflection record and interpretation of reflectors under the Raritan Bay, Section E-E'.

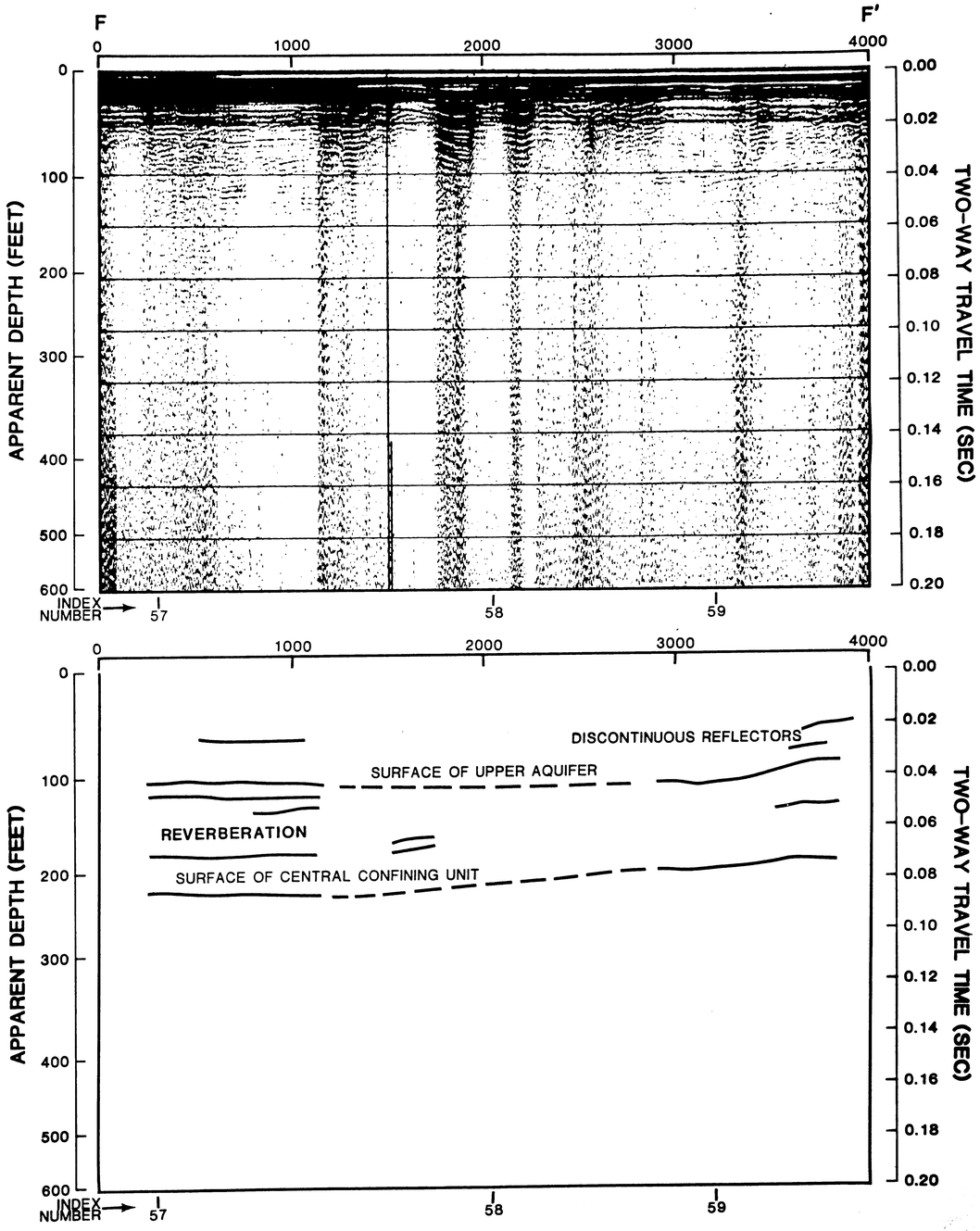


Figure 16f.-- USGS single-channel marine seismic-reflection record and interpretation of reflectors under the Raritan Bay, Section F-F'.

COMPUTER SIMULATION

The primary purpose of this section is to define possible locations of a saltwater interface under the prepumping conditions as a way of testing the concepts of hydrogeologic framework. The method is applied to part of the upper aquifer in the PRM aquifer system in the northern part of the study area. Currently (Schaefer and Walker, 1981, p. 1), saline ground water is present in the Keyport-Union Beach area; this situation gives rise to several questions: Has a saltwater front always existed in the upper aquifer? If so, how extensive is the front? Is the position of the interface dependent upon the leakance of the overlying confining unit? What are plausible locations for this idealized sharp interface under prepumping conditions? Will the developed hydrogeologic framework aid in defining prepumping conditions? These are all pertinent questions that must be addressed when studying the problem of saltwater intrusion in the study area. The following section presents a method and preliminary results that assist in answering these questions. It should be noted that research is ongoing by the USGS, New Jersey District, and the results presented in this report will serve as the groundwork for future research.

Theoretical Background

In order to avoid the numerical problems that often accompany solute-transport simulations, a simple interface-locating technique referred to as "trimming" is used (Buxton, Herbert, U. S. Geol. Survey, written commun., 1985). The interface between fresh and saline water is treated as a sharp interface although it is actually a zone of mixing (Guswa and Le Blanc, 1985, p. 12). The pressure head of the saltwater along the interface increases at a rate greater than that of the freshwater at depth due to its greater density (Buxton, Herbert,U.S. Geol. Survey, written commun., 1985). At steady state along the interface, the pressure exerted by a column of fresh water is equal to that exerted by a column of assumed static saltwater (Meisler and others, 1984, p. 8):

$$P_s = P_f \qquad (1)$$

where:

P_f= pressure exerted by a column of fresh water.

P_s= pressure exerted by a column of salt water.

Along the interface, the freshwater head necessary to balance the static saltwater may be calculated from:

$$h_f = \frac{z(p_s - p_f)}{p_f} \qquad (2)$$

with:

h_f= freshwater total head along interface (ft)

z = depth below sea level (ft)

p_s = density of saltwater (g/cm^3)

p_f = density of freshwater(g/cm^3)

A cross-sectional flow model using the framework along a flow line is developed using the USGS Modular Three-Dimensional Finite-Difference Flow Model (McDonald and Harbaugh, 1984). The IBOUND array dictates the status of each node in the model. The array consists of three numbers: 1 indicates an active node, -1 indicates a node with a specified head, and 0 indicates an inactive node. The method of interface-locating systematically estimates the position of the interface through a trial and error technique. Transmissivity values of zero are assigned to nodes in the IBOUND array repeatedly to approximate the position of the interface in each simulation. These nodes are carefully chopped off until simulated freshwater heads along the interface correspond acceptibly well with the calculated heads required to balance the static saltwater front. The configuration of the chopped blocks represents approximately the position of an idealized sharp saltwater/freshwater interface.

Other research has successfully utilized this interface-locating technique when dealing with a saltwater intrusion

problem. In Puerto Rico, Bennett and Guisti (1971) adapted the method to an analog model in a coastal environment. Interface-locating has also been applied to an unconfined system in Cape Cod, Massachusettes by Guswa and LeBlanc (1980). Meisler and others (1984) simulated the effect of eustatic sea-level changes on the saltwater-freshwater interface of the northern Atlantic Coastal Plain.

Model Design

Discretization

A hydrogeologic section was selected to correspond to the framework along a flow line in the prepumping flow system (fig.17a). The location of this line is estimated from historical water-level data gathered for other reports (fig.17b)(Barksdale and others, 1958, p. 110; Martin, M. M., U.S. Geol. Survey, written commun., 1986). This section was selected for several reasons: (1) it passes through the Keyport-Union Beach area where saltwater intrusion has closed several local wells tapping the upper aquifer (Schaefer and Walker, 1981, p. 15); (2) the section extends through the area of the bay where the greatest density of marine seismic data are available; and (3) the southern part of the section extends through an area where considerable specific-capacity data are available.

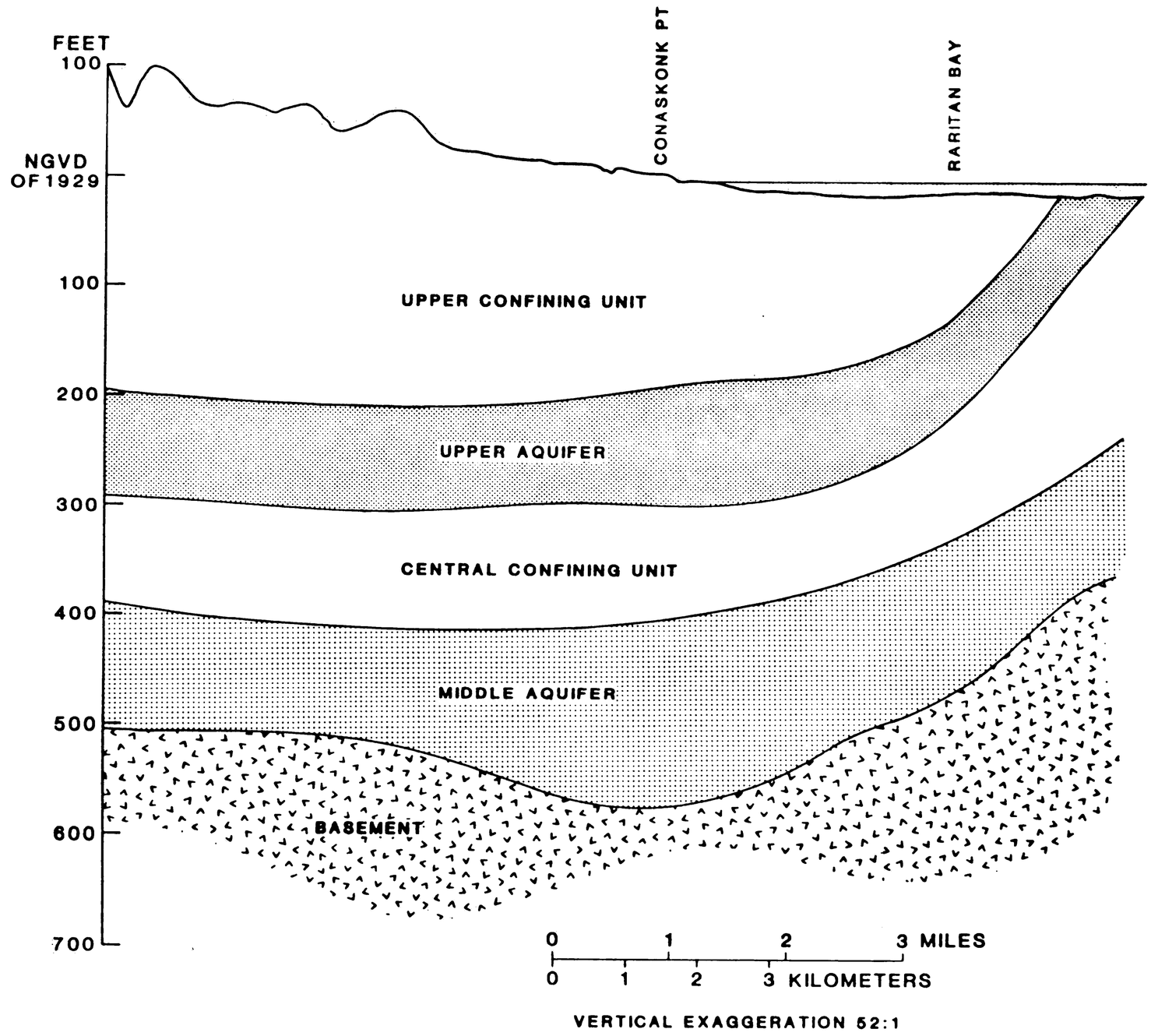


Figure 17a.-- Generalized hydrogeologic cross-section in the Raritan Bay area used in the 2-D computer simulation.

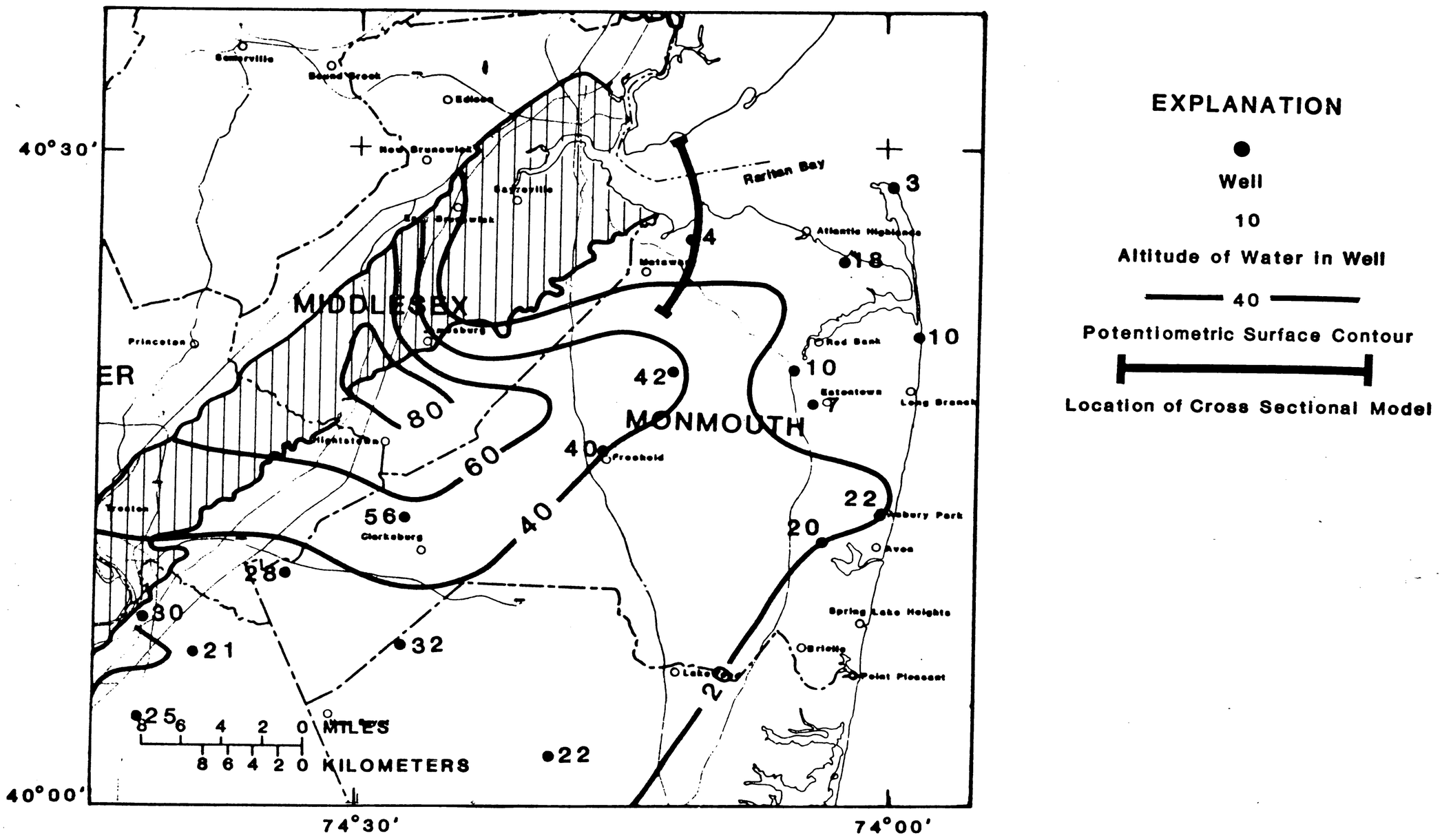


Figure 17b.-- Map showing location of the cross-section in the pre-pumping flow system of the upper aquifer in the Raritan Bay area.

Since the saltwater is present only in the upper aquifer, discretization is limited to this unit and the overlying confining unit. The section was discretized with a finite-difference grid consisting of 12 layers and 47 columns (figure 18a). This configuration of layers and columns was chosen -to allow for leakage between layers. Eight layers, each with a thickness of 25 ft (7.6 meters), were used to represent the upper confining unit whereas the remaining four layers represent the upper aquifer (figure 18b). The thinning of the upper aquifer is represented by varying the transmissivity values in the input data set. Many nodes in the upper right-hand corner of the grid are inactive because they are outside of the physical system (fig. 18b).

Boundary Conditions

Several boundary conditions are simulated to test the sensitivity of the model to arbitrary boundaries.

Boundary configuration 1 (fig. 19a): Specified heads are located around the entire border of the model except along the base where a no-flow boundary is assumed. This assumption comes from the previous work in this report which indicates that the middle confining unit is continuous in the study area and initial assessment of aquifer-test data indicating almost no vertical leakage (Pucci, A. A., Jr., U.S. Geol. Survey, oral commun., 1986). The values for specified heads in the onshore part of the grid (top left) correspond to the altitude of the water table. The values for specified heads under the

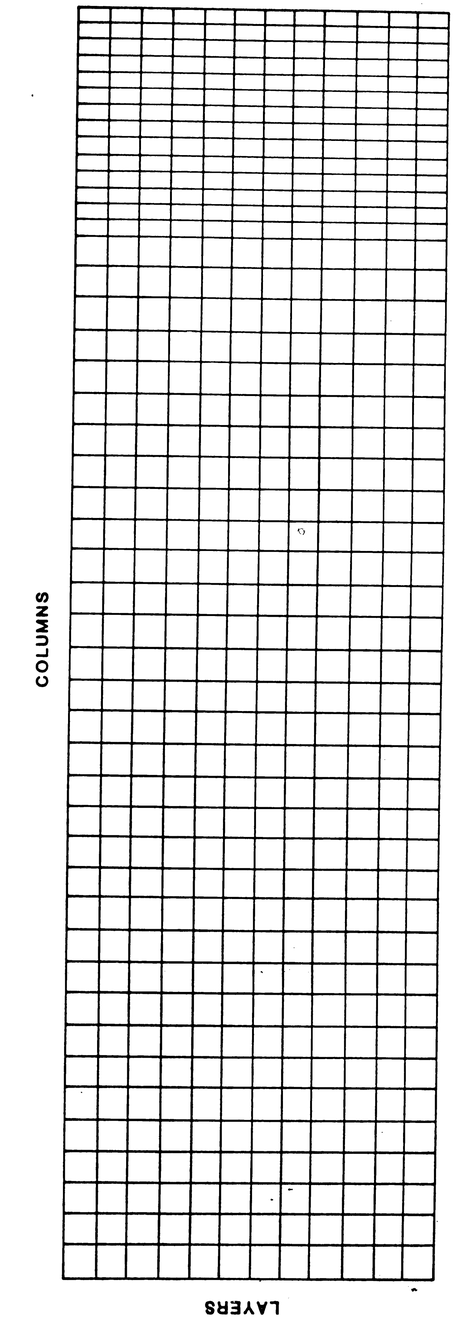


Figure 18a.— Cross sectional grid used for the simulation.

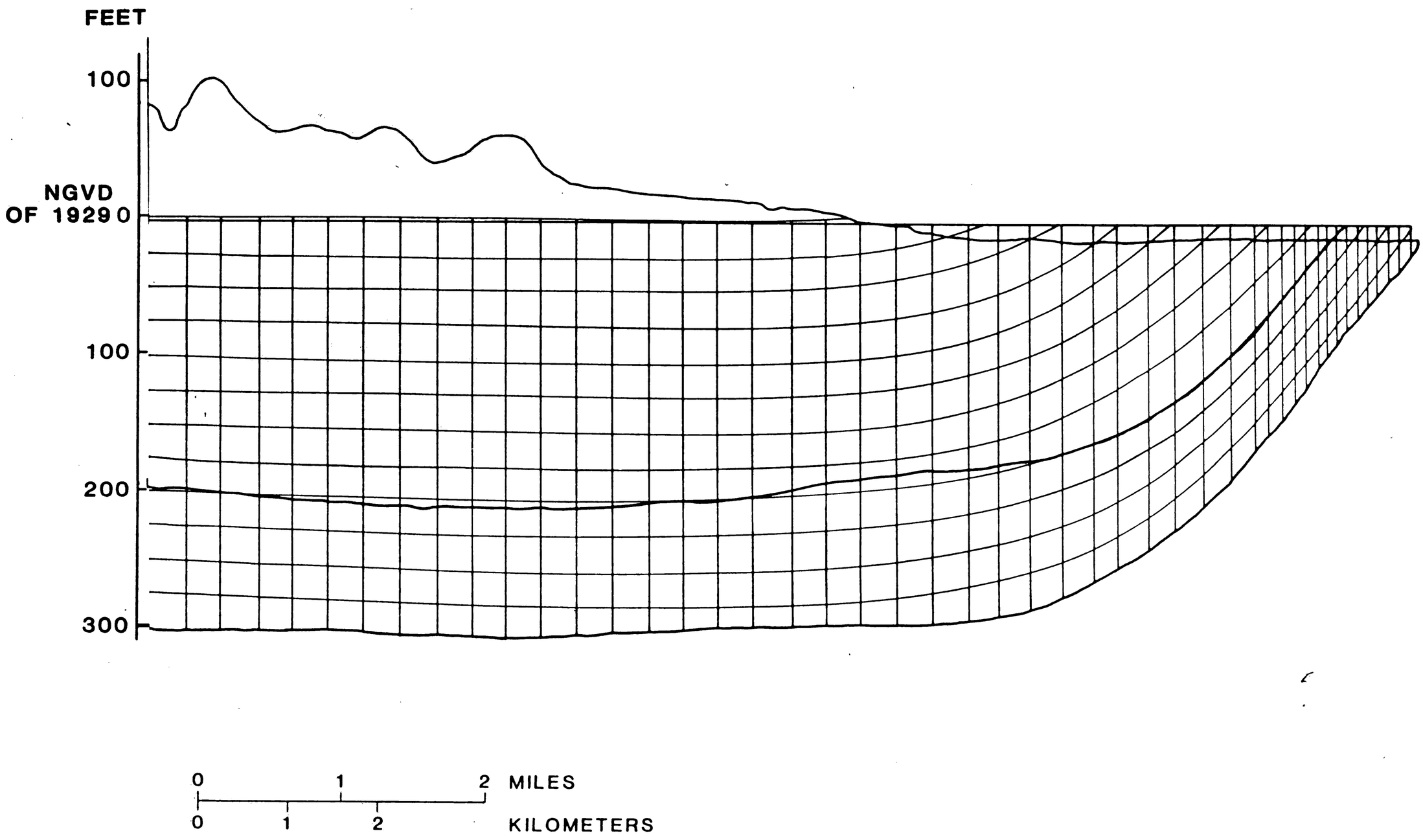


Figure 18b.— Cross sectional model grid and its relation to the physical system.

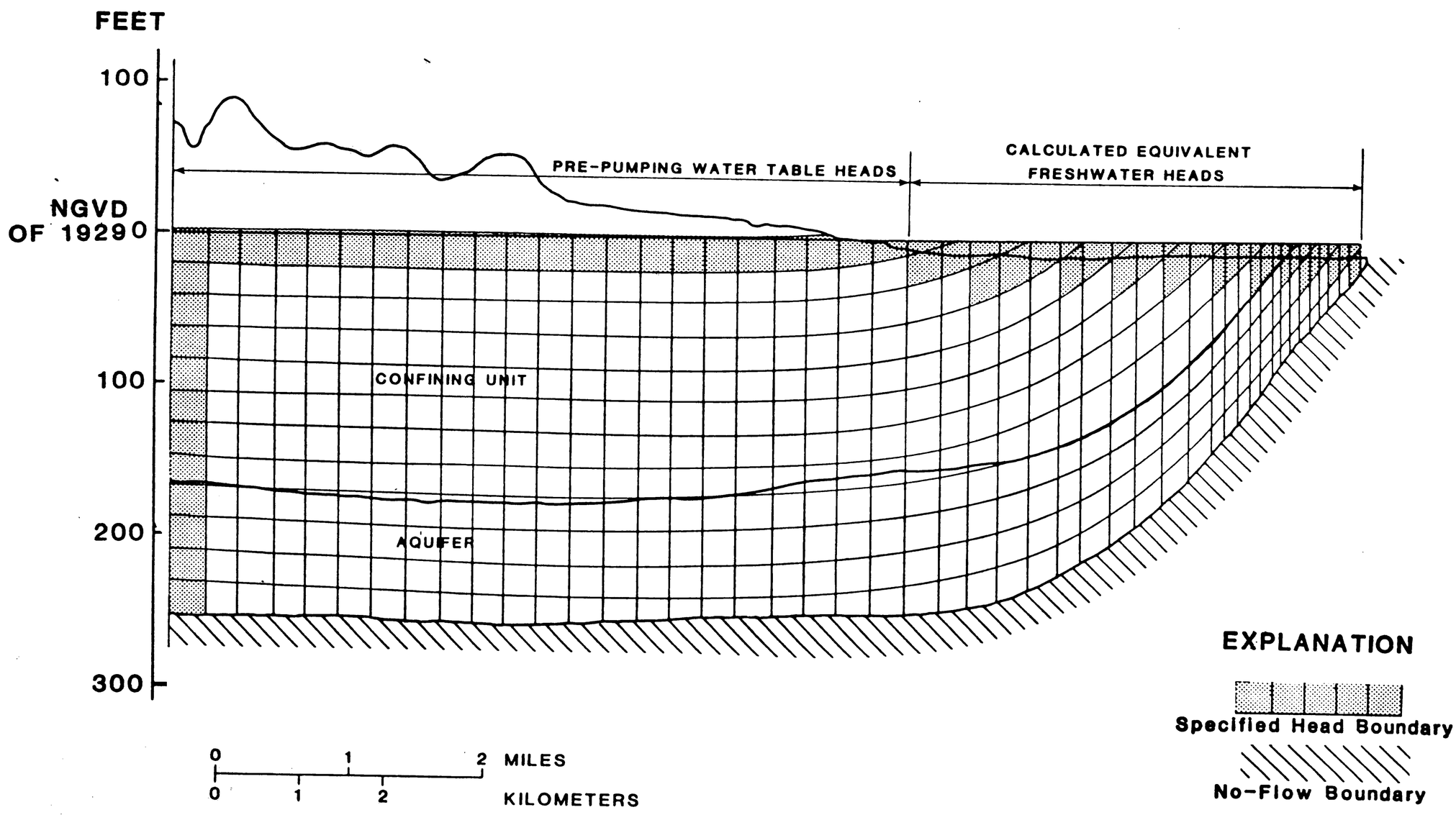


Figure 19a.-- Boundary configuration 1, utilizing specified head nodes.

Bay are assigned by calculating the equivalent freshwater head. This is the most accurate boundary since neither bathymetry or sea level has varied significantly over the last 100 years when ground water development began. Specified head values are assigned to the bordering nodes of the confining unit on the left side of the model grid. These values are assigned according to a best estimate of what they may have been. This is the most arbitrary boundary since prepumping and present-day measurements of head in the confining unit do not exist. However, heads are assigned in these simulations to assess the sensitivity of the model to this discretization. Finally the heads along the landward extent of the aquifer (bottom left) are based on the prepumping head map of the upper aquifer. This map was used previously in the study to locate the flow line (figure 17a). A value is estimated for the southernmost extent of the simulated section.

Boundary configuration 2 (fig. 19b): The conditions represented by this configuration are identical to those of configuration 1 except that no-flow nodes are assigned to the left edge of the confining unit. This configuration is chosen to determine the effect of uncertainty of heads in the upper confining unit.

Boundary configuration 3 (fig. 19c): These conditions combine three types of boundaries: (1) specified head nodes across the top and (2) no-flow nodes along the left edge of the confining unit. However, the general head-boundary

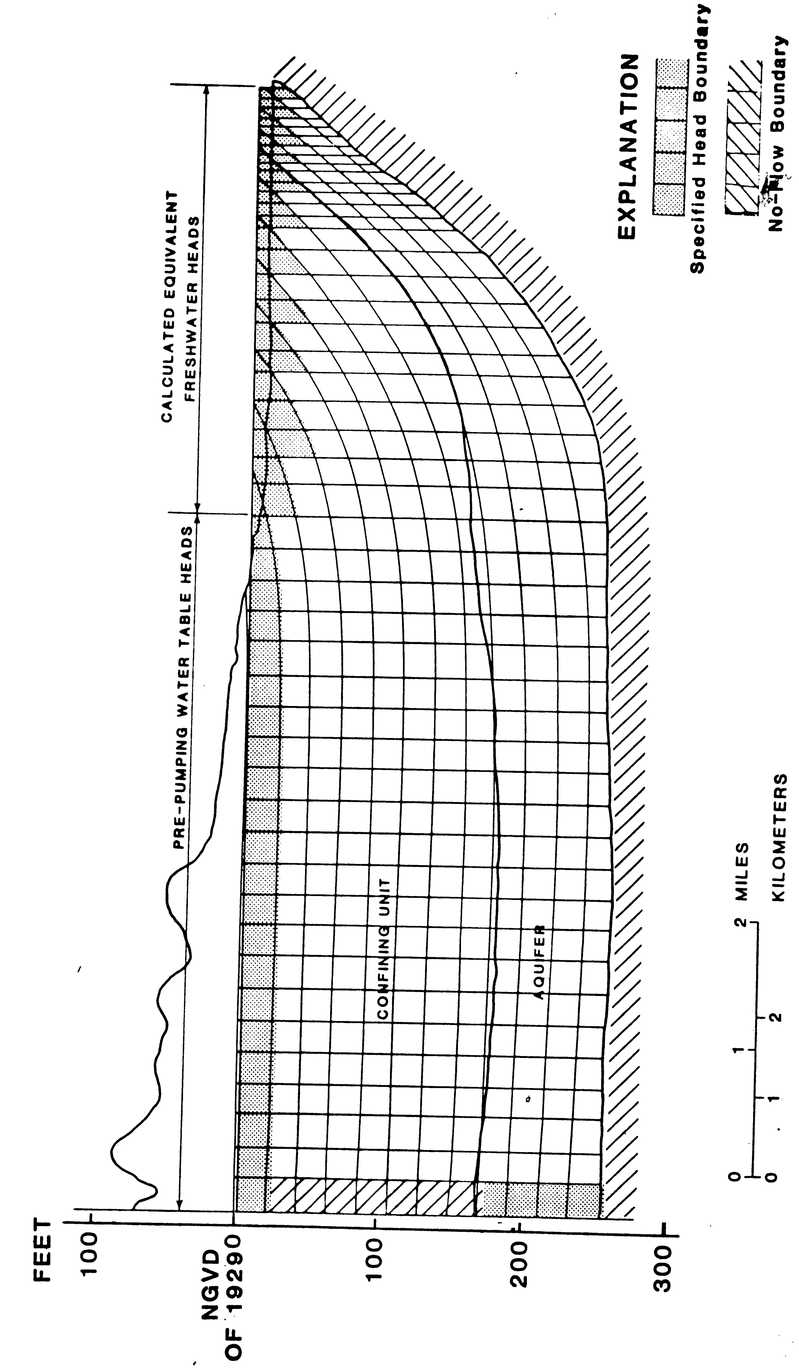


Figure 19b.-- Boundary configuration 2, utilizing specified head nodes and no-flow nodes.

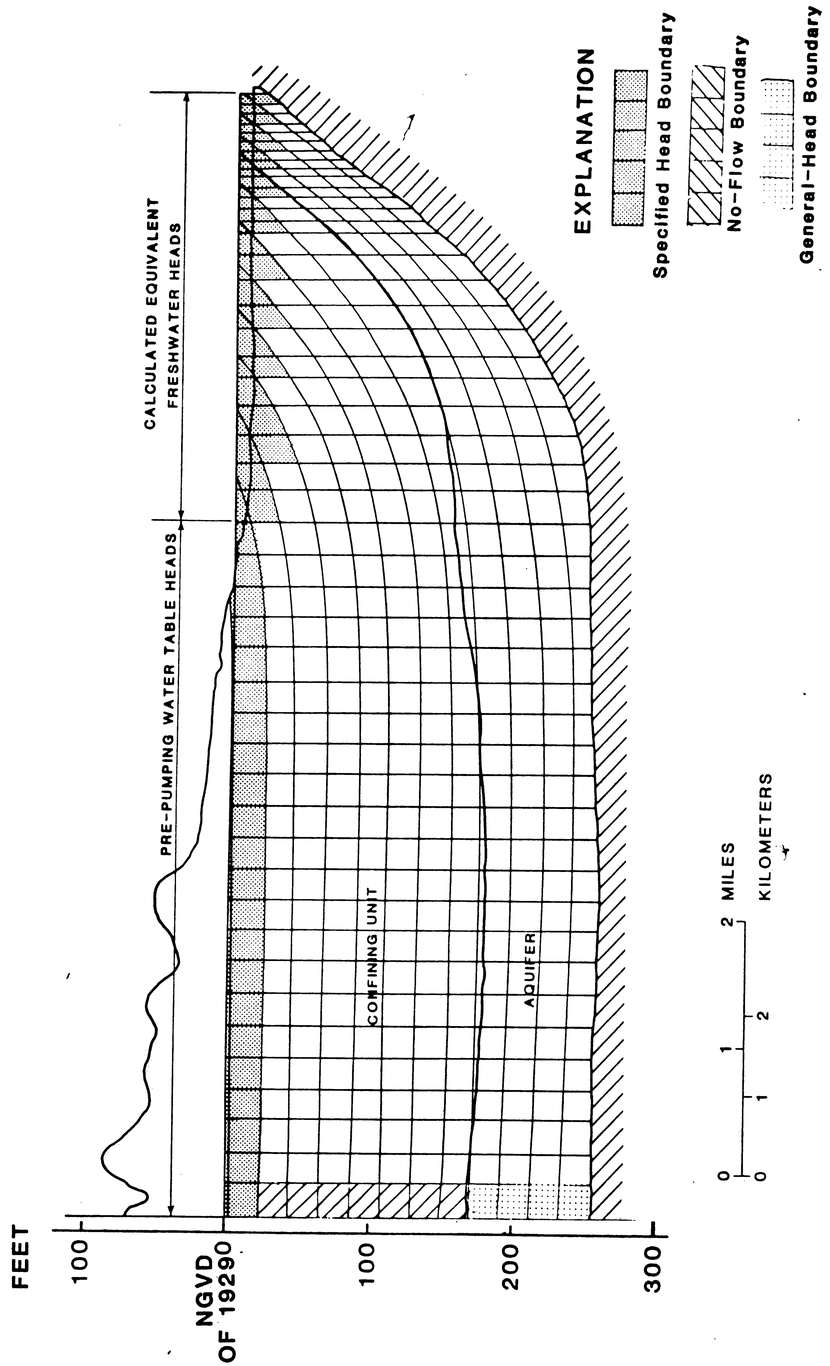


Figure 19c.— Boundary configuration 3, utilizing specified head nodes, no-flow nodes and the general head boundary package.

package (McDonald and Harbaugh, 1984, p. 343) is used to drive flow in the aquifer. This package simulates a source of water outside the modeled area which supplies water to the aquifer nodes at a rate proportional to the head difference between the source and the aquifer nodes (McDonald and Harbaugh, 1984, p. 343). The flux into the aquifer nodes is computed by:

$$Q = C(h_b - h_n) \qquad (3)$$

where:

Q = flow rate into the node (ft^3/d)

C = proportionality constant for boundary (ft^2/d)

h_b = head at the source boundary (ft)

h_n = head at the node (ft)

When the general-head boundary is used in this fashion, the proportionality constant, C, is taken to be the hydraulic conductance of the aquifer between the point where head is known and the limit of the model grid. The conductance is calculated with:

$$C = \frac{KA}{L} \qquad (4)$$

where:

C = hydraulic conductance (ft^2/d)

K = hydraulic conductivity of the aquifer material (ft/d)

A = cross-sectional area perpendicular to flow (ft^2)

L = distance between known head and limit of model grid (ft)

To obtain values required for the general-head boundary package, the flow line is extended back to the outcrop area (fig. 20), because water-table heads in the outcrop area are known. It is less likely that water-table heads have changed as much as those in the confined system. With this assumption and an approximate distance of 14.5 mi (23.3 km) from the limit of the simulated section to the groundwater high of 90 ft (27.4 meters) in the outcrop area, the hydraulic conductance may be calculated. Many assumptions must be made before applying the general-head boundary condition. The aquifer thickness is assumed to be constant and the area from the known head to the limit of the model grid is essentially treated as a stream tube. Leakage into and out of the aquifer is not accounted for over the distance (L). However, the major advantage rests in the high degree of confidence in the water-table heads and the probability that they have not changed significantly since prepumping time.

Hydraulic Parameters

Water-Table Gradient

To properly simulate the hydrologic system, the water-table heads in the unconfined system above the upper confining unit must be read into the model. As mentioned in the previous section these values are assigned to the specified head nodes along the top left extent of the problem domain.

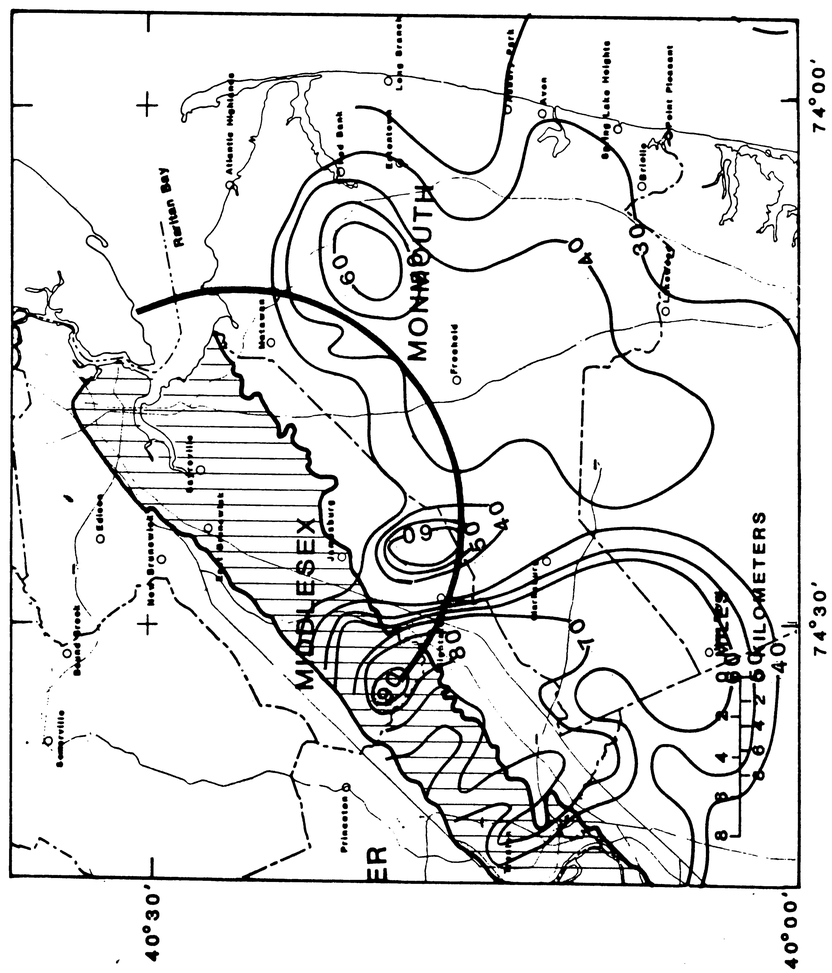


Figure 20.--Map showing extention of cross sectional model into the outcrop area of the Potomac-Raritan-Magothy aquifer system.

Figure 21 shows the prepumping configuration of the water-table. Two separate water-table configurations are simulated (table 3). A low water-table gradient, with a maximum head of 50 ft (15.2 meters) decreasing to zero at the shoreline and a high water-table gradient with a maximum head of 100 ft (30.5 meters) decreasing to zero at the shoreline. These configurations are selected for two reasons: (1) to make up for the fact that the small scale of the map does not allow for precise location of head values and (2) to test the dependence of flow through the aquifer on the altitude of the overlying water-table.

Confining Unit

The USGS Modular Flow Model requires the input of both horizontal and vertical hydraulic conductivity of each layer within the model. The horizontal conductance is calculated by multiplying the saturated thickness of the layer by hydraulic conductivity to obtain transmissivity. Transmissivity is then multiplied by the cell dimension to obtain conductance. The vertical conductance and the vertical grid spacing are used to calculate leakage (VCONT) by:

$$VCONT = \frac{K_v}{b} \qquad (5)$$

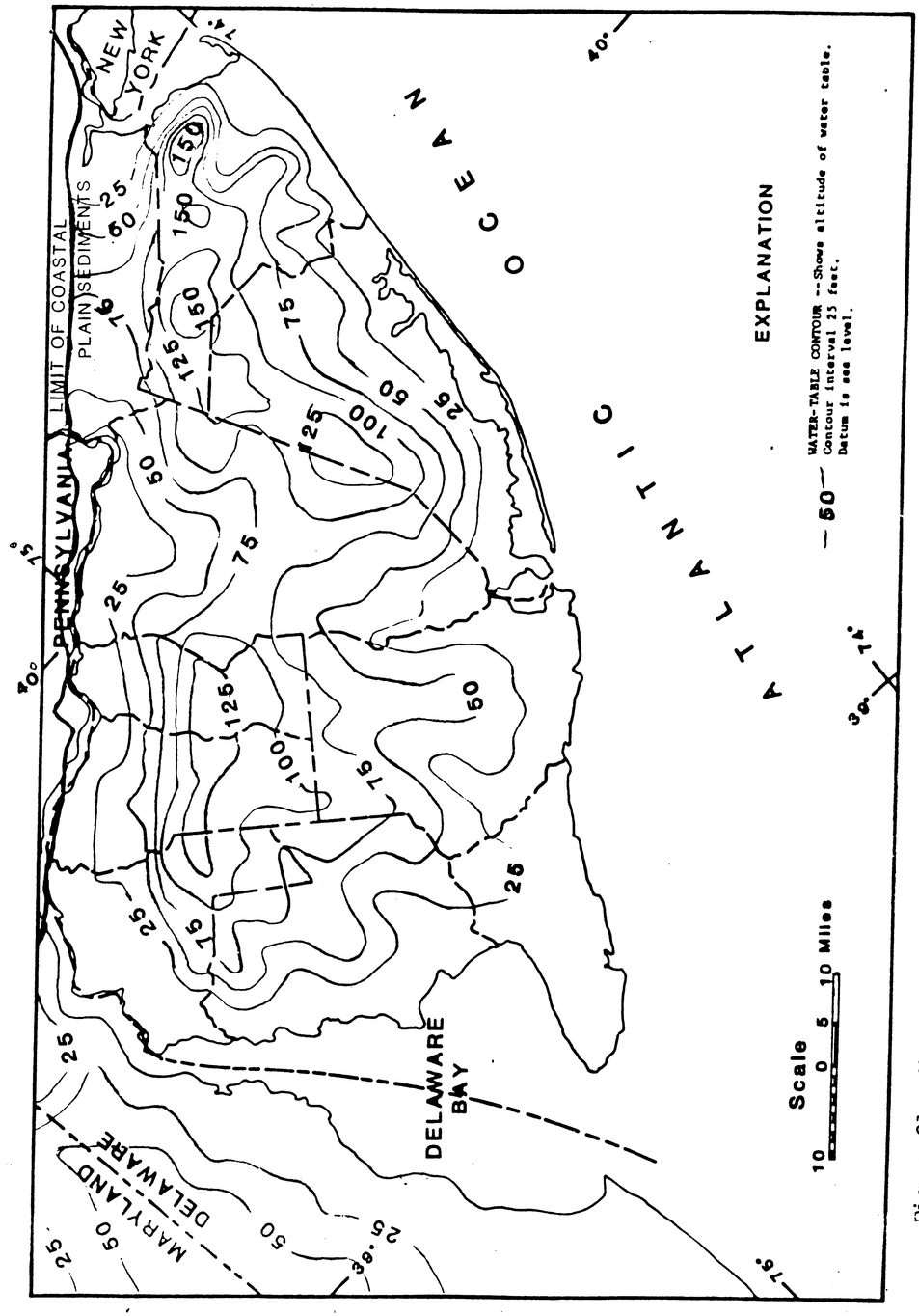


Figure 21.—Map showing generalized surface of the water table for the Coastal Plain, New Jersey. (From Martin, M., U.S. Geol. Survey, written comm., 1986)

Table 3.-- Summary of simulations.

Simulation number	Boundary configuration	Water table (ft)	Aquifer: Lateral hydraulic conductivity (ft/d)	Aquifer: Vertical hydraulic conductivity (ft/d)	Confining unit: Vertical hydraulic conductivity (ft/d)	Confining unit: Lateral hydraulic conductivity (ft/d)
1	1	0-50	98	9.8	.0006	.006
2	1	0-50	98	9.8	.02	.2
3	1	0-100	98	9.8	.0006	.006
4	1	0-100	98	9.8	.02	.2
5	2	0-50	98	9.8	.0006	.006
6	2	0-50	98	9.8	.02	.2
7	2	0-100	98	9.8	.0006	.006
8	2	0-100	98	9.8	.02	.2
9	3	0-50	98	9.8	.0006	.006
10	3	0-50	98	9.8	.02	.2
11	3	0-100	98	9.8	.0006	.006
12	3	0-100	98	9.8	.02	.2

where:

VCONT = vertical leakance (day^{-1})

K_v = vertical hydraulic conductivity (ft/d)

b = thickness of the confining unit (ft)

The values for VCONT are calculated from data used in the New Jersey Regional Aquifer System Analysis (RASA) study (fig. 22, Martin, M. M., U.S. Geol. Survey, written commun., 1986). Two different values are used to simulate either a tight confining unit or a leaky one (table 3). These values are obtained by multiplying the RASA VCONT values by the thickness used to calculate them in order to determine the vertical hydraulic conductivity. This value is then multiplied by the reciprocal of the distance from the node above and below the boundary between each layer representing the confining unit to obtain VCONT. The horizontal hydraulic conductivity is assumed to be ten times that in the vertical (Franke and Cohen, 1972, p. C271). This value is multiplied by layer thickness and input into the model as transmissivity.

An input array is required to compute the leakance between the confining unit and the aquifer (layer 8 and 9). This is because layer thickness in the aquifer decreases to the Bay; therefore, the vertical distance between nodes, d, also decreases. The model multiplies an input array containing the d^{-1} values by a constant vertical conductivity resulting in a leakance for this boundary.

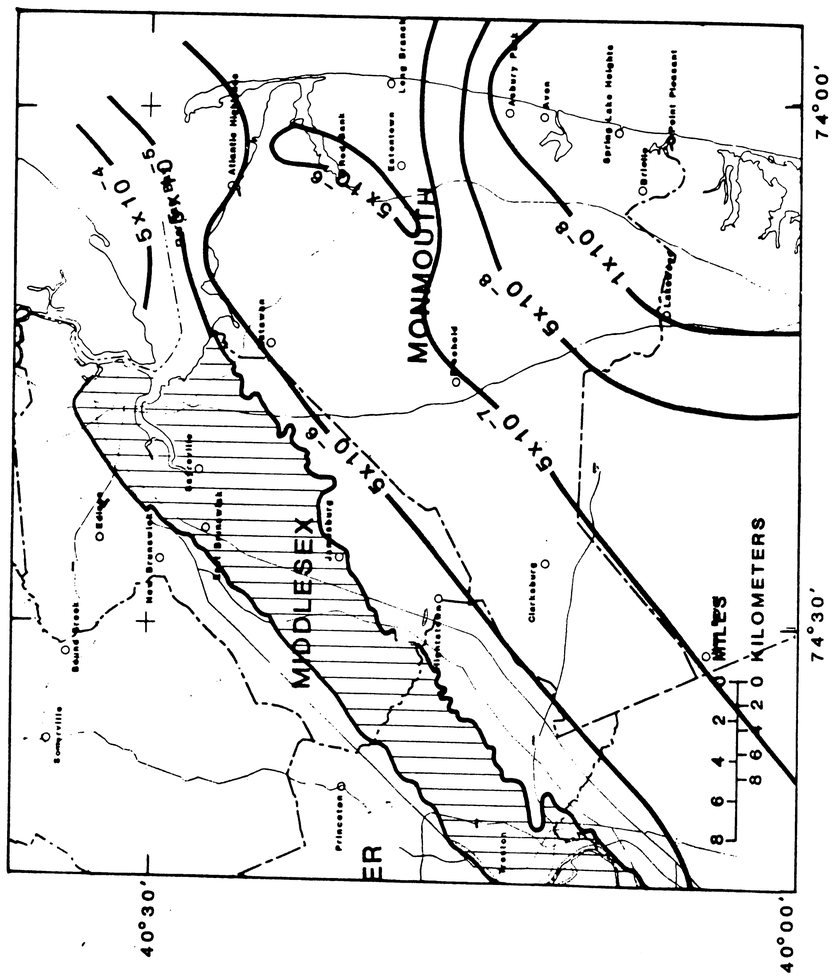


Figure 22.-- Vertical leakance (VCONT) values from RASA study for upper confining unit. (Modified from Martin, M., U.S. Geol. Survey, written comm., 1986)

Aquifer

In this study, the aquifer is assumed to be homogeneous. Lateral hydraulic conductivities are estimated (fig. 23) from specific-capacity data for wells in the vicinity of the simulated section, according to the method of Farlekas (1979, p. 30). These values are averaged to obtain a representative lateral hydraulic conductivity of 98 ft/d (29.9 meters/d) (table 3). This value is multiplied by an array containing the variable thickness of the aquifer to obtain transmissivity. In the Union Beach area, transmissivity is estimated to be 9,800 ft^2/d (910 $meters^2/d$). This value correlates well with preliminary analysis from a recent aquifer test which estimates transmissivity at 9,000 ft^2/d (836 $meters^2/d$) (Pucci, A.A.,Jr., U.S. Geol. Survey, written commun. 1986).

Ten percent of the lateral hydraulic conductivity is used as the vertical hydraulic conductivity of the aquifer (table 3). As done previously this value is multiplied by day^{-1} for the VCONT between aquifer layers. No array is necessary for the basal layer (layer 12) because the base of the model is a no flow boundary and no leakage is assumed to take place.

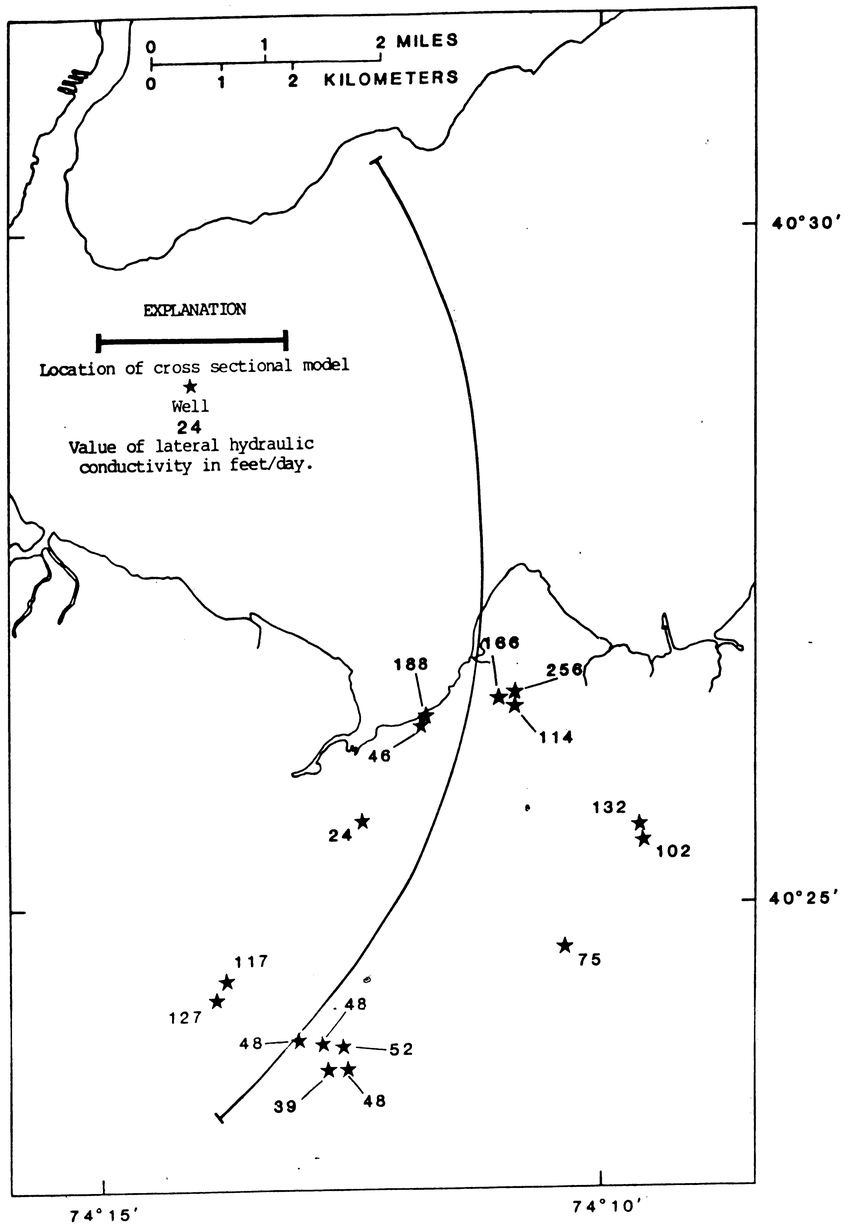


Figure 23.-- Map showing location of lateral hydraulic conductivity data in relation to modeled section.

Equivalent freshwater head used to position the interface

The interface-locating approach requires knowledge of the equivalent freshwater heads necessary to balance the static saltwater front. It is possible to calculate these heads as the depth to each node is given by using equation 2. The approximate depth represented by each node is assigned from Figure 18b. The density of freshwater is assumed to be 1.0 g/cm^3 and the density of seawater is 1.025 g/cm^3. The unit discrepancy between density and head is not a problem since the densities are a ratio. Figure 24 presents the distribution of equivalent freshwater heads.

Results

As with any modeling effort, the results are examined with respect to several items. First, a realistic head distribution must exist in relation to the physical system. Equipotential lines and flow lines must be oriented in a reasonable pattern. More importantly the quantifiable terms must be realistic. These include the overall water budget, flux, flow distribution and flow velocity. The results of each simulation are reviewed according to these criteria.

Three groups of simulations are discussed to determine the interface position for different boundary conditions, water-table conditions, and hydraulic conductivities. The

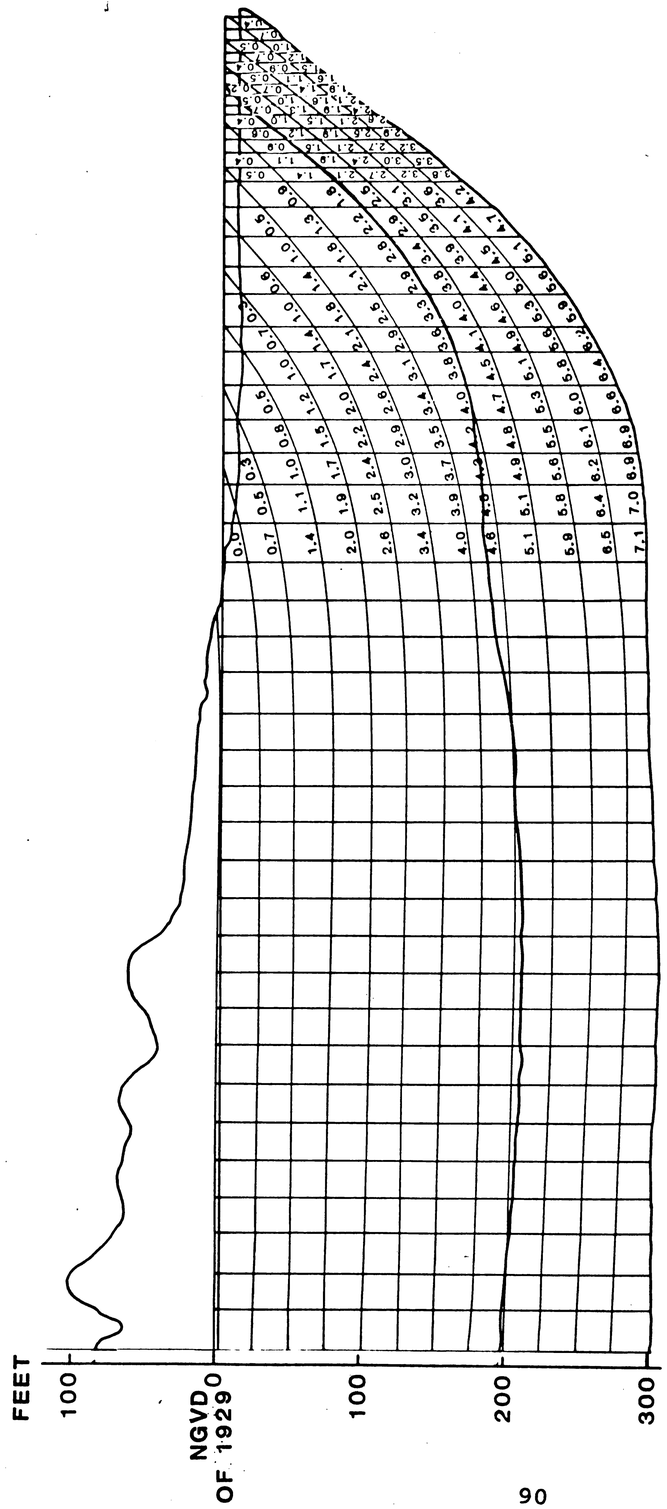


Figure 24.-- Calculated equivalent freshwater heads (required to balance saltwater)and their locations in the model grid with respect to the physical system.

results show the sensitivity of the saltwater-front position to the various parameters.

The first group of simulations utilized boundary configuration 1 (fig. 19a). For simulations 1 and 2, the low water-table gradient is tested and the hydraulic conductivities of the confining unit are varied. Simulation 1 uses a vertical hydraulic conductivity of 6.0×10^{-4} ft/d (2.0×10^{-4} meters/d) and a lateral hydraulic conductivities of 6.0×10^{-3} ft/d (2.0×10^{-3} meters/d). The results (fig.25a) show a reasonable head distribution and limited saltwater encroachment into the outcrop area of the aquifer. Velocity remains constant at .27 ft/d (0.08 meters/d) toward the outcrop area and flow through the system decreases toward the bay. Discharge occurs along the entire surface of the confining unit; increasing as it thins toward the aquifer. The discharge is equivalent to .29 in/yr (inches/year) (0.74 centimeters/yr) across the entire surface. At the aquifer all water discharges through the part of the aquifer not trimmed in layer 9. Negligible volumes of water move laterally into the confining unit through the assigned constant head nodes at the left edge of the model grid.

Simulation 2 assigns a vertical hydraulic conductivity .02 ft/d (0.006 meters/d) and lateral hydraulic conductivity of .2 ft/d (0.06 meters/d) to the confining unit. This value is about two orders of magnitude greater than that used in the previous simulation. The simulated saltwater front is located

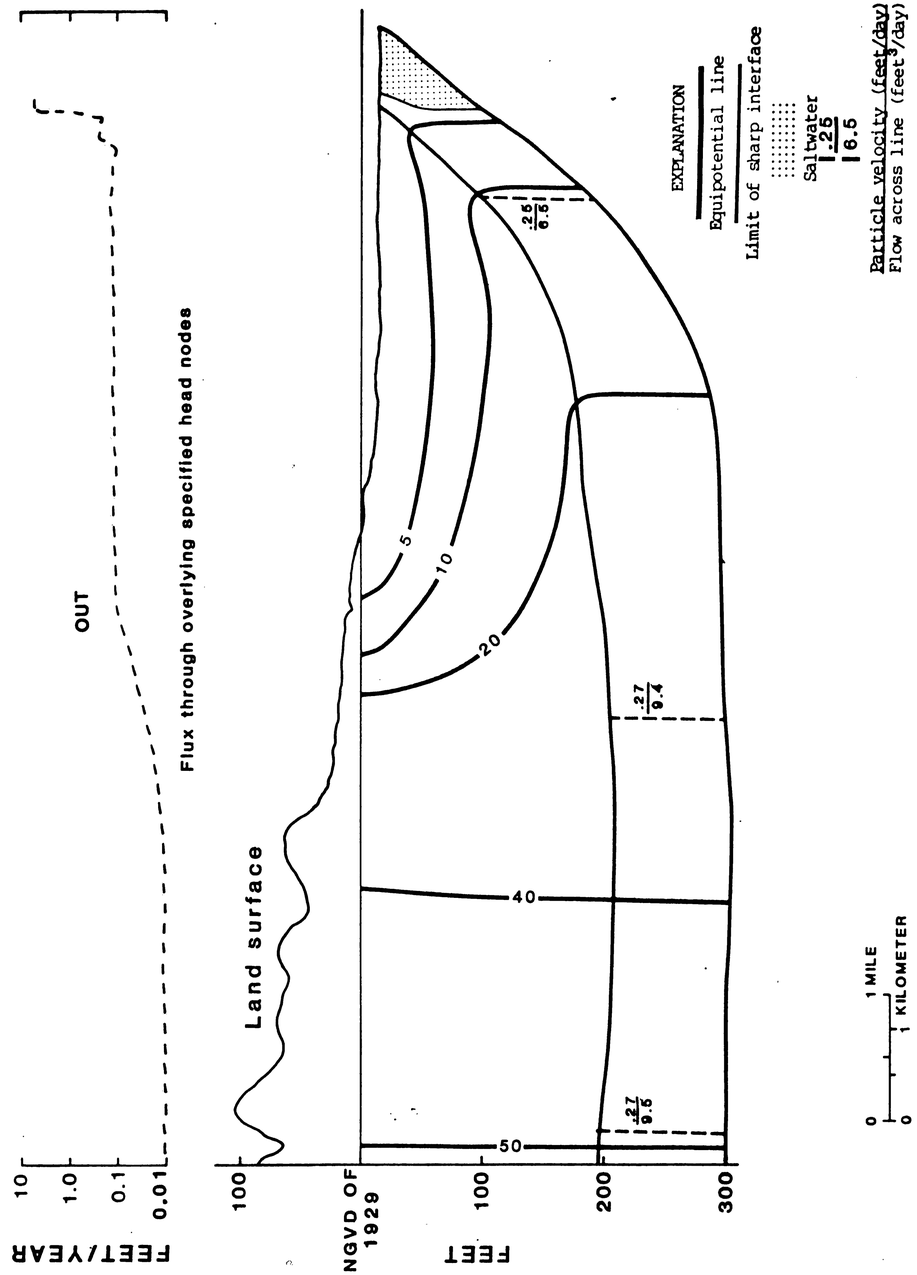


Figure 25a.— Results of simulation 1.

much farther into the aquifer (fig. 25b). It is necessary to chop blocks in the confining unit representing an interface in this unit. The slope of the interface is less than that in simulation 1 and the front lies 1.25 miles (2.0 km) offshore. A 30 percent greater flux enters the aquifer from the specified-head boundary on the left and water enters the system as leakage through part of the overlying confining unit at a rate of 1.2 in/yr (3.0 centimeters/yr). The position of the interface forces freshwater to be discharged entirely through the confining unit at a rate of 3.7 in/yr (9.4 centimeters/yr). The velocity is higher than that in simulation 1, with values ranging from .36-.49 ft/d (0.12-0.15 meters/d). It is also evident that freshwater is being pushed through the confining unit into the aquifer below. This conclusion is drawn from the higher flux values in the central part of the aquifer.

Simulations 3 and 4 both utilize boundary condition 1; however, higher water-table gradients are used to examine their effect on the flow system and interface position. Simulation 3 (fig. 25c), using the lower vertical hydraulic conductivity (6.0×10^{-3} ft/d) (2.0×10^{-3} meters/d), shows no difference in the configuration and position of the interface when compared to simulation 1. Velocities are similar, yet simulation 3 shows increasing velocities closer to the interface. The flow is also lower in the aquifer and the flux into the confining unit is slightly higher. The major

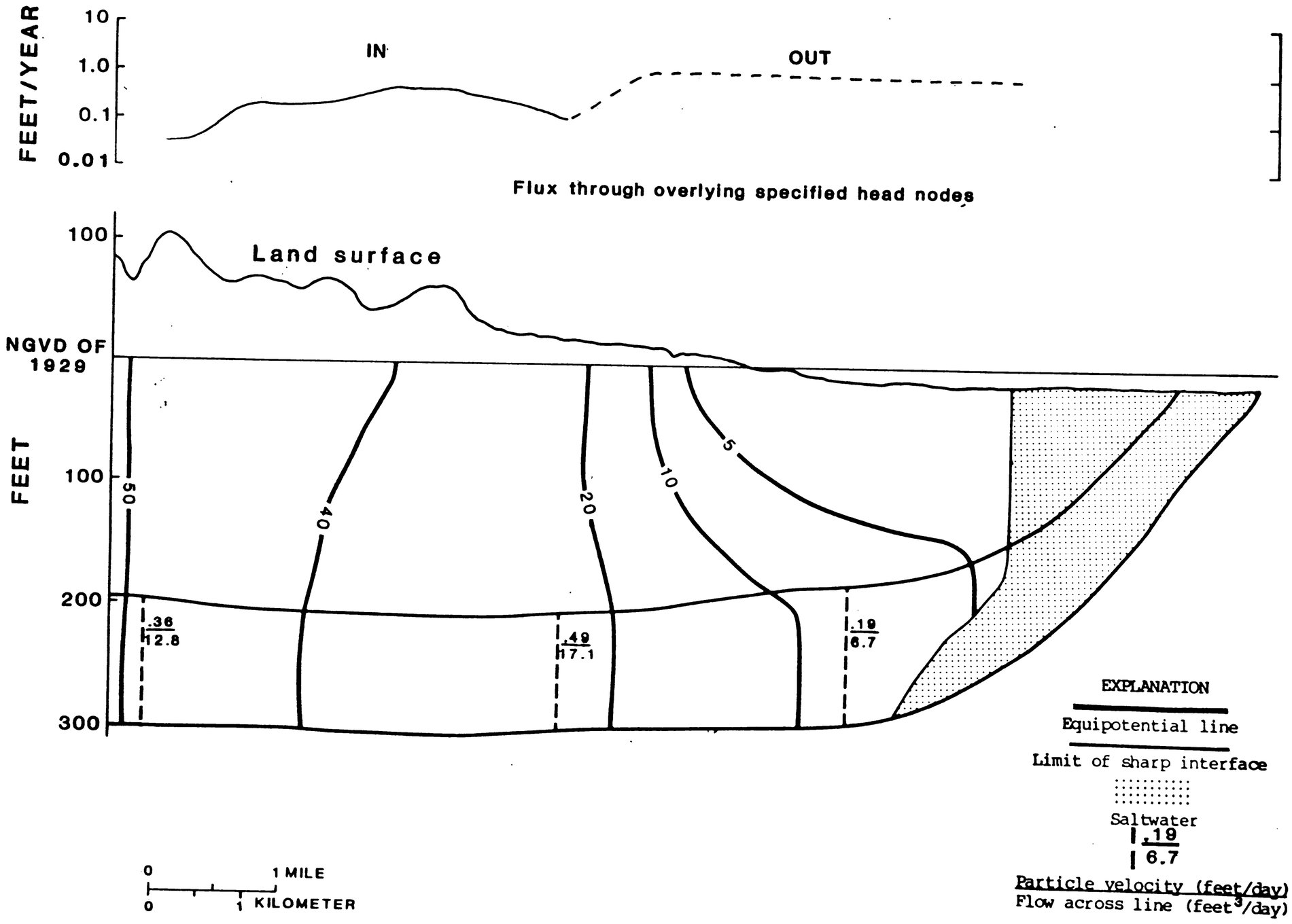


Figure 25b.-- Results of simulation 2.

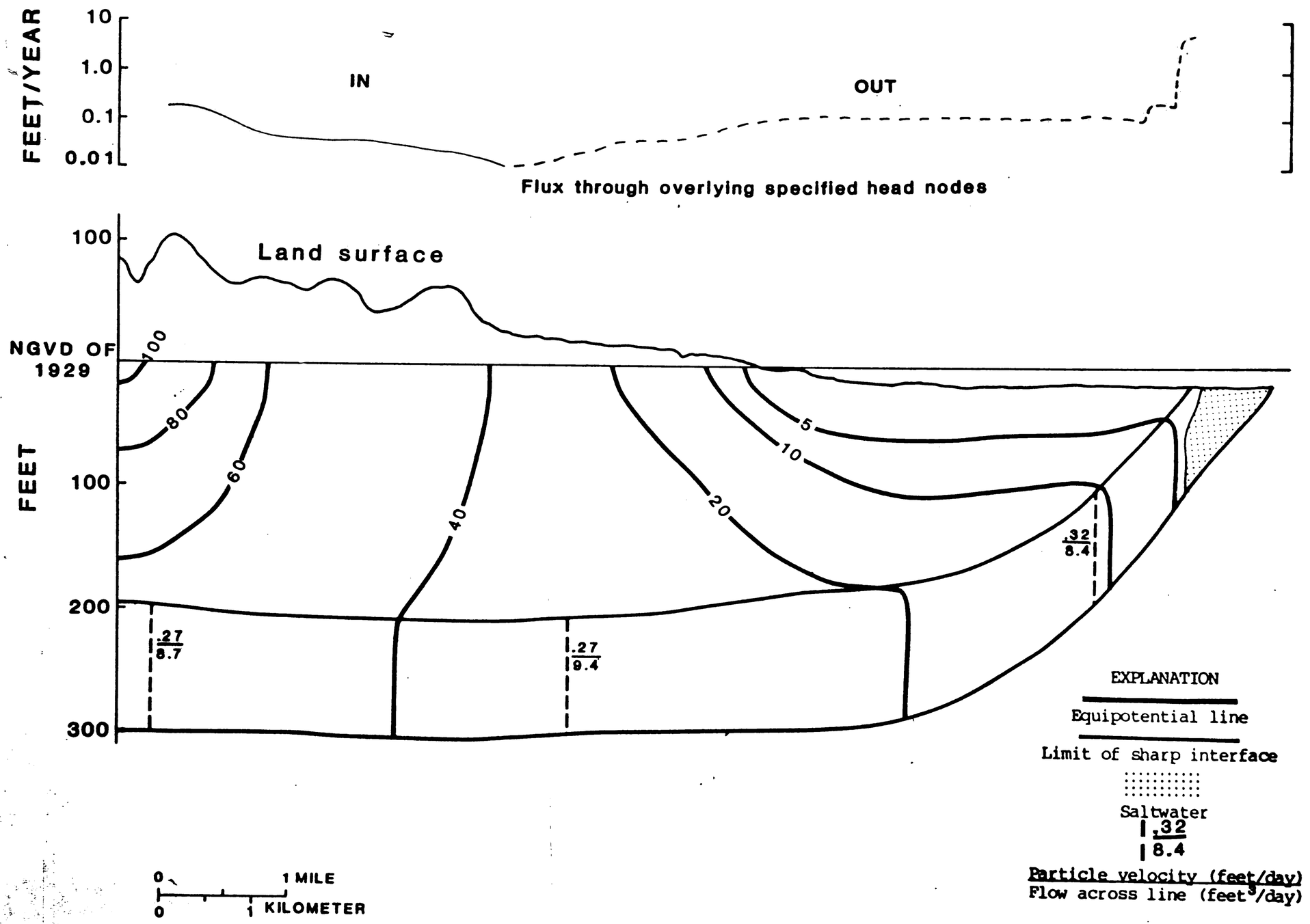


Figure 25c.-- Results of simulation 3.

difference is in the head distribution in the confining unit and in the recharge and discharge distribution.

The increase in water-table gradient causes leakage through the confining unit on the left side of the grid at a rate of .21 in/yr (0.53 centimeters/yr). This subsequently causes an 8 percent increase in flux at the center of the simulated aquifer not seen in simulation 1. Discharge occurs across the remainder of the grid surface at rates of .41 in/yr (1.0 centimeters/yr) through the confining unit and 42.6 in/yr (108.2 centimeters/yr) from the untrimmed part of the aquifer. The discharge through the untrimmed part is quite high and suggests that this simulation does not accurately depict the prepumping flow system.

Simulation 4 (fig. 25d) shows a salt wedge approximately 1.75 mi (2.8 km) offshore in the aquifer and in the confining unit. Increasing the water-table gradient in this simulation causes a reversal of the gradient at the left edge of the model grid. Flow is landward in the portion of the grid located onshore in the aquifer as well as in the confining unit. Closer to the shoreline a gradient reversal occurs and water is again flowing toward the bay. This ground-water divide is not in the present flow system and probably was not present in the predevelopment flow system. The flux computed by this simulation is similar to that of simulation 2. This simulation shows the largest volume of leakage through the confining unit, with a value of 5.6 in/yr (14.2 centimeters/yr). The discharge rate near the shoreline and

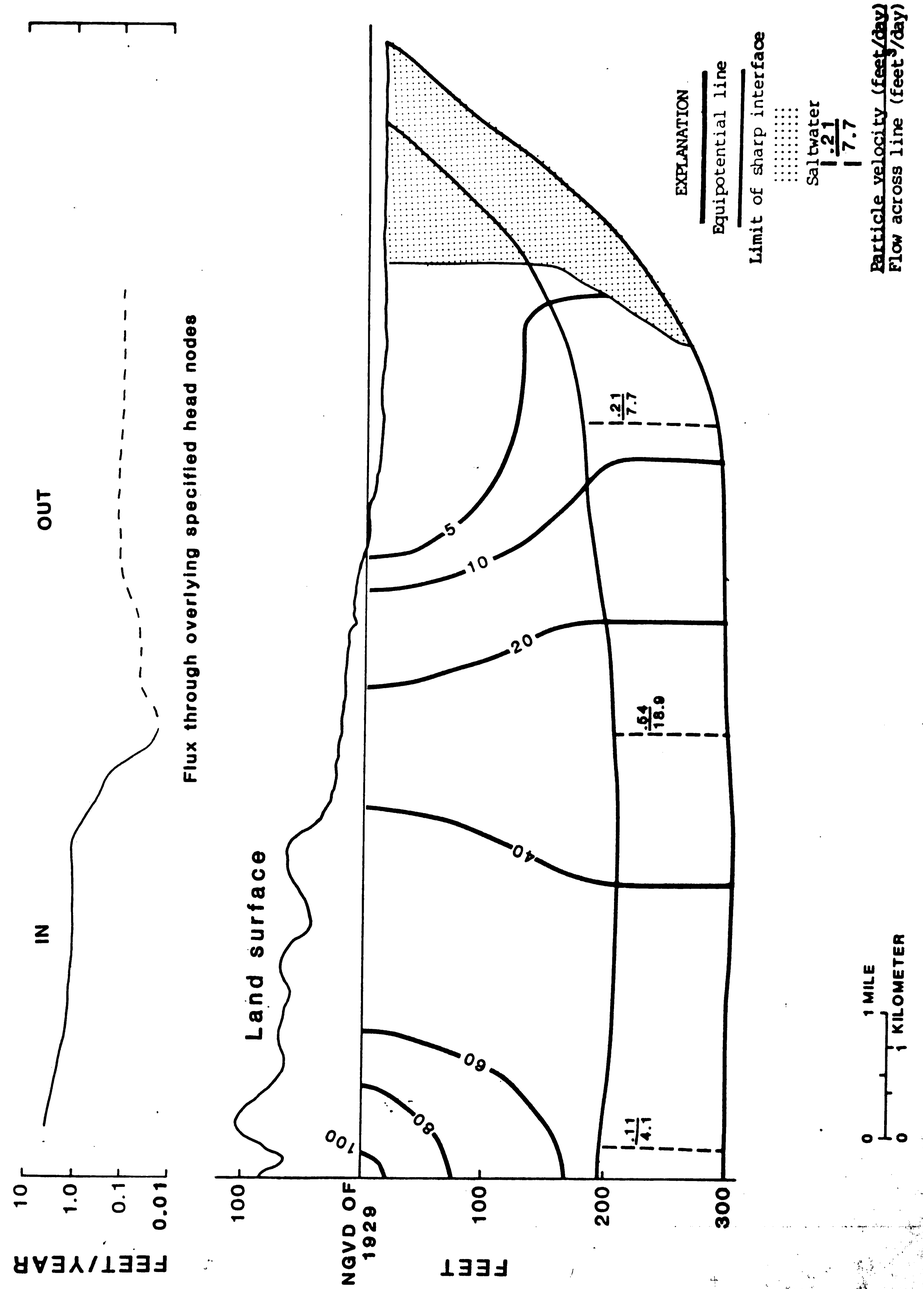


Figure 25d.— Results of simulation 4.

under the bay is similar to that of simulation 2. No evidence exists for the ground-water divide simulated in this run; therefore little confidence is placed in the results.

Simulations 5-8 (fig. 25e-h) use boundary configuration 2 (fig. 19b). The results are identical to those in simulations 1-4, respectively. The negligible volumes of water that entered or left the landward limit of the model in the confining unit layers of simulations 1-4 is distributed across the specified nodes across the top of the grid. The budgets, fluxes, and configuration of the interface, show no dependence upon the boundary condition at the edge of the confining unit.

Boundary configuration 3 (fig 19c) is used for the remaining group of simulations. A general-head boundary package simulates head in the outcrop area outside the modeled area. The no-flow boundary is also used along the left side of the grid in the confining unit because as this boundary has no effect on model results, and accurate head values not available. Four simulations were run to test the two water-table gradients and the various leakances.

Simulation 9 (fig. 25i) represents a low water-table gradient and small amounts of leakage between the confining unit and the aquifer. Use of the general-head boundary package causes the model to simulate lower heads in the landward part of the modeled area. The flow through the aquifer was significantly reduced, although velocities were similar to those computed by the previous simulations.

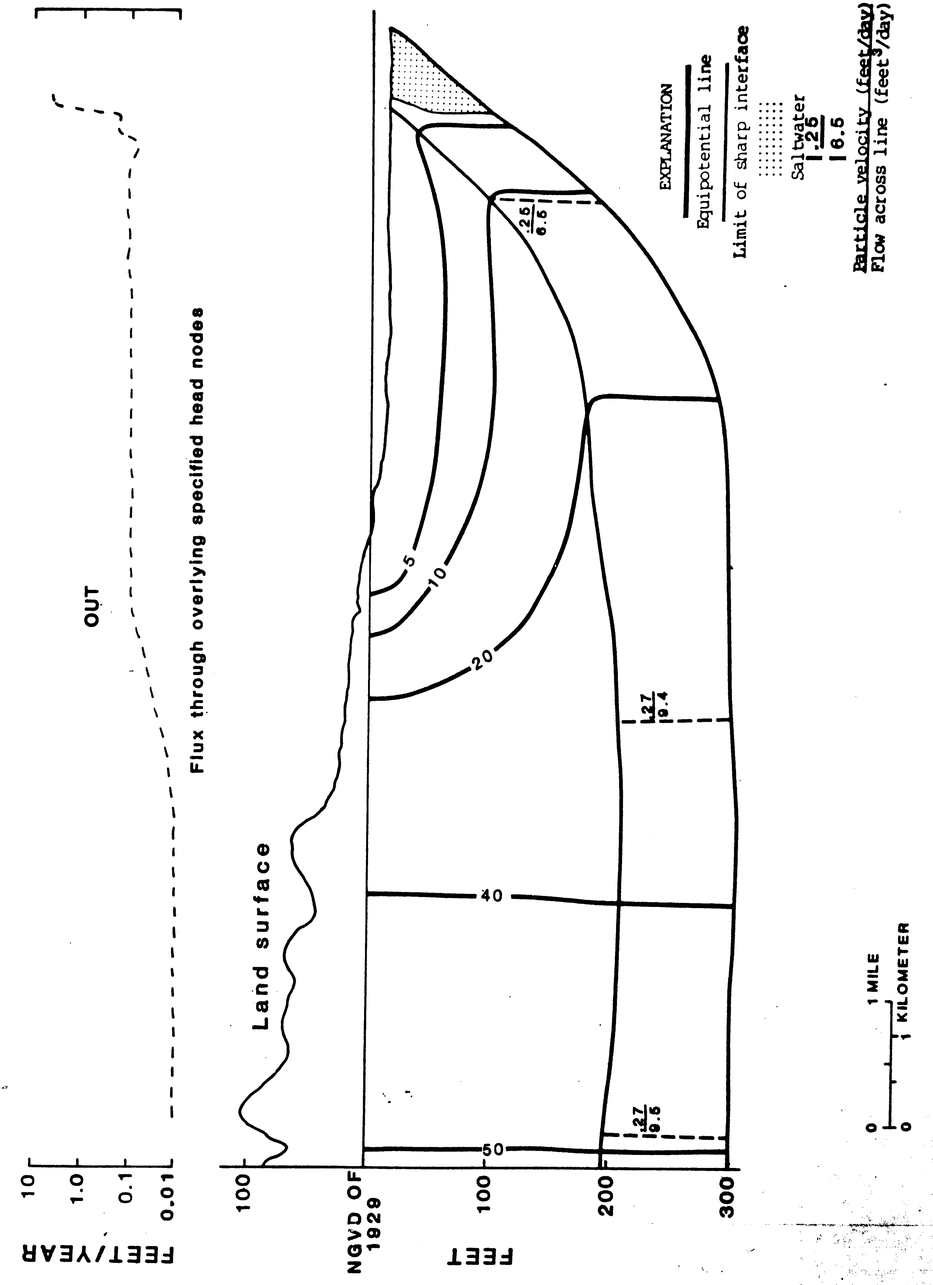


Figure 25e.-- Results of simulation 5.

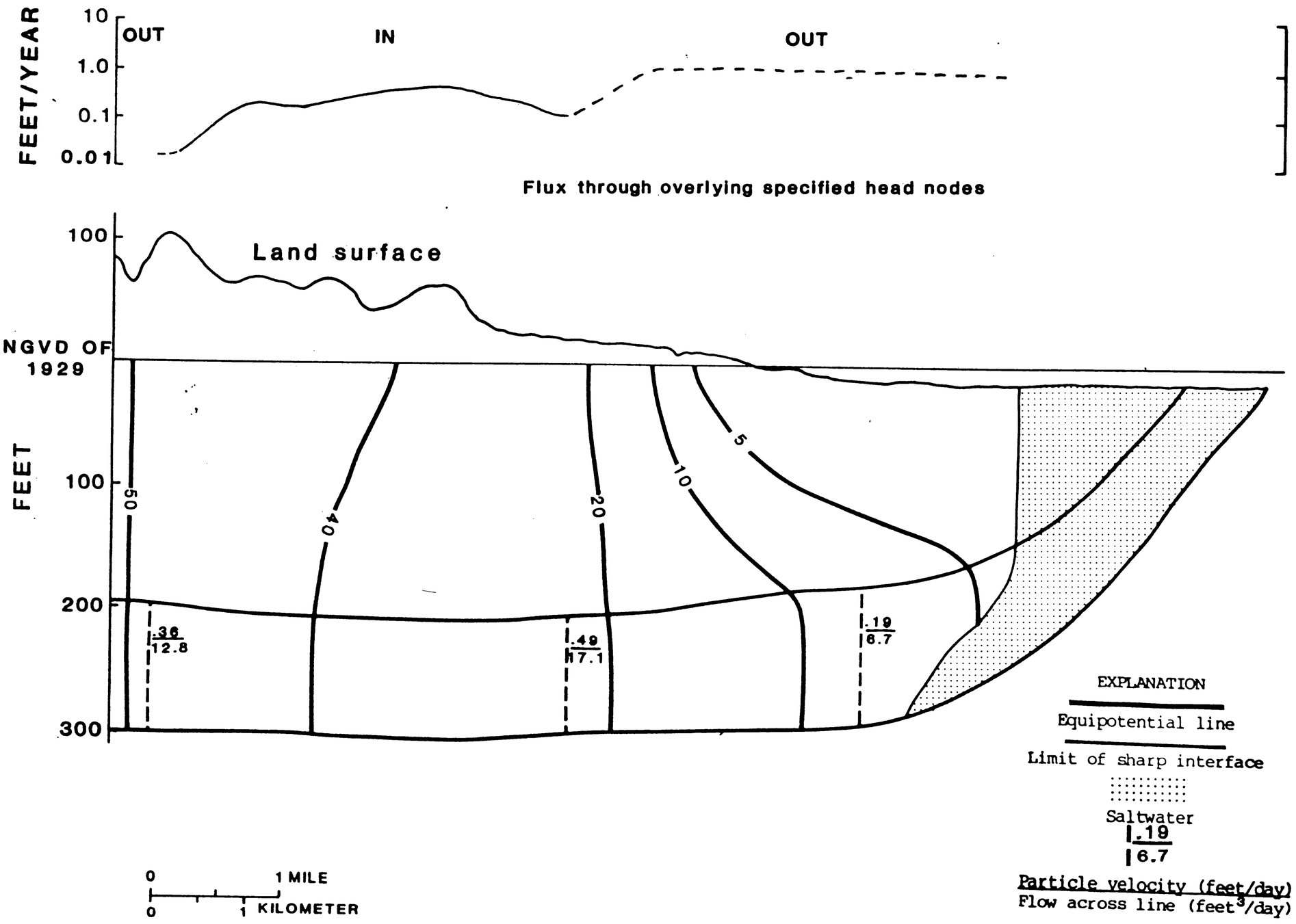


Figure 25f.-- Results of simulation 6.

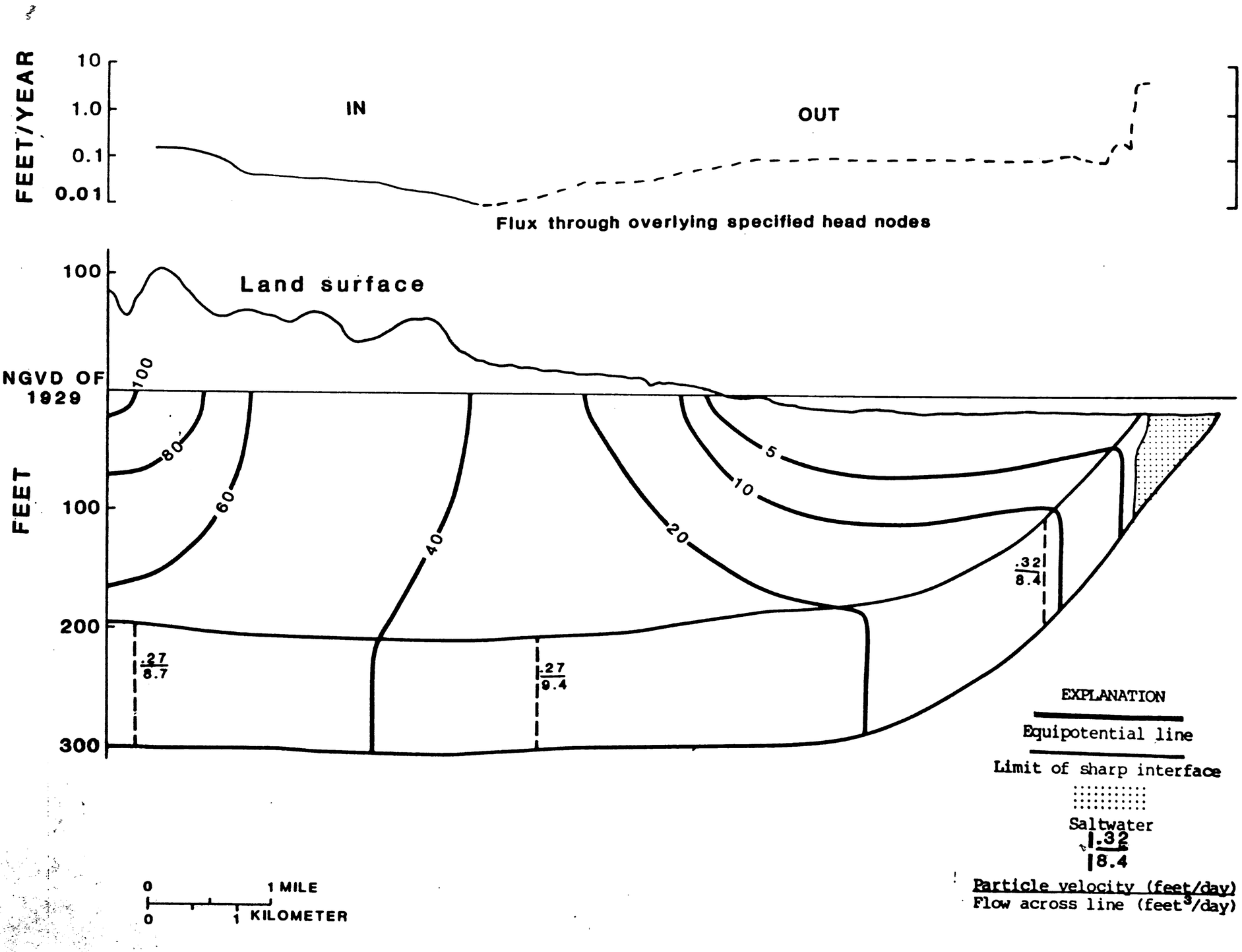


Figure 25g.-- Results of simulation 7.

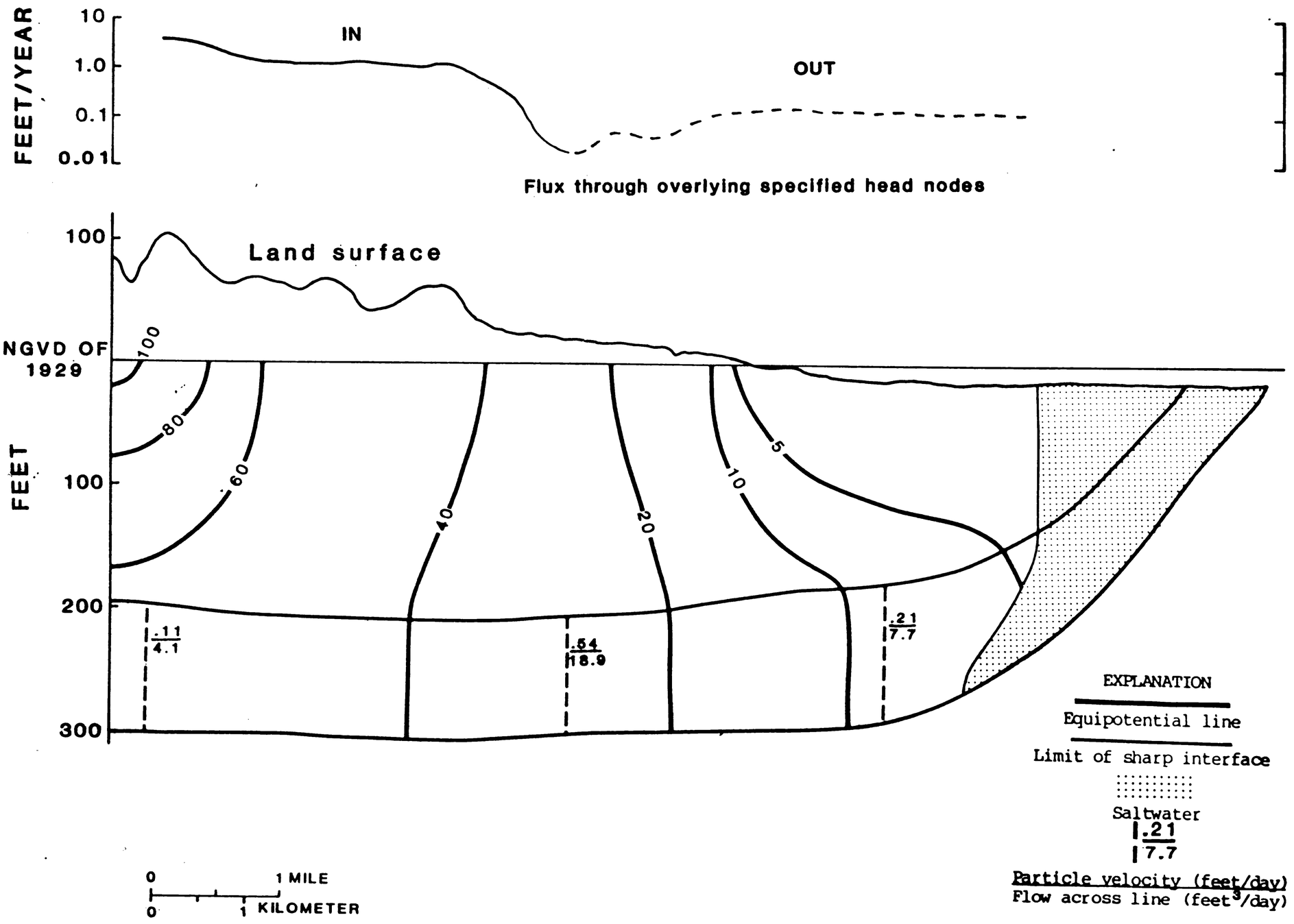


Figure 25h.-- Results of simulation 8.

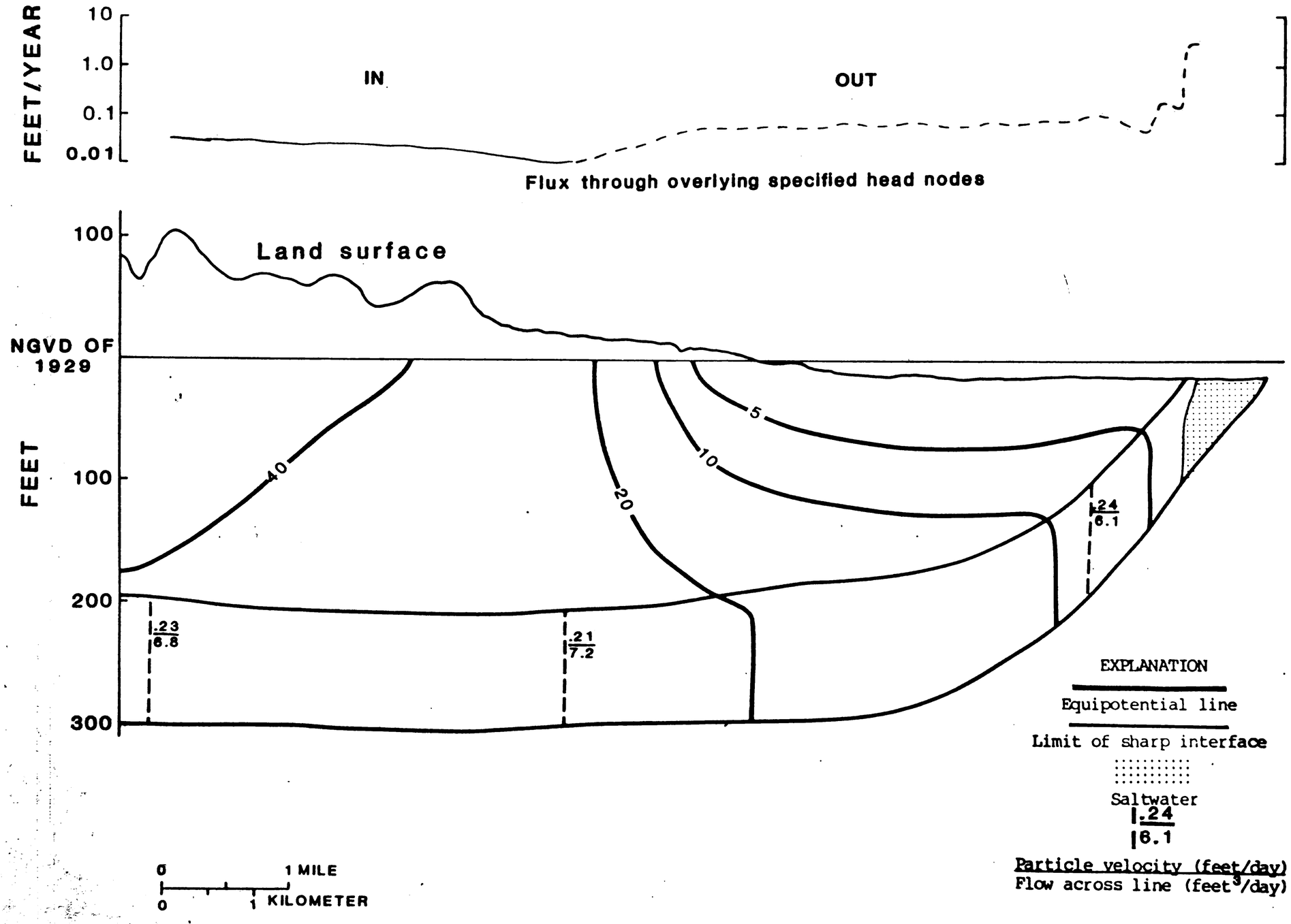


Figure 25i.-- Results of simulation 9.

Recharge occurs through the landward part of the confining unit, unlike the situation when the other two boundary configurations were simulated. Discharge through the confining unit under the bay is .35 in/yr (0.89 centimeters/yr) and 32.6 in/yr (82.8 centimeters/yr) in the untrimmed outcrop area of the aquifer. The position of the interface is the same as in simulations 1 and 5 but simulated headalong the interface are slightly lower.

The leaky confining unit in simulation 10 (fig. 25j) positions the interface 1.25 mi (2.0 km) offshore as in simulations 2 and 6. Flow through the aquifer is significantly less than the previous simulation and water passes through the confining unit to increase the flux in the central portion of the simulated aquifer. The discharge through the confining unit under the Bay has similar values to simulations 2 and 6; however, leakage through the confining unit is twice as great as the latter. The simulated heads using these conditions match closely those shown in Figure 17a. Also, simulated heads along the interface are much closer to the calculated values required to balance the saltwater interface than are those of any previous simulation.

The last two simulations maintain the general-head boundary for the aquifer, in conjunction with higher water-table altitudes at the specified head nodes. Simulation 11 (fig. 25k) assigns the low vertical hydraulic conductivity ($6x10^{-4}$ft/d) ($2.0x10^{-4}$meters/d). The distribution of recharge

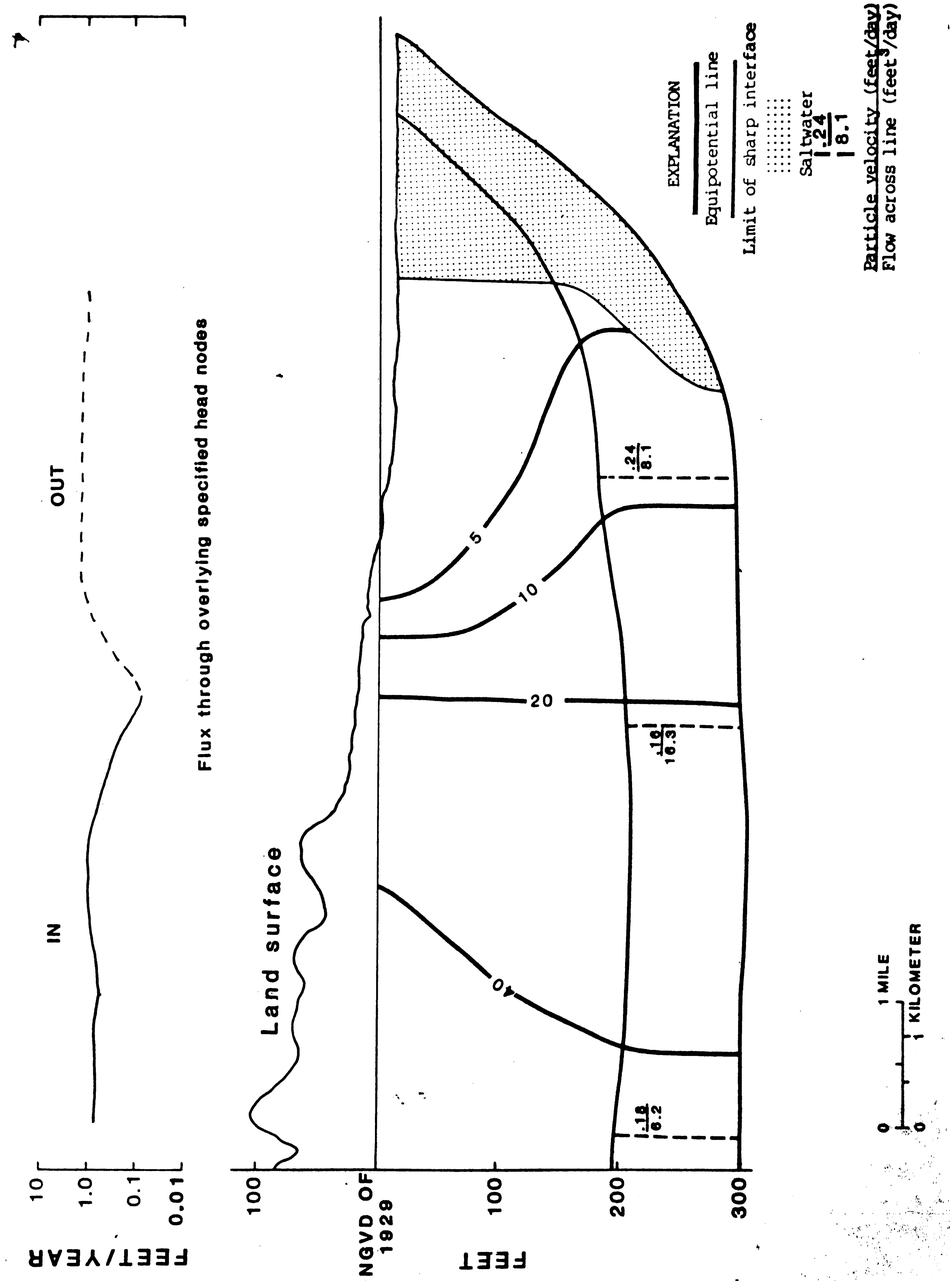


Figure 25j.-- Results of simulation 10.

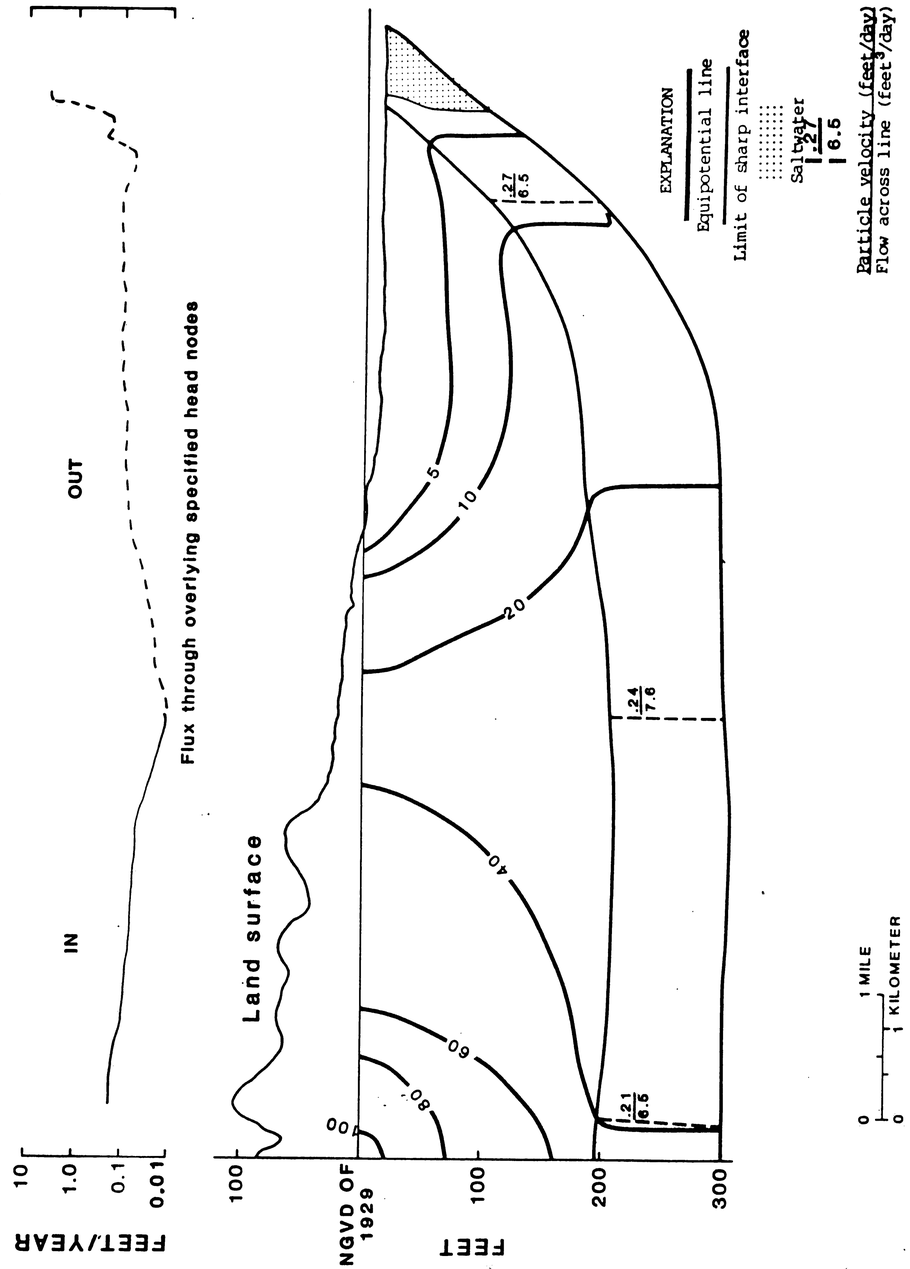


Figure 25k.-- Results of simulation 11.

and discharge is also almost identical to that in simulations 3,7, and 9. However, flux within the aquifer is 30 percent less than that in simulations 3 and 7, which use a specified head boundary across the left border of the aquifer. Velocity values are also consistent with those computed in other simulations using low values of hydraulic conductivity; and show an increasing trend toward the interface.

In simulation 12 (fig. 251), the interface is located 1.75 mi (2.8 km) offshore as in simulations 4 and 8. The head distribution in the aquifer more closely matches that of the measured prepumping surface shown in figure 17b. Fluxes and velocities are similar to those computed in simulation 8. However, all flow is toward the Bay and discharge is through the confining unit under the coast and Bay at a rate of about 4 in/yr (10.2 centimeters/yr).

Model results indicate that all boundary configurations and hydraulic parameters simulated require the presence of saltwater in the aquifer under predevelopment. The major influence on the position of the interface is the leakance between the confining unit and the aquifer. The hydraulic conductivity value of 6.0×10^{-4} ft/d (2.0×10^{-4} meters/d) only indicates saltwater near the outcrop area of the aquifer. The high or low water-table gradient assigned to the particular model run causes minor variations in the position of the interface. However, in general the variation in the water-table gradient mainly affects the heads in the confining unit.

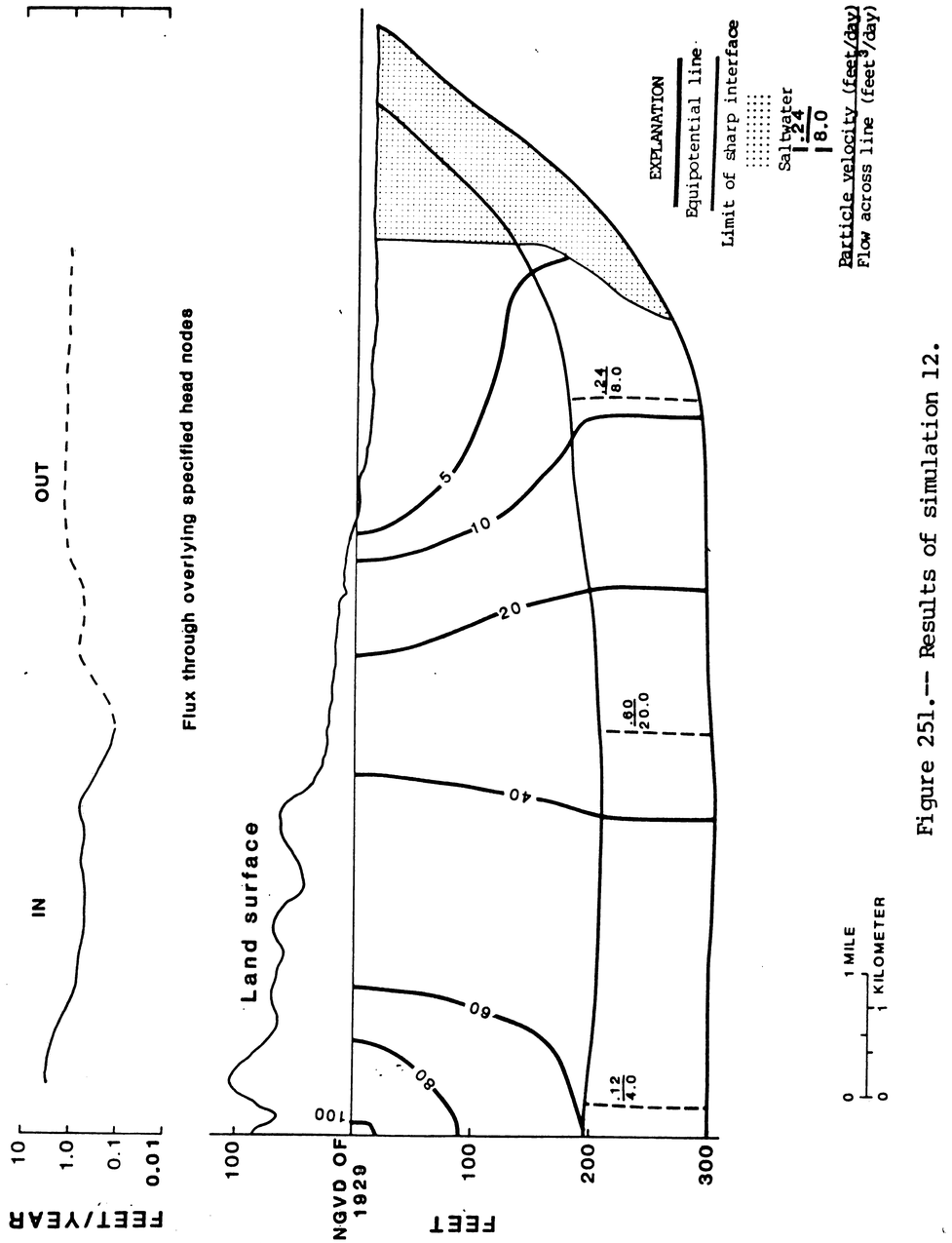


Figure 251.-- Results of simulation 12.

The boundary configuration has an influence on simulation results. Boundary configuration 1 specifies head values around the entire model grid. This has a major influence on shaping the flow system. Accuracy of the results are dependant on confidence of the specified heads. Boundary configuration 2 indicates that the sensitivity of the model to the assigned heads in the confining unit is not high. This is evident by the basically identical model results to those of simulations 1-4. Boundary configuration 3 presents the most accurate depiction of the predevelopment flow system due to the greater confidence in boundary parameters. Future research should concentrate on refinement of this basic model design to define the exact position of the saltwater interface during prepumping conditions.

SUMMARY AND CONCLUSIONS

Increased ground-water pumpage in the Potomac-Raritan-Magothy aquifer system has caused a reversal of the flow system from prepumping conditions. As a result, saltwater is encroaching upon pumping centers in the Raritan Bay area. The hydrogeologic framework in the Raritan Bay area and the prepumping status of the saltwater/freshwater transition zone is important information to future modeling efforts which will be used to manage the ground water resources of the area.

Five major hydrogeologic units of the PRM aquifer system are found in the study area. These units consist of a lower

confining unit, a middle aquifer, a confining unit between the middle and upper aquifer, an upper aquifer, and an upper confining unit.

In the northwestern part of the study area, basement is the lower confining unit. However, downdip, the layer of clay directly below the Farrington Sand Member of the Raritan Formation becomes the lower confining unit. The Farrington Sand Member is the major geologic unit which comprises the middle aquifer. The middle aquifer ranges from 0 - 110 feet (0-33.5 meters) in the study area.

The confining unit between the middle and upper aquifer is composed primarily of the Woodbridge Clay Member of the Raritan formation. Thickness of this confining unit ranges from 100 feet (30.5 meters) near the Raritan River to 230 feet (70.1 meters) in the southeastern reaches of the study area.

The Old Bridge Sand Member of the Magothy Formation and locally the Sayreville Sand Member of the Raritan Formation constitute the upper aquifer. Thickness range from 50 feet (15.2 meters) southeast of the outcrop area to 150 feet (45.7 meters) near Sandy Hook.

The upper confining unit ranges from approximately 200 feet (61 meters) in the outcrop area in Keyport to 350 feet (106.7 meters) near Sandy Hook. The Woodbury Clay and The Merchantville Formation are the fundamental geologic units; however, the Morgan and Cliffwood Beds of the Magothy Formation are also included in the upper confining unit locally.

Both single- and multi-channel marine geophysics confirmed the presence of gently sloping, horizontal strata lying upon a sloping basement surface. The multi-channel data showed resolution to depths greater than 700 feet (213.4 meters) and the single-channel was used primarily for interpretation from 50 to 300 feet (15.2-91.4 meters) below sea level.

Difficulty in tracing reflectors to distant geological units in the logs along the shoreline led to an approach used in several other reports. The data was separated into seismic stratigraphic units. The reflectors which bounded these divisions correlated well with data on both sides of the Bay. An excellent correlation existed between interpretations from both the single- and multi-channel marine seismic data.

Compilation of the land and the marine data resulted in five structure contour maps of the major hydrogeologic units in the study area. The surface of basement and the middle aquifer indicate a steeper gradient than the other units. The surface of both the confining unit between the middle and upper aquifer and the upper aquifer exhibited a prominent decrease in slope directly offshore from Conaskonk Point and Point Comfort. Direct evidence is shown by a reflector in this data confirming the gradient reduction. The outcrop area for the upper aquifer does not exist on Staten Island, New York and the evidence indicates an outcrop area directly off the southern shore of Staten Island.

A hydrogeologic cross section was developed along a prepumping flow line. This section was discretized with a finite-difference grid and a cross section of the system was simulated with the USGS Three-Dimensional Finite Difference Flow Model. An interface-locating technique called "trimming" was applied to estimate the position of the saltwater interface during prepumping conditions.

Three different boundary conditions were simulated to test the effects of the calculated heads, budget, and interface position. In conjunction with each boundary configuration, two water tables and two leakances were simulated. These variations were based on data from the RASA study. The parameters were varied in order to test the sensitivity of the interface to these parameters.

Results indicate that the difference in boundary conditions had no consequence on the position of the interface. The main effect of the variation in boundary conditions was seen in the head distribution and budget terms. Assignment of specified head values to the edge of the confining unit had no effect except to induce flow of negligible volumes of water into the system. The general head boundary configuration produced the most accurate head distribution when compared to RASA prepumping potentiometric surface maps of the upper aquifer.

The leakance of the confining unit was the controlling factor on the interface position. The high leakance of

$6.0x10^{-4}$ft/d ($2.0x10^{-4}$meters/d) positioned the interface 1.25 to 1.75 miles (2.0-2.8 km) from the shoreline. The elevation of the water table had a minor effect on the interface position in only the leaky system. High water-table altitudes caused the interface to be located 0.5 miles (0.8 km) farther out than simulations with a lower water table.

Flux, velocity and budget terms calculated for each simulation were also more realistic in the runs utilizing the general head boundary. Also, this condition produced the closest match between simulated and calculated heads along the interface.

Further research is continuing on locating the precise position of the prepumping saltwedge. From this research it is apparent that salt water did exist in the upper aquifer under prepumping conditions. All simulations indicate the presence of a saltwedge whether in the outcrop area or at a distance into the aquifer. This report will be quite useful as background information to modeling efforts involving the Raritan Bay area.

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APPENDIX 1

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.

Well Number	Top*	Bot-tom*	Lithologic description
23-146	0.0	56.0	CLAY, GRAY
	56.0	75.0	CLAY, GRAY, SANDY
	75.0	119.0	SAND, GRAY, FINE
	119.0	132.0	SAND AND CLAY
	132.0	168.0	CLAY, STREAKS OF SAND, SOFT AND HARD SPOTS
	168.0	234.0	SAND, WHITE, FINE, COARSE, STREAKS OF CLAY
	234.0	241.0	CLAY, TOUGH
	241.0	251.0	CLAY, STREAKS OF SAND
	251.0	252.0	LEDGE
	252.0	284.0	CLAY, SANDY, WITH STREAKS OF SAND
	284.0	288.0	CLAY, TOUGH
	288.0	334.0	CLAY, WITH STREAKS OF SAND AND HARD STREAKS
	334.0	384.0	SAND, FINE, HARD PACKED
	384.0	399.0	SAND, FINE TO COARSE
	399.0	407.0	SAND, WITH STREAKS OF CLAY
	407.0	425.0	CLAY, TOUGH
	425.0	430.0	SAND, WITH STREAKS OF CLAY
	430.0	459.0	SAND, GRAY, FINE TO COARSE
	459.0	463.0	CLAY
	463.0	481.0	SAND, MEDIUM TO COARSE
23-176	0.0	2.0	FILL
	2.0	5.0	SOIL
	5.0	7.0	CLAY, GRAY, RIVER MUD
	7.0	16.0	CLAY, GRAY
	16.0	104.0	CLAY, SANDY, SOME GRAVEL(21-45 FT),
	16.0	104.0	LIGNITE(83-104 FT)
	104.0	185.0	SAND, COARSE, SOME STREAKS OF CLAY
	185.0	306.0	CLAY, SANDY, SOME COARSE SAND
	306.0	330.0	SAND, COARSE, HARD PACKED, STREAKS OF CLAY
	330.0	348.0	SAND AND CLAY
	348.0	373.0	SAND, COARSE, HARD PACKED, STREAKS OF CLAY
	373.0	410.0	CLAY AND SAND
	410.0	418.0	CLAY, WHITE, SANDY
	418.0	446.0	CLAY, SMALL STREAKS OF SAND
	446.0	456.0	ROCK, WEATHERED
23-191	0.0	20.0	SAND, YELLOW, FINE
	20.0	159.0	CLAY, GRAY, ALTERNATING DENSE AND SANDY,
	20.0	159.0	LAYERS, WOOD TRACES(85-96 FT)
	159.0	190.0	SAND, WHITE, GRAY, FINE
	190.0	227.0	SAND, WATER BEARING

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bottom*	Lithologic description
23-201	0.0	21.0	SAND, WITH CLAY STREAKS
	21.0	35.0	CLAY, WITH SAND AND WOOD STREAKS
	35.0	65.0	SAND AND CLAY, WITH WOOD
	65.0	83.0	SAND AND GRAVEL, COARSE, WITH CLAY STREAKS
	83.0	105.0	CLAY, WITH MICA, WOOD AND PYRITE
	105.0	110.0	SAND AND GRAVEL, WITH PYRITE AND CLAY
	110.0	125.0	CLAY, WITH PYRITE AND SAND STREAKS
	125.0	150.0	SAND, WITH CLAY, WOOD AND PYRITE
	150.0	221.0	CLAY, WITH HARD STREAKS
	221.0	238.0	CLAY, WITH SAND STREAKS
	238.0	253.0	SAND AND GRAVEL, SOME CLAY
	253.0	255.0	CLAY
	255.0	303.0	SAND, WITH CLAY STREAKS
	303.0	332.0	SAND AND GRAVEL, COARSE
23-202	0.0	2.0	LOAM AND GRAVEL, SANDY
	2.0	3.0	CLAY, BLACK
	3.0	37.0	SAND, WHITE, YELLOW, FINE
	37.0	61.0	CLAY, SANDY, WITH WOOD
	61.0	67.0	CLAY, GRAY, STIFF
	67.0	157.0	SAND, FINE, WITH WOOD
	157.0	200.0	CLAY, SILTY
	200.0	270.0	CLAY, GRAY, SOME SAND(261-266 FT)
	270.0	288.0	CLAY, RED, TOUGH
	288.0	320.0	SAND, FINE TO COARSE, SLIGHTLY CLAYEY
	320.0	324.0	SAND, GRAY, LAYERS OF GRAY CLAY
23-206	0.0	2.0	FILL
	2.0	15.0	SAND
	15.0	98.0	CLAY
	98.0	108.0	SAND, FINE
	108.0	185.0	CLAY, DARK
	185.0	210.0	SAND, COARSE
	210.0	355.0	CLAY
	355.0	370.0	SAND
	370.0	371.0	CLAY
	371.0	377.0	SAND
	377.0	380.0	CLAY
	380.0	397.0	SAND
23-369	10.0	40.0	SAND
	40.0	58.0	CLAY
	58.0	66.0	SAND
	66.0	82.0	CLAY
	82.0	92.0	SAND
	92.0	122.0	CLAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bottom*	Lithologic description
23-386	0.0	19.0	SAND AND GRAVEL, YELLOW
	19.0	50.0	SAND, COARSE, STREAKS OF CLAY
	50.0	60.0	CLAY
	60.0	71.0	CLAY, SANDY
	71.0	113.0	SAND, FINE TO COARSE
	113.0	122.0	CLAY, SANDY
	122.0	143.0	SAND, COARSE, STREAKS OF CLAY(132-143 FT)
	143.0	165.0	CLAY, BLUE, TOUGH
	165.0	218.0	CLAY, BLUE, SANDY, SOFT
	218.0	225.0	SAND, FINE
	225.0	246.0	CLAY, RED, TOUGH
23-399	0.0	20.0	SAND AND GRAVEL
	20.0	30.0	SAND AND GRAVEL, RED, FINE
	30.0	50.0	CLAY, WHITE, SANDY
	50.0	68.0	SAND, WHITE, FINE
	68.0	82.0	SAND AND GRAVEL, WHITE, FINE
	82.0	98.0	SAND, WHITE, FINE, WITH CLAY BALLS
	98.0	189.0	CLAY, BLUE, WITH PYRITE(157-160 AND
	98.0	189.0	170-172 FT)
	189.0	196.0	CLAY, BLUE, SANDY
	196.0	213.0	SAND, GRAY, MEDIUM
	213.0	246.0	SAND, GRAY, COARSE
	246.0	257.0	CLAY AND ROCK, SANDY
	257.0		ROCK
23-404	0.0	30.0	SAND, WHITE, FINE
	30.0	48.0	CLAY, YELLOW, SANDY
	48.0	89.0	SAND, CLAYEY
	89.0	99.0	SAND, CEMENTED, HARDPAN(89-90 FT)
	99.0	110.0	SAND
	110.0	153.0	CLAY, GRAY, SANDY, CEMENTED(135-136 AND
	110.0	153.0	141-153 FT)
	153.0	160.0	SAND, WITH MICA AND LIGNITE
	160.0	171.0	SAND, HARD PACKED
	171.0	172.0	HARDPAN
	172.0	184.0	SAND, CEMENTED
	184.0	197.0	SAND, FINE, CLAYEY, HARD PACKED
	197.0	230.0	SAND
	230.0	251.0	SAND, FINE TO MEDIUM
	251.0	255.0	CLAY
	255.0	289.0	SAND, FINE TO MEDIUM
	289.0	291.0	HARDPAN
	291.0	313.0	ROCK OR WEATHERED ZONE

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
23-408	0.0	4.0	FILL
	4.0	14.0	CLAY, GRAY, SOLID
	14.0	43.0	CLAY, GRAY, SOLID, WITH LAYERS OF SANDY CLAY
	43.0	53.0	SAND, GRAY, FINE
	53.0	58.0	SAND, GRAY, FINE, WITH SANDY CLAY
	58.0	67.0	SAND AND CLAY, MULTICOLORED, FINE
	67.0	71.0	SAND, GRAY, FINE
	71.0	75.0	SAND, DARK GRAY, MEDIUM TO COARSE, WITH
	71.0	75.0	SANDY CLAY
	75.0	86.0	CLAY, GRAY, SOME FINE SAND
	86.0	93.0	CLAY, GRAY, SOLID
	93.0	107.0	SAND, GRAY, FINE TO COARSE
	107.0	116.0	SAND AND CLAY, GRAY, ALTERNATING LAYERS
	116.0	122.0	SAND, GRAY, COARSE
	122.0	239.0	CLAY, GRAY, LAYERS OF SANDY CLAY
	239.0	258.0	SAND AND CLAY, GRAY, ALTERNATING LAYERS,
	239.0	258.0	WITH LIGNITE
	258.0	278.0	SAND, GRAY, FINE TO COARSE
	278.0	299.0	CLAY, BLUE, GRAY, WITH LAYERS OF SANDY CLAY,
	278.0	299.0	LIGNITIC
	299.0	308.0	CLAY, MULTICOLORED, SOLID, HARD
23-411	0.0	9.0	MARSH
	9.0	59.0	SAND AND CLAY, WHITE, BROWN
	59.0	64.0	SAND, MUDDY
	64.0	115.0	CLAY, SANDY
	115.0	172.0	CLAY AND HARD STREAKS
	172.0	174.0	SAND
	174.0	180.0	CLAY, TOUGH
	180.0	183.0	SAND
	183.0	191.0	CLAY
	191.0	196.0	SAND, COARSE
	196.0	198.0	CLAY
	198.0	233.0	SAND AND GRAVEL, WHITE
	233.0	241.0	CLAY, TOUGH

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
23-421	0.0	39.0	SAND AND GRAVEL, BROWN
	39.0	69.3	CLAY AND GRAVEL
	69.3	96.5	CLAY, BLUE, HARD
	96.5	121.7	SAND, BROWN, COARSE
	121.7	158.4	CLAY, BLUE, SANDY
	158.4	161.4	SAND AND BOULDERS
	161.4	196.3	CLAY, BLUE, TOUGH
	196.3	198.3	SAND AND BOULDERS
	198.3	240.1	CLAY, BLUE, TOUGH, SAND STREAKS(213-220 FT)
	240.1	242.1	SAND
	242.1	244.1	CLAY, BLUE
	244.1	281.8	SAND, GRAY, COARSE, WATER BEARING
	281.8	286.8	CLAY, BLUE, TOUGH
	286.8	329.8	CLAY, RED, HARD
	329.8	331.8	CLAY AND SHALE, RED
	331.8	333.8	SHALE, RED, HARD
23-424	0.0	10.0	SAND AND GRAVEL, YELLOW, BROWN, CLAYEY
	10.0	18.0	SAND, YELLOW, BROWN, CLAYEY
	30.0	40.0	CLAY, GRAY, MICACEOUS
	40.0	100.0	CLAY, GRAY, SANDY
	100.0	105.0	SAND, FINE TO MEDIUM, WITH PYRITE GRAINS
	105.0	115.0	SAND, GRAY, FINE TO COARSE, SLIGHTLY CLAYEY
	115.0	118.0	CLAY, PINK, GRAY, SANDY
	118.0	123.0	CLAY, RED, GREEN
	123.0	129.0	CLAY, RED, GREEN, SOME SAND AND DECOMPOSED
	123.0	129.0	FELDSPAR
23-574	0.0	21.0	SAND, BROWN, FINE TO MEDIUM
	21.0	28.0	SAND, BROWN, FINE, WITH LAYERS OF SILTY CLAY
	21.0	28.0	AND WOOD
	28.0	123.0	CLAY, GRAY, SILTY, WITH LAYERS OF FINE SAND
	28.0	123.0	AND WOOD
	123.0	135.0	SAND, LIGHT GRAY, BROWN, COARSE
	135.0	140.0	CLAY, GRAY, SILTY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
23-576	0.0	10.0	FILL
	10.0	19.0	MUD, RIVER
	19.0	23.0	SAND, BROWN
	23.0	30.0	CLAY, GRAY
	30.0	70.0	SAND AND GRAVEL, CLAYEY
	70.0	97.0	SAND, FINE, CLAYEY
	97.0	103.0	SAND, FINE TO COARSE
	103.0	122.0	CLAY, GRAY
	122.0	135.0	CLAY, BLACK
	135.0	146.0	SAND AND CLAY, FINE, HARD PACKED
	146.0	148.0	CLAY, BLACK
	148.0	153.0	SAND
	153.0	165.0	CLAY, RED, WHITE
23-603	0.0	1.0	SAND, BROWN, FINE TO MEDIUM, WITH ROOTS
	1.0	5.5	SAND, YELLOW, BROWN, FINE TO MEDIUM, TRACE
	1.0	5.5	SILT
	5.5	13.5	SAND, YELLOW, BROWN, FINE TO COARSE, TRACE
	5.5	13.0	GRAVEL AND SILT
	13.5	21.0	SAND, GRAY, FINE TO MEDIUM, TRACE GRAVEL AND
	13.5	21.0	SILT, CLAY LENS(21.1 FT)
	21.0	24.5	SAND, YELLOW, BROWN, FINE TO MEDIUM, TRACE
	21.0	24.5	SILT
	24.5	34.0	SAND, GRAY, FINE TO MEDIUM, TRACE SILT
	34.0	41.0	SAND, GRAY, FINE TO MEDIUM, GRAY CLAY
	34.0	41.0	LENSES, TRACE LIGNITE
	41.0	43.0	SAND, YELLOW, GRAY, FINE TO COARSE, TRACE
	41.0	43.0	SILT
	43.0	56.0	SAND, GRAY, FINE TO MEDIUM, SILTY CLAY
	43.0	56.0	LENSES
	56.0	84.5	SAND, GRAY, FINE, LITTLE SILT, TRACE LIGNITE
	84.5	85.5	SAND, GRAY, MEDIUM
	85.5	93.5	CLAY, LIGHT GRAY, SILTY
	93.5	96.0	CLAY, DARK GRAY, SILTY, TRACE FINE SAND
23-783	0.0	5.0	RED CLAY
	5.0	45.0	YELLOW CLAY AND SAND
	45.0	60.0	LAYERS OF GRAY CLAY AND SAND
	60.0	165.0	GRAY CLAY
	165.0	250.0	FINE GRAY SAND
	250.0	265.0	FINE WHITE SAND
23-842	0.0	3.0	WATER
	3.0	14.0	MUD
	14.0	39.0	CLAY, BLACK, LIGNITIC
	AT	39.0	BEDROCK

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
23-1025	0.0	10.0	SAND AND GRAVEL - FILL
	10.0	65.0	BLUE CLAY
	65.0	126.0	SANDY BLUE CLAY
	AT	126.0	BEDROCK
23-1034	0.0	6.0	RED CLAY AND GRAVEL - FILL
	6.0	21.0	SAND, STREAKS OF BLUE AND RED CLAY AND GRAVEL -
	21.0	90.0	BLUE CLAY
	90.0	114.0	BLACK SANDY CLAY
	AT	114.0	BEDROCK
25-111	0.0	10.0	SAND AND GRAVEL
	10.0	44.0	SAND, GRAY
	44.0	70.0	SAND AND CLAY, GRAY
	70.0	140.0	CLAY, FINE, SANDY
	140.0	150.0	CLAY, SANDY, WITH HARD STREAKS
	150.0	202.0	SAND, FINE, MUDDY, RUSTY
	202.0	305.0	SAND, FINE, MUDDY
	305.0	366.0	SAND, GRAY
	366.0	371.0	CLAY, GRAY
	371.0	409.0	SAND, COARSE
	409.0	432.0	SAND, GRADING TO SAND AND CLAY
	432.0	453.0	CLAY
	453.0	469.0	SAND AND CLAY, WITH PYRITES
	469.0	513.0	CLAY, TOUGH

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-119	0.0	6.0	FILL
	6.0	14.0	SAND AND GRAVEL
	14.0	21.0	CLAY AND SAND, WITH WOOD
	21.0	25.0	HARDPAN
	25.0	46.0	CLAY AND SAND, WITH WOOD
	46.0	47.0	HARDPAN
	47.0	89.0	CLAY, SANDY
	89.0	108.0	CLAY, SANDY, WITH SAND STREAKS
	108.0	293.0	SAND AND CLAY, STREAKS
	293.0	294.0	HARDPAN
	294.0	341.0	CLAY, SANDY, HARD, WITH HARD STREAKS
	341.0	342.0	HARDPAN
	342.0	371.0	CLAY, SANDY, HARD, WITH HARD STREAKS
	371.0	373.0	HARDPAN
	373.0	472.0	CLAY, WITH SAND AND HARD STREAKS
	472.0	548.0	CLAY AND SAND
	548.0	578.0	CLAY, WITH STREAKS OF SAND
	578.0	637.0	CLAY, TOUGH, SOME SAND STREAKS
	637.0	650.0	CLAY AND SAND
	650.0	678.0	SAND, MEDIUM TO COARSE
	678.0	691.0	CLAY, TOUGH
	691.0	693.0	CLAY, TOUGH, WITH SAND STREAKS
	693.0	717.0	SAND, HARD, WITH CLAY STREAKS
	717.0	724.0	CLAY, TOUGH
	724.0	758.0	SAND, HARD PACKED, WITH CLAY
	758.0	762.0	CLAY, WITH SAND STREAKS
	762.0	763.0	HARDPAN
	763.0	812.0	CLAY, SANDY, TOUGH, WITH SAND STREAKS
	812.0	901.0	CLAY, SANDY, HARD, WITH SAND STREAKS

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-145	0.0	19.0	CLAY, BROWN, WITH HARDPAN, STREAKS OF SAND
	0.0	19.0	AND GRAVEL
	19.0	61.0	CLAY, GREEN, GRAY, SANDY, GLAUCONITIC,
	19.0	61.0	MICACEOUS
	61.0	72.0	CLAY, BLUE, LAYERS OF SANDY AND SOLID CLAY
	72.0	80.0	SAND, DARK GRAY, FINE, WITH STREAKS OF CLAY
	80.0	101.0	CLAY, DARK GRAY, FINE, WITH MICA
	101.0	112.0	CLAY, GRAY, FINE, SANDY, WITH STREAKS OF
	101.0	112.0	SOLID CLAY
	112.0	121.0	CLAY, GRAY, LAYERS OF SANDY AND SOLID CLAY
	121.0	132.0	SAND, GRAY, FINE, WITH MICA
	132.0	159.0	CLAY, GRAY, SOLID
	159.0	165.0	SAND, GRAY, FINE, LAYERS OF CLAY
	165.0	220.0	CLAY, GRAY, BLACK, SOLID, HARD
	220.0	259.0	SAND, GRAY, FINE, WITH CLAY AND LIGNITE
	259.0	271.0	SAND, GRAY, FINE
	271.0	333.0	CLAY, BLACK, WITH SANDY CLAY AND PYRITE
	333.0	347.0	CLAY, GRAY, WITH STREAKS OF SHALE
	347.0	373.0	CLAY, BLACK, SOLID
	373.0	391.0	SAND, GREEN, FINE, STREAKS OF CLAY
	391.0	416.0	CLAY, GREEN, SOLID
	416.0	443.0	SAND, GREEN, FINE, WITH LAYERS OF CLAY AND
	416.0	443.0	LIGNITE
	443.0	450.0	CLAY, GREEN, SOLID
	450.0	459.0	CLAY, GREEN, SANDY AND SOLID LAYERS,
	450.0	459.0	LIGNITIC
	459.0	465.0	CLAY, BLACK, SOLID
	465.0	475.0	SAND, FINE, STREAKS OF CLAY AND LIGNITE
	475.0	502.0	CLAY, BLACK, GRAY, SOLID
	502.0	512.0	CLAY, GREEN, FINE, SOLID AND SANDY STREAKS,
	502.0	512.0	LIGNITIC
	512.0	524.0	SAND, GREEN, FINE
	524.0	535.0	SAND, GREEN, FINE, WITH STREAKS OF CLAY
	535.0	541.0	CLAY, GRAY, SANDY AND SOLID LAYERS, LIGNITIC
	541.0	560.0	SAND, GRAY, FINE, STREAKS OF CLAY, LIGNITIC
	560.0	565.0	CLAY, GRAY, FINE, SANDY
	565.0	572.0	CLAY, GRAY, SOLID
	572.0	598.0	SAND, GRAY, FINE, WITH STREAKS OF CLAY
	598.0	625.0	CLAY, WHITE, SOLID
	625.0	642.0	CLAY, GRAY, SOLID, WITH PYRITE
	642.0	679.0	CLAY, GRAY, SOLID
	679.0	692.0	CLAY, GRAY, FINE, SANDY, WITH PYRITE
	692.0	714.0	CLAY, GRAY, SOLID
	714.0	742.0	CLAY, GRAY, SANDY, WITH STREAKS OF SOLID
	714.0	742.0	CLAY
	742.0	753.0	CLAY, GRAY, SOLID, STREAKS OF LIGNITE AND
	742.0	753.0	SCHIST

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-145	753.0	782.0	CLAY, GRAY, SOLID, STREAKS OF SANDY CLAY
	782.0	812.0	CLAY, GRAY, RED, HARD, SOLID
	812.0	817.0	CLAY, GRAY, FINE, SANDY, WITH MICA
	817.0	839.0	CLAY, GRAY, RED, SOLID
	839.0	846.0	SANDY, GRAY, FINE
	846.0	861.0	SAND, GRAY, MEDIUM TO COARSE, STREAKS OF
	846.0	861.0	CLAY
	861.0	892.0	SAND, GRAY, FINE, STREAKS OF LIGNITE
	892.0	898.0	CLAY, GRAY, SOLID, STREAKS OF SANDY CLAY
	898.0	903.0	SAND, GRAY, FINE, STREAKS SANDY CLAY
	903.0	916.0	SAND, GRAY, FINE, MICA
	916.0	919.0	LAYERS OF CLAY
	919.0	929.0	CLAY, GRAY, SOLID
	929.0	934.0	SAND, GRAY, MEDIUM TO COARSE, CLAY STREAKS
	934.0	940.0	SAND, GRAY, FINE
	940.0	945.0	SAND, GRAY, MEDIUM TO COARSE, CLAY STREAKS
	945.0	956.0	SAND, GRAY, FINE, LAYERS OF LIGNITE
	956.0	963.0	CLAY, MULTICOLORED
	963.0	1045.0	ROCK, DECAYED
25-146	0.0	20.0	SAND AND CLAY, YELLOW
	20.0	60.0	MARL, GREEN
	60.0	96.0	CLAY AND MARL, GRAY
	96.0	150.0	SAND, FINE, MIXED WITH CLAY
	150.0	160.0	CLAY, GRAY, SOLID
	160.0	200.0	SAND, FINE, MIXED WITH CLAY
	200.0	224.0	CLAY, GRAY, SOLID
	224.0	230.0	SAND AND CLAY
	230.0	240.0	CLAY, GRAY, SOLID
	240.0	280.0	SAND AND CLAY
	280.0	290.0	CLAY, GRAY, SOLID
	290.0	300.0	SAND AND CLAY
	300.0	340.0	CLAY, GREEN, SOLID
	340.0	495.0	CLAY, GRAY, SOLID
	495.0	585.0	SAND, WHITE,

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-153	0.0	3.0	FILL
	3.0	11.0	CLAY
	11.0	26.0	SAND, WITH IRON PYRITES
	26.0	41.0	SAND, GRAY, FINE
	41.0	45.0	CLAY, WITH WOOD AND PYRITE
	45.0	61.0	CLAY, WITH STREAKS OF SAND AND WOOD
	61.0	71.0	SAND, FINE, WITH CLAY STREAKS
	71.0	77.0	CLAY, SANDY, WITH STREAKS OF SAND AND WOOD
	77.0	89.0	SAND, WITH CLAY AND WOOD
	89.0	93.0	CLAY, SANDY, WITH SAND STREAKS
	93.0	316.0	CLAY, WITH HARD STREAKS
	316.0	345.0	CLAY, WITH WOOD
	345.0	348.0	CLAY, WHITE, GRAY, WITH SAND STREAKS
	348.0	374.0	CLAY, WITH HARD STREAKS AND WOOD
	374.0	394.0	CLAY, WITH HARD STREAKS
	394.0	400.0	SAND, GRAY, WITH CLAY STREAKS
	400.0	401.0	SAND AND CLAY, WITH WOOD
	401.0	410.0	CLAY, WITH SAND STREAKS(405-410 FT)
	410.0	420.0	SAND, GRAY
	420.0	427.0	CLAY, WITH SOME SAND
	427.0	435.0	CLAY, WITH SAND STREAKS
	435.0	438.0	SAND AND CLAY
	441.0	446.0	CLAY
	446.0	453.0	HARDPAN
	453.0	458.0	CLAY, WITH SOME SAND STREAKS
	458.0	460.0	HARDPAN
	460.0	483.0	CLAY, TOUGH, WITH HARD AND SOFT STREAKS
	483.0	493.0	SAND, FINE, SILTY, WITH CLAY AND PYRITES
	493.0	519.0	CLAY AND SAND, WITH STREAKS OF PYRITES
	519.0	522.0	HARDPAN
	522.0	565.0	CLAY, HARD AND SOFT STREAKS
	565.0	602.0	CLAY, WHITE, GRAY, SANDY
	602.0	629.0	CLAY, RED, WHITE, TOUGH
	629.0	632.0	SAND, FINE TO COARSE, SOME WHITE CLAY AND
	629.0	632.0	PYRITES
	632.0	643.0	SAND, FINE, WITH CLAY STREAKS
	643.0	647.0	CLAY AND SAND
	647.0	656.0	SAND, FINE TO COARSE
	656.0	660.0	SAND, COARSE, WITH CLAY STREAKS
	660.0	663.0	CLAY, WHITE, RED
	663.0	672.0	CLAY, GRAY, RED, WHITE

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bottom*	Lithologic description
25-156	0.0	9.0	SAND AND CLAY, BROWN, FINE
	9.0	48.0	CLAY, GRAY, LAYERS OF SANDY AND SOLID CLAY
	48.0	98.0	SAND, GRAY, FINE, LAYERS OF SOLID AND SANDY
	48.0	98.0	CLAY
	98.0	129.0	CLAY, GRAY, SILTY, SANDY, STREAKS OF LIGNITE
	129.0	184.0	CLAY, GRAY, SOLID
	184.0	219.0	CLAY, GRAY, SILTY, SANDY, WITH MICA
	219.0	230.0	SAND, GRAY, FINE, WITH LAYERS OF SOLID GRAY
	219.0	230.0	CLAY
	230.0	262.0	CLAY, GRAY, SOLID
	262.0	271.0	SAND, GRAY, FINE, WITH MICA
	271.0	276.0	CLAY, GRAY, SILTY, SANDY, MICACEOUS
	276.0	413.0	CLAY, GRAY, STREAKS OF PYRITE, LIGNITE AND
	276.0	413.0	SANDY CLAY
	413.0	425.0	SAND, GRAY, FINE TO MEDIUM, STREAKS OF GRAY
	413.0	425.0	CLAY
	425.0	430.0	CLAY, GRAY, WITH LAYERS OF FINE GRAY SAND
	430.0	439.0	SAND, GRAY, FINE TO MEDIUM, STREAKS OF CLAY
	430.0	439.0	AND LIGNITE
	439.0	454.0	SAND AND CLAY, GRAY, FINE TO MEDIUM, STREAKS
	439.0	454.0	OF LIGNITE
	454.0	498.0	CLAY, GRAY, STREAKS OF FINE SAND AND LIGNITE
	498.0	502.0	SAND, GRAY, FINE, CLAYEY
	502.0	539.0	SAND AND CLAY, GRAY, FINE, SILTY, CLAY
	502.0	539.0	LAYERS
	539.0	571.0	CLAY, GRAY, SOLID
	571.0	670.0	CLAY, GARY, WITH LAYERS OF SANDSTONE
	670.0	718.0	CLAY, MULTICOLORED
25-156	718.0	739.0	CLAY, GRAY, SILTY, SANDY LAYERS
	739.0	779.0	CLAY, MULTICOLORED
	779.0	788.0	CLAY, GRAY, STREAKS OF GRAY SAND
25-194	0.0	25.0	SAND
	25.0	81.0	CLAY, BLUE
	81.0	102.0	CLAY, SANDY
	102.0	124.0	CLAY, BLUE
	124.0	142.0	SAND, PACKED
	142.0	151.0	CLAY, BLUE
	151.0	174.0	SAND, BLUE
	174.0	183.0	CLAY, BLUE
	183.0	215.0	SAND, COARSE
	215.0	223.0	CLAY, TOUGH
	223.0	257.0	SAND, COARSE
	257.0	262.0	CLAY, SOFT
	262.0	295.0	SAND, BLUE
	295.0	357.0	SAND, WHITE, COARSE

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bottom*	Lithologic description
25-196	0.0	4.0	SOIL
	4.0	28.0	SAND, BROWN
	28.0	38.0	CLAY, SANDY, SOFT
	38.0	88.0	CLAY, BLUE, TOUGH
	88.0	128.0	CLAY, BLUE, WITH SANDY STREAKS
	128.0	146.0	SAND, FINE, WITH PACKED CLAY
	146.0	163.0	CLAY, SANDY
	163.0	197.0	SAND, WITH CLAY STREAKS
	197.0	253.0	SAND AND GRAVEL
	253.0	263.0	CLAY, HARD
	263.0	285.0	SAND, GRAY, BROWN
	285.0	306.0	CLAY, BLUE, TOUGH
	306.0	354.0	SAND, GRAY, COARSE
	354.0	359.0	CLAY
	359.0	368.0	SAND
	368.0	394.0	CLAY, BLUE, SANDY
25-197	0.0	11.0	SAND
	11.0	38.0	CLAY
	38.0	70.0	CLAY, GRAY, TOUGH
	70.0	78.0	SAND AND CLAY, LIGNITIC
	78.0	88.0	CLAY, TOUGH, WITH SAND AND PYRITES
	88.0	111.0	CLAY, TOUGH, WITH CEMENTED SAND AND PYRITES
	111.0	131.0	CLAY, WITH SAND STREAKS
	131.0	189.0	CLAY, TOUGH, WITH SMALL STREAKS OF SAND
	189.0	221.0	CLAY, WHITE, HARD, WITH HARD STREAKS OF SAND
	221.0	240.0	CLAY AND SAND, STREAKS
	240.0	304.0	SAND, FINE TO MEDIUM, WITH LIGHT STREAKS OF
	240.0	304.0	CLAY
	304.0	325.0	SAND, FINE TO COARSE
	325.0	334.0	SAND, FINE TO COARSE, WITH SOME CLAY
	334.0	346.0	CLAY, WITH STREAKS OF SAND AND HARD STREAKS
	346.0	370.0	CLAY, WHITE, TOUGH, WITH HARD STREAKS
	370.0	381.0	CLAY
	381.0	393.0	SAND
	393.0	414.0	CLAY, WITH SAND STREAKS
25-201	0.0	10.0	SAND, YELLOW
	10.0	70.0	CLAY, GRAY, BLUE
	70.0	90.0	SAND AND WOOD, MUDDY
	90.0	100.0	CLAY, BLACK
	100.0	140.0	CLAY, BLUE, GRAY
	140.0	230.0	CLAY, GRAY
	230.0	250.0	SAND, FINE, WITH ALTERNATING LAYERS OF CLAY
	250.0	282.0	SAND, GRAY, MIXED WITH CHARCOAL

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-203	0.0	48.0	SAND
	48.0	204.0	ALTERNATING SAND AND CLAY, MOSTLY CLAY
	204.0	270.0	SAND
25-206	0.0	30.0	SAND AND GRAVEL
	30.0	50.0	GRAVEL
	50.0	70.0	GRAVEL AND SAND, COARSE
	70.0	90.0	SAND AND CLAY, WHITE
	90.0	100.0	SAND, BROWN
	100.0	134.0	SAND, BROWN, CLAYEY, LIGNITIC
	134.0	152.0	SAND AND CLAY
	152.0	200.0	SAND AND CLAY, WITH WOOD
	200.0	220.0	SAND, FINE
	220.0	240.0	SAND, WITH WOOD
	240.0	285.0	SAND, WHITE, WITH WOOD
	285.0		CLAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-262	0.0	5.0	CLAY AND FILL
	5.0	8.0	MARL, GREEN, SANDY
	8.0	10.0	MARL, GRAY
	10.0	35.0	CLAY, GRAY, SANDY, COMPACT, SOME HARDPAN
	35.0	70.0	MARL AND CLAY, GRAY, SANDY IN PLACES
	70.0	90.0	MARL AND CLAY, WITH STREAKS OF HARDPAN
	90.0	120.0	MARL AND CLAY, WITH TRACES OF HARDPAN
	90.0	120.0	(90-110 FT)
	120.0	160.0	SAND, WHITE, FINE, WITH CLAY AND WOOD
	160.0	165.0	SAND, MEDIUM TO COARSE, SOME GRAVEL AND CLAY
	165.0	187.0	SAND, FINE, WITH CLAY AND WOOD STREAKS
	187.0	215.0	SAND, GRAY, FINE, SOME CLAY
	215.0	255.0	CLAY, GRAY, SANDY, HARD
	255.0	285.0	CLAY, GRAY, SANDY
	285.0	320.0	CLAY, SANDY
	320.0	340.0	CLAY AND HARDPAN
	340.0	420.0	CLAY AND HARDPAN, SANDY
	420.0	515.0	SAND, GRAY, WITH HARDPAN
	515.0	525.0	SAND, HARD PACKED, WITH CLAY STREAKS
	525.0	555.0	SAND, HARD PACKED, WITH GRAVEL STREAKS
	555.0	585.0	SAND, HARD PACKED, WITH CLAY STREAKS
	585.0	645.0	CLAY, GRAY, SANDY, WITH HARDPAN(630-645 FT)
	645.0	660.0	SAND, HARD PACKED, SOME CLAY AND HARDPAN
	660.0	690.0	SAND AND CLAY, GRAY, COMPACT
	690.0	700.0	SAND AND CLAY, GRAY, COMPACT, HARDPAN
	700.0	715.0	CLAY, RED, HARD
	715.0	727.0	SAND, MEDIUM TO COARSE, WITH CLAY SEAMS
	727.0	730.0	CLAY, HARD AND STICKY
	730.0	760.0	SAND, GRAY, SOME CLAY AND HARDPAN STREAKS
	760.0	763.0	CLAY, HARD AND STICKY
	763.0	768.0	SAND, GRAY, WITH CLAY STREAKS
	768.0	773.0	SAND, GRAY, MEDIUM
	773.0	778.0	SAND, GRAY, WITH CLAY STREAKS
	778.0	780.0	SAND, GRAY, MEDIUM
	780.0	812.0	SAND, MEDIUM TO COARSE
	812.0	827.0	ROCK, WEATHERED
	827.0	875.0	ROCK

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-269	0.0	1.0	SOIL
	1.0	12.0	SAND, BROWN
	12.0	17.0	CLAY, GRAY
	17.0	32.0	SAND, GRAY, FINE
	32.0	77.0	CLAY, GRAY
	77.0	96.0	SAND, GRAY
	96.0	107.0	CLAY, GRAY
	107.0	114.0	SAND, GRAY
	114.0	164.0	CLAY, GRAY
	164.0	165.0	HARDPAN
	165.0	169.0	SAND, GRAY
	169.0	170.0	CLAY, SANDY
	170.0	307.0	SAND, LIGHT GRAY
	307.0	317.0	CLAY, GRAY, HARD
	317.0	427.0	CLAY, GRAY, SANDY
	427.0	468.0	CLAY, WHITE
	468.0	472.0	SAND, GRAY, FINE
	472.0	478.0	SAND, WITH STREAKS OF CLAY
	478.0	485.0	CLAY, WHITE
	485.0	492.0	SAND, FINE
	492.0	500.0	SAND, GRAY
	500.0	522.0	SAND, WITH STREAKS OF CLAY
	522.0	527.0	CLAY, GRAY
	527.0	530.0	SAND, GRAY, FINE
	530.0	540.0	CLAY, GRAY
	540.0	547.0	CLAY, GRAY, SANDY
	547.0	594.0	CLAY, GRAY
	594.0	644.0	CLAY, WHITE, SANDY
	644.0	703.0	SAND, WHITE, FINE
	703.0	743.0	SAND, WHITE, FINE TO MEDIUM
	743.0	783.0	SAND, FINE

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-272	0.0	6.0	FILL
	6.0	46.0	CLAY, GRAY, SOLID
	46.0	93.0	SAND, GRAY, FINE, WITH STREAKS OF CLAY
	93.0	111.0	CLAY, GRAY, SOLID
	111.0	151.0	CLAY, GRAY, SOLID, WITH STREAKS OF SANDY CLAY
	151.0	194.0	CLAY, DARK GRAY, SOLID
	194.0	239.0	CLAY, GRAY, SILTY, CEMENTED, WITH MICA
	239.0	249.0	CLAY, GRAY, SILTY, SANDY, WITH MICA AND LIGNITE
	249.0	269.0	SAND, GRAY, FINE, WITH LAYERS OF SOLID CLAY
	269.0	317.0	CLAY, GRAY, SANDY, SILTY
	317.0	340.0	CLAY, GRAY, SANDY, WITH MICA AND LIGNITE
	340.0	428.0	SAND, GRAY, FINE, STREAKS OF CLAY, LIGNITE AND PYRITE
	428.0	474.0	SAND, GRAY, FINE, WITH LAYERS OF CLAY AND PYRITES
	474.0	534.0	CLAY, GRAY, SOLID, WITH PYRITE
	534.0	554.0	CLAY, SOLID, SILTY, SANDY, WITH CEMENTED STREAKS
	554.0	592.0	CLAY, GRAY, SOLID
	592.0	618.0	CLAY, GRAY, SOLID, WITH LAYERS SANDY CLAY AND PYRITE
	618.0	629.0	CLAY, MULTICOLORED, SOLID
	629.0	638.0	SAND, GRAY, FINE, STREAKS OF CLAY
	638.0	651.0	CLAY, GRAY, SOLID, LAYERED WITH SAND AND LIGNITE
	651.0	662.0	SAND, GRAY, FINE TO MEDIUM, STREAKS OF CLAY
	662.0	692.0	SAND, GRAY, FINE TO COARSE, STREAKS OF SANDY CLAY
	692.0	698.0	CLAY, GRAY, SOLID
	698.0	700.0	SAND AND CLAY, GRAY, FINE
25-282	0.0	10.0	BRICK AND FILL
	10.0	15.0	CLAY, BLACK
	15.0	57.0	CLAY, GRAY, SOME STREAKS OF SAND
	57.0	59.0	HARDPAN
	59.0	97.0	CLAY
	97.0	126.0	SAND, FINE, GRADING TO CLAYEY
	126.0	127.0	HARDPAN
	127.0	133.0	CLAY, SANDY
	133.0	135.0	CLAY, SOFT
	135.0	163.0	CLAY, SANDY
	163.0	233.0	SAND, WITH STREAKS OF CLAY
	233.0	285.0	SAND, 1, 2 FT HARDPAN LAYERS(233 AND 238 AND 262 FT)

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-284	0.0	75.0	CLAY
	75.0	130.0	CLAY, SANDY
	130.0	142.0	SAND, FINE
	142.0	159.0	SAND, HARD PACKED
	159.0	207.0	SAND, WITH CLAY STREAKS
	207.0	220.0	CLAY, TOUGH, WITH SOME SAND
	220.0	242.0	SAND
	242.0	243.0	CLAY
	243.0	253.0	SAND
	253.0	273.0	SAND, WHITE, COARSE,
	273.0	286.0	CLAY, HARD
	286.0	291.0	SAND
	291.0	323.0	CLAY
	323.0	352.0	CLAY, TOUGH
	352.0	367.0	SAND
	367.0	420.0	CLAY, WITH SAND STREAKS
	420.0	430.0	SAND
	430.0	457.0	CLAY
25-290	0.0	50.0	SAND
	50.0	270.0	CLAY, SOME SAND
	270.0	290.0	SAND
	290.0	305.0	CLAY
	305.0	370.0	SAND
	370.0	420.0	CLAY
25-291	0.0	270.0	CLAY
	270.0	300.0	SAND
	300.0	318.0	CLAY
	318.0	360.0	SAND
	360.0	394.0	CLAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-292	0.0	102.0	NO DATA
	102.0	138.0	CLAY, GRAY, SILTY, SOME MICA, LIGNITE AND GLAUCONITE
	138.0	168.0	CLAY, GREEN, BROWN, SILTY, WITH GLAUCONITE AND MICA
	168.0	178.0	CLAY, GREEN, BROWN, SILTY, WITH GLAUCONITE, MICA AND AMBER
	178.0	193.0	SILT, GRAY, CLAYEY, WITH MICA AND LIGNITE
	193.0	213.0	SAND, BLACK, FINE, WITH LIGNITE AND MICA, CLAYEY FROM 202 FT
	213.0	273.0	CLAY AND SILT AND SAND, GRAY, FINE, WITH MICA AND LIGNITE
	272.0	285.0	SAND, WHITE, FINE TO COARSE
	285.0	296.0	SAND AND CLAY, GRAY, WHITE, WITH LIGNITE AND MICA
	296.0	299.0	CLAY, BLACK, SILTY, WITH MICA AND LIGNITE
	299.0	306.0	SAND, WHITE, WITH SOME CLAY
	306.0	325.0	CLAY AND SILT AND SAND, GRAY, WITH MICA, LIGNITE AND LIMONITE
	325.0	344.0	SILT AND CLAY, GRAY, WITH MICA AND LIGNITE
	344.0	412.0	SAND AND CLAY, GRAY, FINE, WITH MICA AND SIDERITE
	412.0	631.0	CLAY, GRAY, SOME SILT, WITH MICA, LIGNITE AND LIMONITE
	631.0	636.0	SAND, GRAY, FINE TO MEDIUM, WITH CLAY AND SILT
	636.0	644.0	CLAY, GRAY, BROWN, MICACEOUS
	644.0	654.0	CLAY, GRAY, SILTY, SOME SAND, WITH MICA AND GLAUCONITE
	654.0	675.0	SILT, GRAY, CLAYEY, WITH MICA AND LIGNITE
	675.0	696.0	SAND, GRAY, WITH MICA AND LIGNITE, CLAYEY FROM 685 FT
	696.0	733.0	CLAY, MULTICOLORED, MICACEOUS
25-294	0.0	5.0	SOIL
	5.0	118.0	CLAY, TOUGH
	118.0	146.0	CLAY, SANDY, TOUGH STREAKS
	146.0	204.0	CLAY, BLACK, TOUGH
	204.0	214.0	SAND, GRAY, FINE
	214.0	259.0	SAND, GRAY, MEDIUM TO COARSE
	259.0	282.0	CLAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bottom*	Lithologic description
25-297	0.0	10.0	CLAY AND GRAVEL
	10.0	42.0	CLAY, GRAY
	42.0	80.0	CLAY AND SAND
	80.0	184.0	CLAY, GRAY, WITH HARD STREAKS
	184.0	236.0	SAND, GRAY, FINE
	236.0	256.0	CLAY, GRAY
	256.0	261.0	SAND, GRAY
	261.0	374.0	CLAY AND SAND, GRAY, WHITE, STREAKS
	374.0	383.0	SAND, HARD
	383.0	440.0	CLAY, RED, HARD STREAKS
	440.0	465.0	SAND, COARSE
	465.0	469.0	CLAY
	469.0	486.0	SAND, FINE, COARSE,
	486.0	498.0	CLAY, HARD STREAKS
25-299	0.0	1.0	FILL
	1.0	5.0	CLAY, YELLOW
	5.0	32.0	SAND, GRAY, CLAYEY
	32.0	48.0	CLAY, GRAY
	48.0	88.0	CLAY AND SAND, GRAY, FINE
	88.0	223.0	SAND, GRAY, COARSE, WITH WOOD AND CLAY
	88.0	223.0	STREAKS
	223.0	268.0	SAND, BROWN, WITH WOOD AND CLAY STREAKS
	268.0	403.0	SAND, BROWN, WITH WOOD AND CLAY STREAKS
	403.0	425.0	CLAY, GRAY
	425.0	457.0	SAND, GRAY
	457.0	491.0	CLAY, GREEN

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bottom*	Lithologic description
25-303	0.0	2.0	SOIL
	2.0	5.0	SAND, BROWN
	5.0	51.0	CLAY, GRAY, SANDY
	51.0	78.0	SAND
	78.0	137.0	CLAY, BLACK, SANDY
	137.0	147.0	CLAY, BLACK, HARD
	147.0	175.0	SAND AND LIGNITE
	175.0	193.0	SAND
	193.0	205.0	SAND, WITH STREAKS OF CLAY
	205.0	216.0	CLAY, GRAY
	216.0	240.0	SAND
	240.0	246.0	CLAY
	246.0	252.0	SAND
	252.0	258.0	SAND WITH STREAKS OF CLAY
	258.0	265.0	SAND
	265.0	293.0	CLAY, SANDY
	293.0	294.0	HARDPAN
	294.0	296.0	CLAY
	296.0	307.0	SAND AND CLAY
	307.0	309.0	CLAY
	309.0	318.0	SAND, WITH STREAKS OF CLAY
	318.0	325.0	CLAY
	325.0	348.0	MARL
	348.0	353.0	CLAY, SILTY, SANDY
	353.0	355.0	HARDPAN
	355.0	416.0	CLAY, WITH STREAKS OF SAND
	416.0	485.0	SAND
	485.0	542.0	SAND
	542.0	621.0	SAND, WITH STREAKS OF CLAY
	621.0	650.0	SAND, WITH LIGNITE
	650.0	655.0	HARDPAN AND CLAY, GRAY
	655.0	670.0	SAND AND CLAY
	670.0	726.0	CLAY, GRAY
25-314	0.0	12.0	LOAM AND CLAY, YELLOW
	12.0	40.0	SAND, GRAY, MEDIUM, WITH CHARCOAL
	40.0	45.0	CLAY AND SAND, GRAY, DENSE
	45.0	80.0	SAND, GRAY, FINE, WITH CHARCOAL
	80.0	225.0	CLAY AND SILT, GRAY, DENSE, SOME STONES
	225.0	300.0	CLAY, GRAY
	300.0	340.0	SAND, GRAY, FINE, CLAYEY
	340.0	368.0	SAND AND STONES, GRAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-318	0.0	100.0	SAND, WITH GRAVEL AND SHELLS
	100.0	120.0	SAND, GRAY
	120.0	160.0	CLAY, BLUE, WITH SMALL STONES, SANDY
	120.0	160.0	(140-160 FT)
	160.0	180.0	SAND, YELLOW, FINE
	180.0	200.0	CLAY AND LOAM, BROWN
	200.0	260.0	CLAY, BLUE, SANDY, STIFF, WITH MICA AND SOME
	200.0	260.0	STONES
	260.0	300.0	SAND, GRAY, FINE
	300.0	396.0	SAND, GRAY, FINE, WITH WOOD AND MICA
	396.0	400.0	CLAY, BLUE, WITH WOOD
	400.0	500.0	SAND, WHITE, FINE TO MEDIUM, WITH WOOD
	400.0	500.0	(420-460 FT)
	500.0	503.0	CLAY, WHITE, SANDY, CHALKY
	503.0	508.0	SAND, RED, COARSE, WITH WOOD
	508.0	527.0	SAND, YELLOW
	527.0	537.0	SAND, WHITE, WITH WOOD
	537.0	542.0	GRAVEL AND SAND, SOME WOOD AND STONES
	542.0	552.0	GRAVEL AND SAND, SOME WOOD AND STONES AND
	542.0	552.0	PYRITES
	552.0	560.0	SAND, BLUE, FINE
	560.0	582.0	CLAY, BLUE, WITH IRON ORE LUMPS AND SOME
	560.0	582.0	STONES
	582.0	667.0	CLAY, BLUE, 1 FT SAND LAYERS AT 624 AND
	582.0	667.0	656 FT
	667.0	694.0	SAND, DARK BLUE, FINE, WATER BEARING
	694.0	711.0	SAND, WHITE, WITH WOOD, WATER BEARING
	711.0	715.0	CLAY, BLUE, SANDY, COMPACT
	715.0	754.0	SAND, WHITE, WITH WOOD, WATER BEARING
25-320	0.0	116.0	SAND
	116.0	400.0	ALTERNATING SAND AND CLAY
	400.0	550.0	SAND
	550.0	728.0	CLAY WITH SOME SAND
	728.0	760.0	SAND, WATER BEARING
	760.0	820.0	CLAY WITH SAND (60 FEET)
	820.0	865.0	SAND, WATER BEARING
	865.0	872.0	CLAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-453	0.0	6.0	FILL
	6.0	75.0	CLAY, GRAY, WITH GRAVEL
	75.0	93.0	CLAY, WITH SAND STREAKS AND LIGNITE
	93.0	117.0	SAND, WITH STREAKS OF SANDY CLAY
	117.0	136.0	CLAY, GRAY
	136.0	144.0	SAND
	144.0	162.0	CLAY AND SAND, GRAY
	162.0	195.0	CLAY, SANDY, WITH SAND STREAKS
	195.0	211.0	CLAY, SANDY, HARD
	211.0	222.0	CLAY, SANDY, SOFT
	222.0	234.0	CLAY, SANDY, WITH SOFT AND HARD STREAKS
	234.0	272.0	SAND, FINE
	272.0	291.0	SAND, FINE TO MEDIUM
	291.0	307.0	CLAY, WITH SAND STREAKS
	307.0	312.0	CLAY
	312.0	354.0	CLAY, SANDY, WITH SAND STREAKS
	354.0	377.0	CLAY, SANDY, WITH HARD AND SOFT STREAKS
	377.0	399.0	SAND AND CLAY, STREAKS
	399.0	419.0	SAND AND CLAY, FINE
	419.0	432.0	SAND AND SANDSTONE, FINE TO MEDIUM
	432.0	442.0	CLAY, WITH STREAKS OF SAND
	442.0	463.0	SAND, FINE
	463.0	545.0	SAND, FINE TO MEDIUM, WITH STREAKS OF CLAY
	545.0		SAND, CEMENTED
25-456	0.0	6.0	FILL
	6.0	10.0	SAND, GRAY
	10.0	105.0	CLAY, GRAY, WITH LIGNITE
	105.0	177.0	SAND AND CLAY, GRAY, FINE, WITH LIGNITE
	177.0	210.0	CLAY AND SILT, WITH LIGNITE
	210.0	265.0	SAND, GRAY, FINE
	265.0	266.0	CLAY
	266.0	324.0	SAND, GRAY, MEDIUM
	324.0	345.0	CLAY AND SAND, WITH PYRITE
25-459	0.0	55.0	SAND
	55.0	80.0	CLAY
	80.0	200.0	SAND WITH CLAY
	200.0	240.0	CLAY
	240.0	290.0	SAND
	290.0	550.0	CLAY
	550.0	636.0	SAND
	636.0	761.0	CLAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-462	0.0	28.0	SAND, BROWN, MEDIUM
	28.0	38.0	CLAY, GRAY, SILTY, SOFT
	38.0	45.0	CLAY, GRAY, SOFT, WITH ROCK LEDGE(38 FT)
	45.0	50.0	CLAY, GRAY, , BLUE, GREEN, TOUGH
	50.0	52.0	CLAY, WHITE, WITH LENSES OF FINE GRAY SAND,
	50.0	52.0	LIGNITIC
	52.0	64.0	SAND, CLAYEY
	64.0	72.0	SAND, FINE, LIGNITIC
	72.0	80.0	CLAY, GRAY, FIRM
	80.0	91.0	SAND, FINE, WITH SOFT CLAY STREAKS
	91.0	107.0	CLAY, FIRM, ROCK LEDGE(91-91.5 FT)
	107.0	114.0	SAND
	114.0	123.0	CLAY, FIRM, WITH SOME SOFT SPOTS
	123.0	143.0	CLAY, GRAY, TOUGH, ROCKY(125 FT)
	143.0	145.0	SAND AND CLAY, LENSES
	145.0	154.0	SAND, GRAY, FINE, LIGNITIC
	154.0	160.0	CLAY, GRAY, MEDIUM
	160.0	185.0	CLAY, HARD PACKED
	185.0	187.0	CLAY AND SILT, SOFT
	187.0	198.0	SAND, FINE, WITH FINE PEBBLES, AMBER AND
	187.0	198.0	LIGNITE
	198.0	200.0	CLAY
	200.0	211.0	SAND, FINE, WITH FINE WHITE PEBBLES
	211.0	212.0	CLAY, WHITE, SOFT
	212.0	218.0	SAND, WHITE, CLAYEY
	218.0	227.0	SAND, FINE
	227.0	234.0	SAND, FINE TO MEDIUM
	234.0	238.0	SAND, FINE, WITH FINE WHITE PEBBLES
	238.0	240.0	ROCK
	240.0	245.0	SAND, FINE, WITH FINE WHITE PEBBLES AND
	240.0	245.0	LIGNITE
	245.0	250.0	SAND, MEDIUM, COARSE, SOME FINE GRAVEL
	250.0	252.0	ROCK, WITH SILT AND LIGNITE
	252.0	263.5	CLAY, TOUGH, SILTY AND SOFT(252 FT)
	263.5	273.0	SAND, FINE
	273.0	281.0	SILT, SOFT
	281.0	289.0	SAND, FINE, SILTY
	289.0	304.0	SILT AND CLAY, LAYERS, LIGNITIC, LEDGE(289 FT)
	304.0	310.0	CLAY, WHITE

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-466	0.0	50.0	NO DATA
	59.0	154.0	CLAY, GRAY, TOUGH
	154.0	190.0	SAND, FINE, WITH STREAKS OF GRAY CLAY
	190.0	210.0	CLAY, GRAY, WITH STREAKS OF SAND
	210.0	233.0	CLAY, GRAY
	233.0	243.0	SAND, MEDIUM
	243.0	254.0	CLAY, WITH STREAKS OF SAND
	254.0	271.0	CLAY, SANDY, HARD
	271.0	293.0	SAND, WITH CLAY STREAKS
	293.0	329.0	CLAY, SANDY, WITH SAND STREAKS
	329.0	340.0	SAND
	340.0	357.0	SAND, WITH CLAY STREAKS
	357.0	367.0	SAND AND CLAY
	367.0	402.0	SAND, WITH CLAY STREAKS
	402.0	414.0	CLAY, SANDY, HARD
	414.0	426.0	SAND, WITH CLAY STREAKS
	426.0	473.0	SAND, GRAY, WITH SOME CLAY STREAKS
	473.0	482.0	CLAY AND HARDPAN
	482.0	502.0	CLAY, SANDY
	502.0		ROCK

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-467	0.0	3.0	FILL
	3.0	11.0	SAND, WITH IRON PYRITES
	11.0	26.0	GRAVEL AND SAND AND CLAY
	26.0	53.0	SAND, GRAY, WHITE, FINE, WITH STREAKS OF
	26.0	53.0	LIGNITE
	53.0	60.0	CLAY AND SAND, WITH LIGNITE
	60.0	75.0	SAND AND CLAY, HARD STREAKS
	75.0	105.0	CLAY, BROWN, GRAY, YELLOW, TOUGH
	105.0	129.0	CLAY, SANDY, WITH HARD STREAKS
	129.0	137.0	SAND, GRAY, WHITE, FINE, HARD
	137.0	188.0	CLAY, GRAY, WITH SILTY SAND
	188.0	205.0	SAND, GRAY, FINE, WITH LIGNITE
	205.0	245.0	SAND, GRAY, FINE, WITH STREAKS OF YELLOW
	205.0	245.0	CLAY
	245.0	267.0	SAND AND CLAY, FINE, WITH HARD STREAKS
	267.0	331.0	CLAY, WITH FINE TO MEDIUM SAND AND IRON
	267.0	331.0	PYRITES
	331.0	347.0	CLAY, SANDY
	347.0	397.0	SAND, FINE TO MEDIUM, WITH HARD STREAKS AND
	347.0	397.0	CLAY
	397.0	509.0	CLAY, HARD, WITH STREAKS OF SAND AND
	397.0	509.0	IRON PYRITES
	509.0	532.0	SAND AND GRAVEL, FINE, WITH SANDY CLAY
	532.0	573.0	SAND AND GRAVEL, STREAKS, WITH CLAY AND IRON
	532.0	573.0	PYRITES
	573.0	599.0	CLAY, GRAY, WHITE, HARD
	599.0	620.0	CLAY, GRAY, WHITE, WITH IRON ORE
	620.0	647.0	CLAY AND SANDSTONE, GRAY, WHITE
	647.0	661.0	SAND, FINE TO MEDIUM, WITH CLAY STREAKS
	661.0	666.0	SAND AND CLAY
	666.0	684.0	SAND, HARD PACKED, WITH CLAY
	684.0	689.0	CLAY, SANDY, WITH HARD STREAKS
	689.0	692.0	SAND
	692.0		SAND AND CLAY, GRAY, WITH IRON ORE

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
25-496	0.0	3.0	FILL
	3.0	14.0	CLAY
	14.0	29.0	SAND
	29.0	126.0	MARL
	126.0	133.0	CLAY
	133.0	166.0	SAND, SILTY
	166.0	267.0	CLAY
	267.0	294.0	SAND
	294.0	321.0	CLAY
	321.0	341.0	SAND
	341.0	422.0	CLAY, SANDY
	422.0	432.0	SAND
	432.0	497.0	CLAY, SANDY
	497.0	608.0	SAND
	608.0	660.0	CLAY
25-513	0.0	14.0	SAND, YELLOW, CLAYEY
	14.0	25.0	SAND
	25.0	122.0	MARL
	122.0	129.0	CLAY
	129.0	162.0	SAND, SILTY
	162.0	256.0	MARL, WITH SHELLS
	256.0	266.0	CLAY
	266.0	277.0	SAND
	277.0	316.0	CLAY
	316.0	366.0	SAND
	366.0	388.0	CLAY
	388.0	396.0	SAND
	396.0	421.0	CLAY, SILTY
	421.0	457.0	SAND, WITH STREAKS OF CLAY
	457.0	498.0	SAND, FINE
	498.0	529.0	SAND, MEDIUM
	529.0	596.0	CLAY
25-547	0.0	55.0	NO DATA
	55.0	80.0	SAND AND STONES, GRAY
	80.0	211.0	CLAY, BLACK
	211.0	250.0	CLAY AND STONES, BLACK
	250.0	265.0	SAND, GRAY

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
85-13	0.0	29.0	CLAY
	29.0	40.0	CLAY,SAND AND GRAVEL
	40.0	56.0	SAND, COARSE AND GRAVEL
	56.0	86.0	SAND, GRAVEL AND CLAY, NO WATER
	86.0	90.0	SAND, YELLOW
	90.0	124.0	SAND, GRAY AND CLAY MIXED
	124.0	136.0	SAND, GRAY, WATER STRUCK AT 124 FEET AND LOST A
	136.0	138.0	SAND AND CLAY
	138.0	145.0	CLAY
	145.0	148.0	CLAY, BLUE
	148.0	158.0	SAND, MEDIUM, GRAY, AND CLAY, MIXED
	158.0	170.0	CLAY AND FINE SAND, WATER STRUCK AT 158-166 FEE
	170.0	181.0	SAND, FINE AND WHITE CLAY
	181.0	187.0	SAND, FINE AND GRAY CLAY
	187.0	205.0	CLAY, BLUE
	205.0	250.0	CLAY, BLUE AND GRAY MIXED
	250.0	282.0	CLAY, BLUE, HEAVY
	282.0	298.0	CLAY
	298.0	303.0	CLAY AND SAND
	303.0	360.0	MICA SCHIST
85-14	0.0	26.0	CLAY
	26.0	27.0	SAND
	27.0	43.0	SAND AND CLAY
	43.0	47.0	CLAY, LIGHT
	47.0	55.0	SAND AND GRAVEL
	55.0	90.0	CLAY, GRAY
	90.0	177.0	CLAY
	177.0	182.0	SAND
	182.0	228.0	SAND

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
85-15	0.0	2.0	CLAY, RED, AND GRAVEL
	2.0	3.0	SAND, BROWN
	3.0	30.0	SAND, YELLOW
	30.0	60.0	CLAY AND GRAVEL
	60.0	63.0	SAND, BROWN, WATER
	63.0	69.0	SAND, COARSE, AND CLAY
	69.0	72.0	SAND, LIGHT BROWN, WATER
	72.0	73.0	SAND COARSE, AND CLAY
	73.0	78.0	CLAY, LIGHT
	78.0	116.0	CLAY, BLUE AND SAND
	116.0	117.0	SAND FINE, LIGHT
	117.0	128.0	CLAY, PINK
	128.0	130.0	CLAY, BLACK
	130.0	134.0	SAND, LIGHT WATER
	134.0	147.0	SAND, LIGHT , AND CLAY MIXED
	147.0	151.0	SAND, LIGHT, WATER
	151.0	154.0	SAND, COARSE, WHITE, WATER
	154.0	163.0	SAND LIGHT

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
85-16	0.0	5.0	TOPSOIL
	5.0	8.0	CLAY, SAND, GRAVEL AND BOULDERS
	8.0	20.0	SAND, RED
	20.0	26.0	SAND, FINE, BROWN
	26.0	33.0	SAND, COARSE, BROWN
	33.0	39.0	SAND, FINE
	39.0	50.0	SAND, COARSE, AND GRAVEL
	50.0	55.0	SAND COARSE, BROWN, AND GRAVEL
	55.0	56.0	CLAY, WHITE
	56.0	59.0	SAND, BEACH, AND SOME GRAVEL
	59.0	62.0	SAND, BEACH, LIGHT BROWN
	62.0	65.0	SAND, BEACH, LIGHT BROWN
	65.0	72.0	SAND, COARSE, BROWN
	72.0	75.0	SAND, COARSE, BROWN, AND GRAVEL
	75.0	77.0	CLAY, WHITE, AND GRAVEL
	77.0	100.0	CLAY, WHITE
	100.0	110.0	SAND, BEACH, LIGHT BROWN
	110.0	121.0	CLAY, BLUE
	121.0	122.0	CLAY, WHITE
	122.0	149.0	CLAY, BLUE
	149.0	151.0	CLAY, BLUE AND HARDPAN
	151.0	192.0	CLAY, BLUE
	192.0	206.0	CLAY, GRAY, TRACE OF HARDPAN
	206.0	210.0	CLAY, GRAY
	210.0	214.0	CLAY, RED, BLUE, AND GRAY IN STREAKS
	214.0	218.0	CLAY, GRAY, TRACE OF HARDPAN
	218.0	229.0	CLAY, DARK RED, MIXED WITH GRAY CLAY
	229.0	238.0	CLAY, LIGHT RED, MIXED WITH SAND
	238.0	242.0	CLAY, RED, BLUE AND GRAY
	242.0	246.0	SAND, BEACH, WHITE
	246.0	250.0	CLAY, GRAY, TRACES OF LIGNITE
	250.0	270.0	CLAY, BLUE, RED AND GRAY, SOME MICA
	270.0	319.0	BEDROCK, SOAPSTONE WITH MICA
85-17	0.0	18.0	FILL
	18.0	73.0	HARDPAN, SAND AND A LITTLE RED CLAY
	73.0	84.0	SAND AND GRAVEL, WATER BEARING
	84.0	160.0	CLAY, GRAY, AND A LITTLE RED CLAY
	160.0	197.0	CLAY, GRAY, WITH A LITTLE SAND
	197.0	217.0	CLAY, GRAY
	217.0	275.0	CLAY, RED
	275.0	301.0	HARDPAN, SAND AND CLAY, MIXED
	301.0	308.0	CLAY, HARD, PIECES OF RED SANDSTONE
	308.0	353.0	CLAY, HARD
	AT	353.0	BEDROCK

Appendix 1-- Lithologic logs of wells used in the interpretation of the hydrogeologic frame work on land.--Continued

Well Number	Top*	Bot-tom*	Lithologic description
85-18	0.0	16.0	SAND
	16.0	31.0	SAND, COARSE, AND GRAVEL
	31.0	56.0	MUD
	56.0	70.0	SAND,COARSE AND GRAVEL
	70.0	120.0	MUD
	120.0	121.0	SAND, FINE
	121.0	124.0	HARDPAN AND GRAVEL
	124.0	147.0	SAND, FINE, WHITE

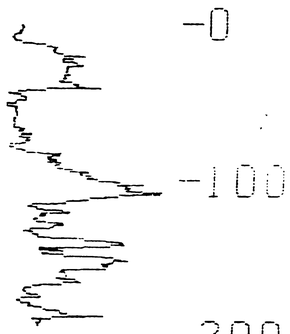
Footnote: * Depth below land surface in feet

APPENDIX 2

WELL NUMBER 25-119

GAMMA LOG

RADIATION INCREASING →



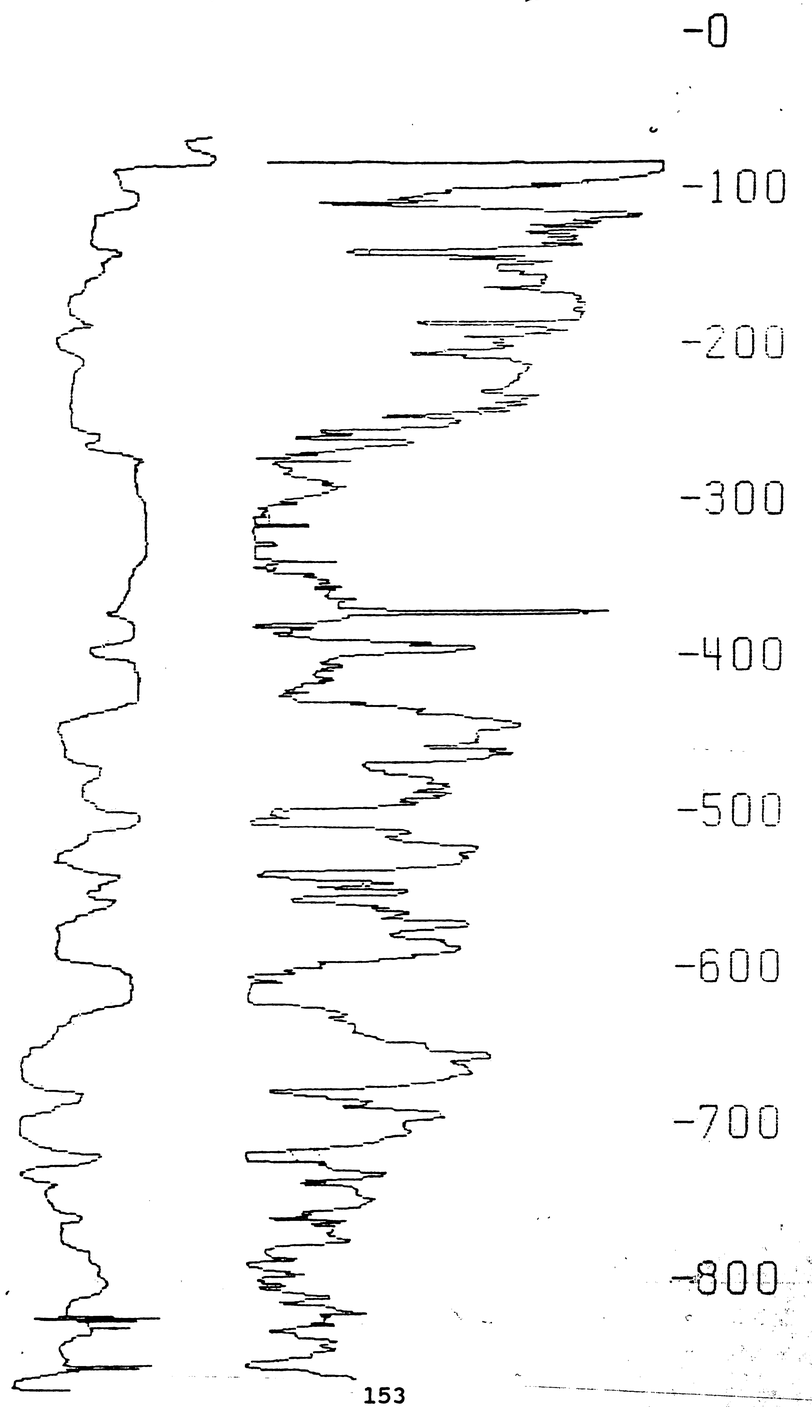
DEPTH BELOW LAND SURFACE IN FEET

WELL NUMBER 25-119

ELECTRIC LOG

SPONTANEOUS POTENTIAL
– +

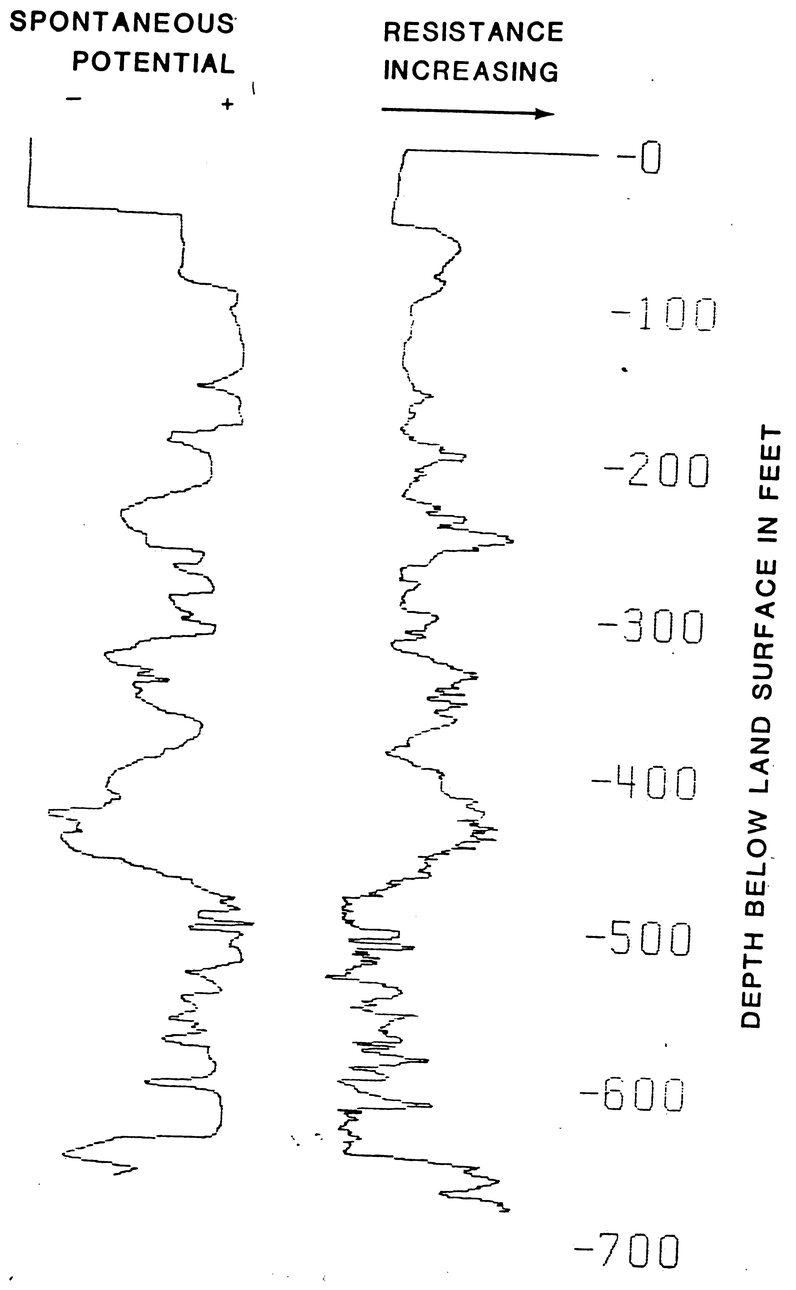
RESISTANCE INCREASING →



DEPTH BELOW LAND SURFACE IN FEET

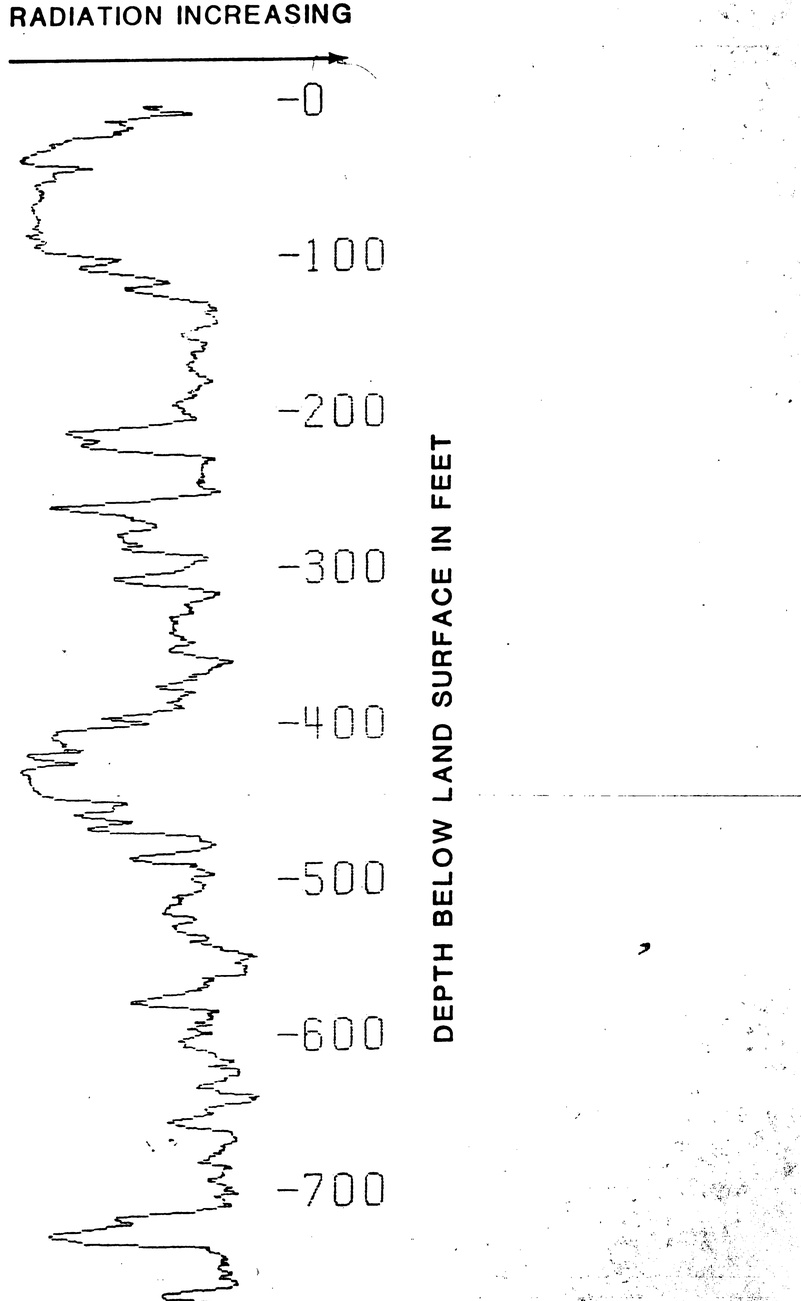
WELL NUMBER 25-153

ELECTRIC LOG



WELL NUMBER 25-156

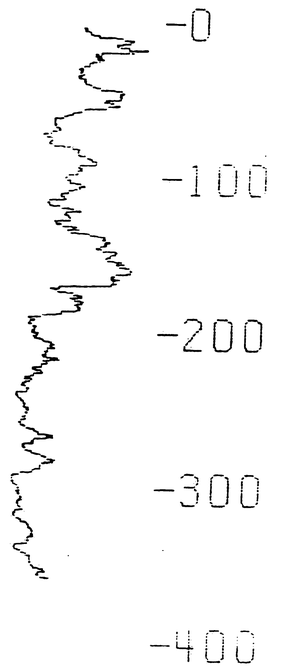
GAMMA LOG



WELL NUMBER 25-197

GAMMA LOG

RADIATION INCREASING



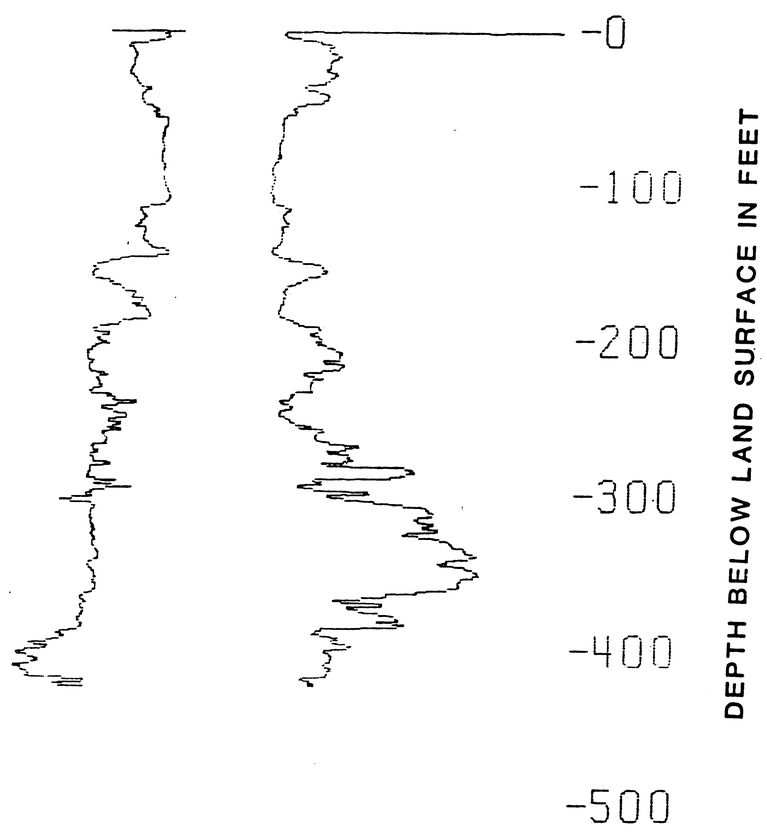
WELL NUMBER 25-290

ELECTRIC LOG

SPONTANEOUS POTENTIAL

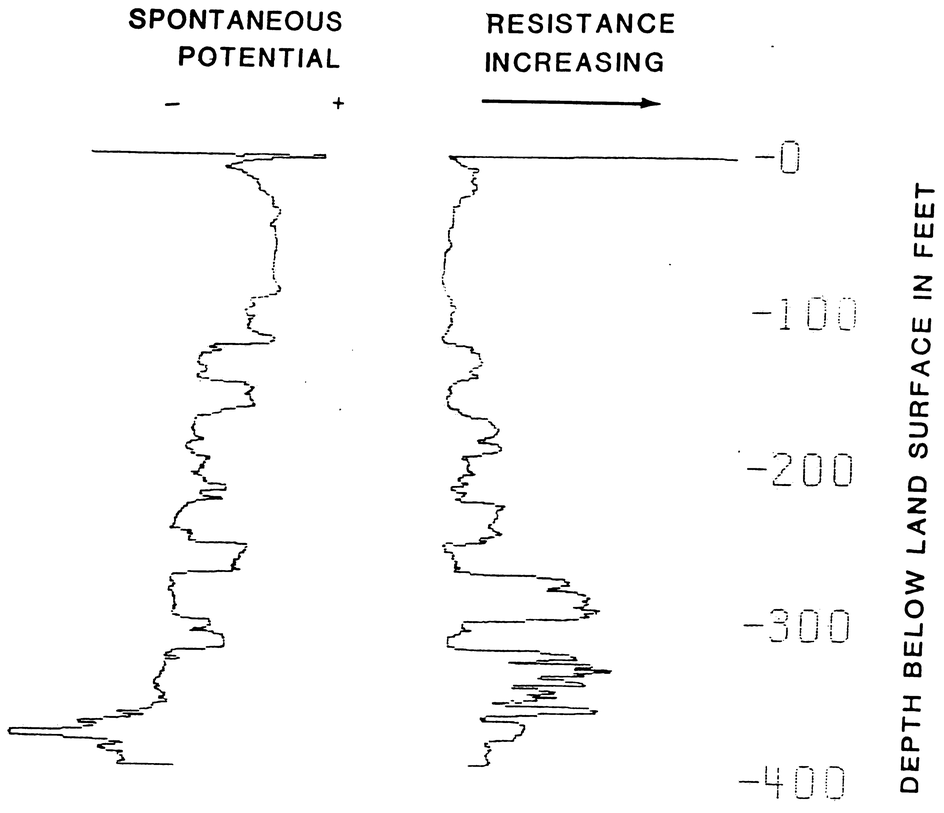
\- +

RESISTANCE INCREASING



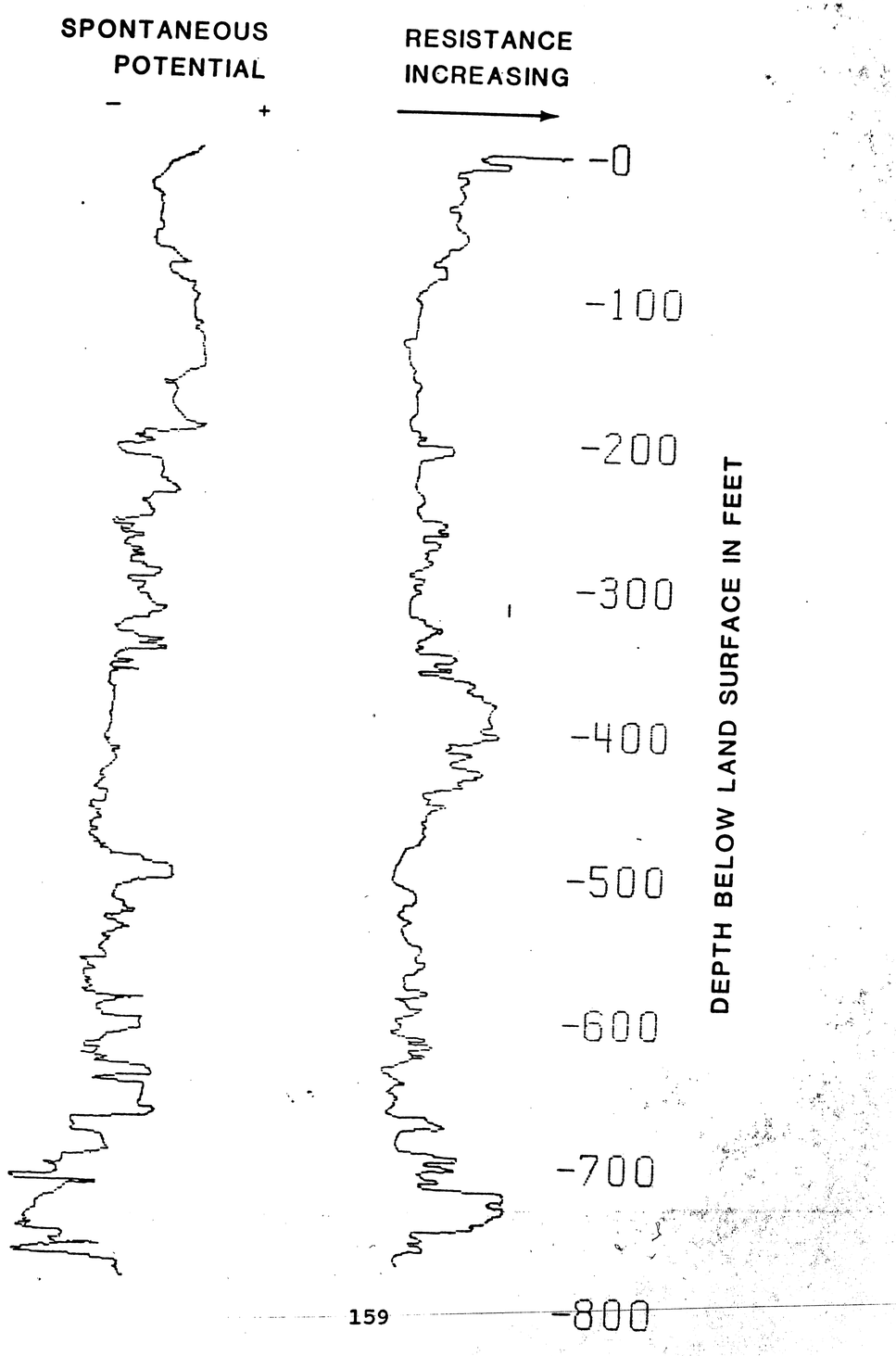
WELL NUMBER 25-291

ELECTRIC LOG



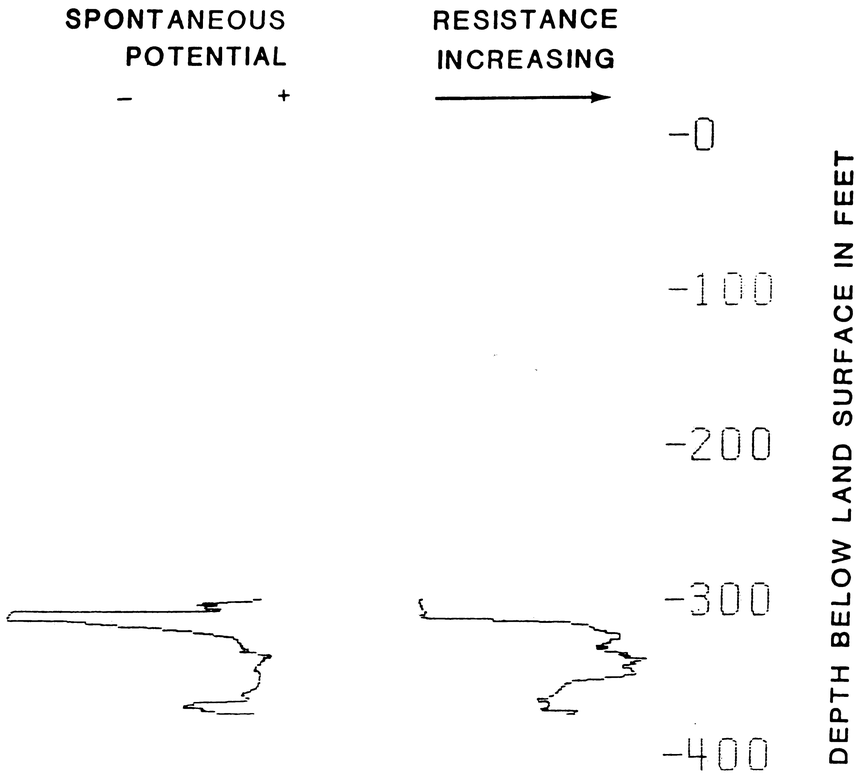
WELL NUMBER 25-292

ELECTRIC LOG



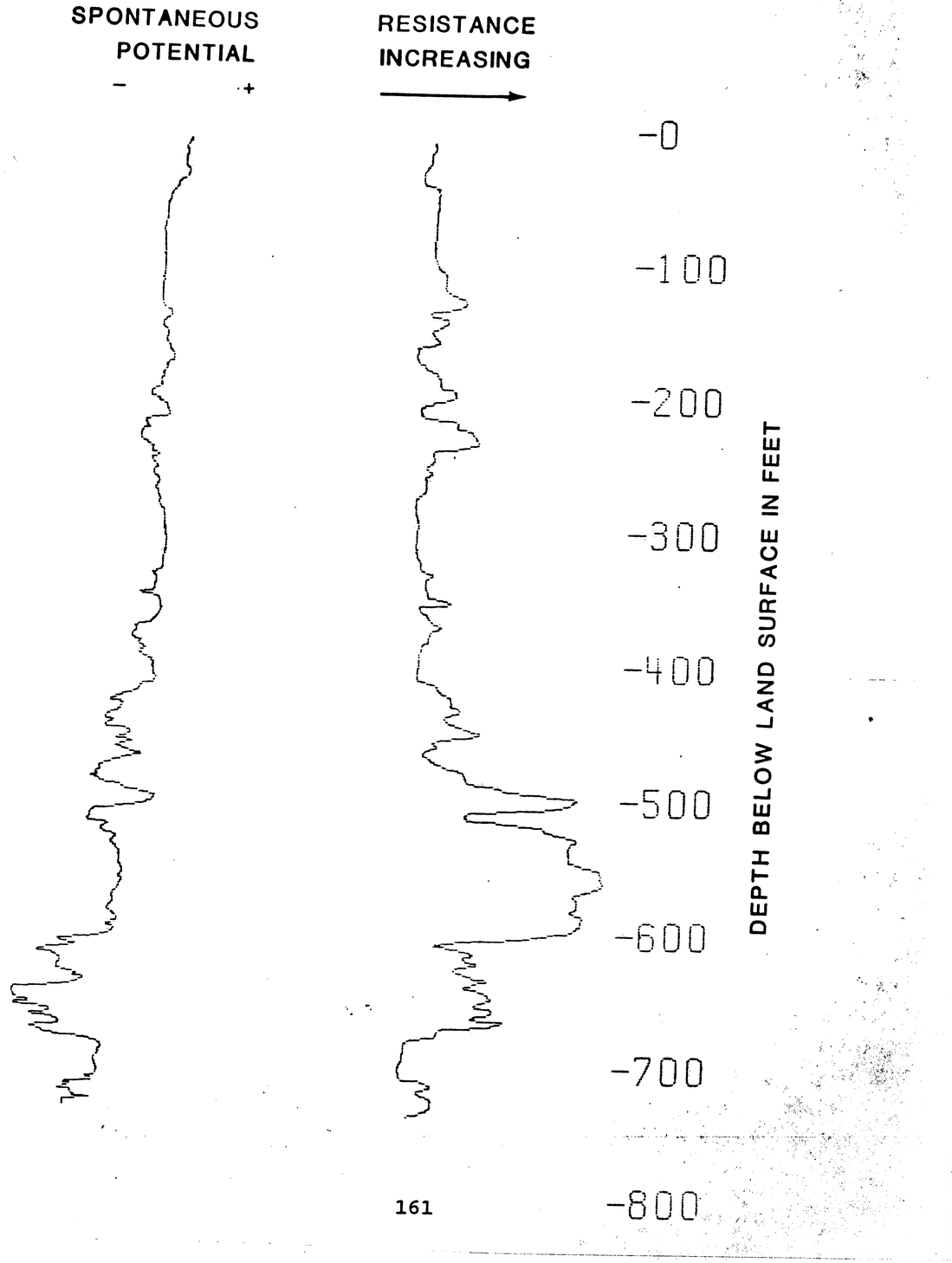
WELL NUMBER 25-293

ELECTRIC LOG



WELL NUMBER 25-303

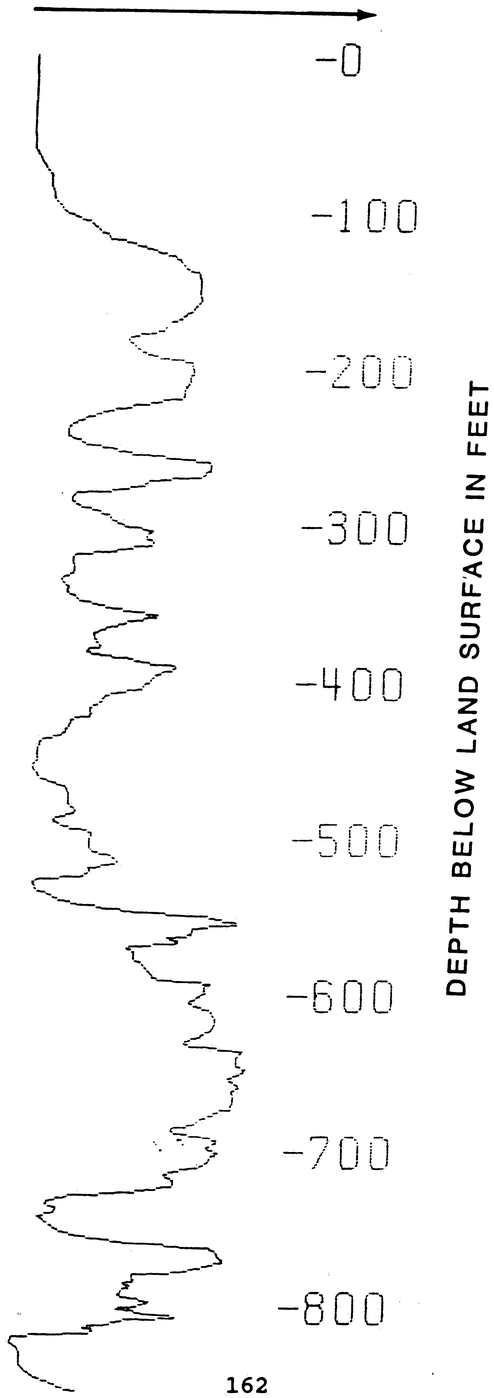
ELECTRIC LOG



WELL NUMBER 25-320

GAMMA LOG

RADIATION INCREASING



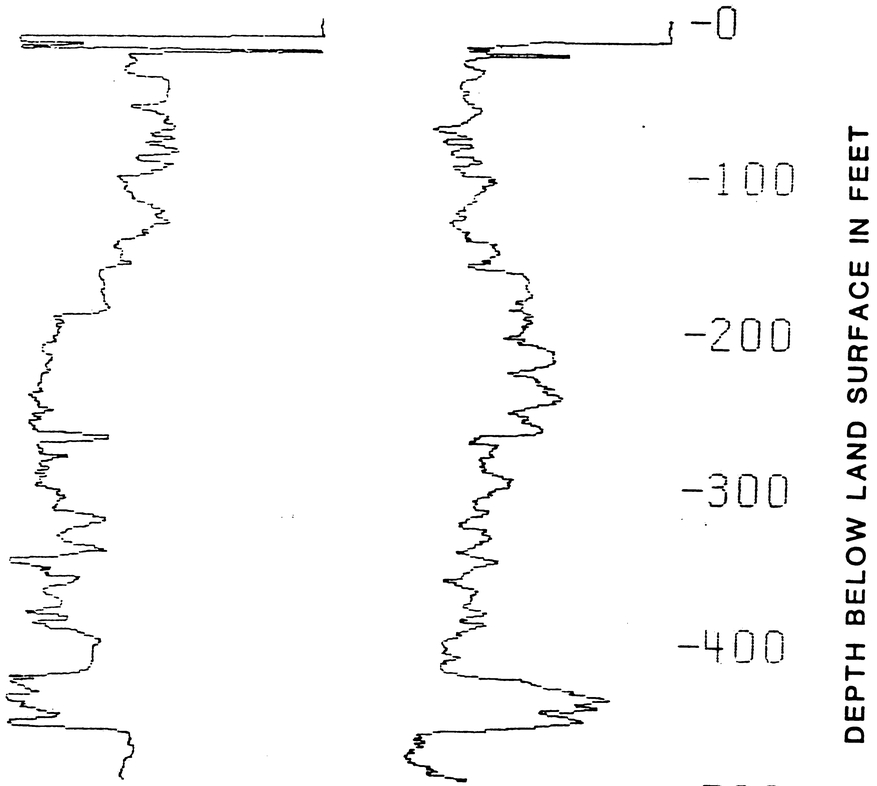
WELL NUMBER 25-299

ELECTRIC LOG

SPONTANEOUS POTENTIAL

\- +

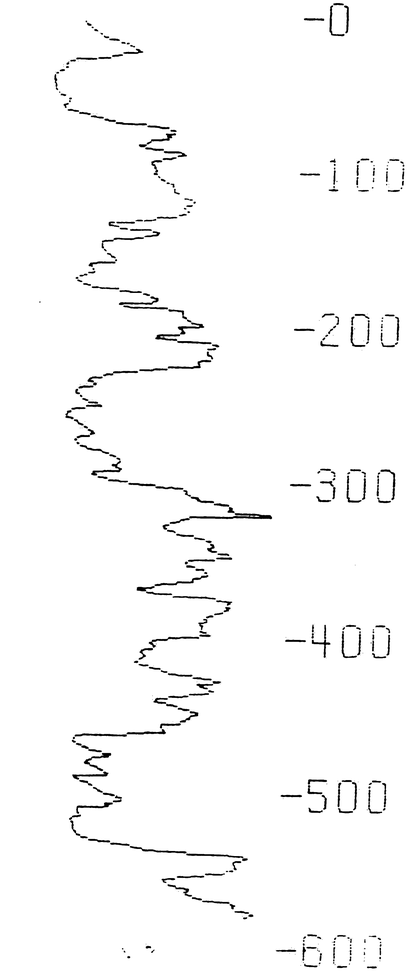
RESISTANCE INCREASING



WELL NUMBER 25-453

GAMMA LOG

RADIATION INCREASING



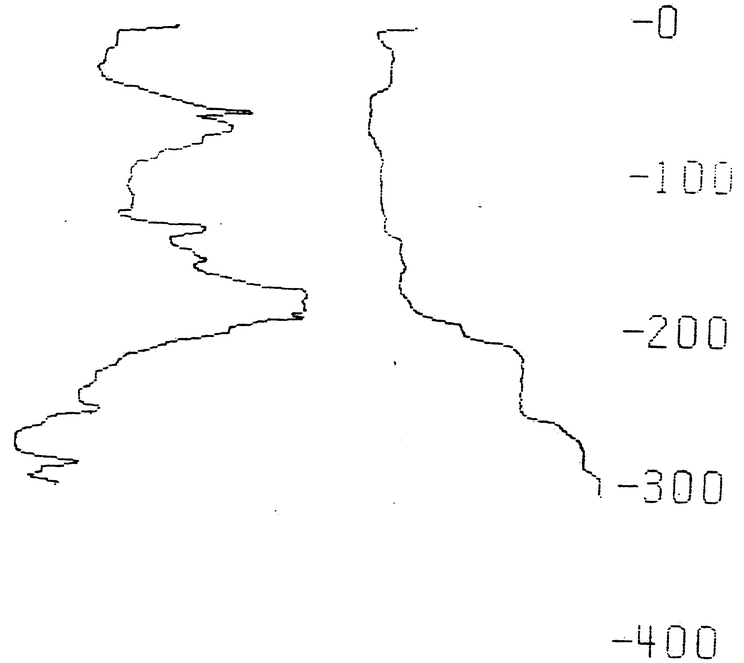
WELL NUMBER 25-453

ELECTRIC LOG

SPONTANEOUS POTENTIAL

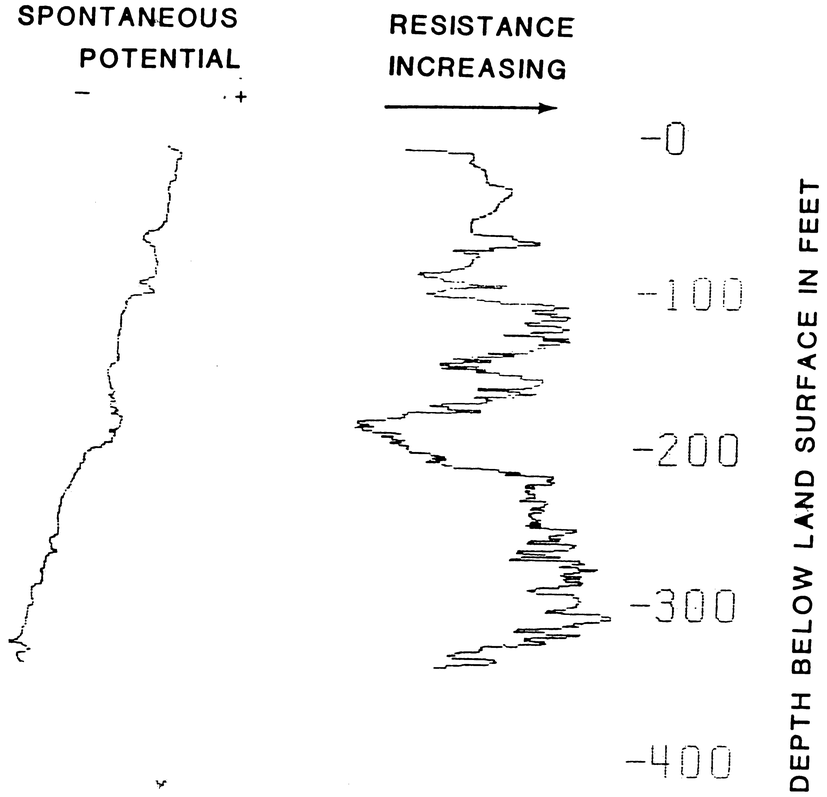
– +

RESISTANCE INCREASING



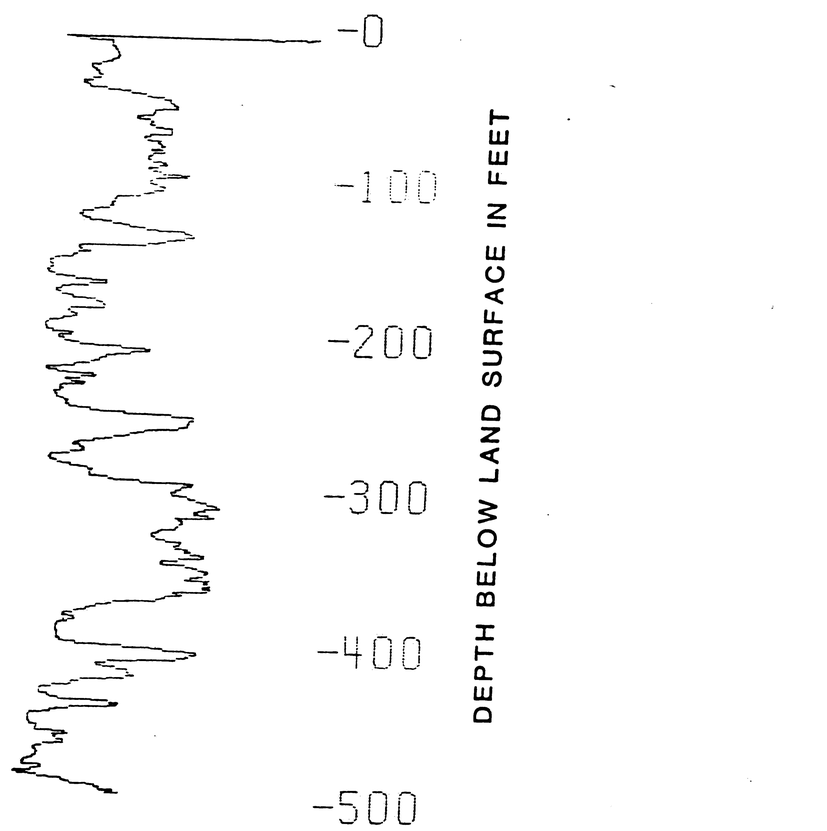
WELL NUMBER 25-456

ELECTRIC LOG



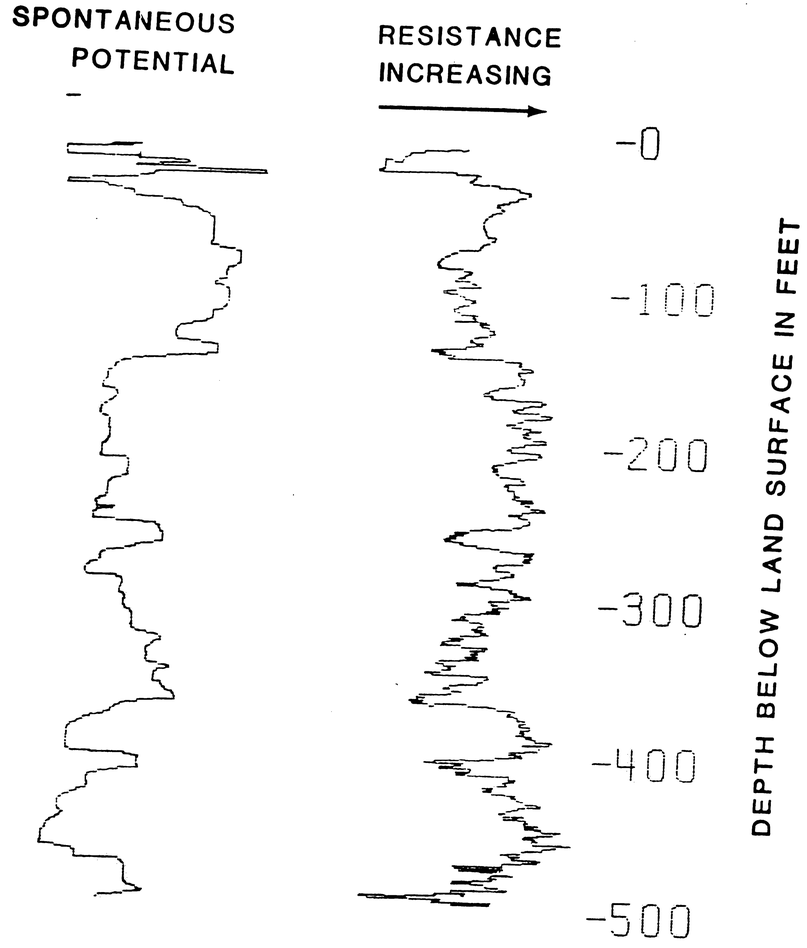
WELL NUMBER 25-466

GAMMA LOG



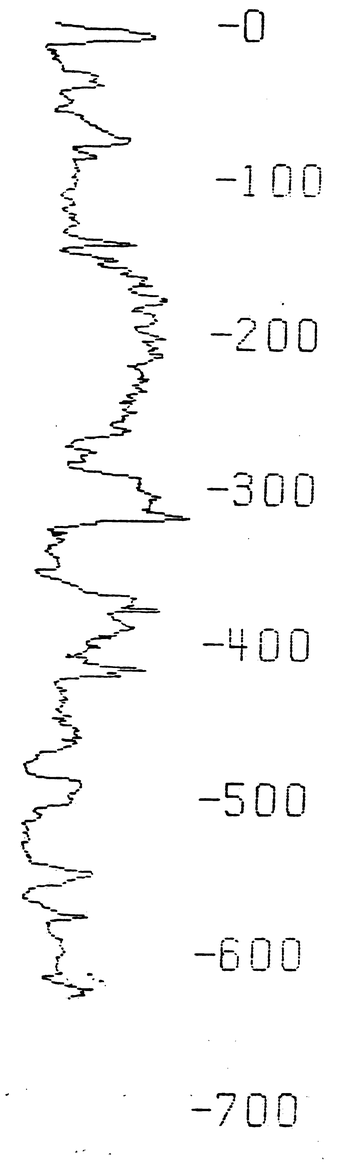
WELL NUMBER 25-466

ELECTRIC LOG



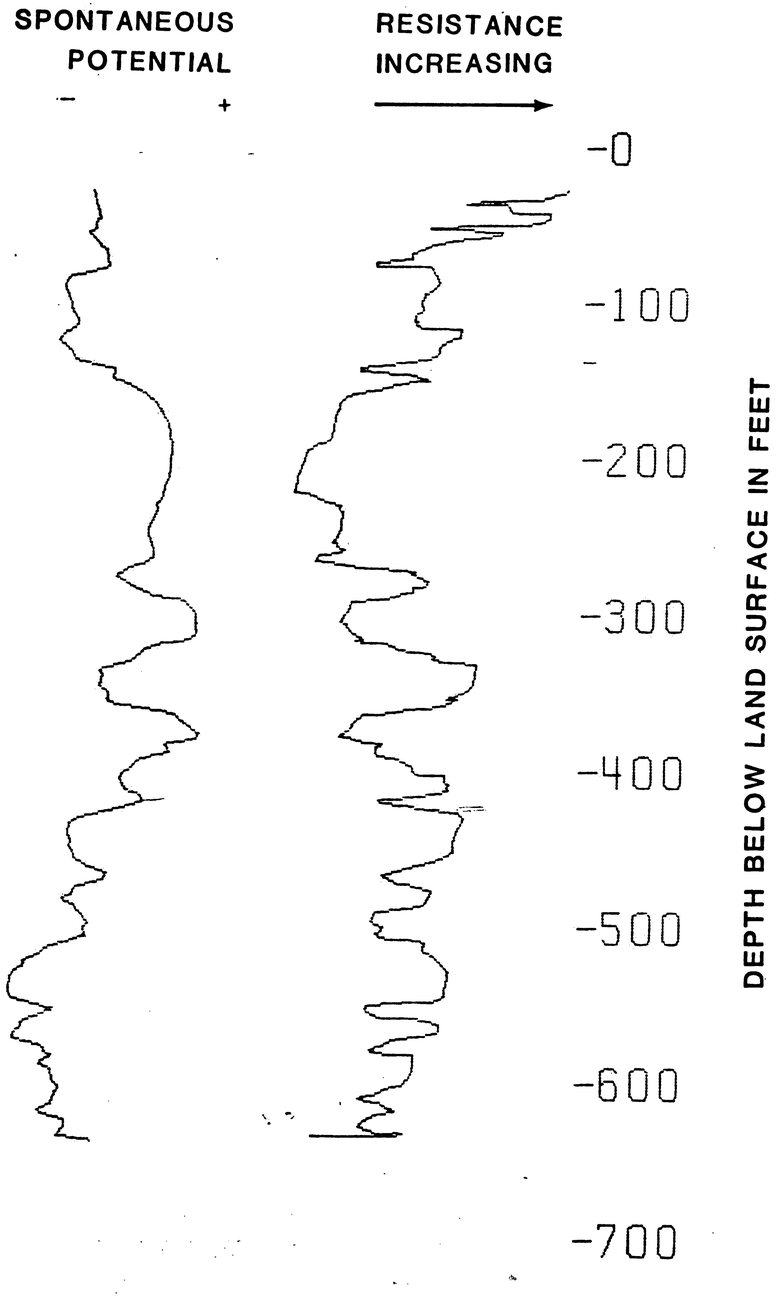
WELL NUMBER 25-496

GAMMA LOG



WELL NUMBER 25-496

ELECTRIC LOG



VITA

Eric Paul Declercq was born on March 23, 1962 in St. Joseph's Hospital in Kansas City, Missouri to Wilfred and Rose Marie Declercq. At the age of 1 he moved to Belgium. Two years later, Declercq traveled to Hertzliah, Israel and began his academic career. After first grade, the family moved to Belgrad, Yugoslavia where Eric attended the International School for two years. In 1970 the family moved to Vienna, Virginia and established roots. Eric attended Our Lady of Good Counsel until the eight grade and Bishop Denis J. O'Connell High School from which he graduated. He left home in 1980 to attend the University of Delaware and study Geology while the family moved to Rome, Italy. Four years later Bethlehem , Pennsylvania was home for Declercq while he completed his Master of Science degree in Geological Sciences at Lehigh University. Through the thoughtful guidance of Dr. Gerard P. Lennon, Eric specialized in ground water hydrology and worked part-time for the U.S. Department of the Interior, Geological Survey. After completing his degree under the supervision of Dr. P.B. Myers, Lehigh University, and Dr. P. Patrick Leahy, U.S. Geological Survey, Eric P. Declercq will carry his training into the Camden Bonds Study where he will be responsible for assisting with the digital simulation aspect of the project.

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HYDROGEOLOGIC INVESTIGATION OF THE RARITAN BAY AREA, MIDDLESEX-MONMOUTH COUNTIES, NEW JERSEY

by
Eric P. Declercq

ABSTRACT

Data from 64 wells was used to construct 9 hydrogeologic sections onshore in the Raritan Bay area, Middlesex and Monmouth counties, New Jersey. In conjunction with these data approximately 7.5 miles (12.1 km) of single-channel and 2.0 miles (3.2 km) of multi-channel marine seismic-reflection data were used to construct structure-contour maps extending the hydrogeologic framework out into Raritan Bay. Saltwater has intruded into the Potomac-Raritan-Magothy aquifer system at several localities south of the Bay. A two-dimensional finite-difference model was developed to simulate the predevelopment flow system; a "trimming" technique was adapted to the simulation to estimate the position of the freshwater-saltwater interface in the upper aquifer of the system. The interface-locating technique is used to test the sensitivity of the interface location to proposed hydrologic concepts including hydrogeologic framework, leakage, and historical water-table conditions.

Five major hydrogeologic units of the Potomac-Raritan-Magothy aquifer system are found in the Raritan Bay area: a lower confining unit, a middle aquifer, a confining unit between the middle and upper aquifers, an upper aquifer, and the Woodbury-Merchantville confining unit. Interpretation of marine seismic data concludes that these units are continuous under the Bay. The lower confining unit, middle aquifer, and middle confining unit are evident across the Bay on Staten Island, New York; however, the upper aquifer and Woodbury-Merchantville confining unit crop out under the bay suggesting a possible cause for saltwater intrusion.

Results of the cross-sectional model developed along a flow line in the predevelopment flow system suggests the presence of saltwater in the upper aquifer. Leakance between the aquifer and confining unit is the major factor regarding the position of the interface. The interface is also sensitive to water-table gradient; however, this factor is not as critical as leakance. Boundary conditions are tested, including use of the general-head boundary package. Results using this package prove to be the most reasonable and further research should concentrate on simulations of this design.