HYDROGEOLOGIC FRAMEWORK OF THE COASTAL PLAIN OF MARYLAND, DELAWARE, AND THE DISTRICT OF COLUMBIA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1404–E

Hydrogeologic Framework of the Coastal Plain of Maryland, Delaware, and the District of Columbia

By DON A. VROBLESKY *and* WILLIAM B. FLECK

REGIONAL AQUIFER-SYSTEM ANALYSIS—NORTHERN ATLANTIC COASTAL PLAIN

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1404–E

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1991

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

Vroblesky, Don A.
Hydrogeologic framework of the coastal plain in Maryland, Delaware, and the District of Columbia.
(U.S. Geological Survey professional paper ; 1404–E)
Bibliography: p.
Supt. of Docs. no. : I 19.16 : 1404E
1. Water, Underground—Maryland. 2. Water, Underground—Delaware. 3. Water, Underground—Washington (D.C.) I. Fleck, William B. II. Title. III. Series: U.S. Geological Survey professional paper ; 1404–E.
GB1025.M3V76 1989 551.49′0975 87–600120

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425, Denver, CO 80225

FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent important components of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and any changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply	*By*	*To obtain*
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
square foot per day (ft^2/d)	0.0929	square meter per day (m^2/d)
gallon per minute (gal/min)	0.06308	liter per second (L/s)

ALTITUDE DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

HYDROGEOLOGIC FRAMEWORK OF THE COASTAL PLAIN OF MARYLAND, DELAWARE, AND THE DISTRICT OF COLUMBIA

By DON A. VROBLESKY and WILLIAM B. FLECK

ABSTRACT

The Coastal Plain of Maryland, Delaware, and the District of Columbia encompasses an area of about 8,500 square miles. The sediments form an eastward-thickening wedge that ranges in thickness from zero at the Fall Line to about 8,000 feet at Ocean City, Maryland. As part of the U.S. Geological Survey's Regional Aquifer System Analysis Program of the northern Atlantic Coastal Plain, the sediments of Maryland, Delaware, and the District of Columbia have been grouped into 11 predominantly sandy aquifers that are separated by 10 predominantly silty and clayey confining units. Maps showing the altitude of the tops of aquifers and the thickness of confining units, as well as charts showing correlations of aquifers and confining units at selected wells, were developed by using data that were taken primarily from existing literature. In addition, data from a well drilled in Cambridge, Maryland, and a well drilled in Lexington Park, Maryland, and reinterpretations of borehole data were used. The regional aquifers and confining units delineated in Maryland, Delaware, and the District of Columbia provide a basis for understanding the regional ground-water flow in the northern Atlantic Coastal Plain.

INTRODUCTION

The U.S. Geological Survey has conducted a Regional Aquifer System Analysis (RASA) to develop a comprehensive understanding of the northern Atlantic Coastal Plain aquifer system that extends from Long Island to North Carolina. The investigation involved a study of the geology, hydrology, and geochemistry of the flow system. Major components of RASA include development of a hydrogeologic framework of regional aquifers and confining beds and construction of a multilayer ground-water flow model. The present report concentrates on the hydrogeology of the emergent Atlantic Coastal Plain of Maryland, Delaware, and the District of Columbia (fig. 1).

PURPOSE AND SCOPE

This report presents a hydrogeologic framework of regional aquifers and confining beds for the Coastal Plain of Maryland, Delaware, and the District of Columbia. The 11 aquifers and 10 confining units that are described in this report are depicted in a series of contour maps showing the altitude of the top of each aquifer and the thickness of each confining unit. These hydrogeologic units correlate with the hydrogeologic units established for RASA studies to the south (Virginia) and north (New Jersey). They provide a basis for construction of a digital multilayer ground-water flow model of the regional aquifer system of Maryland, Delaware, and the District of Columbia and for a part of the regional flow model covering these areas.

WELL-NUMBERING SYSTEM

The wells that are described in this report are numbered according to a coordinate system in which the counties of Maryland and Delaware are divided into 5-minute quadrangles of latitude and longitude, and the District of Columbia is divided into 2.5-minute quadrangles of latitude and longitude. A graphic illustration of the numbering system is shown in figure 2. In Maryland, the first two letters of the well number are a code identifying the county in which the well is located. For example, the letters "AA" indicate that the well is in Anne Arundel County. In Maryland, 5-minute quadrangles are identified by a two-letter code following the county-identification code. The first letter of the quadrangle code identifies a 5-minute segment of latitude, and the second letter identifies a 5-minute segment of longitude. The final digits in a Maryland code are assigned to

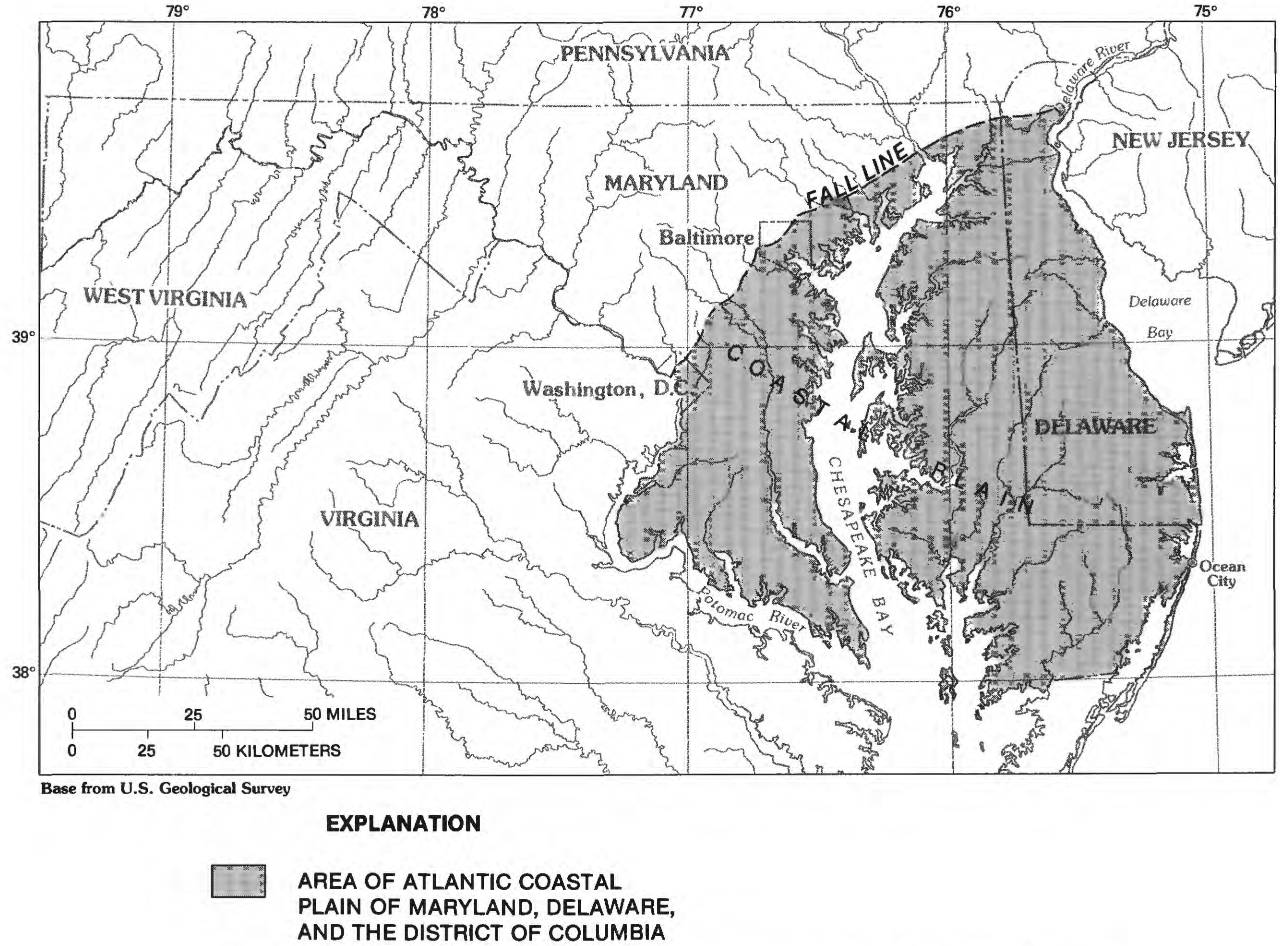


FIGURE 1.—Location of the Coastal Plain of Maryland, Delaware, and the District of Columbia.

wells chronologically. Thus, well AA-Fe 47 is the 47th well inventoried in quadrangle Fe in Anne Arundel County, Md.

The first and second letters in a Delaware well number refer to a 5-minute segment of latitude and a 5-minute segment of longitude, respectively. Each 5-minute quadrangle is further divided into 1-minute segments. The row and column numbers of the 1-minute quadrangles are the third and fourth digits, respectively, of a Delaware well number. The final digits are assigned to wells chronologically. Thus, well Gd 34–2 is the second well inventoried in row 3, column 4, of 5-minute quadrangle Gd in Delaware.

The well-numbering system in the District of Columbia is based on U.S. Geological Survey nomenclature of 7.5-minute quadrangles. The first two letters of the well code refer to the name of the quadrangle in which the well is located. Each 7.5-minute quadrangle is further divided into 2.5-minute segments. The third and fourth letters of the code indicate 2.5-minute segments of latitude and longitude, respectively. The final digits of the code are assigned chronologically. Thus, well WW Cc-12 is the 12th well inventoried in 2.5-minute quadrangle Cc, in the Washington West 7.5-minute quadrangle.

DESCRIPTION OF STUDY AREA

The Atlantic Coastal Plain is a low-lying area bounded on the west by the Fall Line, which is a major physiographic and geologic boundary marking the contact of the Atlantic Coastal Plain sediments with the Piedmont crystalline rocks. The eastern boundary of the Coastal Plain is the shoreline of the Atlantic Ocean; however, hydrogeologic interpretations are extrapolated a few miles farther offshore for some aquifers to account for continuity of the aquifers in continental shelf sediments beneath the Atlantic Ocean. The Atlantic Coastal Plain extends from the vicinity of Cape Cod in the north to Florida in the south.

The Coastal Plain of Maryland, Delaware, and the District of Columbia encompasses an area of about 8,500 mi^2 (fig. 1). The sediments extend approximately another

75 mi eastward from the present coastline to the edge of the Continental Shelf. The Coastal Plain is underlain by a series of eastward- and southeastward-dipping deposits of mostly unconsolidated gravel, sand, silt, and clay. These sediments form a wedge-shaped body overlying a basement complex of Precambrian to Paleozoic crystalline rocks and Mesozoic rift-basin sedimentary rocks. The sediments of the Coastal Plain range in thickness from zero at the Fall Line, where the basement rock is exposed, to about 7,700 ft at Ocean City, Md. (Hansen and Edwards, 1986). The approximate altitude of the top of pre-Cretaceous basement rock is shown in figure 3.

In the present study, the Coastal Plain sediments of Maryland, Delaware, and the District of Columbia have been divided into 11 aquifers and 10 confining units. Listed in ascending order, the layers are the Patuxent aquifer, the Potomac confining unit, the Patapsco aquifer, the Patapsco confining unit, the Magothy aquifer, the Matawan confining unit, the Matawan aquifer, the Severn confining unit, the Severn aquifer, the lower Brightseat confining unit, the Brightseat aquifer, the upper Brightseat confining unit, the Aquia-Rancocas aquifer, the Nanjemoy-Marlboro confining unit, the Piney Point-Nanjemoy aquifer, the lower Chesapeake confining unit, the lower Chesapeake aquifer, the St. Marys confining unit, the upper Chesapeake aquifer, the upper Chesapeake confining unit, and the surficial aquifer. Relations among these informal hydrologic units and formal stratigraphic units, as well as generalized hydrologic descriptions and lithologic descriptions, are shown on plate 1.

PREVIOUS INVESTIGATIONS

The stratigraphy of the Atlantic Coastal Plain has been the subject of numerous investigations. Studies that encompass the entire Coastal Plain include those of Richards (1948), LeGrand (1961), Maher (1965, 1971), the U.S. Geological Survey (1967), and Brown, Miller, and Swain (1972).

In addition to regional studies, a number of studies of specific formations have been conducted. Glaser (1969, p. 8) summarized the stratigraphic work on the Cretaceous Potomac Group in Maryland and Delaware up to 1969. The current practice in Maryland (Doyle and Robbins, 1977; Hansen, 1982, p. 3; and Jordan and Smith, 1983) is to divide the Potomac Group into three formations near the outcrop, a concept first introduced by Clark (1910). Listed in ascending order, the three formations are the Patuxent, the Arundel, and the Patapsco.

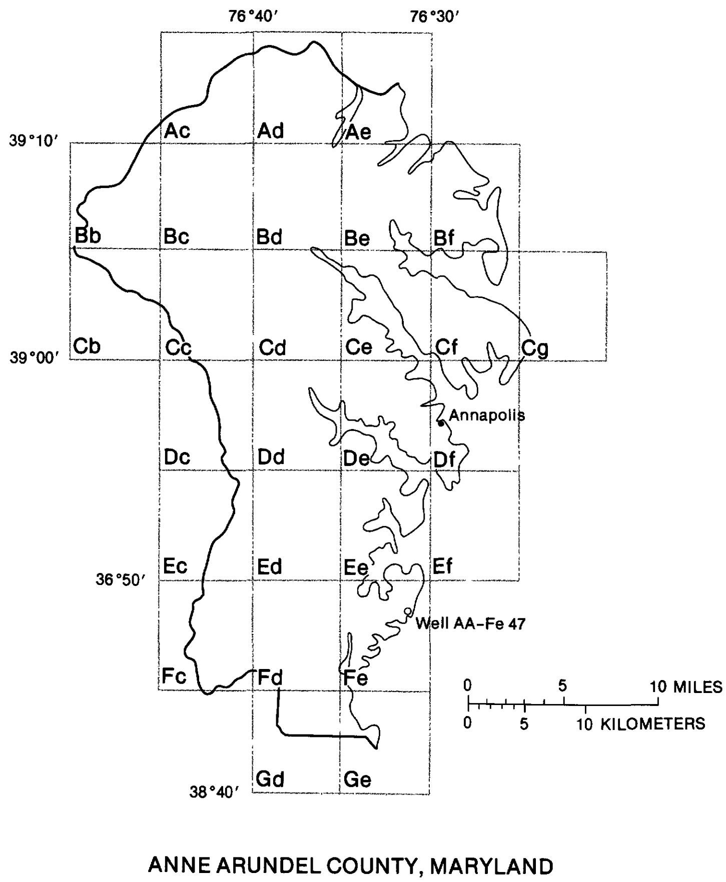
Several attempts have been made to subdivide the Potomac Formation, the Delaware equivalent of Maryland's Potomac Group, into smaller units on the basis of stratigraphy; however, the results of the studies showed that individual sand or clay units could not be successfully correlated over even short distances. The stratigraphic difficulties in correlating these sediments have been discussed by Spoljaric (1967, p. 3), Jordan (1968, p. 79; 1983, p. 33–35), and Hansen (1969a, p. 1924; 1969b, p. 329). Despite the stratigraphic ambiguities, hydrologic evidence has been useful in subdividing the Potomac Formation into two (Sundstrom and others, 1967, p. 21) or three (Rasmussen and others, 1957, p. 111; Martin, 1984) sandy units that are interbedded with clay lenses and are separated by clayey units interbedded with sand lenses.

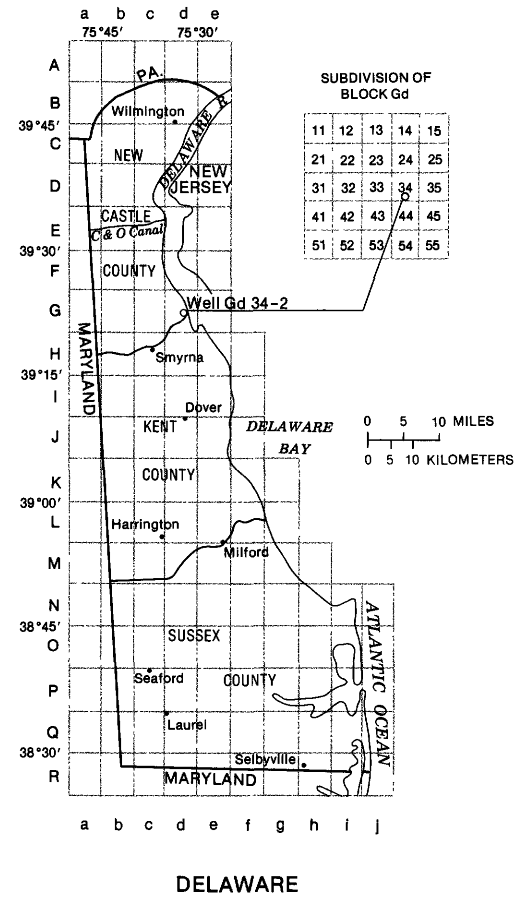
The hydrogeology and ground-water resources of the Coastal Plain in Maryland, Delaware, and the District of Columbia have been investigated since the 1800's. Among the earliest investigations was a discussion by Levi Disbrow (Silliman, 1827) of the ground-water supplies in the area of Baltimore, Md. The first multi-State hydrogeologic studies were those by Darton (1896, 1902) and Clark, Matthews, and Berry (1918).

Back (1966) investigated the regional ground-water flow patterns of the Atlantic Coastal Plain. Discussions of the Coastal Plain ground-water system of Maryland and the District of Columbia include those by the Maryland State Planning Department (1969), Hansen (1972), and Miller and others (1982). Sundstrom and others (1976) and Miller (1971) discussed the Coastal Plain aquifers of Delaware. Cushing and others (1973) studied the Coastal Plain aquifers east of the Chesapeake Bay. The water resources of the Delaware River basin were studied by Parker and others (1964).

The hydrogeology of Maryland has been discussed in a series of county reports that began in 1949 and a series of investigative reports that began in 1966. These reports were published by the Maryland Geological Survey. The Delaware Geological Survey has also published ground-water investigations that deal with the Coastal Plain. In general, the earlier reports established a basic hydrogeologic framework that the later investigations expanded upon and applied to more quantitative investigations of the aquifer system.

The hydrology of aquifers in the Potomac Group in Maryland has been studied by Hansen (1968, 1978, and 1981a), Mack (1966), and Otton and Mandle (1984). Sundstrom and others (1967) and Martin and Denver (1982) examined the hydrology of the Potomac Formation in Delaware. Mack (1974) and Mack and Mandle (1977) studied the Magothy aquifer west of the Chesapeake Bay. The Aquia aquifer in Maryland was studied by Hansen (1974), Kapple and Hansen (1976), and Chapelle and Drummond (1983). The Piney Point aquifer





Well prefixes of Maryland Coastal Plain counties

Anne Arundel	AA	Kent	KK
Baltimore	BA	Prince Georges	PG
Calvert	CA	Queen Annes	QA
Caroline	CO	Somerset	SO
Cecil	CK	St. Marys	SM
Charles	CH	Talbot	TA
Dorchester	DO	Wicomico	WI
Harford	HA	Worchester	WO

DISTRICT OF COLUMBIA

0 5 10 MILES
0 5 10 KILOMETERS

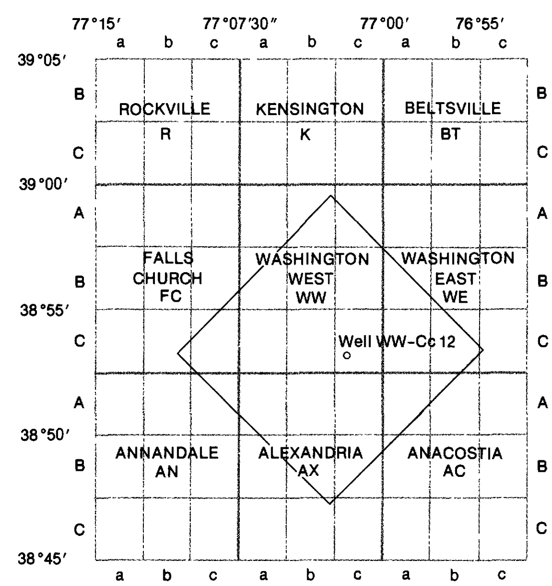
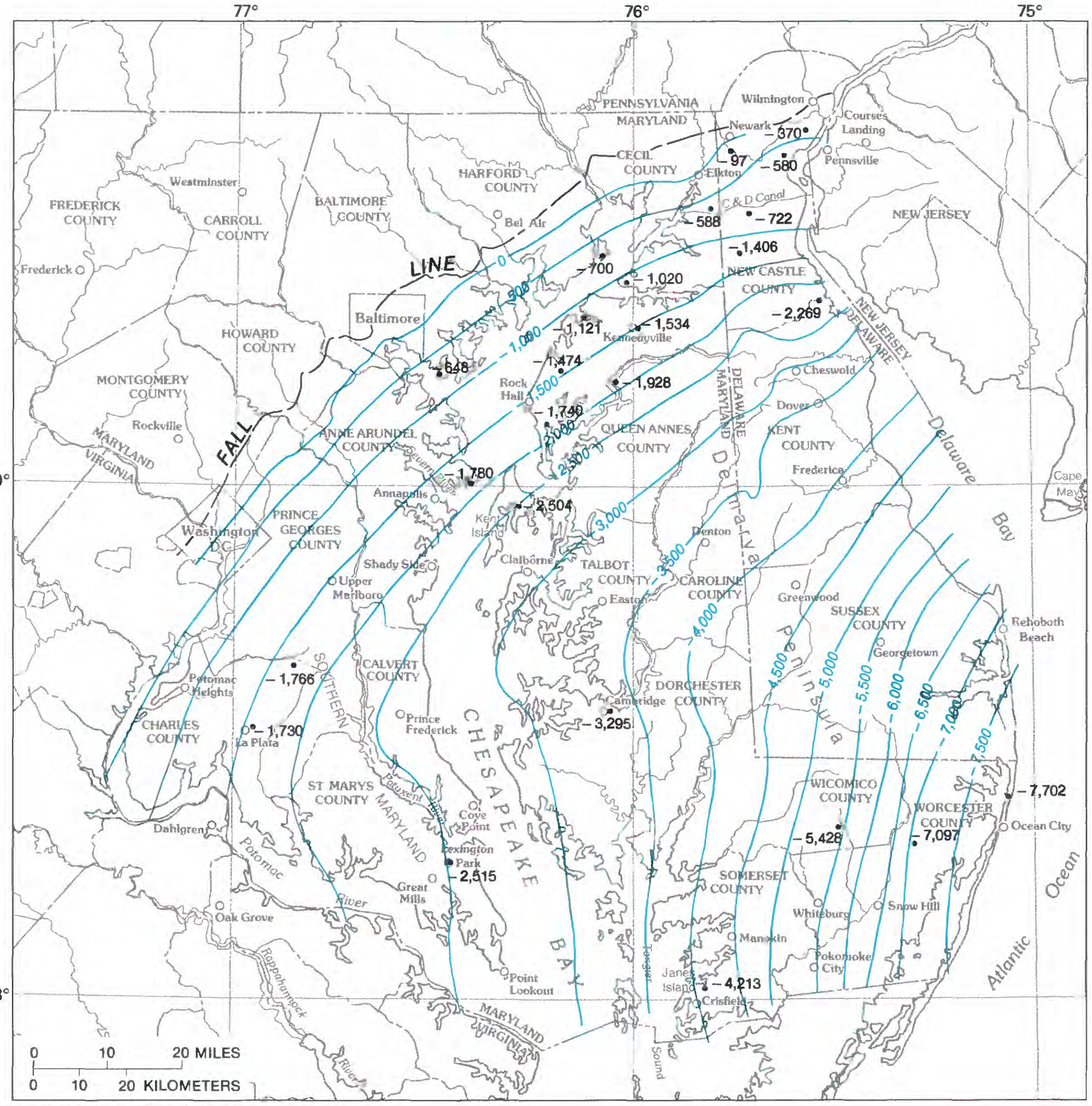


FIGURE 2.—Well-numbering systems used in Maryland, Delaware, and the District of Columbia.



Base from U.S. Geological Survey

EXPLANATION

— −500 — STRUCTURE CONTOUR—Shows altitude of the top of the pre-Cretaceous basement complex. Contour interval 500 feet. Datum is sea level

• −3,295 WELL—Number is altitude of the top of the pre-Cretaceous basement complex, in feet below sea level

FIGURE 3.—Altitude of the top of pre-Cretaceous basement rock of Maryland, Delaware, and the District of Columbia (modified from Cushing and others, 1973; Hansen and Edwards, 1986).

was investigated in Maryland by Williams (1979) and Chapelle and Drummond (1983) and was investigated in Delaware by Al-Saad (1971) and Leahy (1976, 1979, and 1982). The Miocene aquifers were studied by Achmad and Weigle (1979), Hansen (1981b), Leahy (1982), and Hodges (1984). The surficial aquifer was studied in Delaware by Jordan (1964), Spoljaric and Woodruff (1970), and Johnston (1973, 1977).

The following is a list of selected references for publications that discuss the hydrogeology of specific counties in Delaware, Maryland, and the District of Columbia.

Selected references for publications discussing the hydrogeology of specific counties in Delaware, Maryland, and the District of Columbia

County	Reference
DELAWARE	
Kent	Sundstrom and Pickett (1968).
New Castle	Rasmussen and others (1957), Rima and others (1964), Woodruff and others (1972).
Sussex	Rasmussen and others (1960), Sundstrom and Pickett (1969,1970).
MARYLAND	
Anne Arundel	Bennion and Brookhart (1949), Hansen (1968), Mack (1962), Otton (1955).
Baltimore	Bennett and Meyer (1952), Otton and others (1964).
Calvert	Otton (1955), Overbeck (1951), Weigle and others (1970).
Caroline	Rasmussen and Slaughter (1957).
Cecil	Overbeck and Slaughter (1958), Sundstrom and others (1967).
Charles	Dryden and Overbeck (1948), Hansen (1968), Otton (1955), Slaughter and Laughlin (1966), Slaughter and Otton (1968), Weigle and others (1970).
Dorchester	Mack and others (1971), Rasmussen and Slaughter (1957).
Harford	Bennett and Meyer (1952).
Kent	Overbeck and Slaughter (1958).
Prince Georges	Hansen (1968), Mack (1966), Meyer (1952), Otton (1955).
Queen Annes	Overbeck and Slaughter (1958).
St. Marys	Ferguson (1953), Otton (1955), Weigle and others (1970).
Somerset	Hansen (1967), Rasmussen and Slaughter (1955).
Talbot	Mack and others (1971), Rasmussen and Slaughter (1955).
Wicomico	Boggess and Heidel (1968), Mack and Thomas (1968), Rasmussen and Slaughter (1955).
Worcester	Rasmussen and Slaughter (1955), Slaughter (1962), Weigle (1974), Weigle and Achmad (1982).
DISTRICT OF COLUMBIA	
	Johnston (1964), Papadopulos and others (1974).

METHODS OF INVESTIGATION

A literature review provided the primary source of information that was used in the development of the contour maps of aquifers and confining-unit thicknesses and the correlation charts that are included in this report. An additional source of information that was used is well DO-Ce 88, drilled in Cambridge, Md. (pl. 2) during this study. The boring for the well reached basement rock at a depth of 3,299 ft (Trapp and others, 1984, fig. 2). Stratigraphic designations at the well (Trapp and others, 1984, table 2) are based on geophysical and palynological data that were obtained from the well and from correlation with existing control points. Well SM-Df 84, drilled in 1983 to basement in Lexington Park, Md. (pl. 2), provided an additional data source (Hansen and Wilson, 1984).

The correlations of regional aquifers and confining units at selected wells, as shown in figures 4, 5, and 6 and plate 1, are based on the interpretation of gamma, resistance, and self-potential logs and are supplemented by palynological data. Because high gamma values typically correlate with low resistance values, the gamma logs in this report have been reversed. Thus, peaks on the right side of both gamma and resistance logs indicate sand layers in figures 4, 5, and 6. The amplitude of the geophysical log peaks is not directly comparable between wells because the logs may have been run under different conditions and because the log traces have been adjusted for clarity of presentation.

ACKNOWLEDGMENTS

The cooperation of Robert Jordan, Delaware State Geologist, and his staff and of Harry J. Hansen, Maryland Geological Survey, is gratefully appreciated.

RELATION BETWEEN DEPOSITIONAL HISTORY AND AQUIFER TRANSMISSIVITY

The Coastal Plain sediments of Maryland, Delaware, and the District of Columbia were deposited in a variety of sedimentary environments that are related to sediment input and sea-level changes. The sorting and grain size of sediments, as well as the thickness and distribution of sand and clay bodies, are determined by the environment of deposition and have a profound influence on aquifer characteristics. Decreasing grain size or degree of sorting results in decreasing hydraulic conductivity values. A thick aquifer having low hydraulic conductivity may have a lower transmissivity than a thin aquifer having high hydraulic conductivity.

For convenience, the environments of deposition can be grouped into three major classes or lithotypes, as

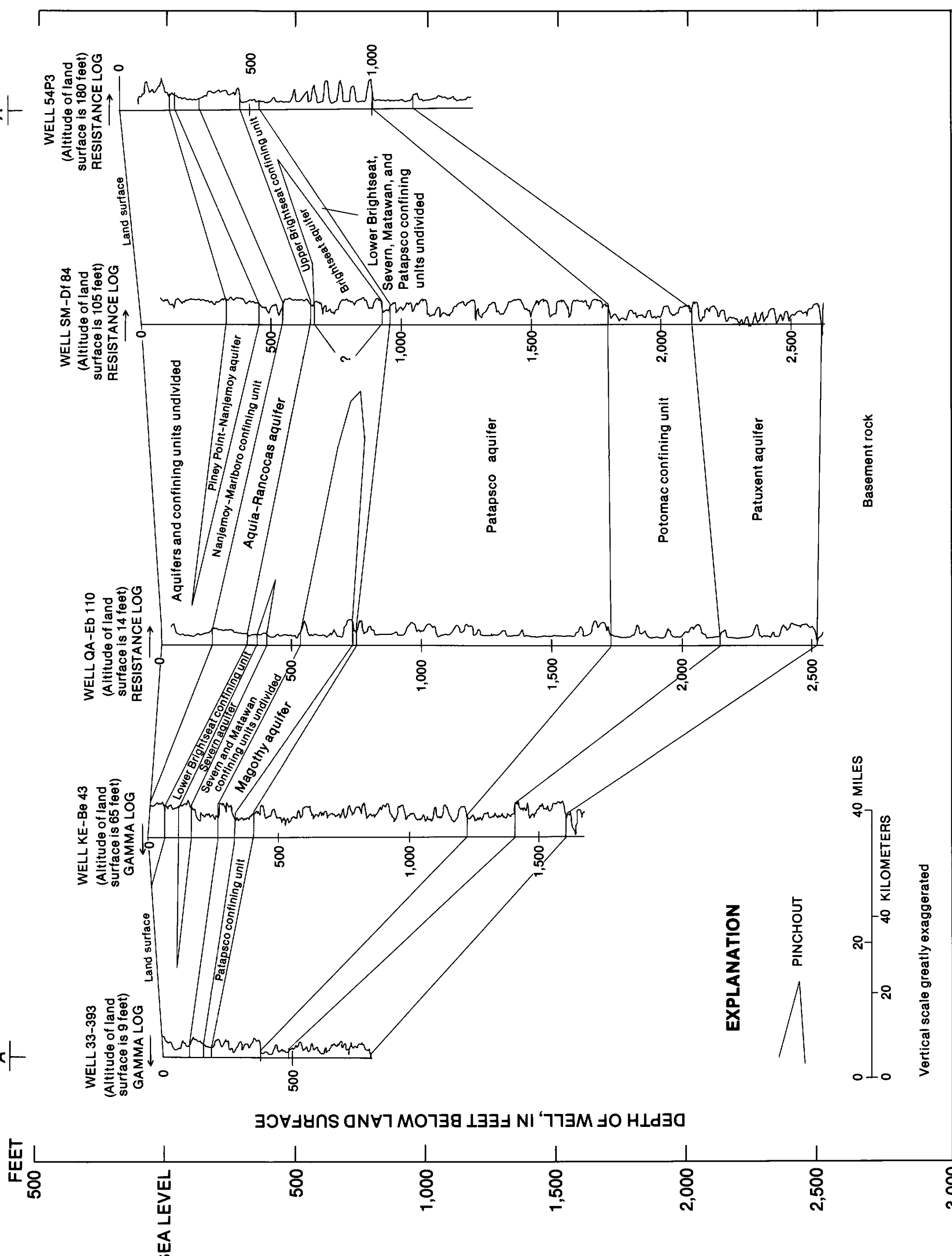


FIGURE 4.—Correlation of regional aquifers and confining units described in this report at selected wells along section *A–A′*. See plate 2 for location of *A–A′*.

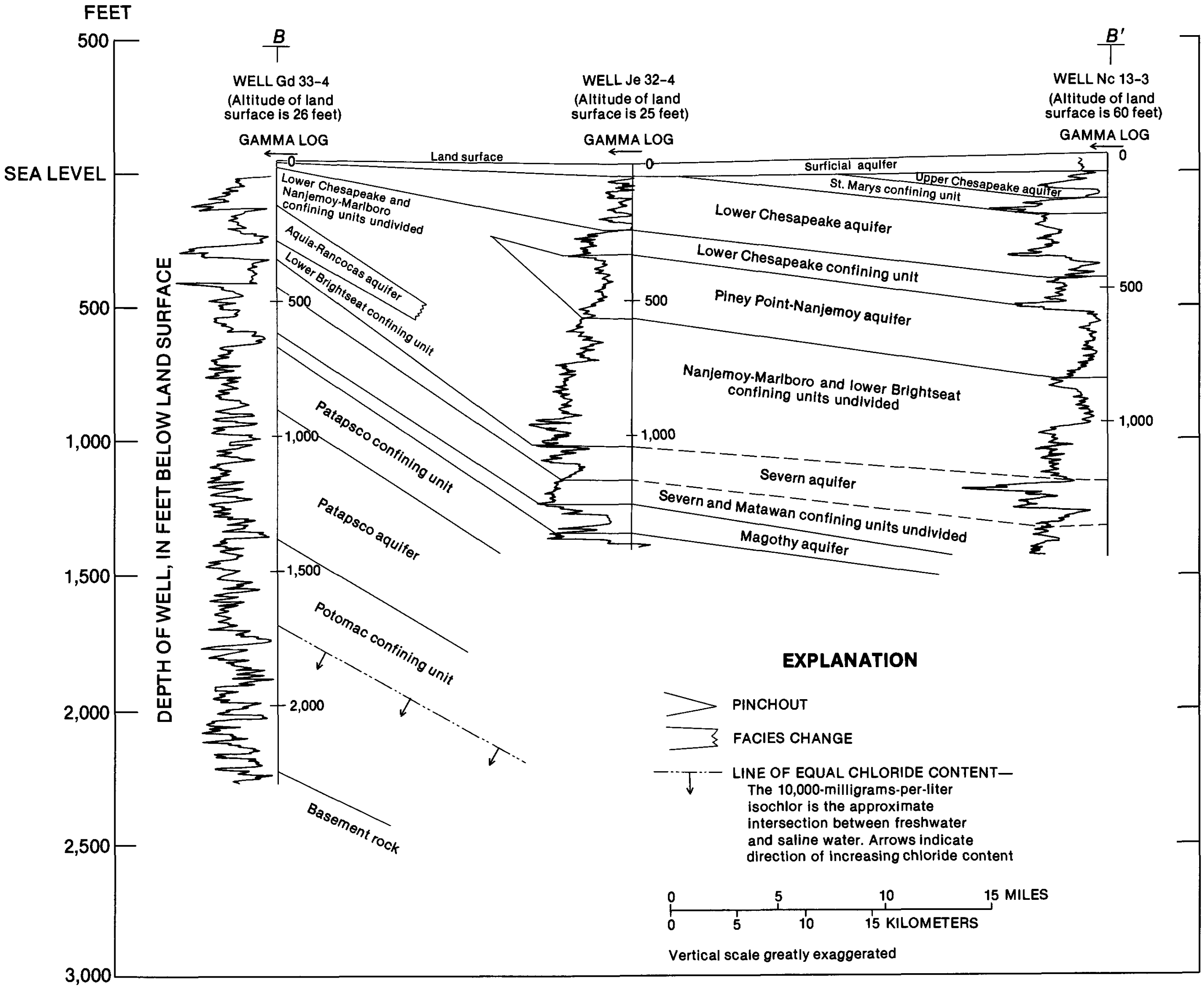


FIGURE 5.—Correlation of regional aquifers and confining units described in this report at selected wells along section *B–B'*. See plate 2 for location of *B–B'*.

defined by Dunbar and Rogers (1957). The lithotypes are nonmarine (or fluviodeltaic), strand zone (or fluviomarginal), and marine (or shelf). The lithotypes can occur together as either transgressive or regressive associations. Transgression results in deposition of an upward succession of increasingly deep-water sediments. Regression usually results in deposition of an upward succession of increasingly shallow-water sediments.

The relation between depositional environment and the distribution of transmissivity in the Maryland Coastal Plain has been studied by Hansen (1971). He pointed out that areas of high transmissivity in nonmarine sediments generally are subparallel to regional dip and reflect fluvial processes such as channel filling. Hansen also noted that areas of high transmissivity in marine sediments generally occur in tracts that are subparallel to regional strike and reflect sediment redistribution due to processes such as longshore drift. The nearshore facies receive sediment from both fluvial systems and longshore drift. Waves, particularly storm waves, winnow out the fine material that eventually settles out in the deeper, less energetic water (Hansen, 1972, p. 63). Thus, nearshore facies (above wave base) are predominantly silt and sand, but, farther offshore (below wave base), the sediments are generally finer grained and are mostly clay and silt (Hansen, 1971, p. 138).

Variations within fluvial environments of deposition characteristically produce different types of aquifers. In braided streams, repetition of bar formation and channel

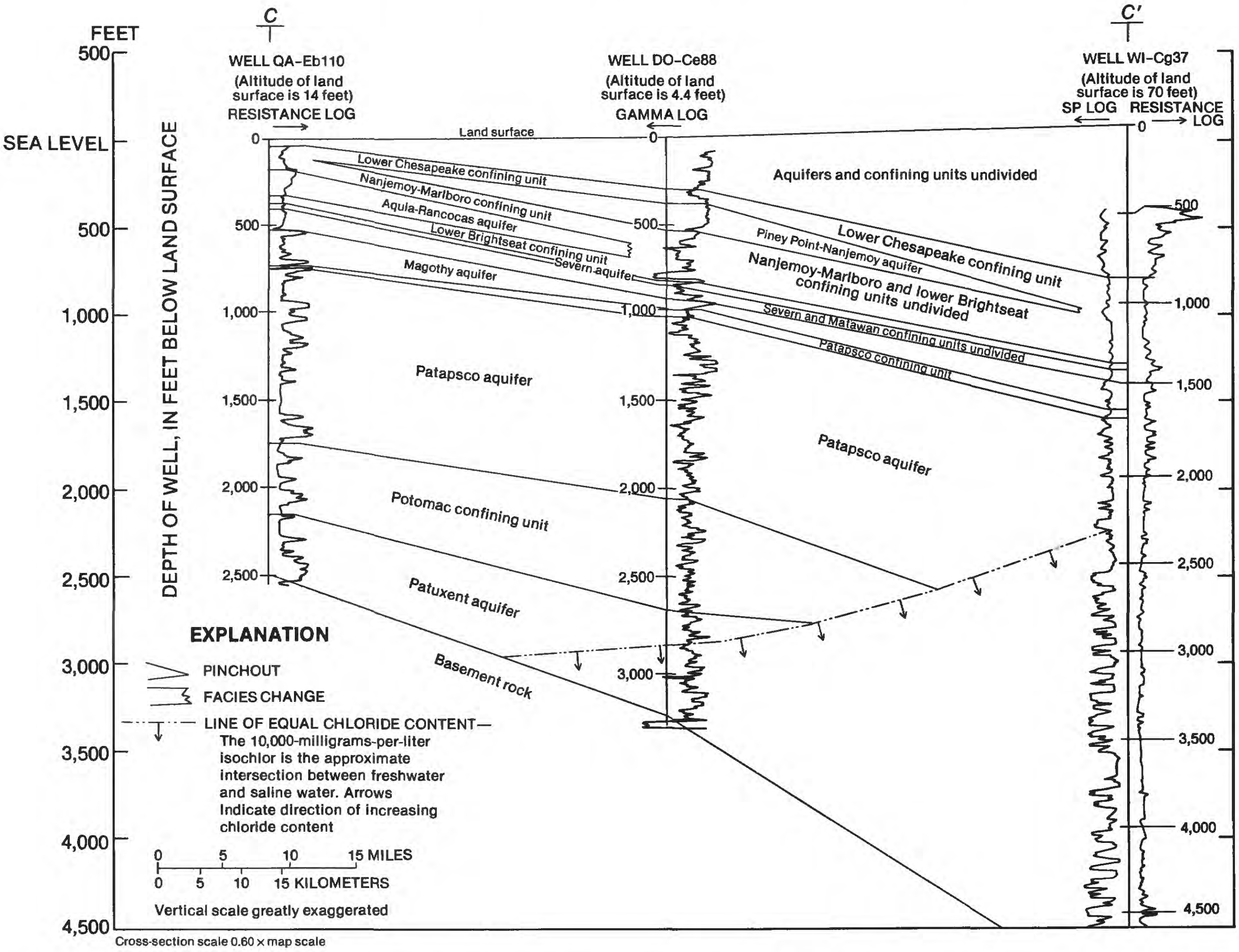


FIGURE 6.—Correlation of regional aquifers and confining units described in this report at selected wells along section *C–C′*. See plate 2 for location of *C–C′*.

branching creates a network of channels over the whole depositional area and generally precludes deposition of silt and clay. Therefore, braided-stream deposits tend to be sheetlike, thick, laterally extensive gravel and coarse sand. Examples of sources that would produce such deposits are glaciers and highlands where water is abundant, slopes are steep, coarse-grained material is available, and discharges fluctuate (Fahnestock, 1963).

Meandering-stream sediments are deposited under less variable and less energetic conditions than are braided-stream sediments, and they are typically finer grained with more silt and clay. Thus, the aquifers in meandering-stream deposits tend to be laterally and vertically discontinuous having lower hydraulic conductivity and transmissivity than the aquifers in braided fluvial deposits.

Deposits of deltaic environments can differ widely in the amount and distribution of sand, depending upon whether the deltas are dominated by fluvial or basinal processes. Figure 7 shows the sand thickness distribution in a variety of delta types. In those dominated by fluvial processes (type 1) and by tidal processes having low (type 2) and intermediate (type 3) wave energy, sand tends to be laterally discontinuous and elongate more or less perpendicular to the shoreline, and the thickest deposits occur along the axis or in channels. Intermediate wave energy, low offshore slope, and low sediment yield (type 4) may cause channel and mouth bar sands to coalesce and may result in sand bodies that are parallel to the shoreline. The configuration of sand deposits in deltas where wave action is strong—but littoral drift is minimal (type 5)—tends to be sheetlike, laterally continuous, and lobate. Where wave action and littoral drift are both strong influences (type 6), the sand bodies may be elongate and parallel to the shoreline. Thus, the dominance of fluvial or basinal processes is a major control

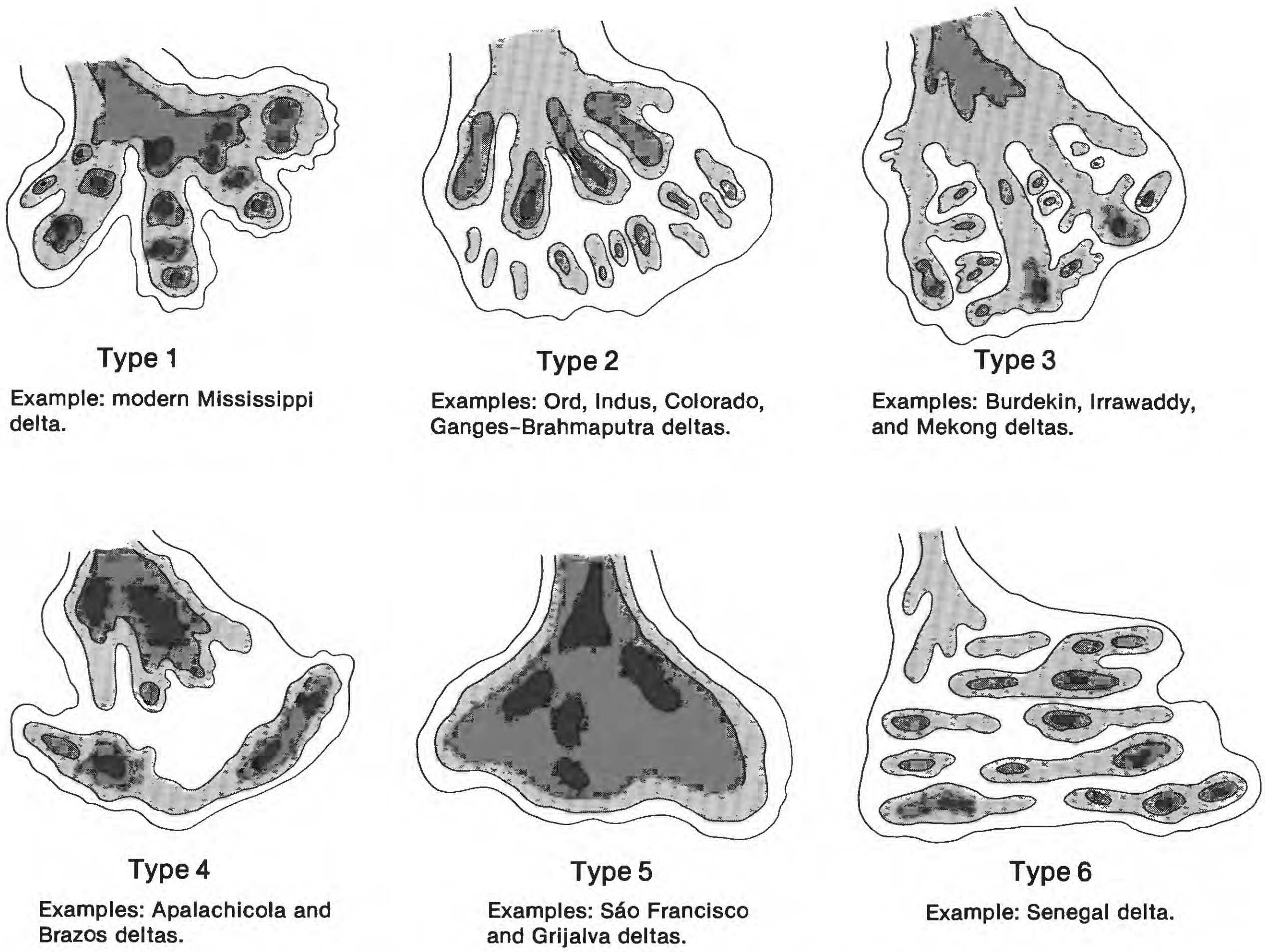


FIGURE 7.—Distribution and thickness of sand in modern deltas (from Coleman and Wright, 1975). Increasing density of tone indicates increasing sand thickness.

on the distribution of transmissivity tracts in deltaic deposits.

Other deltaic processes exert additional controls on transmissivity. Progradation of the delta front produces an upward coarsening sand body (Selley, 1982, p. 105); therefore, hydraulic conductivity typically increases upward. Low-gradient streams that drain swamps and lower deltaic plains often do not have the energy necessary for lateral erosion and migration; therefore, the resulting deposits tend to occur as ribbons of fine sand rather than as sheet sand and gravel (Schumm, 1968). Thus, the aquifers of the lower deltaic plain generally are less transmissive than those of the upper delta plain (Hansen, 1971, p. 135).

Variations in rates and direction of movement of marine transgressions and regressions are also major controls on transmissivity distribution. Regressive sequences usually coarsen upward; thus, the sand near the top of the sequence should have a greater hydraulic conductivity than that at the bottom. The reverse is true for transgressive sequences (Selley, 1982, p. 18). If transgression occurs without major stillstands, then the resulting fluviomarginal deposits may have hydraulic conductivities and transmissivities that are uniform over a broad area (Hansen, 1971, p. 142–144). If regression is rapid or if there is no sediment influx during the regression, then erosion may dominate over deposition—often removing portions of the underlying beds (Selley, 1982, p. 135). Rapidly fluctuating transgressive-regressive conditions can produce multiaquifer systems or isolated pods of sand that may vary significantly in hydraulic conductivity, thickness, and, therefore, transmissivity values.

HYDROGEOLOGIC FRAMEWORK

CONCEPTUALIZATION

The Coastal Plain of Maryland, Delaware, and the District of Columbia consists of an eastward-thickening wedge of sand, silt, and clay (fig. 6). The sediments have been grouped into 11 aquifers and 10 confining units on the basis of sediment geometry and permeability contrasts among the sediments. Aquifer and confining-unit boundaries may transect time-stratigraphic boundaries. Locally, each aquifer may contain confining beds, or a confining unit may contain water-bearing zones. However, on a regional basis, the aquifers and confining units form continuous hydrogeologic units in the Coastal Plain of Maryland, Delaware, and the District of Columbia. These hydrogeologic units are correlated to hydrogeologic units identified by RASA studies in New Jersey and in Virginia. The relations of the hydrogeologic units that are described in this report to stratigraphic units and to hydrogeologic units in adjacent States are shown on plate 1.

The fresh ground-water flow system of the Coastal Plain and Continental Shelf has several natural boundaries. Fresh ground water discharges upward into the ocean along the freshwater-saltwater interface (Hubbert, 1940, p. 924–926). In the Atlantic Coastal Plain, the freshwater-saltwater interface is gradational, and the boundary is arbitrarily placed midway between freshwater and seawater at the approximate intersection of the 10,000-mg/L isochlor (Meisler, 1981, fig. 4; Harold Meisler, U.S. Geological Survey, written commun., 1984) with the top of an aquifer. On a regional level, the 10,000-mg/L isochlor can be thought of as a barrier to fresh ground-water flow. The isochlor therefore constitutes the eastern boundary of the study area. The western boundary of the ground-water flow system is the Fall Line—the intersection of coastal plain sediments with the Piedmont. In updip areas, the base of the flow system is the contact of Coastal Plain sediments with crystalline or basement rock of Triassic or Jurassic age. Farther downdip, the 10,000-mg/L isochlor is above basement rock and is assumed to define the lower boundary of the freshwater flow system (fig. 6). The upper boundary is the surface of the water table.

The hydrogeologic units are described in the following sections in ascending order, from the oldest deposits to the youngest deposits.

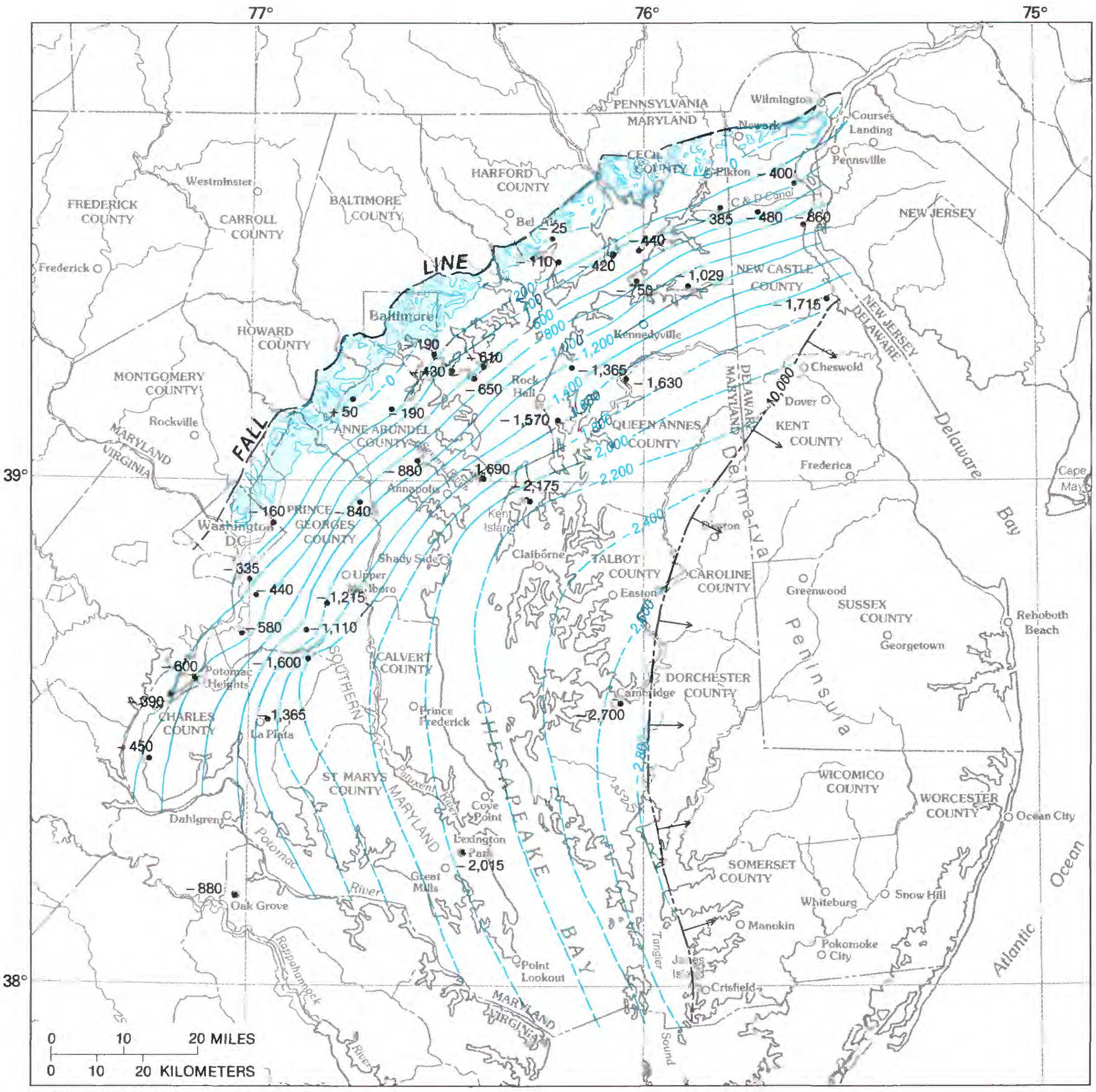
PATUXENT AQUIFER AND POTOMAC CONFINING UNIT

Aquifer definition.—The Patuxent aquifer in Delaware corresponds generally to the lower hydrologic zone of the Cretaceous Potomac Formation (Sundstrom and others, 1967, p. 21). The Patuxent aquifer in the Cretaceous Patuxent Formation of the Potomac Group in Maryland was mapped by Hansen (1968, p. 15; 1972, p. 19–23; 1981a, p. 24–25) and Mack (1966, p. 15). The western limit of the aquifer is the outcrop area at the Fall Line. The eastern boundary of the freshwater flow system in the aquifer is arbitrarily defined as the intersection of the top of the aquifer with the 10,000-mg/L isochlor, as approximately delineated by Meisler (U.S. Geological Survey, written commun., 1984). The base of the aquifer is basement rock or the 10,000-mg/L isochlor, depending on which is shallower. Where the aquifer is confined, the top of the aquifer (fig. 8) is the contact with the overlying Potomac confining unit. In the outcrop area, the top of the aquifer is the water table. The aquifer extends northward into New Jersey and southward into Virginia.

Depositional history of the aquifer.—The sediments of the Patuxent aquifer were the first to be deposited in updip areas of the Coastal Plain in Maryland, Delaware, and the District of Columbia after the uplift of the Piedmont-Blue Ridge province to the west in Early Cretaceous time (Glaser, 1969, p. 74). In central Maryland, the nonmarine basal sediments were probably deposited by braided streams. Increasing amounts of clay in higher parts of the section suggest that a decrease in river gradients preserved overbank sediments, channel fills, minor carbonaceous backswamp sediments (Glaser, 1969, p. 72), and possibly estuarine deposits (Groot, 1955). Hansen (1971, p. 135) considered the sediments of the Patuxent aquifer to be part of a delta complex having its axis in the vicinity of Baltimore, Md. Insufficient data are available from the lower deltaic plain deposits to determine whether deposition was dominated by basinal or fluvial processes.

Lithologic description of aquifer.—Sediments in the Patuxent aquifer are typically medium to coarse sand or pebbly sand and gravel, interbedded with relatively thin clay (Glaser, 1969, p. 7–9). In the Baltimore area and in northern Anne Arundel County, Md., the Patuxent aquifer contains substantial amounts of gravel and consists of more than 60 percent sand (Bennett and Meyer, 1952, p. 35). Toward the south in Charles County, the aquifer becomes increasingly interbedded with clay lenses. Clay beds are typically dense and light gray to buff colored, but they may be variegated red to purple or dark gray to black and lignitic. The aquifer sand in Charles County constitutes 20 percent or less of the combined clay and sand thickness (Hansen, 1969a, p. 1930). Lateral as well as vertical facies changes are large and abrupt.

Aquifer characteristics.—The Patuxent aquifer is a multilayer system. Sand layers associated with the basal sediments tend to be thick, irregularly bounded sheets having relatively high permeability. Near the upper part of the Patuxent aquifer, the sand layers are thin, isolated lenses or ribbons having low permeability. The aquifer pinches out at the Fall Line and thickens downdip toward the southeast, reaching at least 358 ft, as penetrated by well QA-Eb 110 in Queen Annes County, Md. Farther southeast, as at well DO-Ce 88 in Cambridge, Md., the



Base from U.S. Geological Survey

EXPLANATION

OUTCROP AREA OF THE PATUXENT AQUIFER

– 200 STRUCTURE CONTOUR—Shows altitude of top of Patuxent aquifer. Dashed where inferred. Contour interval 200 feet. Datum is sea level

APPROXIMATE UPDIP BOUNDARY OF THE PATUXENT AQUIFER

10,000 LINE OF EQUAL CHLORIDE CONCENTRATION—The 10,000-milligrams-per-liter isochlor is the approximate intersection between freshwater and seawater. Arrows indicate direction of increasing chloride concentration

– 2,700 WELL—Number is altitude of top of Patuxent aquifer, in feet above or below sea level

FIGURE 8.—Altitude of the top of the Patuxent aquifer in the Coastal Plain of Maryland, Delaware, and the District of Columbia.

freshwater part thins due to a thickening wedge of saline water beneath it (fig. 6).

In general, the percentage of sand, sand thickness, and transmissivity of the aquifer decrease southward from Baltimore to the Potomac River (Hansen, 1969a, p. 9–12) and northward from Baltimore to the Chesapeake and Delaware Canal in Cecil County, Md. (Sundstrom and others, 1967, p. 14). Transmissivities of individual sand layers within the Patuxent aquifer near Baltimore are approximately 7,000 ft^2/d, and the average storage coefficient is reported to be about 0.00026 (Bennett and Meyer, 1952, p. 44–58). Transmissivities of water-bearing zones in the Potomac Formation in New Castle County, Del., are reported to range from 454 to 8,480 ft^2/d (Martin and Denver, 1982, p. 13).

Delineation of a single sand layer within the Patuxent aquifer is difficult over even short distances (Groot and Penny, 1960; Jordan, 1962, p. 79, 1983, p. 33–35). Because of problems of correlation and scale and because of assumed hydraulic interconnection, the sand layers are considered to act as a single hydrologic unit in this report.

The Potomac confining unit.—The Potomac confining unit overlies the Patuxent aquifer. The thickness of the confining unit is shown in figure 9. During the drilling process, the unit can be identified by its toughness or resistance to penetration. Near the outcrop in Maryland, it corresponds to the sediments of the Cretaceous Arundel Formation of the Potomac Group as mapped by Matthews (1933) and modified by Hansen (1968, p. 16). In updip areas, it is composed of thick, variegated, dense clay, apparently laid down in shallow, discontinuous backswamp basins maintained by ponded drainage and slow sediment influx (Glaser, 1969, p. 75–76). Locally, the clay contains sand sequences representing stream-channel deposits that are thick enough to function as minor aquifers (Hansen, 1981a, p. 24–25).

Farther than a few miles downdip from the outcrop area, sand and clay interfingering becomes extensive and makes distinguishing aquifer and confining-bed boundaries difficult (Groot and Penny, 1960; Jordan, 1962, 1983). In these areas, the Potomac confining unit generally corresponds to a zone of clay and sand lenses separating two predominantly sandy zones in the Potomac Group (or Formation), as described by Sundstrom and others (1967, p. 21). The downdip extent of the Potomac confining unit, in this report, is arbitrarily considered to be the same as the limit of freshwater flow in the underlying Patuxent aquifer, as defined by the approximate location of the 10,000-mg/L isochlor.

PATAPSCO AQUIFER AND PATAPSCO CONFINING UNIT

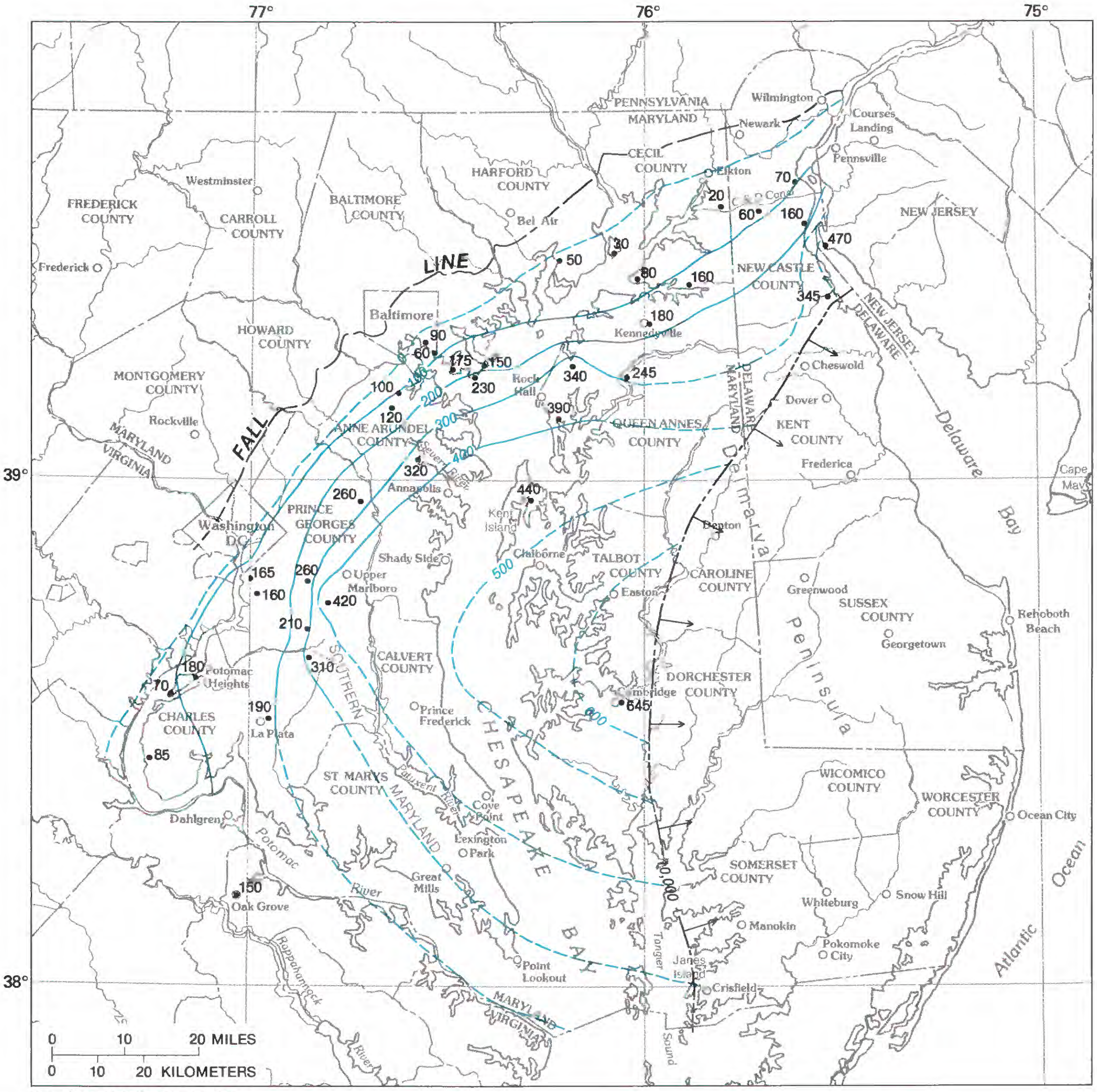
Aquifer definition.—The Patapsco aquifer in Delaware generally corresponds to the upper hydrologic zone of the Potomac Formation as described by Sundstrom and others (1967, p. 21). In Maryland, it corresponds to the aquifer in the lower part of the Cretaceous Patapsco Formation of the Potomac Group as mapped by Hansen (1968, p. 15; 1972, p. 33–46; 1981a, p. 24–25). The aquifer is bounded on the west by the outcrop of the Potomac confining unit. To the east and downward, the limit of fresh ground-water flow is assumed to be along the freshwater-saltwater interface, as represented by the 10,000-mg/L isochlor approximated by Meisler (1981, fig. 4; U.S. Geological Survey, written commun., 1984). Thus, the base of the aquifer is defined by the top of the Potomac confining unit, or the 10,000-mg/L isochlor, depending on which is shallower. Where the aquifer is confined, the top of the aquifer (fig. 10) is the base of the Patapsco confining unit. In the outcrop area, the top is the surface of the water table.

The aquifer extends northward into New Jersey. In Virginia, sediments correlative with Maryland's Patapsco aquifer are interpreted as two major aquifers separated by a confining unit (Meng and Harsh, 1984). The lower aquifer contains Lower Cretaceous sediments, and the upper aquifer contains Upper Cretaceous sediments.

Depositional history of the aquifer.—The sediments of the Patapsco aquifer mark the reestablishment of through drainage after the low-energy deposition of the Arundel Formation. Near its outcrop, the aquifer material was probably deposited on a low deltaic plain by sluggish, low-gradient, possibly meandering rivers (Glaser, 1969, p. 73). The axis of the deltaic complex is near Baltimore (Hansen, 1971, p. 135). The fluviodeltaic complex becomes increasingly distributary eastward (Robbins, Perry, and Doyle, 1975, p. 64) and may include marginal marine beds (Hansen, 1982, p. 4). Insufficient data are available from the lower deltaic plain deposits to determine whether deposition was dominated by fluvial or by basinal processes. The sediments north and south of Baltimore were probably laid down in marshes or swamps (Hansen, 1971, p. 135).

Lithologic description of the aquifer.—The sediments of the Patapsco aquifer are typically white to yellow, crossbedded, fine to medium, clayey sand and subordinate amounts of gravel. Associated clay is dense, massive or laminated, and variegated in shades of red, gray, brown, and purple (Glaser, 1969, p. 9). The aquifer is predominantly sand in Anne Arundel County. Clay content increases southward into Charles County (Hansen, 1969a, p. 130).

Aquifer characteristics.—The Patapsco aquifer is a multilayer system. Sand layers near Baltimore form relatively thick, irregularly bounded sheets that are mappable over several miles (Hansen, 1981a, p. 24–25). Elsewhere, however, delineation of a single sand layer is difficult over even short distances (Groot and Penny,



Base from U.S. Geological Survey

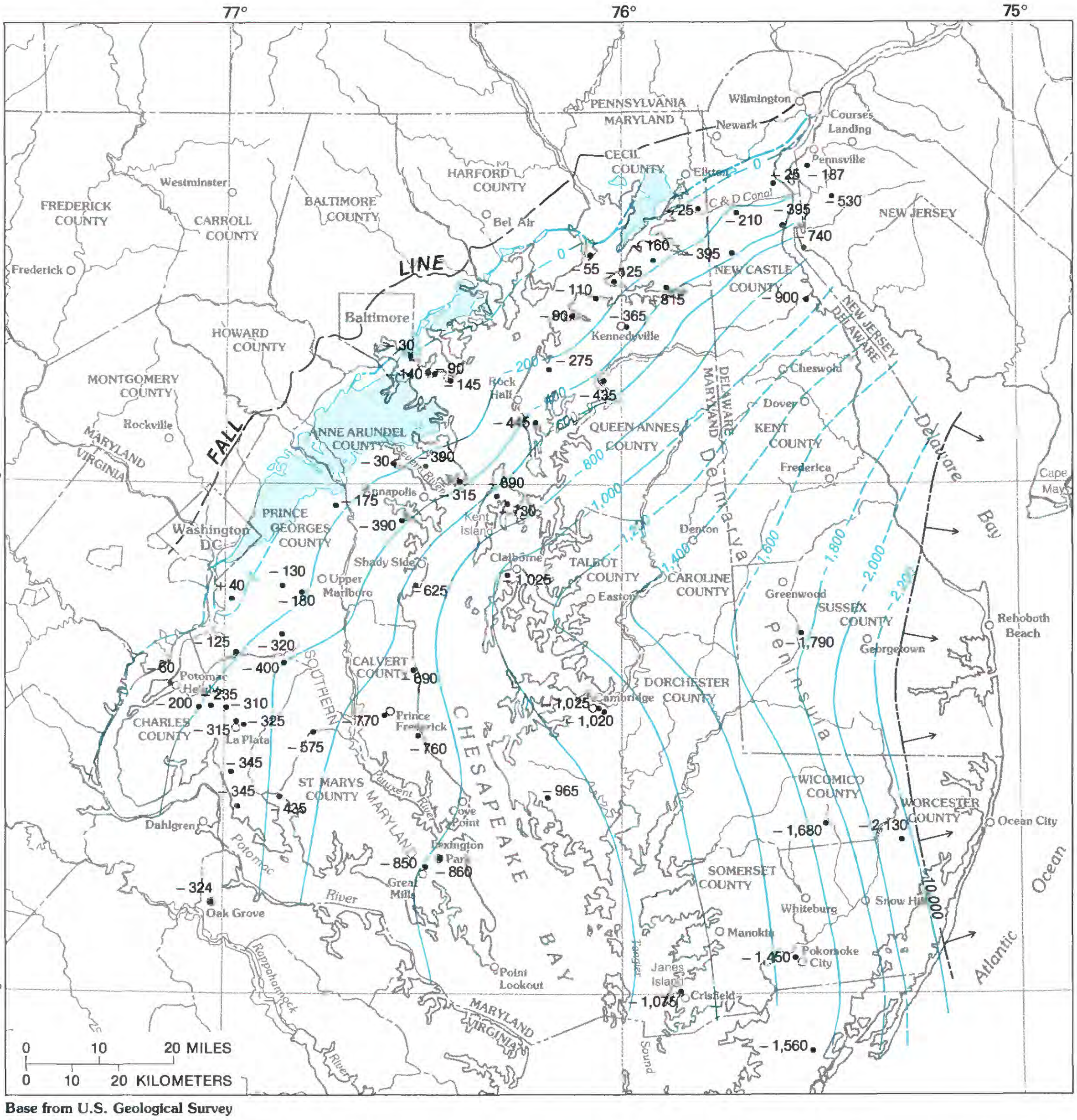
EXPLANATION

200 — LINE OF EQUAL THICKNESS OF THE POTOMAC CONFINING UNIT— Dashed where inferred. Interval 100 feet

10,000 — LINE OF EQUAL CHLORIDE CONCENTRATION— The 10,000-milligrams-per-liter isochlor is the approximate intersection between freshwater and seawater. Arrows indicate direction of increasing chloride concentration

•160 WELL—Number is thickness of the Potomac confining unit, in feet

FIGURE 9.—Thickness of the Potomac confining unit in the Coastal Plain of Maryland, Delaware, and the District of Columbia.



Base from U.S. Geological Survey

EXPLANATION

OUTCROP AREA OF THE PATAPSCO AQUIFER

– 200 STRUCTURE CONTOUR—Shows altitude of the top of the Patapsco aquifer. Dashed where inferred. Contour interval 200 feet. Datum is sea level

APPROXIMATE UPDIP BOUNDARY OF THE PATAPSCO AQUIFER

10,000 LINE OF EQUAL CHLORIDE CONCENTRATION—The 10,000-milligrams-per-liter isochlor is the approximate intersection between freshwater and seawater. Arrows indicate direction of increasing chloride concentration

–145 WELL—Number is altitude of the top of the Patapsco aquifer, in feet above or below sea level

FIGURE 10.—Altitude of the top of the Patapsco aquifer in the Coastal Plain of Maryland, Delaware, and the District of Columbia.

1960; Jordan, 1962, 1983, p. 33–35). Moreover, the clayey strata may also contain lenses or ribbons of sand that may function as minor aquifers. Because of problems of correlation and scale and because of assumed hydraulic interconnection, the sand layers are considered to be a single hydrologic unit in this report. The aquifer pinches out at the updip limit of its outcrop area and thickens downdip, reaching 1,020 ft at Cambridge, Md., as penetrated by well DO-Ce 88. Farther east, the freshwater part of the aquifer thins due to a seaward-thickening wedge of saline water beneath the aquifer (fig. 6).

In general, sand percentage, sand thickness, and transmissivity of the Patapsco aquifer decrease southward from Baltimore to the Potomac River (Hansen, 1969a, p. 9–12) and northward from Baltimore to the Chesapeake and Delaware Canal in Cecil County (Sundstrom and others, 1967, p. 14). The sediments are predominantly fine to medium sand (riverine deposition), silt, and thick clay bed (swamp deposits) having fewer beds of gravel and coarse sand beds than in the Patuxent aquifer.

Reported transmissivities for individual sand layers range from about 180 ft^2/d in Prince Georges County, Md., to about 10,200 ft^2/d in northern Anne Arundel County. Storage-coefficient values for the confined portion have been reported to average 0.0002 (Otton, 1955, p. 53–56). In Delaware, Martin (1984, p. 56) reported transmissivity values ranging from less than 1,000 ft^2/d to 6,000 ft^2/d.

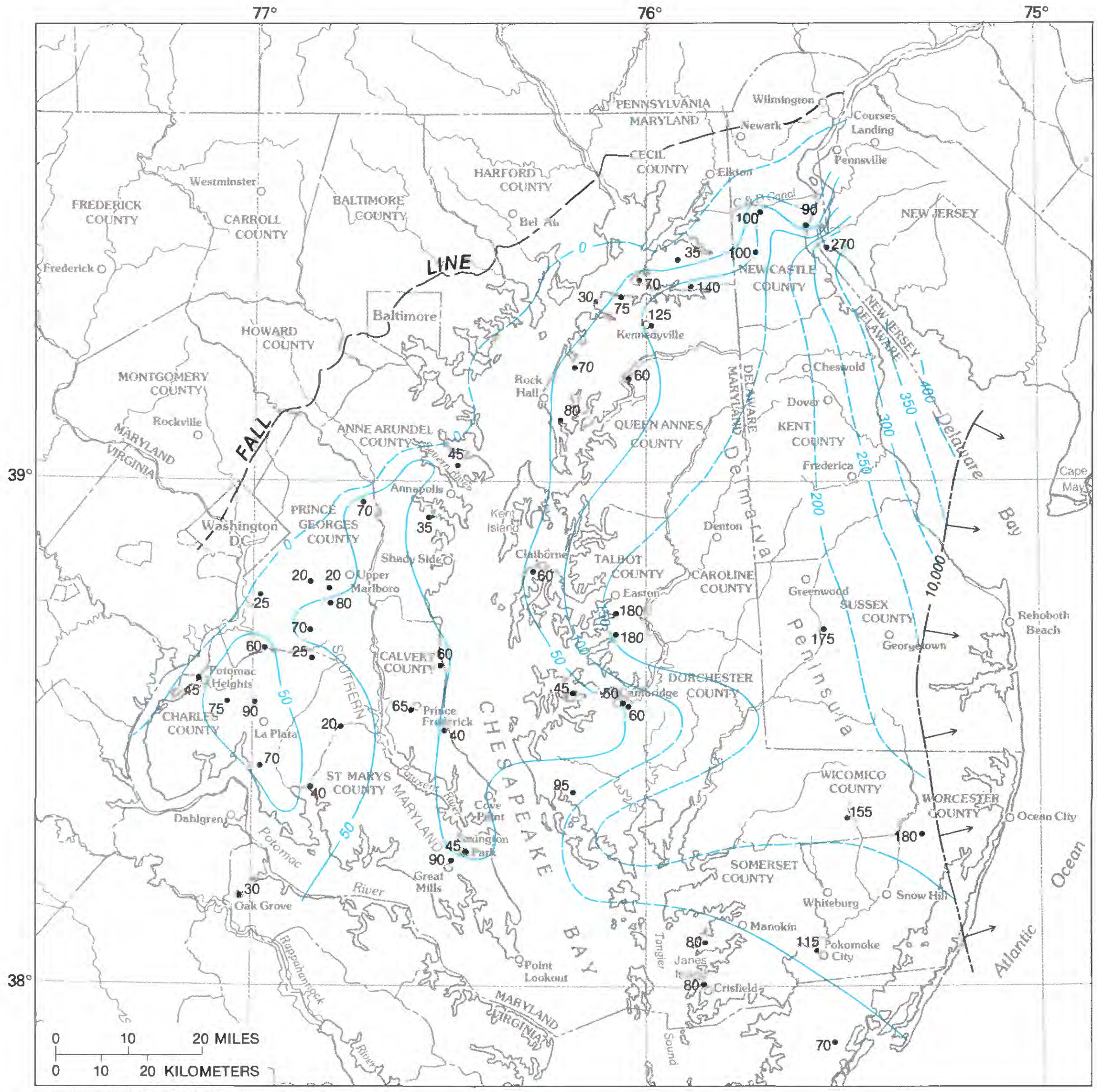
The Patapsco confining unit.—The Patapsco aquifer is overlain by the red, plastic clay of the Patapsco confining unit in the upper part of the Patapsco Formation. The thickness of the confining unit is shown in figure 11. Its base is defined by the top of the uppermost sand beds in the Patapsco aquifer. The top of the Patapsco confining unit is the contact with the lowermost sand bed in the overlying aquifer. However, the overlying aquifers are not continuous over the entire area of the confining unit; thus, the top of the Patapsco confining unit is defined by the base of the Brightseat aquifer in the extreme southern part of Maryland, by the base of the Aquia aquifer in parts of St. Marys, Charles, and Somerset Counties, Md., and by the base of the Magothy aquifer in most other areas. The thickness of the Patapsco confining unit that is shown in figure 11 is generalized because of the abrupt lithological changes in the underlying Patapsco aquifer and the discontinuity of the overlying aquifers. In this report, the downdip limit of the Patapsco confining unit is arbitrarily considered to be the same as the limit of freshwater flow in the underlying Patapsco aquifer, as defined by the approximate location of the 10,000-mg/L isochlor.

MAGOTHY AQUIFER AND MATAWAN CONFINING UNIT

Aquifer definition.—The Magothy aquifer, in the Cretaceous Magothy Formation, has been defined in the area east of the Chesapeake Bay by Cushing and others (1973, pl. 3) and in the area west of the Chesapeake Bay by Mack and Mandle (1977, p. 7–11). Slight modifications have been made for this study on the basis of more recent data. The eastern freshwater-flow boundary in the aquifer is based on the approximate intersection of the 10,000-mg/L isochlor with the top of the aquifer. The western boundary is the updip limit of the aquifer defined by Mack and Mandle (1977, p. 11) and by Cushing and others (1973, pl. 3). The aquifer is bounded on the bottom by the Patapsco confining unit or by the 10,000-mg/L isochlor, depending on which is shallower. The upper boundary in confined areas is the Matawan confining unit. In the outcrop area, the top of the aquifer is the surface of the water table. The top of the aquifer is shown in figure 12.

The Magothy aquifer thins southward and apparently is truncated near southern Calvert County, Md. (Mack and Mandle, 1977, p. 8). Sediments palynologically correlative with those of the Magothy aquifer are absent near Crisfield, Md. (Hansen, 1978, fig. 10), and Oak Grove, Va. (Reinhardt, Christopher, and Owens, 1980, p. 4). The southern boundary of the Magothy aquifer (fig. 12) is therefore considered to be along the apparent truncation line, which extends from north-central Charles County across northern St. Marys County to the southeastern part of Maryland east of the Chesapeake Bay (Hansen, 1978, p. 22). The aquifer extends north into New Jersey.

Depositional history of the aquifer.—The transgressive phase of sedimentation began at the base of the Patuxent aquifer and continued through deposition of the Magothy aquifer. The latter is an Upper Cretaceous strand-zone deposit of fluviomarine origin (Clark, 1916; Overbeck and Slaughter, 1958, p. 55). Magothy sedimentation appears to have occurred during a continuous landward shift of the strandline (Hansen, 1971, p. 143–144), thus resulting in generally uniform sand thicknesses throughout the aquifer. An exception is in eastern Anne Arundel County where the aquifer abruptly thickens and coarsens (Mack, 1962, p. 25). Hansen (1971, p. 144) noted that (1) the anomalously thick section is probably a fluvial deposit, because of its orientation subparallel to regional dip and its proximity to a major source of fluvially derived sediments, and (2) the same fluvial system apparently also dominated during deposition of the Potomac Group, because the tract of high transmissivity in the Magothy coincides in general with areas of high transmissivity in the Patapsco aquifer and the Patuxent aquifer.



Base from U.S. Geological Survey

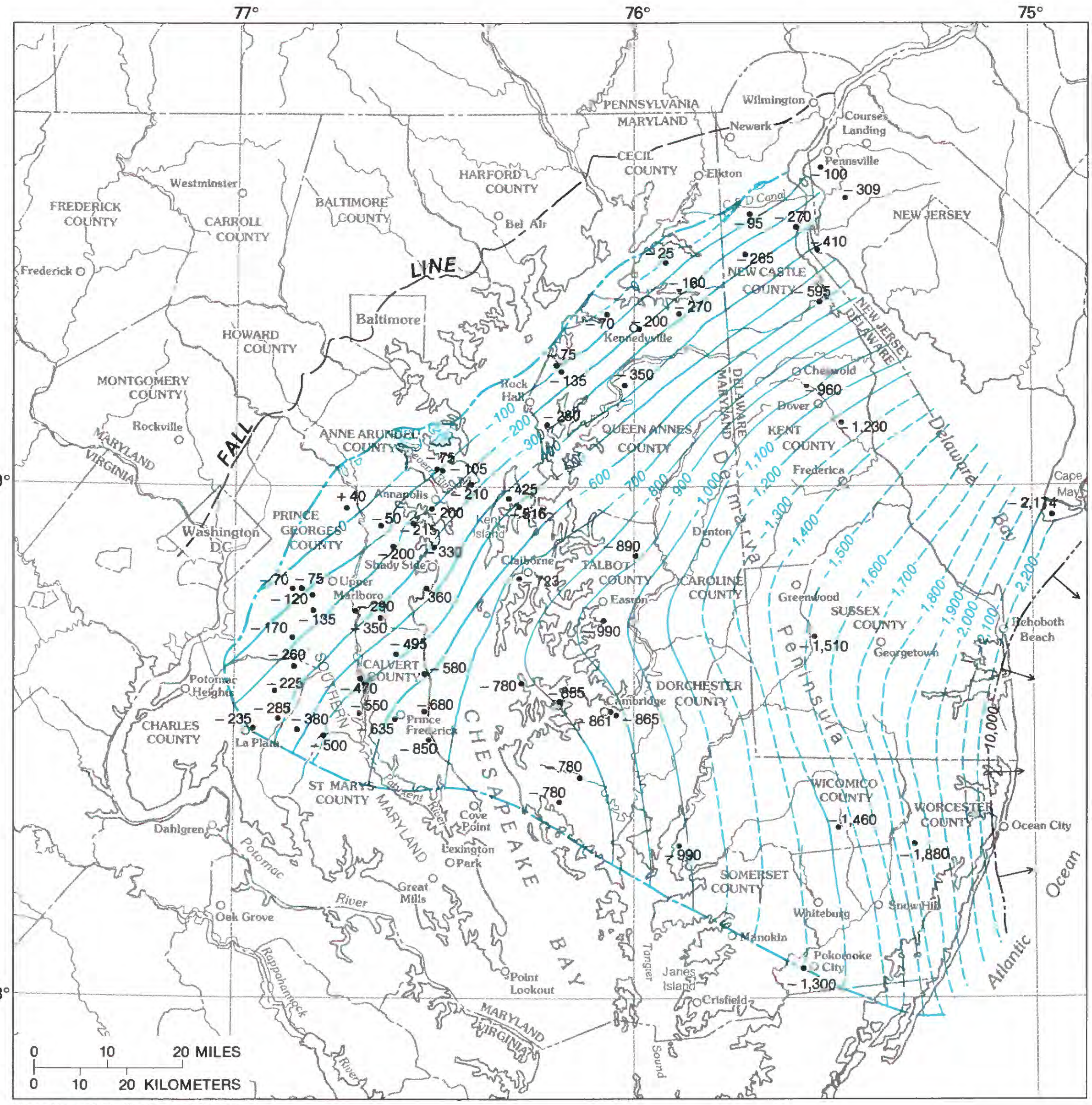
EXPLANATION

—— 200 – – – LINE OF EQUAL THICKNESS OF THE PATAPSCO CONFINING UNIT—Dashed where inferred. Interval 50 feet

– – 10,000 – – LINE OF EQUAL CHLORIDE CONCENTRATION—The 10,000-milligrams-per-liter isochlor is the approximate intersection between freshwater and seawater. Arrows indicate direction of increasing chloride concentration

90 • WELL—Number is thickness of the Patapsco confining unit, in feet

FIGURE 11.—Thickness of the Patapsco confining unit in the Coastal Plain of Maryland and Delaware.



Base from U.S. Geological Survey

EXPLANATION

OUTCROP AREA OF THE MAGOTHY AQUIFER

– 200 STRUCTURE CONTOUR—Shows altitude of the top of the Magothy aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

APPROXIMATE BOUNDARY OF THE MAGOTHY AQUIFER

10,000 LINE OF EQUAL CHLORIDE CONCENTRATION—The 10,000-milligrams-per-liter isochlor is the approximate intersection between freshwater and seawater. Arrows indicate direction of increasing chloride concentration

–210 WELL—Number is altitude of the top of the Magothy aquifer, in feet above or below sea level

FIGURE 12.—Altitude of the top of the Magothy aquifer in the Coastal Plain of Maryland and Delaware.

Lithologic description of the aquifer.—The Magothy aquifer is primarily composed of unconsolidated, white, commonly lignitic, fine to medium quartzose sand. In eastern Anne Arundel County, the sediments are coarse to very coarse, are interbedded with ferruginous quartzose gravel, and contain limonite cementation. Black lignitic clay and laminated bluish-gray silty clay are common throughout the aquifer (Glaser, 1969, p. 12–14; Mack, 1962, p. 10). Sediments in the Magothy aquifer grade upward into the overlying confining unit.

Aquifer characteristics.—The transmissivity of the Magothy aquifer generally ranges from about 1,000 to 3,000 ft^2/d and does not change abruptly (Hansen, 1971, p. 133–144; 1972, p. 60–61). An exception is a tract of locally high transmissivity, which ranges from about 10,000 to 12,000 ft^2/d in eastern Anne Arundel County (Mack, 1962, p. 25–26) and trends subparallel to regional dip (Hansen, 1971, p. 61). In the area of maximum transmissivity, the aquifer thickness is about 300 ft (Mack, 1974, p. 53). In most other places, the aquifer thickness is a few tens of feet (Hansen, 1972 p. 49; Sundstrom and others, 1976, p. 15). The storage coefficient in confined areas is probably about 0.0003 (Mack and Mandle, 1977, p. 19).

In some areas west of the Chesapeake Bay, the upper 60 ft of the Magothy aquifer is separated from the lower section by a clay layer 10 to 20 ft thick. Mack (1974, p. 13) conducted pumping tests at two sites with screens set in observation wells above and below the clay layer. At each site, water levels in the upper sand changed significantly in response to short-term pumping in the lower sand; these changes in water levels indicate that the clay layer is leaky or not laterally continuous. At other locations in Maryland (wells QA-Eb 109, TA-Cb 89), the aquifer is divided by two clay layers. Because of the hydraulic interconnection between sand layers in the aquifer, the Magothy is considered to act as a single hydrologic unit.

The Matawan confining unit.—The Magothy aquifer grades upward into the glauconitic clay and silt of the Matawan confining unit. The thickness of the confining unit (fig. 13) is based on geophysical and lithologic well logs. The clay and silt are primarily from the Upper Cretaceous Matawan Formation, but, in places, silt from the Magothy Formation may be included. The Matawan Formation thins southward and is truncated in southern Calvert County (Hansen, 1978). In this report, the downdip extent of the Matawan confining unit is arbitrarily considered to be the same as the limit of freshwater flow in the underlying Patuxent aquifer, as defined by the approximate location of the 10,000-mg/L isochlor. The sediments are thought to be a product of the continuing transgression and were laid down below wave base (Hansen, 1971, p. 138).

MATAWAN AQUIFER AND SEVERN CONFINING UNIT

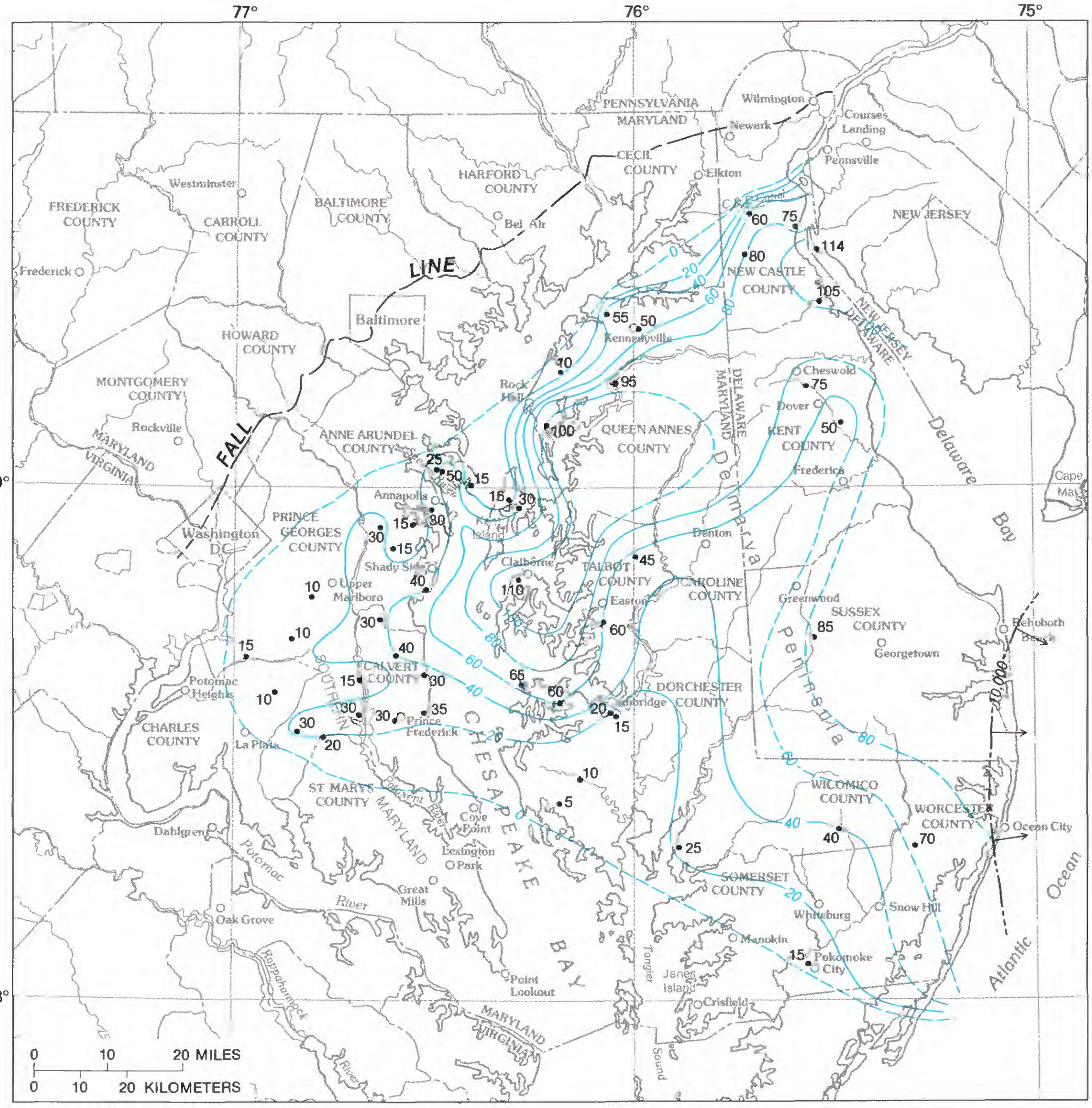
Aquifer definition.—The Matawan aquifer corresponds to those parts of the Matawan Formation that are sandy enough to yield water for domestic supply. The limits of the aquifer shown in figure 14 are approximations that enclose the occurrences reported by Kraft and Maisano (1968), Overbeck and Slaughter (1958, p. 58–60), and Rasmussen and Slaughter (1960, p. 21). It is bounded on the top by the Severn confining unit and on the bottom by the Matawan confining unit. The altitude of the top of the aquifer is shown in figure 14.

Depositional history of the aquifer.—The sediments of the Matawan aquifer are Upper Cretaceous in age. They mark the beginning of marine sedimentation below wave base as the strandline continued to move landward during the ongoing transgression (Hansen, 1971, p. 129).

Lithologic description of the aquifer.—The sediments of the Matawan aquifer are typically dark gray, micaceous, silty or clayey sand (Overbeck and Slaughter, 1958, p. 58–59). The generally finer nature and high glauconite content of the Matawan sediments differentiate them from sediments in the underlying aquifers.

Aquifer characteristics.—In Maryland, the Matawan aquifer is reported to be transmissive enough to yield water for domestic supply in all areas of Queen Annes County except the southeast and throughout most of Kent County (Overbeck and Slaughter, 1958, p. 26); however, the clayey nature of the aquifer results in low transmissivity throughout. Even in Kent County, Md., where the aquifer utilization is greatest, the transmissivity for the combined thickness of the Matawan and the next overlying aquifer, the Severn, is less than 700 ft^2/d, according to one pumping test. The reported average storage coefficient in Kent County is about 0.0002 (Overbeck and Slaughter, 1958, p. 63–66). In areas to the south, west, and east of Kent County, sediments associated with the Matawan Formation are too clayey to function as an aquifer, according to Hansen (1972, p. 46), Mack and others (1971, p. 68–70), Otton (1955, p. 17), Rasmussen and Slaughter (1955, p. 37), and Rasmussen and others (1957, p. 95). The thickness of the water-bearing sand is typically from 5 to 10 ft (Overbeck and Slaughter, 1958).

The Severn confining unit.—The Severn confining unit, in the lower part of the Upper Cretaceous Severn Formation in Maryland, is composed of the clay and silt between the Matawan aquifer and the overlying Severn aquifer. In areas where the Matawan Formation is not sandy enough to be an aquifer, the confining unit includes clay and silt from both the Matawan Formation and the overlying Severn Formation. The limits of the confining unit shown in figure 15 coincide with the limits of the



Base from U.S. Geological Survey

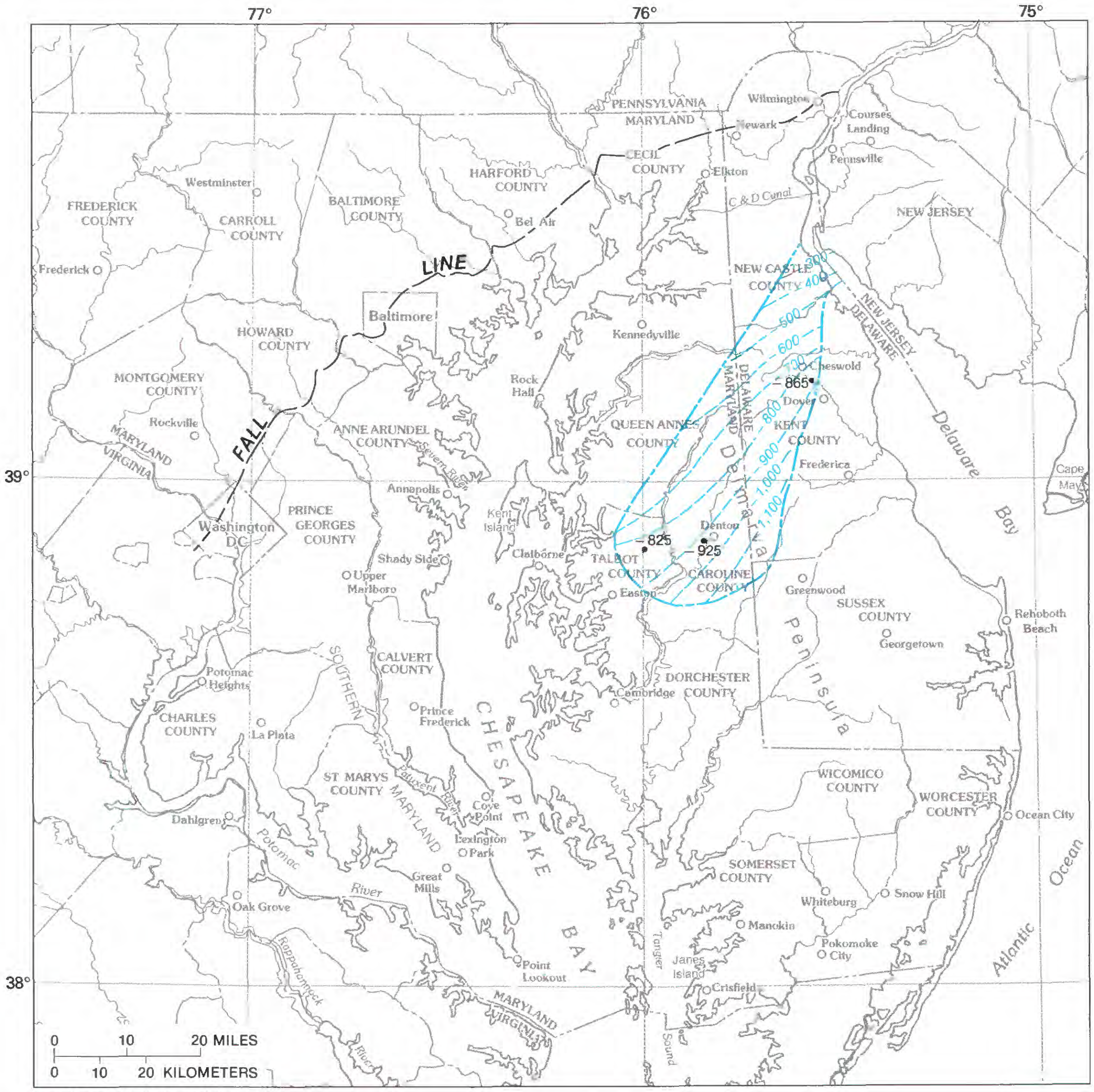
EXPLANATION

100 — LINE OF EQUAL THICKNESS OF THE MATAWAN CONFINING UNIT—Dashed where inferred. Interval 20 feet

10,000 — LINE OF EQUAL CHLORIDE CONCENTRATION—The 10,000-milligrams-per-liter isochlor is the approximate intersection between freshwater and seawater. Arrows indicate direction of increasing chloride concentration

•40 WELL—Number is thickness of the Matawan confining unit, in feet

FIGURE 13.—Thickness of the Matawan confining unit in the Coastal Plain of Maryland and Delaware.



Base from U.S. Geological Survey

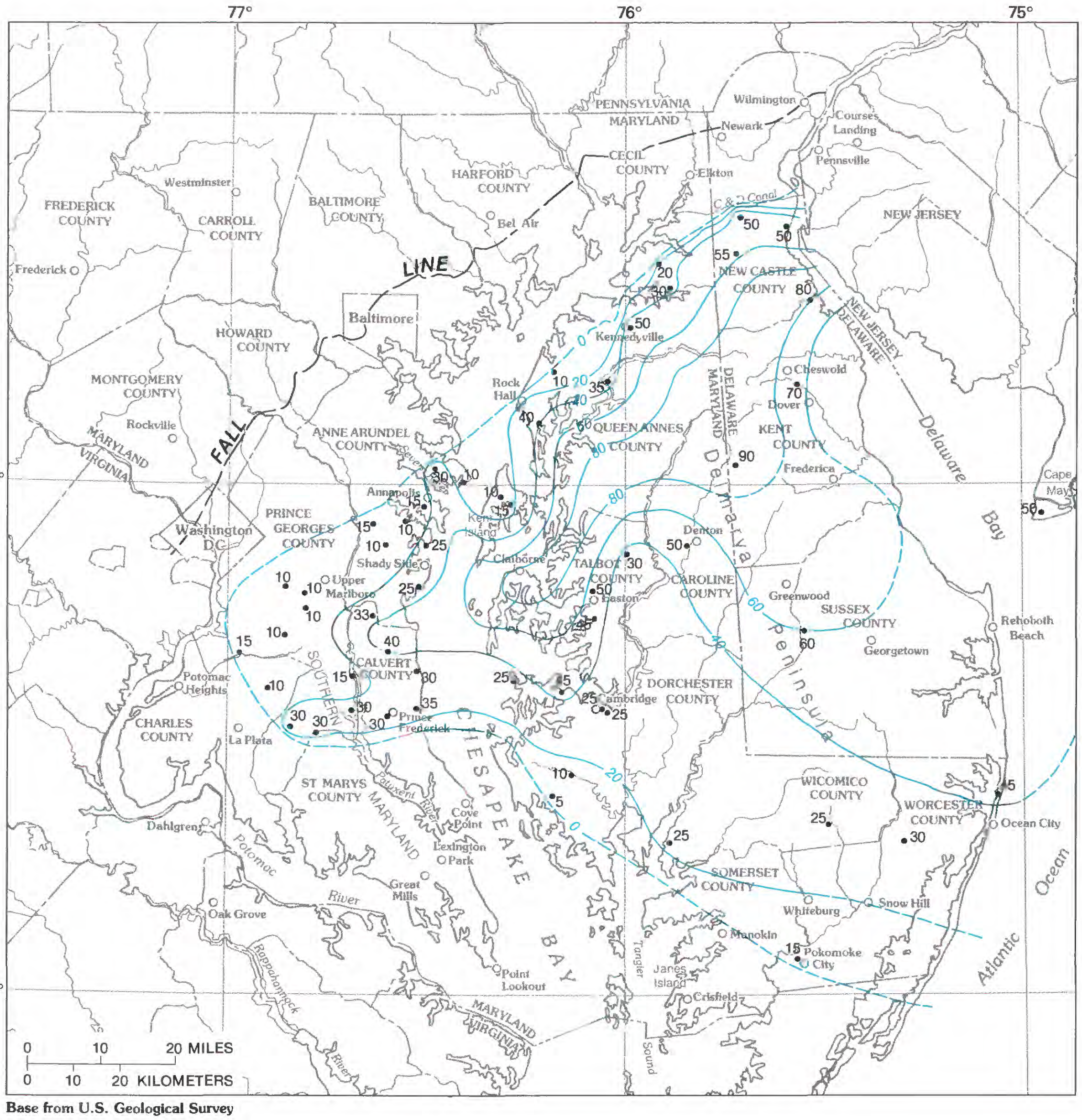
EXPLANATION

— 600 — — — STRUCTURE CONTOUR—Shows altitude of the top of the Matawan aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

— · — · — APPROXIMATE BOUNDARY OF THE MATAWAN AQUIFER

• −925 WELL—Number is altitude of the top of the Matawan aquifer, in feet below sea level

FIGURE 14.—Altitude of the top of the Matawan aquifer in the Coastal Plain of Maryland and Delaware.



EXPLANATION

—— 40 ———— LINE OF EQUAL THICKNESS OF THE SEVERN CONFINING UNIT—Dashed where inferred. Interval 20 feet

25• WELL—Number is thickness of the Severn confining unit, in feet

FIGURE 15.—Thickness of the Severn confining unit in the Coastal Plain of Maryland and Delaware.

Matawan and the Severn Formations, as mapped by Hansen (1968, p. 20). Hansen (1971, p. 129) stated that the sediments were deposited during the late stages of a marine transgression.

SEVERN AQUIFER AND LOWER BRIGHTSEAT CONFINING UNIT

Aquifer definition.—The Severn aquifer corresponds to those sandy parts of the Upper Cretaceous Severn

Formation in Maryland (Minard and others, 1977, p. A132–A133) and the Monmouth Formation in Delaware (Jordan and Smith, 1983) that are permeable enough to function as an aquifer. The lateral boundaries of the aquifer, as shown in figure 16, are approximations that enclose the locations where pumpage has been reported (Hansen, 1972; Mack and others, 1971, p. 68–70; Overbeck and Slaughter, 1958, p. 60–66; Marine and Rasmussen, 1955, p. 95) and extend across Delaware into New Jersey where the stratigraphically equivalent sand is productive near the Delaware River. In most other areas, the Severn Formation is not sandy enough to be an aquifer (Hansen, 1972, p.111; Mack and others, 1971, p. 12; Otton, 1955, p. 68–70; Overbeck and Slaughter, 1958, p. 61–66; Rasmussen and Slaughter, 1955, p. 37). The upper boundary (fig. 16), downdip from the outcrop areas, is the lower Brightseat confining unit. The lower boundary is the Severn confining unit.

Depositional history of the aquifer.—The sediments of the Severn aquifer are Upper Cretaceous in age. According to Hansen (1971, p. 129), they were deposited below wave base as the transgression that began at the base of the Patuxent aquifer continued.

Lithologic description of the aquifer.—Sand in the Severn aquifer is generally fine grained but poorly sorted; coarse-grained sand occurs locally (Goldman, 1916). The sand is silty or clayey and reddish-brown in color, and it contains more glauconite than does the underlying Matawan sediment. The lack of uniformity among well logs indicates that the sand beds are not continuous (Overbeck and Slaughter, 1958, p. 61–62).

Aquifer characteristics.—The Severn aquifer is typically less than 100 ft thick. Transmissivity is low due to the clayey nature of the sediments. Even in Kent County, Md., where its utilization is greatest, transmissivity reported for the combined thicknesses of the Severn and the next underlying aquifer, the Matawan, is less than 700 ft^2/d. An average storage coefficient in Kent County is about 0.0002 (Overbeck and Slaughter, 1958, p. 63–66).

The lower Brightseat confining unit.—The lower Brightseat confining unit typically consists of the silt and clay between the Severn aquifer and the overlying Aquia-Rancocas aquifer. Where either of the aquifers is absent, the confining unit includes the clayey facies of the Severn Formation and may include the lower part of the Paleocene Brightseat Formation (Bennett and Collins, 1952, p. 114–116).

The Brightseat Formation marks the beginning of a regressive phase of sedimentation and coarsens upward. Its silt and clay are marine sediments, parts of which are thought to have been deposited in the sublittoral zone in about 300 ft of water (Nogan, 1964, p. 13). The thickness of the lower Brightseat confining unit is shown in figure 17. The unit is absent where sediments of the Severn Formation are missing, as mapped by Hansen (1968, p. 20).

BRIGHTSEAT AQUIFER AND UPPER BRIGHTSEAT CONFINING UNIT

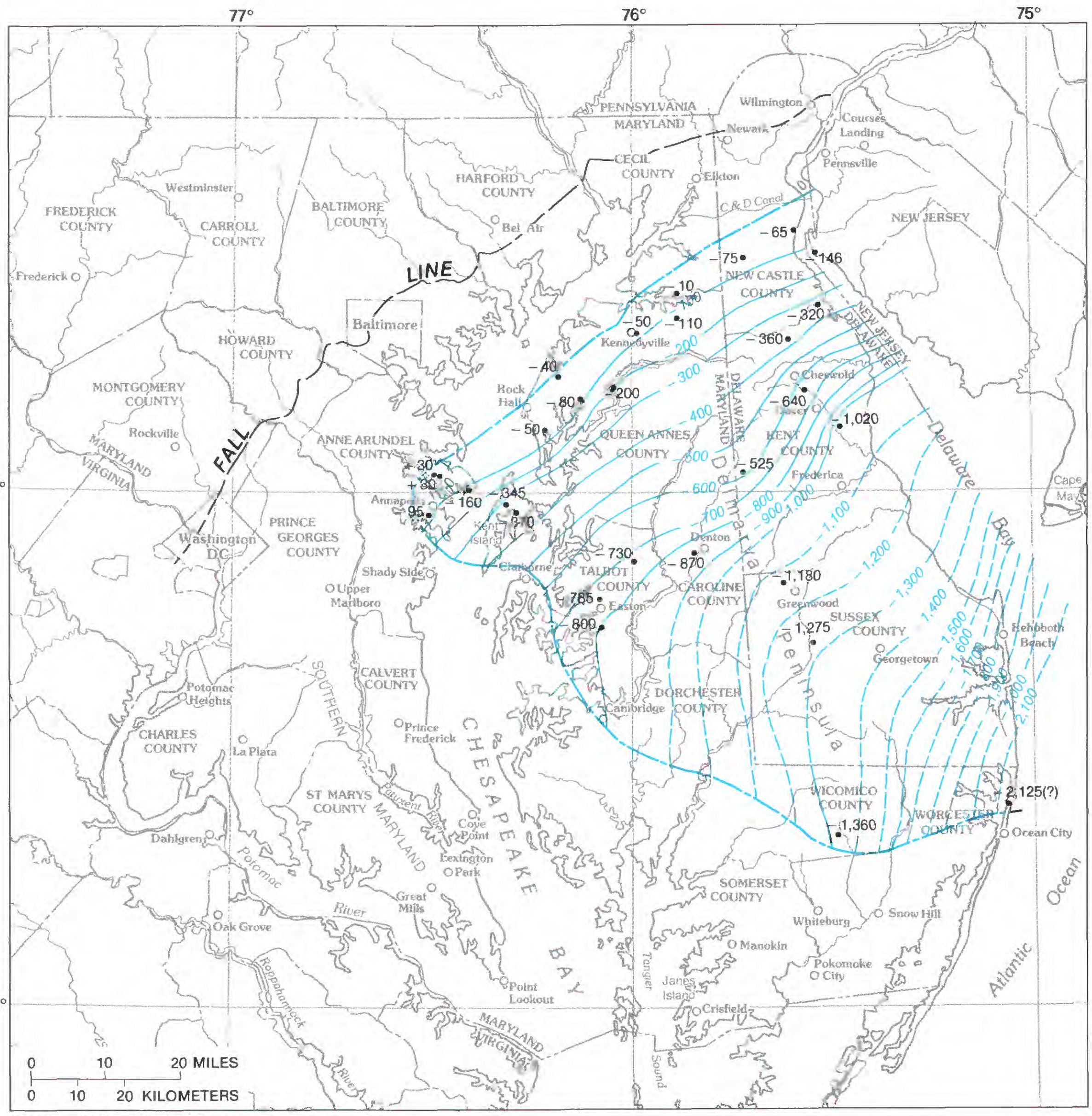
Aquifer definition.—The Brightseat aquifer is restricted to the southernmost part of the study area. It includes sediments that are located primarily in St. Marys County, Md., that earlier studies assigned to the Magothy aquifer (Hansen, 1972, p. 47; Weigle and Webb, 1970, p. 32). Palynological evidence from cores collected in St. Marys County suggests a possible Paleocene age for the sediments (Hansen and Wilson, 1984).[1] Hansen and Wilson (1984) tentatively assigned these beds to the Mattaponi(?) Formation, but they noted that these beds may be correlative with the Brightseat Formation (Bennett and Collins, 1952). In Somerset County, Md., the aquifer corresponds to a water-bearing sand body that Hansen (1967, fig. 5) has named the Paleocene(?) aquifer. The Brightseat aquifer extends southward into Virginia.

The Brightseat aquifer is bounded on the top by the upper Brightseat confining unit and on the bottom by the Patapsco confining unit. The Magothy, Matawan, and Severn aquifers, along with their respective confining units, are absent below the Brightseat aquifer. The Brightseat aquifer is probably absent north of Lexington Park (Hansen and Wilson, 1984). In this report, the lateral boundaries, as well as the contour lines showing the top of the Brightseat aquifer (fig. 18), are generalized in Maryland beyond the vicinities of Lexington Park, Great Mills, and Crisfield, because little is known about the extent and continuity of the aquifer. Moreover, the hydraulic continuity of the sediments in St. Marys County with those in Somerset County is uncertain.

Depositional history of the aquifer.—The sediments of the Brightseat aquifer were deposited as the marine transgression continued. Biostratigraphic evidence suggests that at least part of the sediment represents inner-shelf deposition in less than 65 ft of water (Hansen and Wilson, 1984).

Lithologic description.—In St. Marys County, the aquifer is composed of very fine to fine, light-gray to yellowish or purple quartzose sand and muscovite, lignite, and minor glauconite (Weigle and Webb, 1970, p 32). In Somerset County, it is characterized by poorly sorted, gray, very fine quartzose sand to fine gravel and

[1]Recent work on cores from two drill holes in southern Maryland and northern Virginia has identified fossil pollen and spores of late Early Cretaceous (Albian) age (Ronald Litwin, U.S. Geological Survey, written commun., 1987; D.J. Nichols, U.S. Geological Survey, written commun., 1985) in deposits designated "Brightseat aquifer" in this report.



Base from U.S. Geological Survey

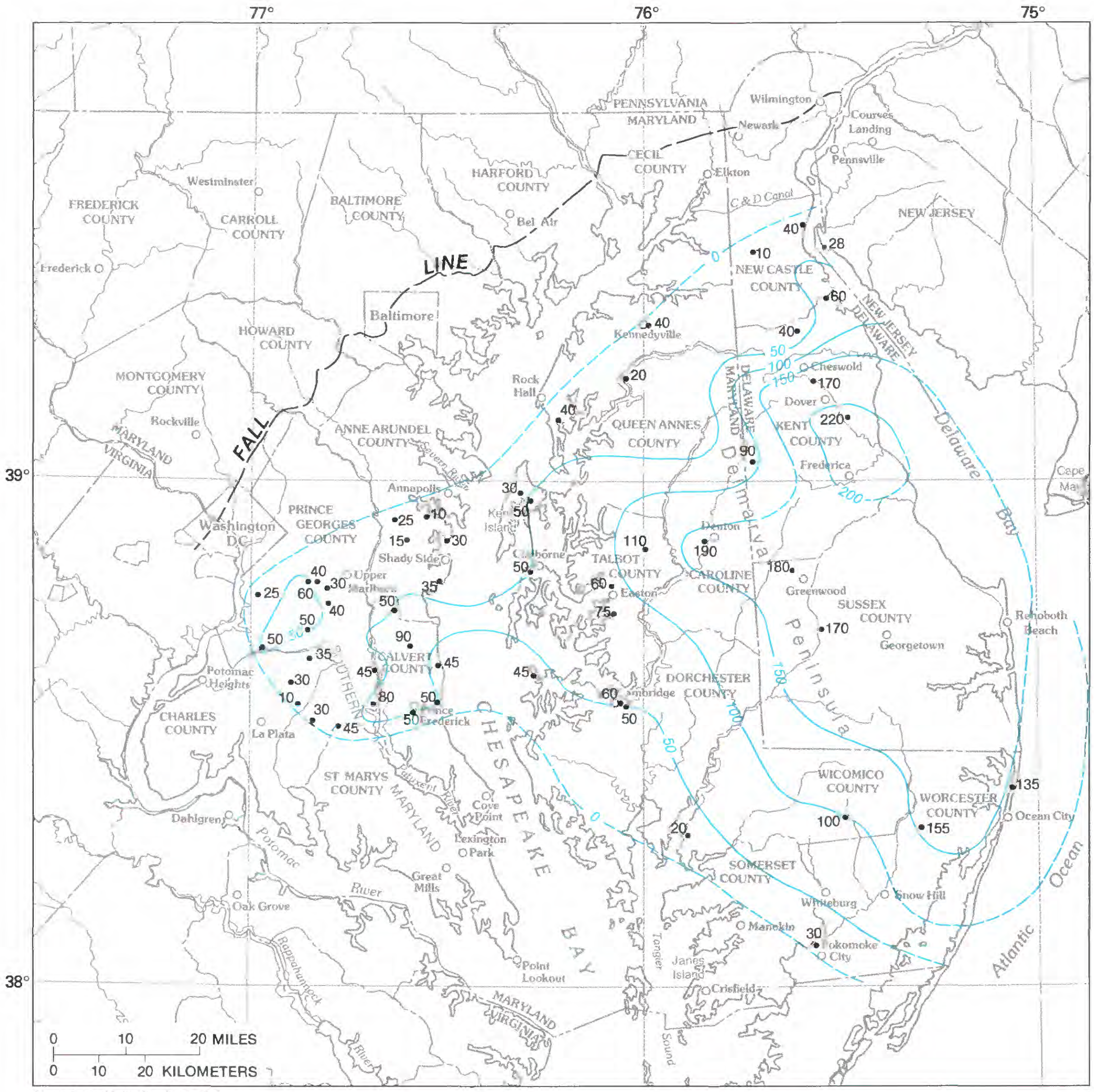
EXPLANATION

— 200 — STRUCTURE CONTOUR—Shows altitude of the top of the Severn aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

—·—·— APPROXIMATE BOUNDARY OF THE SEVERN AQUIFER

•-200 WELL—Number is altitude of the top of the Severn aquifer, in feet above or below sea level

FIGURE 16.—Altitude of the top of the Severn aquifer in the Coastal Plain of Maryland and Delaware.



Base from U.S. Geological Survey

EXPLANATION

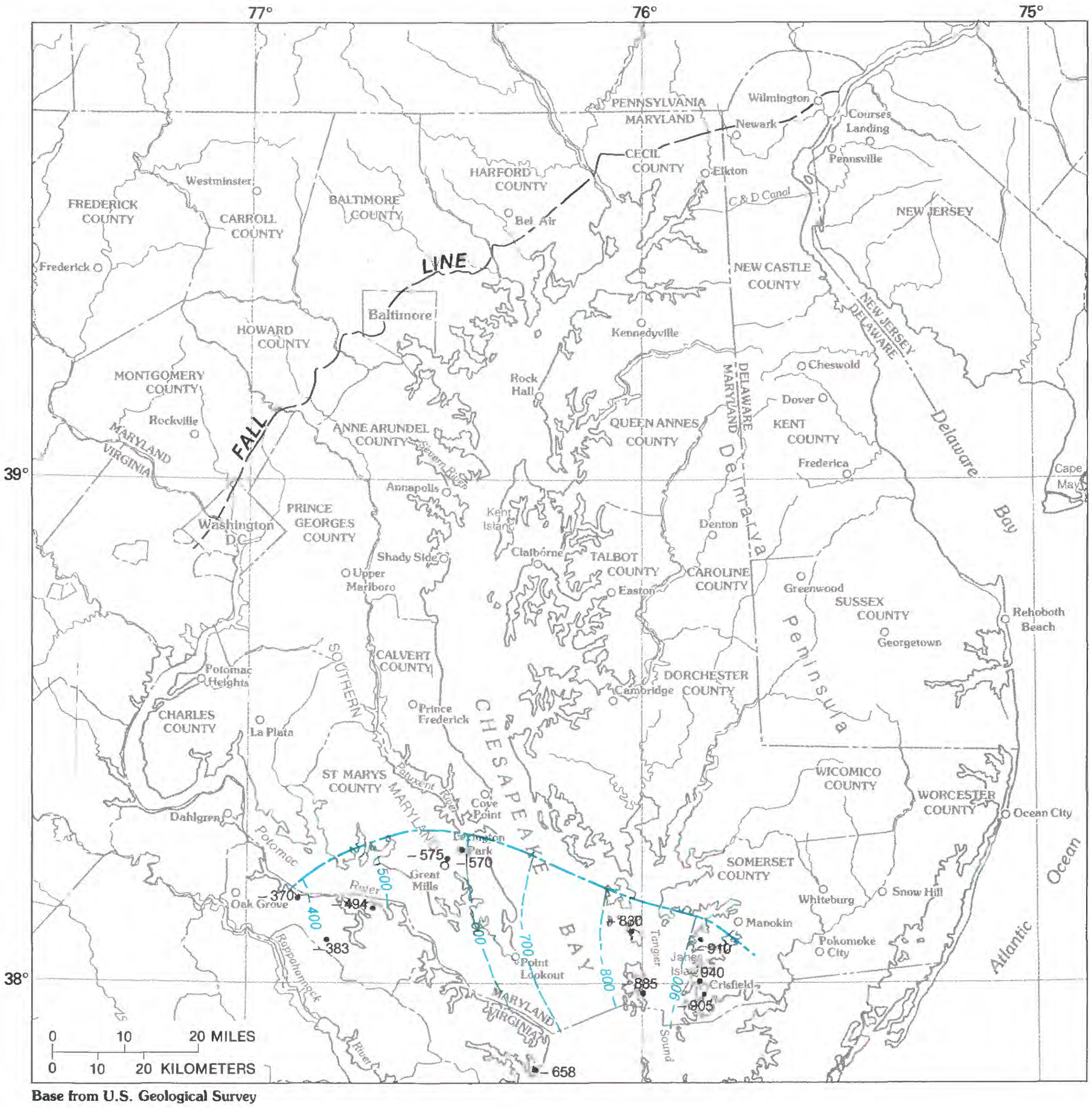
50 —— LINE OF EQUAL THICKNESS OF THE LOWER BRIGHTSEAT CONFINING UNIT—Dashed where inferred. Interval 50 feet

45 • WELL—Number is thickness of the lower Brightseat confining unit, in feet

FIGURE 17.—Thickness of the lower Brightseat confining unit in the Coastal Plain of Maryland and Delaware.

associated variegated green, black, and violet clay, lignite, and streaks of glauconite (Hansen, 1967, p. 11).

Aquifer characteristics.—At Lexington Park in St. Marys County, the aquifer consists of two sand bodies 30 ft thick and 42 ft thick that are separated by 42 ft of clayey material; transmissivity ranges from about 2,300 ft^2/d to about 2,700 ft^2/d. A storage coefficient of 0.0002 was estimated from the barometric efficiency of the aquifer (Hansen and Wilson, 1984, p. 1). The transmissivity of the aquifer in Somerset County has not been



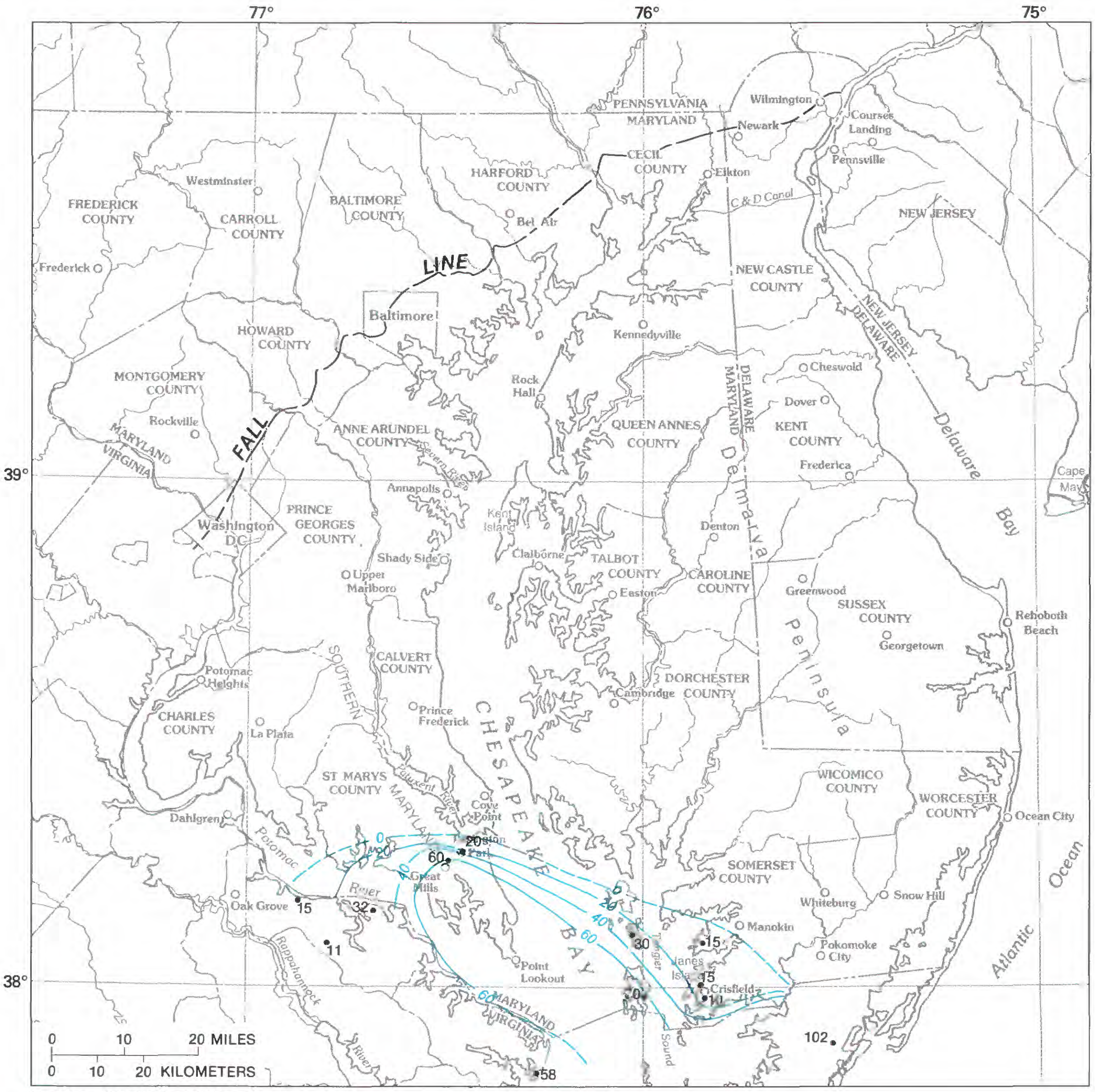
EXPLANATION

-600 — STRUCTURE CONTOUR—Shows altitude of the top of the Brightseat aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

— · — APPROXIMATE BOUNDARY OF THE BRIGHTSEAT AQUIFER

-940 • WELL—Number is altitude of the top of the Brightseat aquifer, in feet below sea level

FIGURE 18—Altitude of the top of the Brightseat aquifer in the Coastal Plain of Maryland.



Base from U.S. Geological Survey

EXPLANATION

40 — LINE OF EQUAL THICKNESS OF THE UPPER BRIGHTSEAT CONFINING UNIT—Dashed where inferred. Interval 20 feet

60• WELL—Number is thickness of the upper Brightseat confining unit, in feet

FIGURE 19.—Thickness of the upper Brightseat confining unit in the Coastal Plain of Maryland.

determined. Individual sand beds in Somerset County are about 5 to 15 ft thick (Hansen, 1967, p. 11).

The upper Brightseat confining unit.—The upper Brightseat confining unit, in what may be the upper part of the Brightseat Formation (Bennett and Collins, 1952), overlies the Brightseat aquifer. The thickness of the unit is shown in figure 19. Its limits are interpreted as being the same as those of the Brightseat aquifer.

The confining unit is composed of greenish-gray to black, glauconitic silt and clay, having interbedded glauconitic, fine-grained sand (Weigle and Webb, 1970, p. 32). It may represent a deeper marine environment of deposition than that of the Brightseat aquifer.

AQUIA-RANCOCAS AQUIFER AND NANJEMOY-MARLBORO CONFINING UNIT

Aquifer definition.—The Aquia-Rancocas aquifer is composed of the sandy portions of the Paleocene Aquia Formation in Maryland and the Paleocene Rancocas Group in Delaware. In places, it may include sandy portions of the underlying Brightseat Formation. The aquifer corresponds, in general, to the Aquia aquifer as mapped by Chapelle and Drummond (1983, p. 11) west of the Chesapeake Bay and to the Aquia-Rancocas aquifer as mapped by Cushing and others (1973, pl. 4) east of the Chesapeake Bay. It is bounded on the west by the updip limit of its outcrop and on the east by a facies change to predominantly clay. The aquifer extends northeastward into New Jersey and southward into Virginia. The configuration of the top of the aquifer is shown in figure 20.

Depositional history of the aquifer.—The Brightseat Formation marks the beginning of a regressive phase, which continued through the deposition of the Aquia-Rancocas aquifer (Hansen, 1971, p. 129). In most areas west of the Chesapeake Bay and in some areas east of the bay, the Aquia-Rancocas aquifer was apparently deposited in a nearshore, littoral to shallow marine environment. East of a line extending from north of Point Lookout, Md., to north of Dover, Del., sediments lithologically and stratigraphically correlative with the Aquia-Rancocas aquifer were deposited in a deeper marine environment (Hansen, 1971, p. 139) and are predominantly clay.

Lithologic description of the aquifer.—The Aquia-Rancocas aquifer is predominantly glauconitic and quartzose, medium- to coarse-grained, and medium- to well-sorted sand (Chapelle and Drummond, 1983, p. 7). Carbonate shell material typically constitutes 1 to 5 percent of the aquifer material but locally may be up to 20 percent (Chapelle and Drummond, 1983, p. 7).

Aquifer characteristics.—The areas having highest transmissivity in the Aquia-Rancocas aquifer extend roughly parallel to regional strike. Transmissivity decreases southward (Hansen, 1971, p. 139). The maximum reported transmissivity is in southern Queen Annes and northern Talbot Counties, Md., where values of 5,100 and 3,300 ft^2/d, respectively, are attained (Chapelle and Drummond, 1983, p. 13). Reported storage-coefficient values in the aquifer range from 0.0001 to 0.0004 (Hansen, 1972, p. 74–75).

The transmissivity decreases significantly in a downgradient direction southeastward across the facies change. In St. Marys County, for example, the aquifer is a ground-water source for public supply at Great Mills, but the sediments are not sandy enough to be an aquifer at Point Lookout, which is approximately 15 mi downdip. A similar situation is present at Easton (updip) and Cambridge (downdip), Md. (Hansen, 1972, p. 67).

Along the outcrop, typical thicknesses of the Aquia-Rancocas aquifer range from 90 ft near the Potomac River to about 150 ft in Anne Arundel County (Chapelle and Drummond, 1983). Subsurface thicknesses increase toward the northeast and decrease toward the southwest (Chapelle and Drummond, 1983, p. 7).

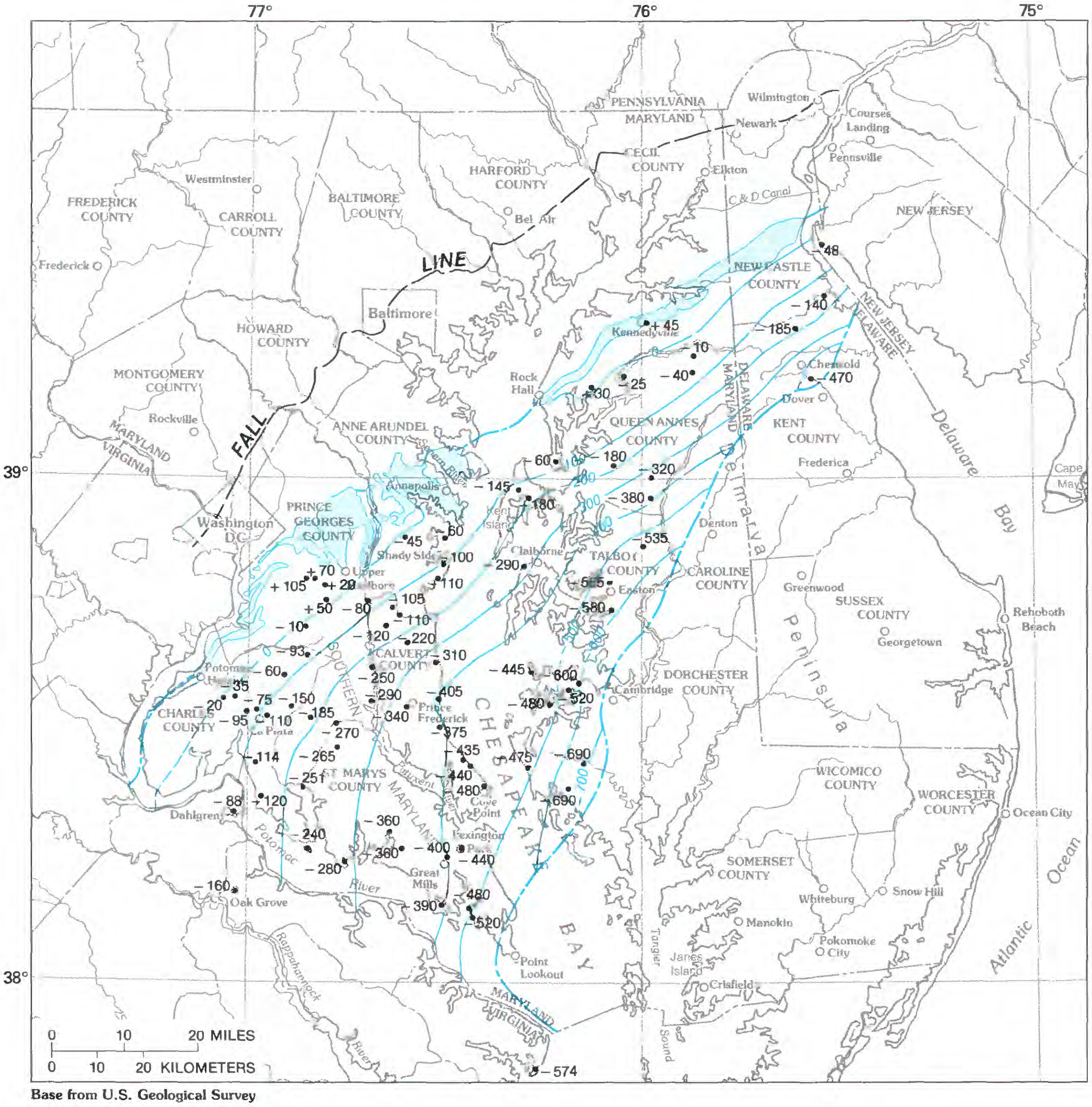
The Nanjemoy-Marlboro confining unit.—The Nanjemoy-Marlboro confining unit is typically the clayey material between the sharp upper contact of the Aquia-Rancocas aquifer and the gradational lower contact of the Piney Point-Nanjemoy aquifer. In areas where the Piney Point and underlying Nanjemoy Formations of Eocene age do constitute an aquifer, the confining unit is defined by an arbitrary assignment of clayey material between two or more confining beds. The thickness is shown in figure 21.

The fluviomarine Marlboro Clay, a reddish-brown to pink or gray clay of Paleocene and Eocene age (Reinhardt, Newell, and Mixon, 1980, p. 22–25), constitutes part of the Nanjemoy-Marlboro confining unit. In updip areas, the Marlboro directly overlies the Aquia-Rancocas sediments and marks the end of the regressive sequence that was initiated with deposition of the Brightseat Formation (Hansen, 1971, p. 130).

A rapid marine transgression followed deposition of the Marlboro Clay and is indicated by the clay and silt beds of the overlying basal Nanjemoy Formation (Hansen, 1974, p. 129) of Eocene age (Shifflet, 1948). The Nanjemoy Formation coarsens upward; this coarsening indicates reversal of the transgression and progressive shallowing of the sea. In Calvert and St. Marys Counties, the upper part of the Nanjemoy Formation becomes sandy enough to function as a low-yield aquifer (Otton, 1955, p. 83). Elsewhere, the sediments are olive-green silty clay and function as a part of the Nanjemoy-Marlboro confining unit.

PINEY POINT-NANJEMOY AQUIFER AND LOWER CHESAPEAKE CONFINING UNIT

Aquifer definition.—The Piney Point-Nanjemoy aquifer (fig. 22) corresponds, in general, to the Piney Point aquifer mapped by Cushing and others (1973, pl. 5) east of the Chesapeake Bay and to the Piney Point-Nanjemoy aquifer mapped by Chapelle and Drummond (1983, p. 25) west of the bay. The aquifer includes sandy parts of both the Eocene Nanjemoy Formation and the overlying Eocene Piney Point Formation. Although the two



EXPLANATION

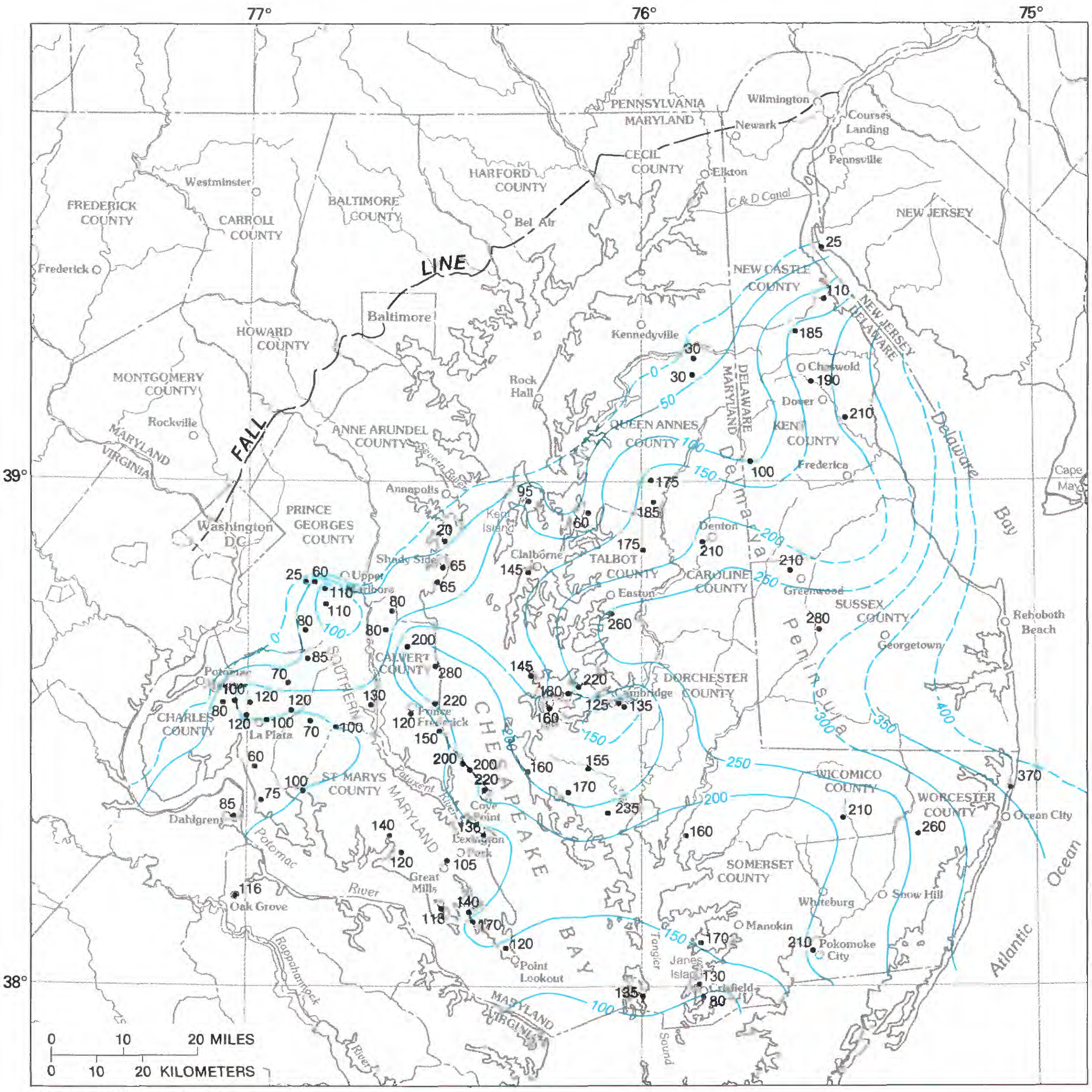
OUTCROP AREA OF THE AQUIA-RANCOCAS AQUIFER

– 200 STRUCTURE CONTOUR—Shows altitude of the top of the Aquia-Rancocas aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

APPROXIMATE BOUNDARY OF THE AQUIA-RANCOCAS AQUIFER

–60 WELL—Number is altitude of the top of the Aquia-Rancocas aquifer, in feet above or below sea level

FIGURE 20.—Altitude of the top of the Aquia-Rancocas aquifer in the Coastal Plain of Maryland and Delaware.



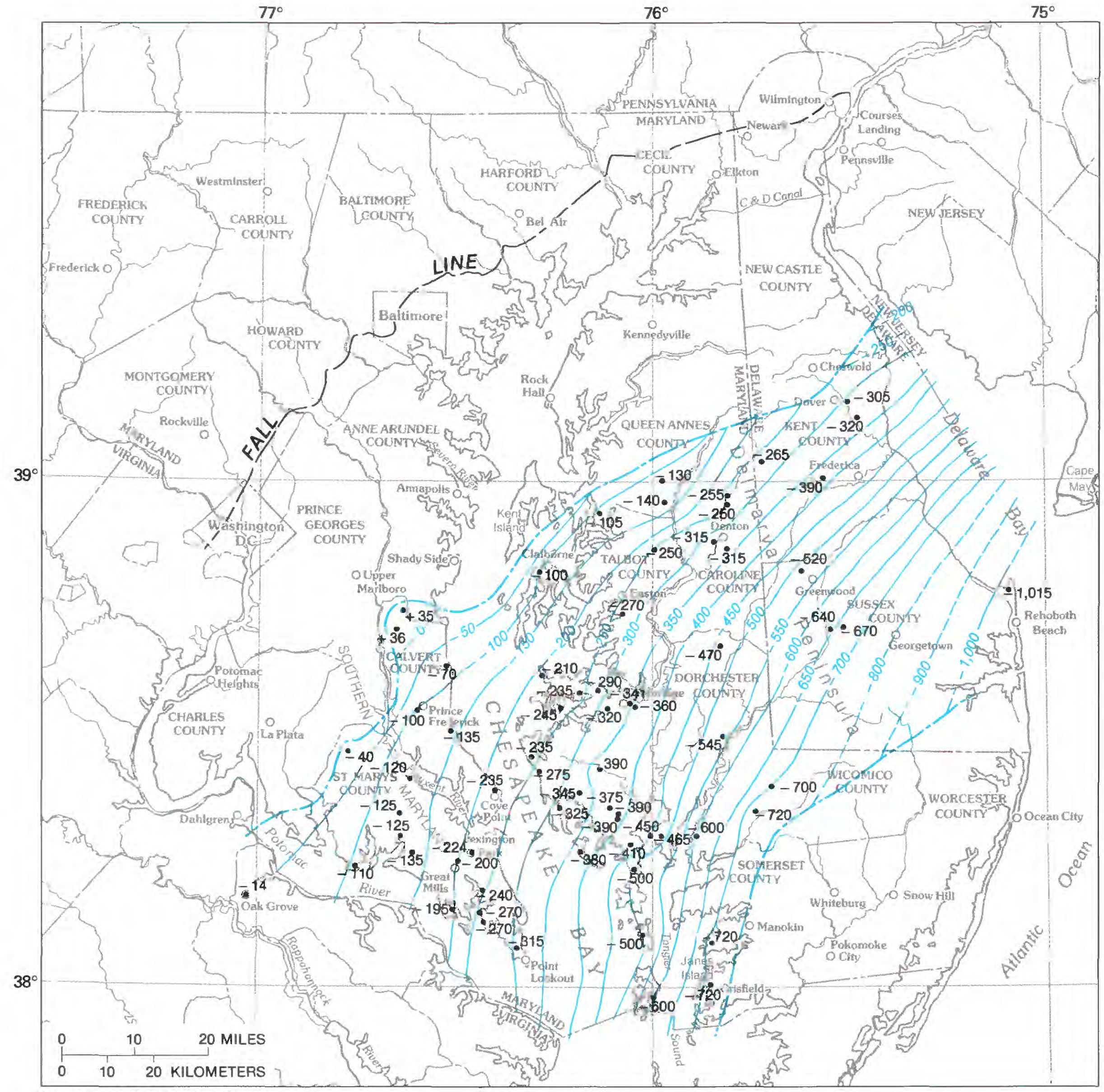
EXPLANATION

200 — LINE OF EQUAL THICKNESS OF THE NANJEMOY-MARLBORO CONFINING UNIT—Dashed where inferred. Intervals 50 and 100 feet

145 • WELL—Number is thickness of the Nanjemoy-Marlboro confining unit, in feet

FIGURE 21.—Thickness of the Nanjemoy-Marlboro confining unit in the Coastal Plain of Maryland and Delaware.

formations are lithologically and paleontologically distinct (Otton, 1955, p. 79–88), Piney Point sand directly overlies the upper sandy part of the Nanjemoy Formation in many places (Williams, 1979, p. 11); this position suggests that the two sands act hydraulically as a single aquifer (Chapelle and Drummond, 1983, p. 23; Weigle and others, 1970). The western boundary of the aquifer is a subsurface truncation of the sand, and the eastern boundary is a facies change to increasing amounts of clay (Leahy, 1979, p. 7–8). The aquifer extends northward



Base from U.S. Geological Survey

EXPLANATION

– 200 — STRUCTURE CONTOUR—Shows altitude of the Piney Point-Nanjemoy aquifer. Dashed where inferred. Intervals 50 and 100 feet. Datum is sea level

APPROXIMATE BOUNDARY OF THE PINEY POINT-NANJEMOY AQUIFER

–100 WELL—Number is altitude of the top of the Piney Point-Nanjemoy aquifer, in feet above or below sea level

FIGURE 22.—Altitude of the top of the Piney Point-Nanjemoy aquifer in the Coastal Plain of Maryland and Delaware.

into New Jersey and southward into Virginia. It is bounded above by the lower Chesapeake confining unit and below by the Nanjemoy-Marlboro confining unit.

Depositional history.—The marine regression that began with the Nanjemoy Formation continued through deposition of the Piney Point Formation (Hansen, 1972, p. 129). The sediments were laid down in sublittoral to shallow neritic environments (Hansen, 1971, p. 139). The updip portion represents above-wave-base deposition, and the downdip portion, as defined by a major facies change, represents below-wave-base deposition (Hansen, 1971, p. 139).

As the regression continued during Oligocene and Miocene time, parts of the Piney Point Formation in updip areas were eroded and removed. Oligocene beds do not crop out in the Coastal Plain of Maryland, and their subsurface extent has not been determined.[2] During the middle Miocene, a marine transgression deposited the Miocene Calvert Formation of the Chesapeake Group on top of the truncated Piney Point Formation. Thus, the Piney Point Formation does not crop out in Maryland or Delaware.

Lithologic description of the aquifer.—The Piney Point-Nanjemoy aquifer is an upward coarsening sequence of greenish-gray to grayish-white, medium- to coarse-grained, slightly glauconitic quartz sand, interbedded beds of calcite-cemented sand, and shell beds. Glauconite generally constitutes less than 5 percent of the aquifer material (Chapelle and Drummond, 1983, p. 11-12). The sand becomes increasingly coarse toward the top of the aquifer.

The Piney Point and Nanjemoy Formations can be differentiated by the lack of indurated light-colored layers in the Nanjemoy Formation. The Piney Point Formation also contains less clay and glauconite than does the Nanjemoy Formation.

Aquifer characteristics.—Because the Piney Point-Nanjemoy aquifer does not crop out in Maryland or Delaware, all of its recharge consists of leakage from other aquifers through confining units. The aquifer is about 90 ft thick in eastern St. Marys County, and it thickens northeastward and attains a thickness of 251 ft in Greenwood, Kent County, Del. (Hansen, 1971, p. 141; Leahy, 1982, p. 9). The upper part of the aquifer is the most productive zone because of the upward coarsening of the sediment. Reported transmissivity values are generally in the range of 1,200 to 6,000 ft^2/d (Cushing and others, 1973, p. 43), having values up to 7,350 ft^2/d near Dover, Del. (Leahy, 1979, p. 39). Storage coefficients range from 0.0003 to 0.0004 (Chapelle and Drummond 1983, p. 23).

The lower Chesapeake confining unit.— The lower Chesapeake confining unit consists of the silt, clay, fine sand, and diatomaceous earth between the Piney Point-Nanjemoy aquifer and the overlying lower Chesapeake aquifer. It consists of clay and minor sand overlying the Piney Point-Nanjemoy and Aquia-Rancocas aquifers beyond the updip limit of the lower Chesapeake aquifer. In eastern Maryland, the confining unit typically consists of clayey beds of the lowermost part of the Miocene Chesapeake Group (Otton, 1955, p. 90–95). West of the Chesapeake Bay, it includes Nanjemoy and stratigraphically lower strata, as well as younger clayey beds of the Chesapeake Group that Williams (1979, fig. 9) suggested are stratigraphic equivalents of aquifers to the east. The thickness of the lower Chesapeake confining unit is shown in figure 23.

LOWER CHESAPEAKE AQUIFER AND ST. MARYS CONFINING UNIT

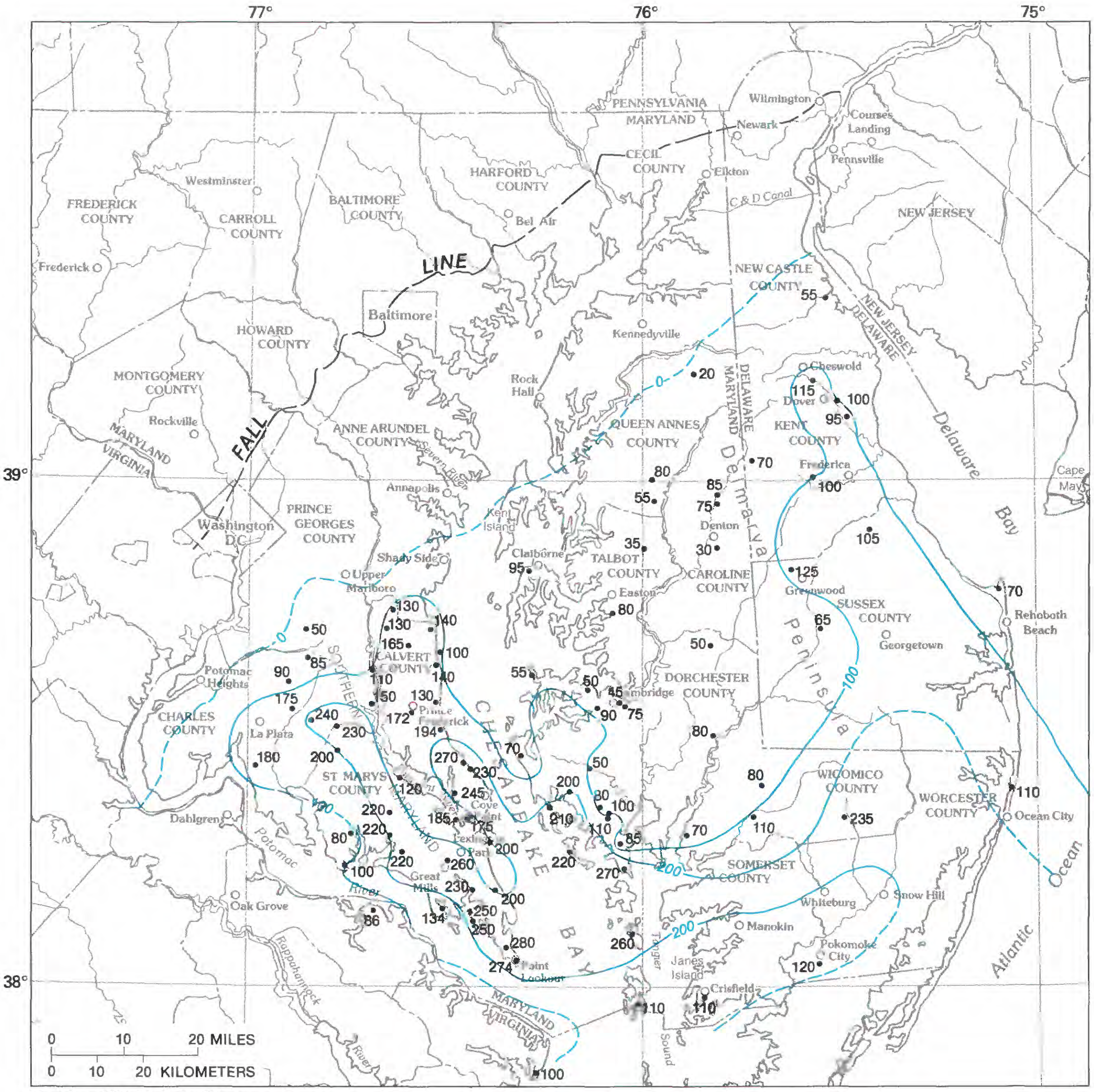
Aquifer definition.—The lower Chesapeake aquifer (fig. 24) is that part of the Miocene Calvert and Choptank Formations in the Chesapeake Group that is sandy enough to function as an aquifer. Three major sand bodies can be differentiated (Cushing and others, 1973). Listed in ascending order, they are the Cheswold aquifer, the Federalsburg aquifer, and the Frederica aquifer. In this report, the Cheswold, Federalsburg, and Frederica aquifers are considered as a single hydrologic unit constituting the lower Chesapeake aquifer.

The eastward limit of fresh ground-water flow in the lower Chesapeake aquifer is assumed to be the 10,000-mg/L isochlor, which is outside of the area of investigation. East of the Chesapeake Bay, the updip boundary of the aquifer is the updip limit of the Cheswold.

The subcrop zone shown in figure 24 is an area where the aquifer sand is directly overlain by sand of the surficial aquifer. The zone is a combination of the subcrops of the Cheswold and the Frederica aquifers. Locations of the individual subcrop areas of the Cheswold and Frederica aquifers can be found in Sundstrom and others (1976, p. 11). Downdip from the subcrop zone, the lower Chesapeake aquifer is overlain by the St. Marys confining unit. The aquifer extends northward into New Jersey as the Kirkwood aquifer and southward into Virginia as the St. Marys-Choptank aquifer.

Depositional history of the aquifer.—Small quartz pebbles in the basal sands of the Calvert Formation suggest a nearshore origin (Dryden and Overbeck, 1948, p. 53). The remainder of the Calvert Formation and the overlying Choptank and St. Marys Formations were deposited in a marine environment (Cooke, Martin, and

[2]Since this report was prepared, the Old Church Formation (a new unit) of the latest Oligocene and earliest Miocene age has been assigned to the base of the Chesapeake Group in the subsurface of Maryland and possibly Delaware (Ward, 1986).



Base from U.S. Geological Survey

EXPLANATION

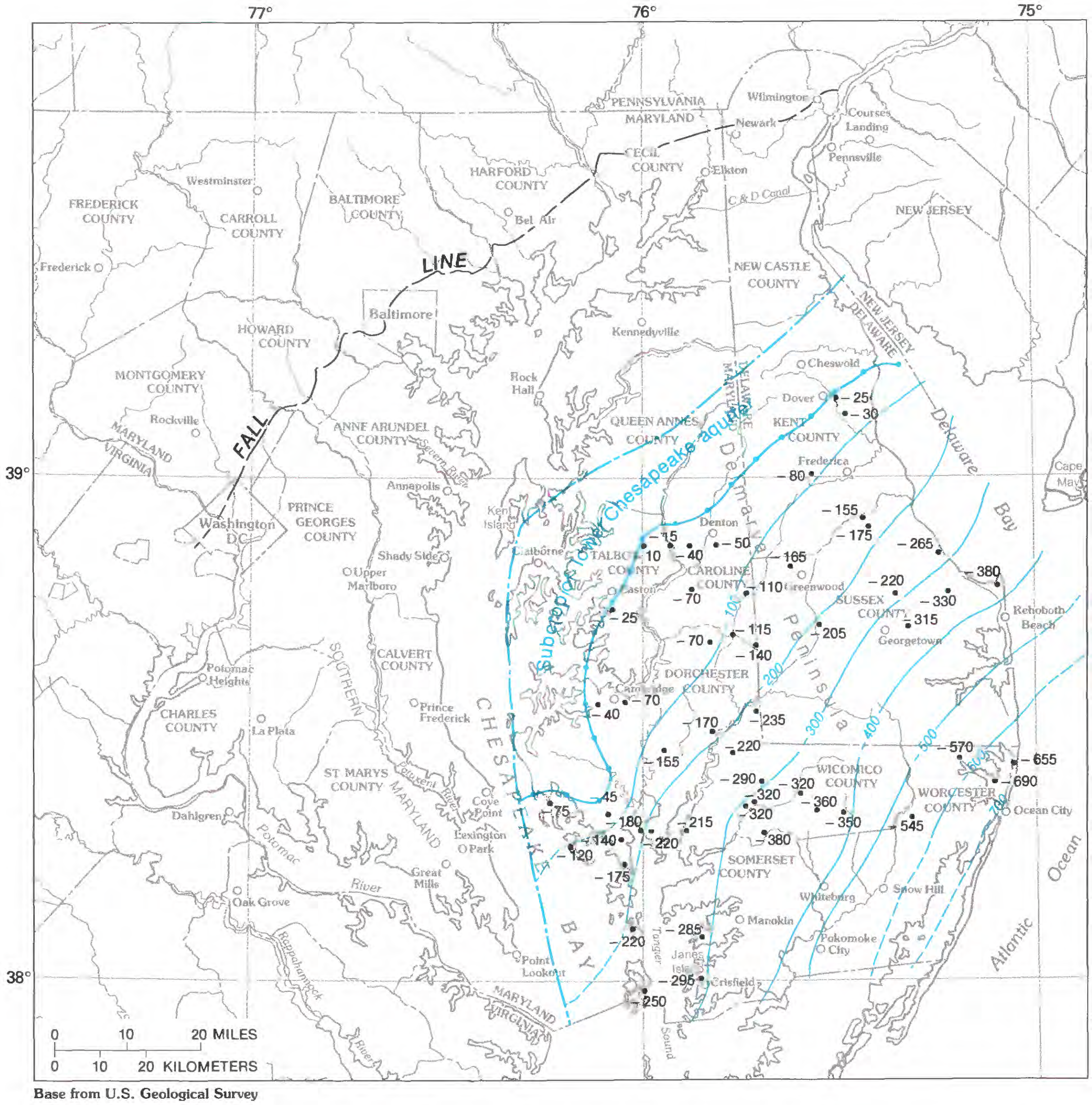
—— *100* – – – – LINE OF EQUAL THICKNESS OF THE LOWER CHESAPEAKE CONFINING UNIT—Dashed where inferred. Interval 100 feet

130• WELL—Number is thickness of the lower Chesapeake confining unit, in feet

FIGURE 23.—Thickness of the lower Chesapeake confining unit in the Coastal Plain of Maryland and Delaware.

Meyer, 1952, p. 34) and reflect minor transgression-regression cycles (Gibson, 1962, p. 66–70).

Lithologic description of the aquifer.—The sediments of the lower Chesapeake aquifer consist of medium to coarse silty sand and clay having locally abundant shells. The aquifer can be differentiated from the underlying glauconitic Piney Point-Nanjemoy aquifer by the virtual absence of glauconite. However, it is difficult to distinguish the lower Chesapeake aquifer from the overlying surficial aquifer in subcrop areas because of similar



Base from U.S. Geological Survey

EXPLANATION

– 200 — — — STRUCTURE CONTOUR—Shows altitude of the top of the lower Chesapeake aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

APPROXIMATE BOUNDARY OF THE LOWER CHESAPEAKE AQUIFER

DOWNDIP LIMIT OF SUBCROP AREA OF THE LOWER CHESAPEAKE AQUIFER (Sundstrom and Pickett, 1968)

–•320 WELL—Number is altitude of the top of the lower Chesapeake aquifer, in feet below sea level

FIGURE 24.—Altitude of the top of the lower Chesapeake aquifer in the Coastal Plain of Maryland and Delaware.

lithologies, although the lower Chesapeake aquifer sediments have been reported to be grayer and better sorted (Sundstrom and Pickett, 1969, p. 17-20).

Aquifer characteristics.—The lower Chesapeake aquifer is a multilayer aquifer. In Delaware, most of the sand is contained in two major sand bodies—the Cheswold and the Frederica aquifers. Locally, as in Kent County, Del. (Sundstrom and Pickett, 1968, p. 20–26), the interfingering of minor subsurface sand beds makes determining the exact boundaries of individual sand layers difficult.

Another sand body within the lower Chesapeake aquifer, generally thinner and not as laterally extensive as the Cheswold and Frederica aquifers, is the Federalsburg aquifer, which lies between the Cheswold and Frederica aquifers and is generally separated from the two by silt and clay layers. In many places, the separation is so thin that all three aquifers may act as a single hydrologic unit (Cushing and others, 1973, p. 44).

Reported transmissivities range from 200 to 4,000 ft^2/d in the Cheswold aquifer and from 450 to 1,400 ft^2/d in the Federalsburg aquifer. Transmissivity, determined from a pump test in one location (Cushing and others, 1973, p. 45), is about 1,400 ft^2/d in the Frederica aquifer. Storage coefficients are reported to range from 0.0001 to 0.006 in the Cheswold and from 0.0001 to 0.003 in the Federalsburg, although they may reach 0.15 in updip areas where the Federalsburg is unconfined. No storage coefficient for the Frederica aquifer is available. In the most productive areas, the Cheswold and the Frederica aquifers attain a thickness of 150 ft, and the Federalsburg aquifer attains a thickness of 100 ft (Cushing and others, 1973, p. 43–45). However, individual sand layer thicknesses of 40 ft to less than 10 ft are more common over most of the aquifer area.

The St. Marys confining unit.—The St. Marys confining unit (fig. 25), which overlies the lower Chesapeake aquifer, is composed of gray clay, clayey silt, and very fine sand of the Miocene St. Marys Formation in the middle part of the Chesapeake Group. The contact of the St. Marys confining unit with the lower Chesapeake aquifer shows as a sharp peak on gamma logs from wells in Snow Hill, Whiteburg, and Rehoboth, Md; this peak may be indicative of phosphate accumulation due to an interval of nondeposition prior to St. Marys sedimentation (Hansen, 1981b, p. 126). Biostratigraphic data suggest that the St. Marys Formation was deposited on a shoaling midshelf, possibly during a climatic shift from subtropical to temperate climate (Hansen, 1981b, p. 128). Although the St. Marys Formation is reported to yield small quantities of water to wells in Calvert and St. Marys Counties (Otton, 1955, p. 98–99), it acts as a confining unit over most of its range. The St. Marys Formation coarsens upward into the overlying so-called Yorktown and Cohansey(?) Formations (Rasmussen and Slaughter, 1955).

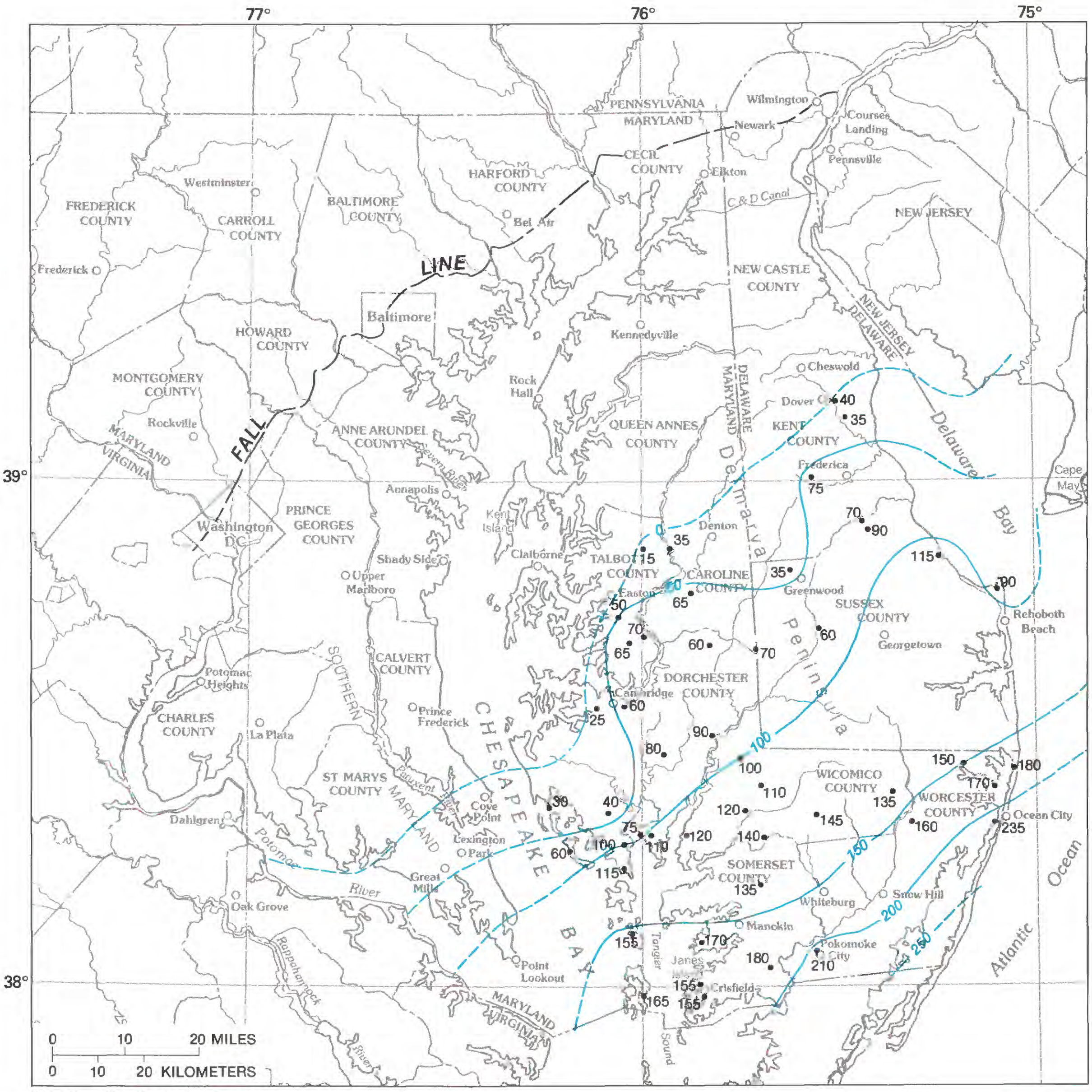
UPPER CHESAPEAKE AQUIFER AND UPPER CHESAPEAKE CONFINING UNIT

Aquifer definition.—The sediments composing the upper Chesapeake aquifer, in the upper part of the Chesapeake Group, were mapped by Rasmussen and Slaughter (1955, p. 93) as the Yorktown and Cohansey(?) Formations undivided. Later investigations have shown that these sediments are not correlative with the recognized Yorktown Formation toward the south. The stratigraphy of the upper Chesapeake sediments remains unclear; however, at least part of the aquifer in Wicomico and Somerset Counties is composed of sediments of the Eastover Formation (Ward and Blackwelder, 1980, p. D17). The extent of Eastover sediments in Maryland is not known.

The upper Chesapeake aquifer contains three major sand bodies. They are, from lowermost to uppermost, the Pocomoke aquifer, the Ocean City aquifer, and the Manokin aquifer (Weigle, 1974, p. 31–33; Hansen, 1981b). However, on a regional scale, the Pocomoke, Ocean City, and Manokin aquifers can be considered to be a single hydrologic unit—the upper Chesapeake aquifer. This complex aquifer system, the area where the upper Chesapeake aquifer directly underlies the surficial aquifer (fig. 26), in this report, includes the subcrop areas of the Pocomoke and Manokin aquifers (Sundstrom and Pickett, 1970, p. 8; Maryland State Planning Department, 1969, maps 8 and 9). Some sand at Greenwood, Del., which may be correlative with the Manokin aquifer (Talley, 1975, p. 26), is also included. The top of the upper Chesapeake aquifer (fig. 26) outside the subcrop area conforms to the top of the Pocomoke aquifer as mapped by Cushing and others (1973, pl. 10).

Depositional history of the aquifer.—Rasmussen and Slaughter (1955, p. 43) suggested that their Yorktown and Cohansey(?) Formations, now considered to be of Pliocene and Miocene age, respectively, were laid down in a shallow marine to deltaic or estuarine environment similar to that of the Magothy Formation. However, unlike the Magothy Formation, the so-called Yorktown Formation is part of a regressive sequence. The distribution of transmissivity suggests that some of the Yorktown's deposition was by consequent streams (Hansen, 1971, p. 131, 144). Minor transgressions and regressions resulted in a complex interfingering of sand and clay.

Lithologic description of the aquifer.—The water-bearing zones that make up the upper Chesapeake aquifer are described as follows. The Pocomoke aquifer consists of gray, fine- to medium-grained sand and some



Base from U.S. Geological Survey

EXPLANATION

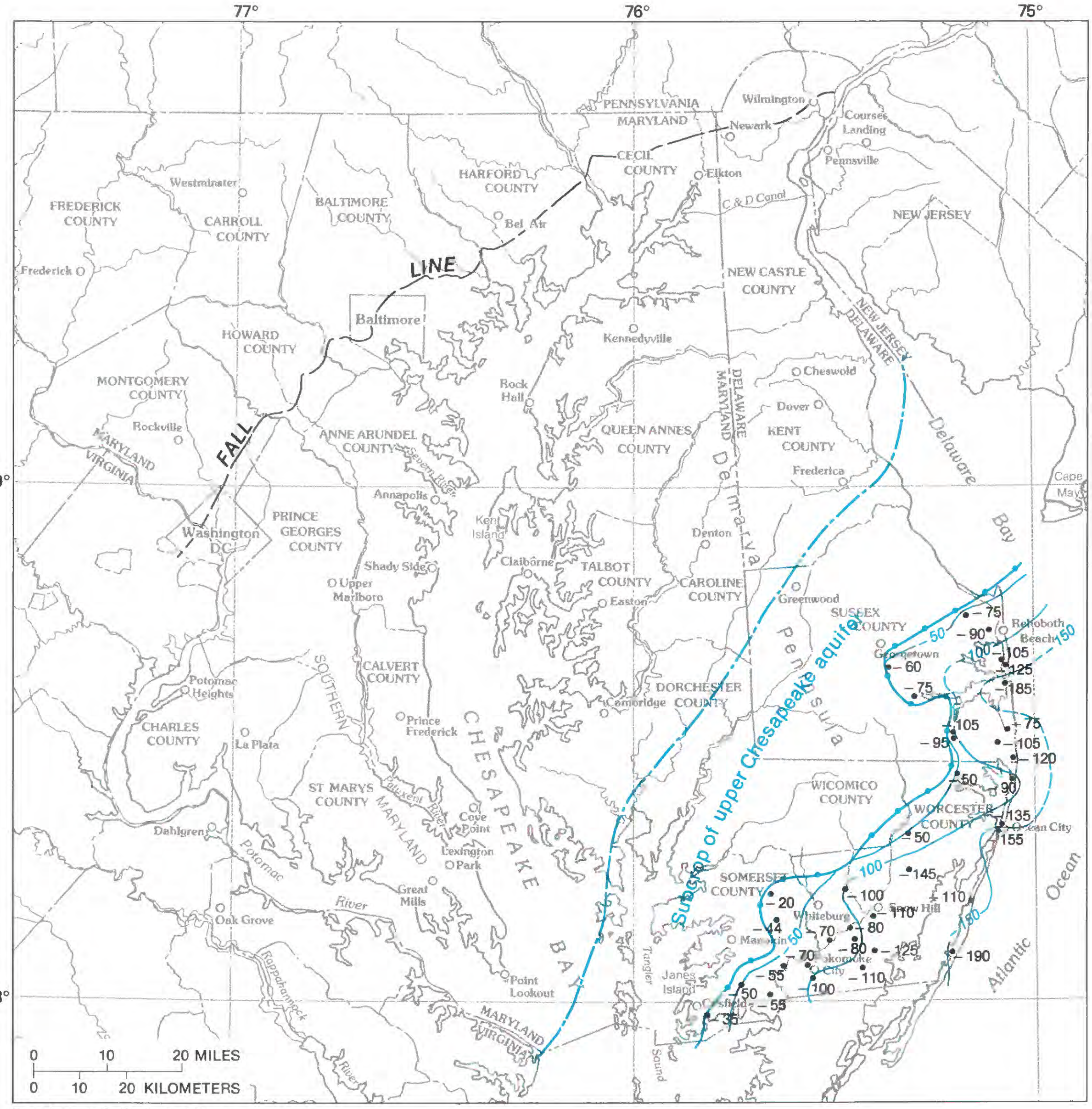
100 —— LINE OF EQUAL THICKNESS OF THE ST. MARYS CONFINING UNIT—Dashed where inferred. Interval 50 feet

90• WELL—Number is thickness of the St. Marys confining unit, in feet

FIGURE 25.—Thickness of the St. Marys confining unit in the Coastal Plain of Maryland and Delaware.

interbedded silt and clay. The Manokin aquifer is composed of the same general material and may contain coarse sand and pea-sized gravel in basal units. The Pocomoke and Manokin aquifers are separated by a sequence of clay, silt, and fine sand, ranging in thickness from 20 to 50 ft in Delaware (Miller, 1971, p. 14, 16). The Ocean City aquifer is composed of fine to coarse, light-gray, quartzose sand and occasional fine gravel (Hodges, 1984, p.15).

Aquifer characteristics.—The interfingering of sand and clay results in a multilayer system. The Pocomoke and Ocean City aquifers are well defined in Maryland in



Base from U.S. Geological Survey

EXPLANATION

— —100 — — STRUCTURE CONTOUR—Shows altitude of the top of the upper Chesapeake aquifer. Dashed where inferred. Contour interval 50 feet. Datum is sea level

—·—·— APPROXIMATE BOUNDARY OF THE UPPER CHESAPEAKE AQUIFER

—•—•— APPROXIMATE DOWNDIP LIMIT OF THE SUBCROP AREA OF THE UPPER CHESAPEAKE AQUIFER (Sundstrom and Pickett, 1969, 1970; Maryland State Planning Department, 1969)

•−145 WELL—Number is altitude of the top of the upper Chesapeake aquifer, in feet below sea level

FIGURE 26.—Altitude of the top of the upper Chesapeake aquifer in the Coastal Plain of Maryland and Delaware.

the cities after which they are named. Elsewhere, interbedding makes correlation difficult. The Pocomoke and Manokin aquifers tend to coarsen upward and have more permeable sand occurring in the upper part of the section (Hansen, 1972, p. 92). Abundant facies changes, unconformities, and pinchouts make delineation of transmissivity tracts difficult; however, scattered data suggest that a tract of high transmissivity extends southeastward across Wicomico and Worcester Counties, normal to the depositional strike (Hansen, 1971, p. 144). Reported values for transmissivity range from 2,500 to 10,000 ft^2/d for the Manokin aquifer, from 2,500 to 7,500 ft^2/d for the Ocean City aquifer, and from 200 to 8,000 ft^2/d for the Pocomoke aquifer (Miller, 1971, p. 18 and 20; Weigle and Achmad, 1982, p. 18–19). Weigle and Achmad (1982, p. 18 and 22) reported the storage coefficients of the Pocomoke and Manokin aquifers to range from 0.00009 to 0.00012 in Maryland and the average storage coefficient for the Ocean City aquifer to be approximately 0.00009.

The Pocomoke and Manokin aquifers subcrop beneath the surficial aquifer at their extreme updip limit and dip southeastward beneath the upper Chesapeake confining unit. Computer simulations of the Pocomoke and Manokin aquifers suggest that the confining unit between them is characterized by substantial leakage (Weigle and Achmad, 1982, p. 11). The high rate of leakage supports the assumption that the individual sand bodies separated by interbedded silt and clay function as a single hydrologic unit.

The upper Chesapeake confining unit.—The upper Chesapeake confining unit (fig. 27), in the uppermost part of the Chesapeake Group, is a discontinuous unit of lenticular silt, clay, and fine sand separating the Upper Chesapeake aquifer from the overlying surficial aquifer downdip from the subcrop area. Vertical leakage through the confining unit is highly variable (Weigle and Achmad, 1982, p. 7).

SURFICIAL AQUIFER

Aquifer definition.—The surficial aquifer is composed of a veneer of Upper Miocene to Holocene age sediments that mantle Cretaceous and older Tertiary sediment in Maryland and Delaware. In this report, the aquifer is bounded on the west by the Aquia-Rancocas aquifer outcrop. Although Quaternary sediments occur farther west, they are, in general, too discontinuous to provide significant quantities of water.

The part of the surficial aquifer east of the Chesapeake Bay has previously been called the Columbia aquifer (Bachman, 1984), the Quaternary aquifer (Cushing and others, 1973), the Pleistocene aquifer (Sundstrom and Pickett, 1970), and the Salisbury aquifer (Boggess and Heidel, 1968). West of the Chesapeake Bay, the aquifer is composed primarily of Quaternary and possibly Tertiary sediments from what Bennett and Meyer (1952, p. 68) called upland and lowland deposits. The upland deposits are those that lie higher than about 40 ft above sea level, and the lowland deposits are those that lie below about 40 ft above sea level.

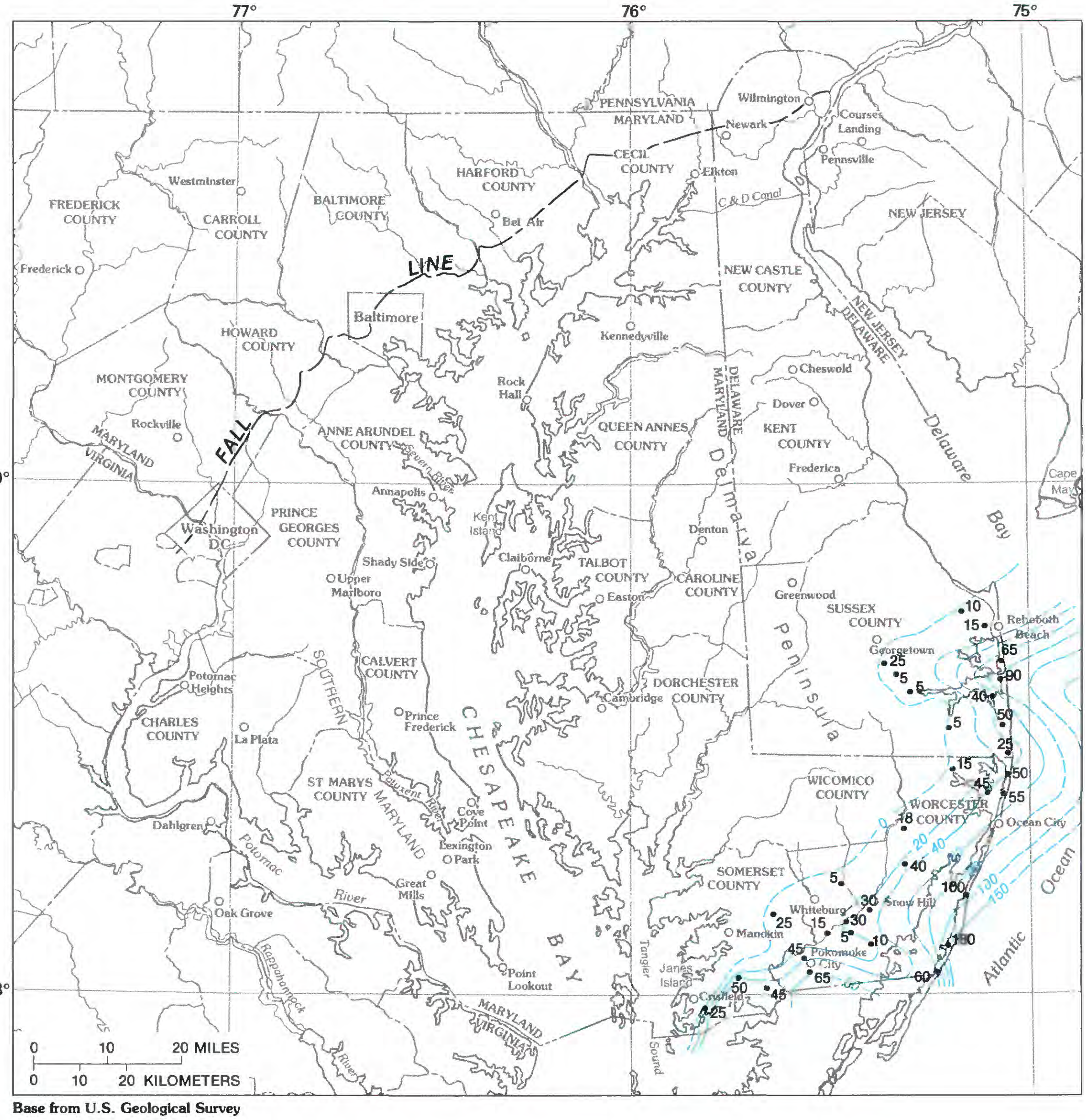
The top of the surficial aquifer, which is the water table, and the areal extent of the aquifer are shown in figure 28. Contours east of the Chesapeake Bay were taken from Cushing and others (1973) and Bachman (1984). West of the bay, the configuration of the water table is more uncertain because of the limited data available. The configuration of the water table in the west is largely based on the intersection of topographic-map contour lines with streams and is modified to include some water-level measurements from Otton (1955).

Depositional history of the aquifer.—Most investigators, including Rasmussen and Slaughter (1955, p. 108–119), Jordan (1964), and Hansen (1981b), regard the eastern part of the surficial aquifer to be Pleistocene or Pliocene in age, but Owens and Denny (1979) proposed a Miocene age for much of the section. Holocene sediments also constitute part of the aquifer. Hansen (1971, p. 135) stated that deposition was largely the product of bedload deposition by braided streams sweeping across a wide flood plain, and he noted that a belt of high transmissivity values extending southeast across Maryland may be the result of a former major consequent stream of pre-Wisconsin age. For the most part, the streams originated in the north and spread south and southeastward across Delaware (Jordan, 1964) and eastern Maryland. In extreme southern Delaware and eastern Maryland, deposits of beach, dune, estuarine, offshore bar, and lagoonal facies record several minor transgressive-regressive oscillations (Jordan, 1964).

The upland deposits on Maryland's western shore are probably of fluvial origin and were deposited by the ancestral Susquehanna or Potomac River systems (Dryden and Overbeck, 1948, p. 72). The lowland deposits are chiefly of marine or estuarine origin (Otton, 1955, p. 99).

Lithologic description of the aquifer.—Otton (1955, p. 104) has divided the lowland deposits into three lithologic units—a basal sand and gravel, an intermediate tough clay, and an upper bed or beds of sandy clay or clayey gravel. Diatoms, marine shells, plant debris, and vivianite are common in the clay. The sand is typically angular and often contains small pieces of plant debris.

The upland deposits and those east of the Chesapeake Bay are generally less clayey than the lowland deposits. The sediments are moderately sorted, are yellow to red, light gray, or cream colored, and are mostly coarse quartzose sand having much gravel and occasional cobbles. Thin silt beds are present in southern Delaware. The sand is generally more poorly sorted, less rounded,

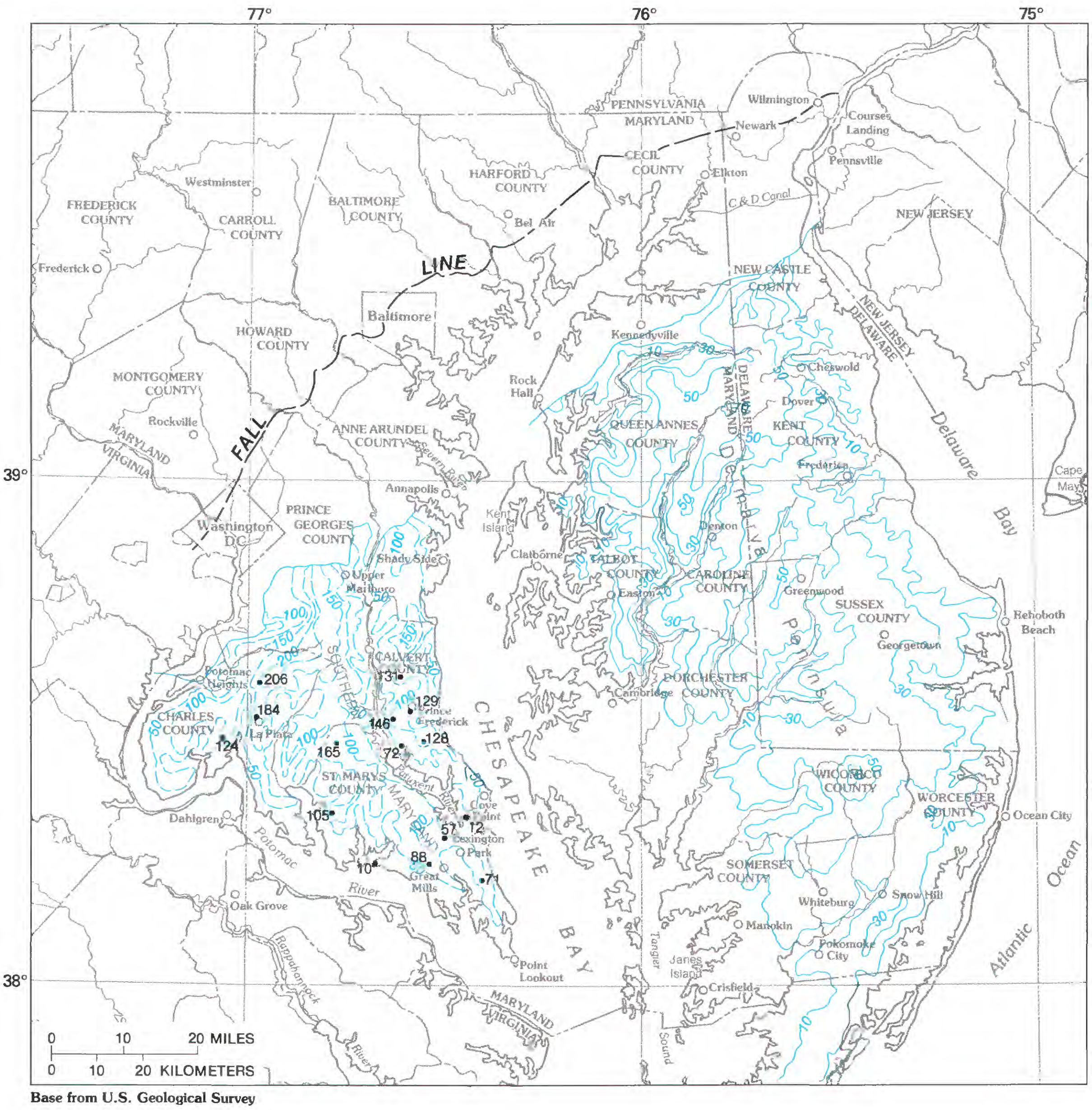


EXPLANATION

60 — LINE OF EQUAL THICKNESS OF THE UPPER CHESAPEAKE CONFINING UNIT—Dashed where inferred. Intervals 20 and 50 feet

•40 WELL—Number is thickness of the upper Chesapeake confining unit, in feet

FIGURE 27.—Thickness of the upper Chesapeake confining unit in the Coastal Plain of Maryland and Delaware.



Base from U.S. Geological Survey

EXPLANATION

200 — STRUCTURE CONTOUR—Shows altitude of the top of the surficial aquifer. Dashed where inferred. Contour intervals 20 feet east of the Chesapeake Bay and 50 feet west of the Chesapeake Bay. Datum is sea level

•12 WELL—Number is altitude of the top of the surficial aquifer, in feet above sea level

FIGURE 28.—Top of the surficial aquifer (approximate altitude of the long-term water table) in the Coastal Plain of Maryland and Delaware.

and lighter in color than that of the underlying aquifers (Sundstrom and Pickett, 1969, p. 25).

Aquifer characteristics.—The surficial aquifer east of the Chesapeake Bay is a major source of water for industrial and municipal use, particularly in areas where the sand occurs as thick fill in paleochannels cut into older sediment. West of the Chesapeake Bay, the aquifer is largely undeveloped but is a source for numerous rural water supplies.

Over most of the area, the surficial aquifer is unconfined. Areas of local confinement (Weigle, 1974, p. 32) are probably not extensive enough to be considered as a regional confined aquifer. The sand occurs as isolated patches of channel fill in northern Delaware and occurs as a broad sheet in central and southern Delaware. Sand thickness increases southward across Delaware and attains a saturated thickness greater than 180 ft in southeastern Delaware (Johnston, 1973, p. 11). The thickest sand in Maryland occurs along a narrow paleochannel in Wicomico County where more than 200 ft of sediment has accumulated.

Transmissivity also increases southeastward across Delaware, ranges up to 22,000 ft^2/d, and averages about 9,000 ft^2/d (Johnston, 1973, p. 32). East of the Chesapeake Bay in Maryland, transmissivity ranges from about 4,000 ft^2/d in Queen Annes County to about 53,600 ft^2/d in Wicomico County (Mack and Thomas, 1968, p. 53). West of the Chesapeake Bay, transmissivities are substantially lower. In Charles County, for example, values are reported to be less than 130 ft^2/d (Slaughter and Otton, 1968, p. 39). The aquifer storage coefficient has been reported to be about 0.15 in both Maryland (Rasmussen and Slaughter, 1957) and Delaware (Johnston, 1973).

SUMMARY

The Coastal Plain sediments in Maryland and Delaware form an eastward-thickening wedge of sand and clay that was deposited in a variety of sedimentary environments related to sediment input and sea-level changes. The pre-Pleistocene depositional history can be divided into three major transgressive-regressive cycles (Glaser, 1968). The first marine transgression began following deposition of the Lower Cretaceous Potomac Group and continued through deposition of the Upper Cretaceous Severn Formation. Formations constituting the first regressive sequence are the Brightseat and Aquia Formations and the Marlboro Clay, all Paleocene and early Eocene in age. A rapid marine transgression followed and is marked by the basal clay and silt beds of the Eocene Nanjemoy Formation. The Nanjemoy Formation coarsens upward and indicates reversal of the transgression and progressive shallowing of the sea. The sediments of the Eocene Piney Point Formation were deposited by the regression that continued into Oligocene and Miocene time and that resulted in erosion of parts of the Piney Point Formation in updip areas. Initiation of the third transgressive sequence is marked by the basal beds of the middle Miocene Calvert Formation. By the late Miocene, a major regression was occurring, as evidenced by the shallow marine or fluvial deposits of the so-called Yorktown and Cohansey(?) Formations (Rasmussen and Slaughter, 1955). In addition to the major sedimentary sequences described above, the Miocene and younger beds record numerous minor transgressive and regressive cycles.

As part of the U.S. Geological Survey's Region Aquifer System Analysis of the northern Atlantic Coastal Plain, the sediments of Maryland, Delaware, and the District of Columbia are grouped into 11 predominantly sandy aquifers separated by 10 predominantly silty and clayey confining units. Listed from stratigraphically lowest to highest, the layers are the Patuxent aquifer, the Potomac confining unit, the Patapsco aquifer, the Patapsco confining unit, the Magothy aquifer, the Matawan confining unit, the Matawan aquifer, the Severn confining unit, the Severn aquifer, the lower Brightseat confining unit, the Brightseat aquifer, the upper Brightseat confining unit, the Aquia-Rancocas aquifer, the Nanjemoy-Marlboro confining unit, the Piney Point-Nanjemoy aquifer, the lower Chesapeake confining unit, the lower Chesapeake aquifer, the St. Marys confining unit, the upper Chesapeake aquifer, the upper Chesapeake confining unit, and the surficial aquifer. The grouping of aquifers and confining units into a complex aquifer system is useful within certain constraints to understand ground-water flow in the Coastal Plain of Maryland, Delaware, and the District of Columbia on a regional basis.

SELECTED REFERENCES

Achmad, Grufron, and Weigle, J.M., 1979, A quasi three-dimensional finite-difference ground-water flow model with a field application: Maryland Geological Survey Report of Investigations 33, 21 p.

Al-Saad, A.A., 1971, Electric analog model study of Piney Point aquifer, Kent County, Delaware: Masters thesis, University of Delaware, Newark, Del., 79 p.

Anderson, J.L., 1948, Cretaceous and Tertiary subsurface geology of three deep test wells on the Eastern Shore of Maryland: Maryland Department of Geology, Mines and Water Resources[3] Bulletin 2, 456 p.

Back, William, 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498–A, 41 p.

[3]The name of this agency was changed to the Maryland Geological Survey in June 1964.

Bachman, J.L., 1984, The Columbia aquifer of the Eastern Shore of Maryland, Part 1—Hydrogeology: Maryland Geological Survey Report of Investigations 20, 44 p.

Bennett, R.R., and Collins, G.G., 1952, Brightseat Formation, a new name for sediments of Paleocene age in Maryland: Washington Academy of Science Journal, v. 42, p. 114–116.

Bennett, R.R., and Meyer, R.R., 1952, Geology and ground-water resources of the Baltimore area: Maryland Department of Geology, Mines and Water Resources[4] Bulletin 4, 573 p.

Bennion, V.R., and Brookhart, J.W., 1949, The water resources of Anne Arundel County: Maryland Department of Geology, Mines and Water Resources[4] Bulletin 5, 149 p.

Boggess, D.H., and Heidel, S.G., 1968, Water resources of the Salisbury area: Maryland Geological Survey Report of Investigations 3, 69 p.

Brenner, G.J., 1963, The spores and pollen of the Potomac Group of Maryland: Maryland Department of Geology, Mines and Water Resources[3] Bulletin 27, 215 p.

Brown, P.M., Miller, J.A., and Swain, F.M., 1972, Structural and stratigraphic framework and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U.S. Geological Survey Professional Paper 796, 79 p.

Chapelle, F.K., and Drummond, D.D., 1983, Hydrogeology, digital simulation and geochemistry of the Aquia and Piney Point-Nanjemoy aquifer system in southern Maryland: Maryland Geological Survey Report of Investigations 38, 100 p.

Clark, W.B., 1910, Results of a recent investigation of the Coastal Plain formations in the area between Massachusetts and North Carolina: Geological Society of America Bulletin, v. 20, p. 646–654.

———1916, The Upper Cretaceous deposits of Maryland, *in* Upper Cretaceous volume: Maryland Geological Survey Special Publication, p. 1–109.

Clark, W.B., Matthews, E.B., and Berry, E.W., 1918, The surface and underground water resources of Maryland, including Delaware and the District of Columbia: Maryland Geological Survey Special Publication, v. 10, pt. 2, 542 p.

Cleaves, E.T., Edwards, Jonathan, Jr., and Glaser, J.D., compilers and editors, 1968, Geologic map of Maryland: Maryland Geological Survey, scale 1:250,000, 1 sheet.

Coleman, J.M., and Wright, L.D., 1975, Modern river deltas—Variability of processes and sand bodies, *in* Broussard, M.L., ed., Deltas, models for exploration: Houston Geological Society, Houston, p. 99–149.

Cooke, C.W., Martin, R.O.R., and Meyer, Gerald, 1952, Geology and water resources of Prince George's County: Maryland Department of Geology, Mines and Water Resources[3] Bulletin 10, p. 82–270.

Cushing, E.M., Kantrowitz, I.H., and Taylor, K.R., 1973, Water resources of the Delmarva Peninsula: U.S. Geological Survey Professional Paper 822, 58 p.

Darton, N.H., 1896, Maryland, *in* Artesial well prospects in the Atlantic Coastal Plain region: U.S. Geological Survey Bulletin 138, p. 124–136.

———1902, Preliminary list of deep borings in the United States, Part I, Alabama-Montana: U.S. Geological Survey Water-Supply Paper 57, 60 p.

Doyle, J.A., 1977, Spores and pollen—The Potomac Group (Cretaceous) angiosperm sequence, *in* Kauffman, I.G., and Hazel, J.E., eds., Concepts and methods of biostratigraphy: Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross, Inc., p. 339–363.

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

Dryden, Lincoln, and Overbeck, R.M., 1948, The physical features of Charles County: Maryland Department of Geology, Mines and Water Resources[4], 267 p.

Dunbar, C.O., and Rogers, J.R., 1957, Principles of stratigraphy: New York, John Wiley and Sons, Inc., 356 p.

Edwards, J.E., and Hansen, H.J., 1978, New data bearing on the structural significance of the upper Chesapeake Bay magnetic anomaly: Maryland Geological Survey Report of Investigations 30, 42 p.

Estabrook, James, and Reinhardt, Juergen, 1980, Lithologic log of the core, *in* Geology of the Oak Grove core: Virginia Division of Mineral Resources Publication 20, pt. 4, 88 p.

Fahnestock, R.K., 1963, Morphology and hydrology of a glacial stream, White River, Mount Rainier, Washington: U.S. Geological Survey Professional Paper 422–A, 70 p.

Ferguson, H.F., 1953, The ground-water resources, *in* The water resources of St. Marys County: Maryland Department of Geology, Mines and Water Resources[3] Bulletin 11, p. 16–195.

Gibson, T.G., 1962, Benthonic Foraminifera and paleoecology of the Miocene deposits of the middle Atlantic Coastal Plain: Princeton, New Jersey, Princeton University, unpublished Ph.D. dissertation, 359 p.

Gibson, T.G., and others, 1980, Biostratigraphy of the Tertiary strata of the core, *in* Geology of the Oak Grove core: Virginia Division of Mineral Resources Publication 20, pt. 2, 88 p.

Glaser, J.D., 1968, Coastal Plain geology of southern Maryland: Maryland Geological Survey Guidebook 1, 56 p.

———1969, Petrology and origin of Potomac and Magothy (Cretaceous) sediments, middle Atlantic Coastal Plain: Maryland Geological Survey Report of Investigations 11, 101 p.

Goldman, M.I., 1916, The petrology and genesis of the sediments of the Upper Cretaceous of Maryland, *in* Upper Cretaceous: Maryland Geological Survey, p. 111–182.

Groot, J.J., 1955, Sedimentary petrology of the Cretaceous sediments of northern Delaware in relation to paleogeographic problems: Delaware Geological Survey Bulletin 5, 157 p.

Groot, J.J., and Penny, J.S., 1960, Plant microfossils and age of nonmarine Cretaceous sediments of Maryland and Delaware: Micropaleontology, v. 6. p. 225–236.

Hack, J.T., 1957, Submerged river system of Chesapeake Bay: Geological Society of America Bulletin, v. 68, p. 817–830.

Hansen, H.J., 1967, Hydrogeologic data from the Jane's Island State Park test well, Somerset County, Maryland: Maryland Geological Survey Basic Data Report 3, 24 p.

———1968, Geophysical log cross-section network of the Cretaceous sediments of southern Maryland: Maryland Geological Survey Report of Investigations 7, 76 p.

———1969a, Depositional environments of subsurface Potomac Group in southern Maryland: American Association of Petroleum Geologists Bulletin, v. 53, no. 9, p. 1923–1937.

———1969b, A geometric method to subdivide the Patapsco Formation of southern Maryland into informal mapping units for hydrogeologic use: Geological Society of America Bulletin, v. 80, p. 329–336.

———1971, Transmissivity tracts in the coastal plain aquifers of Maryland: Southeastern Geology, v. 13, no. 3, p. 127–149.

———1972, A user's guide for the artesian aquifers of the Maryland Coastal Plain, Part 2—Aquifer characteristics: Maryland Geological Survey, 123 p.

[4]The name of this agency was changed to the Maryland Geological Survey in June 1964.

———1974, Sedimentary facies of the Aquia Formation in the subsurface of the Maryland Coastal Plain: Maryland Geological Survey Report of Investigations 21, 47 p.

———1978, Upper Cretaceous (Senonian) and Paleocene (Danian) pinchouts on the south flank of the Salisbury embayment, Maryland, and their relationship to antecedent basement structures: Maryland Geological Survey Report of Investigations 29, 34 p.

———1981a, Figure 3—Cross section of upper Eastern Shore wells showing distribution of fresh and brackish waters, in 1979 Annual report of the Maryland Geological Survey: Maryland Geological Survey Information Circular 33, p. 24–25.

———1981b, Stratigraphic discussion in support of a major unconformity separating the Columbia Group from the underlying Upper Miocene aquifer complex in eastern Maryland: Southeastern Geology, v. 22, no. 3, p. 123–138.

———1982, Hydrogeologic framework and potential utilization of the brine aquifers of the Waste Gate Formation, a new unit of the Potomac Group underlying the Delmarva Peninsula, *in* Waste Gate Formation, Part 1: Maryland Geological Survey Open-File Report, 50 p.

Hansen, H.J., and Edwards, Jonathan, 1986, The lithology and distribution of pre-Cretaceous basement rocks beneath the Maryland Coastal Plain: Maryland Geological Survey Report of Investigations 44, 27 p.

Hansen, H.J., and Wilson, J.M., 1984, Summary of hydrogeologic data from a deep (2,678 feet) well at Lexington Park, St. Marys County, Maryland: Maryland Geological Survey Open-File Report 84–02–1, 61 p.

Hodges, A.H., 1984, Hydrology of the Manokin, Ocean City, and Pocomoke aquifers of southeastern Delaware: Delaware Geological Survey Report of Investigations 38, 60 p.

Hubbert, M.K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, p. 785–944.

Johnston, P.M., 1964, Geology and ground-water resources of Washington, D.C., and vicinity: U.S. Geological Survey Water-Supply Paper 1776, 97 p.

Johnston, R.H., 1973, Hydrology of the Columbia (Pleistocene) deposits of Delaware—An appraisal of a regional water-table aquifer: Delaware Geological Survey Bulletin 14, 78 p.

———1977, Digital model of the unconfined aquifer in central and southeastern Delaware: Delaware Geological Survey Bulletin 15, 47 p.

Jordan, R.R., 1962, Stratigraphy of the sedimentary rocks in Delaware: Delaware Geological Survey Bulletin 9, 51 p.

———1964, Columbia (Pleistocene) sediments of Delaware: Delaware Geological Survey Bulletin 12, 69 p.

———1968, Observations on the distribution of sands within the Potomac Formation of northern Delaware: Southeastern Geology, v. 9, no. 2, p. 77–85.

———1983, Stratigraphic nomenclature of nonmarine Cretaceous rocks of inner margin of Coastal Plain in Delaware and adjacent States: Delaware Geological Survey Report of Investigations 37, 43 p.

Jordan, R.R., and Smith, R.V., regional coordinators, 1983, Atlantic Coastal Plain, correlation of stratigraphic units of North America (COSUNA) project: The American Association of Petroleum Geologists, 1 sheet.

Kapple, G.W., and Hansen, H.J., 1976, A digital simulation model of the Aquia aquifer in southern Maryland: Maryland Geological Survey Information Circular 20, 33 p.

Kraft, J.C., and Maisano, M.D., 1968, A geologic cross section of Delaware: Newark, Delaware, Water Resources Center: University of Delaware, 1 sheet.

Leahy, P.P., 1976, Hydraulic characteristics of the Piney Point aquifer and overlying confining bed near Dover, Delaware: Delaware Geological Survey Report of Investigations 26, 26 p.

———1979, Digital model of the Piney Point Aquifer in Kent County, Delaware: Delaware Geological Survey Report of Investigations 29, 81 p.

———1982, Ground-water resources of the Piney Point and Cheswold aquifers in central Delaware as determined by a flow model: Delaware Geological Survey Bulletin 16, 68 p.

LeGrand, H.E., 1961, Summary of geology of Atlantic Coastal Plain: Association of Petroleum Geologists Bulletin, v. 45, no. 9, p. 1557–1571.

Lucas, R.C., 1976, Anne Arundel County ground-water information—Selected well records, chemical-quality data, pumpage, appropriation data, and selected well logs: Maryland Geological Survey Water Resources Basic Data Report 8, 149 p.

Mack, F.K., 1962, Ground-water supplies for industrial and urban development in Anne Arundel County: Maryland Department of Geology, Mines and Water Resources[5] Bulletin 26, 90 p.

———1966, Ground water in Prince Georges County: Maryland Geological Survey Bulletin 29, 101 p.

———1974, An evaluation of the Magothy aquifer in the Annapolis area, Maryland: Maryland Geological Survey Report of Investigations 22, 75 p.

Mack, F.K., and Mandle, R.J., 1977, Digital simulation and prediction of water levels in the Magothy aquifer in southern Maryland: Maryland Geological Survey Report of Investigations 28, 42 p.

Mack, F.K., and Thomas, W.D., 1968, Hydrologic testing of buried valley near Salisbury, Maryland: U.S. Geological Survey Professional Paper 600–A, 53 p.

Mack, F.K., Webb, W.E., and Gardner, R.A., 1971, Water resources of Dorchester and Talbot Counties in Maryland: Maryland Geological Survey Report of Investigatons 17, 107 p.

Maher, J.C., 1965, Correlation of subsurface Mesozoic and Cenozoic rocks along the Atlantic Coast: American Association of Petroleum Geologists, Tulsa, Oklahoma, 18 p.

———1971, Geologic framework and petroleum potential of the Atlantic Coastal Plain and Continental Shelf: U.S. Geological Survey Professional Paper 659, 98 p.

Marine, I.W., and Rasmussen, W.C., 1955, Preliminary report on the geology and ground-water resources of Delaware: Delaware Geological Survey Bulletin 4, 336 p.

Martin, M.M., 1984, Simulated ground-water flow in the Potomac aquifers, New Castle County, Delaware: U.S. Geological Survey Water Resources Investigations Report 84–4007, 85 p.

Martin, M.M., and Denver, J.M., 1982, Hydrologic data for the Potomac Formation in New Castle County, Delaware: U.S. Geological Survey Water Resources Investigations Open-File Report 81–916, 148 p.

Maryland State Planning Department, 1969, Ground-water aquifers and mineral commodities of Maryland: Maryland State Planning Department Publication, no. 152, 36 p.

Matthews, E.B., 1933, Map of Maryland showing geological formations: Maryland Geological Survey, scale 1:380,160 (6 miles to 1 inch), 1 sheet.

Meisler, Harold, 1981, Preliminary delineation of salty ground water in the northern Atlantic Coastal Plain: U.S. Geological Survey Open-File Report 81–71, 12 p.

Meng, A.A., III, and Harsh, J.F., 1984, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Open-File Report 84–728, 78 p.

[5] The name of this agency was changed to the Maryland Geological Survey in June 1964.

Meyer, Gerald, 1952, Ground-water resources, *in* Geology and ground-water resources of Prince Georges County: Maryland Department of Geology, Mines and Water Resources[6] Bulletin 10, p. 82–254.

Miller, J.C., 1971, Ground-water geology of the Delaware Atlantic seashore: Delaware Geological Survey Report of Investigations 17, 33 p.

Miller, R.D., Troxell, C.E., and Lucas, R.C., 1982, The quantity and natural quality of groundwater in Maryland: Maryland Department of Natural Resources Administration, 150 p.

Minard, J.P., Sohl, N.F., and Owens, J.P., 1977, Reintroduction of the Severn Formation (Upper Cretaceous) to replace the Monmouth Formation in Maryland, *in* Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1976: U.S. Geological Survey Bulletin 1435–A, p. A132–A133.

Nogan, D.S., 1964, Foraminifera, stratigraphy, and paleontology of the Aquia Formation of Maryland and Virginia: Cushman Foundation for Foraminiferal Research Special Publication No. 7, 50 p.

Otton, E.G., 1955, Ground-water resources, *in* The water resources of the southern Maryland Coastal Plain: Maryland Department of Geology, Mines and Water Resources[6] Bulletin 15, 347 p.

Otton, E.G., and Mandle, R.J., 1984, Hydrogeology of the Upper Chesapeake Bay area, Maryland, with emphasis on aquifers in the Potomac Group: Maryland Geological Survey Report of Investigations 39, 62 p.

Otton, E.G., and others, 1964, Water resources of the Baltimore area, Maryland: U.S. Geological Survey Water-Supply Paper 1499–F, 105 p.

Overbeck, R.M., 1951, Ground-water resources, *in* The water resources of Calvert County: Maryland Department of Geology, Mines and Water Resources[6] Bulletin 8, p. 4–100.

Overbeck, R.M., and Slaughter, T.S., 1958, The ground-water resources, *in* The water resources of Cecil, Kent, and Queen Anne's Counties: Maryland Department of Geology, Mines and Water Resources[6] Bulletin 21, 382 p.

Owens, J.P., and Denny, C.S., 1979, Upper Cenozoic deposits of the central Delmarva Peninsula, Maryland and Delaware: U.S. Geological Survey Professional Paper 1067–A, 28 p.

Parker, G.G., Hely, A.G., Keighton, W.B., and Olmsted, F.H., 1964, Water resources of the Delaware River basin: U.S. Geological Survey Professional Paper 381, 200 p.

Papadopulos, S.S., Bennett, R.R., Hook, F.K., and Trescott, P.C., 1974, Water from the coastal plain aquifers in Washington, D.C., metropolitan area: U.S. Geological Survey Circular 697, 11 p.

Rasmussen, W.C., and Slaughter, T.H., 1955, The ground-water resources, *in* The water resources of Somerset, Wicomico, and Worcester Counties: Maryland Department of Geology, Mines, and Water Resources[6] Bulletin 16, 469 p.

———1957, The ground-water resources, *in* The water resources of Caroline, Dorchester, and Talbot Counties: Maryland Department of Geology, Mines and Water Resources[6] Bulletin 18, 371 p.

Rasmussen, W.C., Groot, J.J., Martin, R.O.R., McCarren, E.F., Vaughn, C.B., and others, 1957, The water resources of northern Delaware: Delaware Geological Survey Bulletin 6, v. 1, 223 p.

Rasmussen, W.C., Wilkins, R.A., Beall, R.M., and others, 1960, Water resources of Sussex County, Delaware: Delaware Geological Survey Bulletin 8, 228 p.

Reinhardt, Juergen, Christopher, R.A., and Owens, J.P., 1980 , Lower Cretaceous stratigraphy of the core, *in* Geology of the Oak Grove core: Virginia Division of Mineral Resources Publication 20, pt. 3, 88 p.

Reinhardt, Juergen, Newell, W.L., and Mixon, R.B., 1980, Tertiary lithostratigraphy of the core, *in* Geology of the Oak Grove core: Virginia Division of Mineral Resources Publication 20, pt. 1, 88 p.

Richards, H.G., 1948, Studies on the subsurface geology and paleontology of the Atlantic Coastal Plain: Philadelphia Academy of Natural Sciences Proceedings, v. 100, p. 39–76.

Rima, D.R., Coskery, O.J., and Anderson, P.W., 1964, Ground-water resources of southern New Castle County, Delaware: Delaware Geological Survey Bulletin 11, 54 p.

Robbins, E.I., Perry, W.J., and Doyle, J.A., 1975, Palynological and stratigraphic investigations of four deep wells in the Salisbury Embayment of the Atlantic Coastal Plain: U.S. Geological Survey Open-File Report 75–307, 120 p.

Schumm, S.A., 1968, Speculations concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, no. 11, p. 1573–1588.

Selley, R.C., 1982, Ancient sedimentary environments (2d ed.): New York, Cornell University Press, 287 p.

Shifflet, Elaine, 1948, Eocene stratigraphy and foraminifera of the Aquia Formation: Maryland Department of Geology, Mines and Water Resources[6] Bulletin 3, 93 p.

Silliman, Benjamin, 1827, Notice of some recent experiments in boring for fresh water and a pamphlet on that subject: American Journal of Science, v. 12, p. 136–143.

Slaughter, T.H., 1962, Beach-area water supplies between Ocean City, Maryland, and Rehoboth Beach, Delaware: U.S. Geological Survey Water-Supply Paper 1619–T, 10 p.

Slaughter, T.H., and Laughlin, C.P., 1966, Records of wells and springs, chemical analyses and selected well logs in Charles County, Maryland: Maryland Geological Survey Water Resources Basic Data Report 2, 93 p.

Slaughter, T.H., and Otton, E.G., 1968, Availability of ground water in Charles County: Maryland Geological Survey Bulletin 30, 100 p.

Spoljaric, Nenad, 1967, Quantitative lithofacies analysis of the Potomac Formation, Delaware: Delaware Geological Survey Report of Investigations 12, 26 p.

Spoljaric, Nenad, and Woodruff, K.D., 1970, Geology, hydrology, and geophysics of Columbia sediments in the Middletown-Odessa area, Delaware: Delaware Geological Survey Bulletin 13, 156 p.

Sundstrom, R.W., and others, 1967, The availability of ground water in the Potomac Formation in the Chesapeake and Delaware Canal area, Delaware: Newark, Delaware, Water Resources Center, University of Delaware, 95 p.

Sundstrom, R.W., and Pickett, T.E., 1968, The availability of ground water in Kent County, Delaware, with special reference to the Dover area: Newark, Delaware, Water Resources Center, University of Delaware, 123 p.

———1969, The availability of ground water in eastern Sussex County, Delaware: Newark, Delaware, Water Resources Center, University of Delaware, 136 p.

———1970, The availability of ground water in western Sussex County, Delaware: Newark, Delaware, Water Resources Center, University of Delaware, 117 p.

———1971, The availability of ground water in New Castle County, Delaware: Newark, Delaware, Water Resources Center, University of Delaware, 156 p.

Sundstrom, R.H., Pickett, T.E., and Varrin, R.D., 1976, Hydrology, geology, and mineral resources of the coastal zone of Delaware: Delaware Coastal Zone Management Program, Technical Report 3, 245 p.

Talley, J.H., 1975, Cretaceous and Tertiary section—Deep test well, Greenwood, Delaware: Delaware Geological Survey Report of Investigations 23, 51 p.

[6]The name of this agency was changed to the Maryland Geological Survey in June 1964.

Teifke, R.H., 1973, Geologic studies, Coastal Plain of Virginia: Virginia Department of Conservation and Economic Development Bulletin 83, pts. 1 and 2, 101 p.

Trapp, Henry, Jr., Knobel, L.L., Meisler, Harold, and Leahy, P.P., 1984, Test well DO-Ce 88 at Cambridge, Dorchester County, Maryland: U.S. Geological Survey Water-Supply Paper 2229, 48 p.

U.S. Geological Survey, 1967, Engineering geology of the northeast corridor Washington, D.C., to Boston, Massachusetts—Coastal plain and surficial deposits: U.S. Geological Survey Miscellaneous Investigations Map I–514–B, scale 1:500,000, 1 sheet.

Ward, L.W., 1986, Stratigraphy and characteristic mollusks of the Pamunky Group (lower Tertiary) and Old Church Formation of the Chesapeake Group—Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1346, 78 p.

Ward, L.W., and Blackwelder, B.W., 1980, Stratigraphic revision of Upper Miocene and Lower Pliocene beds of the Chesapeake Group, Middle Atlantic Coastal Plain: U.S. Geological Survey Bulletin 1482–D, 61 p.

Weigle, J.M., 1974, Availability of fresh ground water in northeastern Worcester County, Maryland—With special emphasis on the Ocean City area: Maryland Geological Survey Report of Investigations 24, 64 p.

Weigle, J.M., and Achmad, Grufron, 1982, Geohydrology of the freshwater aquifer system in the vicinity of Ocean City, Maryland, *with a section on* simulated water-level changes: Maryland Geological Survey Report of Investigations 37, 55 p.

Weigle, J.M., and Webb, W.E., 1970, Southern Maryland records of selected wells, water levels, and chemical analyses of water: Maryland Geological Survey Basic Data Report 4, 48 p.

Weigle, J.M., Webb, W.E., and Gardner, R.A., 1970, Water resources of southern Maryland: U.S. Geological Survey Hydrologic Atlas HA–365.

Williams, J.F., III, 1979, Simulated changes in water level in the Piney Point aquifer in Maryland: Maryland Geological Survey Report of Investigations 31, 50 p.

Woodruff, K.D., Miller, J.C., Jordan, R.R., Spoljaric, Nenad, and Pickett, T.E., 1972, Geology and ground water, University of Delaware, Newark, Delaware: Delaware Geological Survey Report of Investigations 29, 80 p.