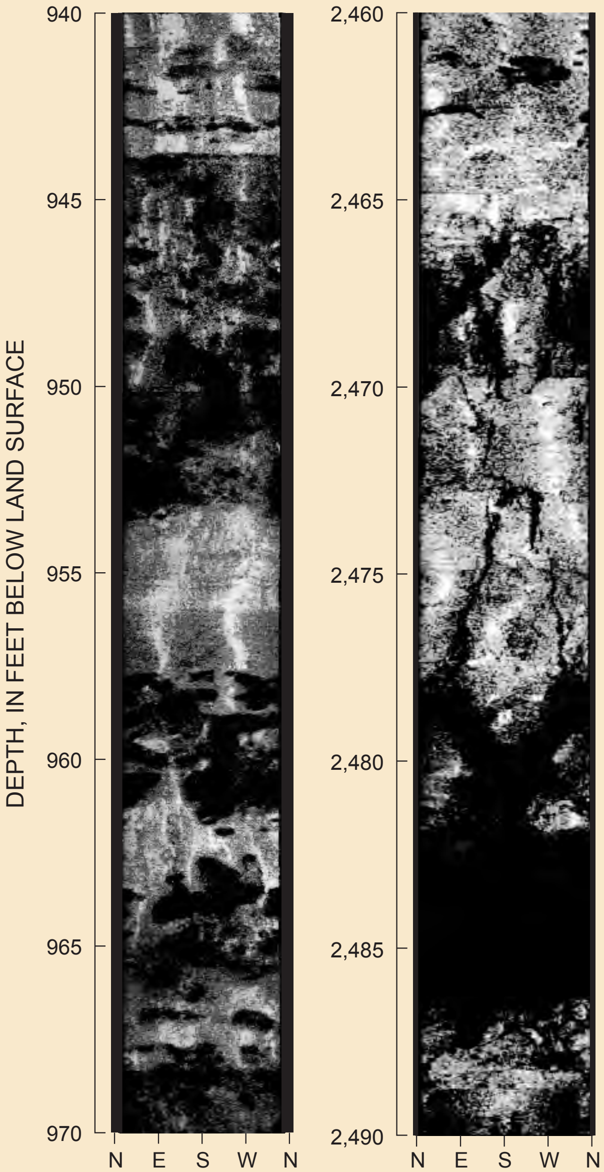
Hydrogeology and Water Quality (1978) of the Floridan Aquifer System at U.S. Geological Survey TW-26, on Colonels Island, near Brunswick, Georgia

Water-Resources Investigations Report 02-4020



Prepared in cooperation with the
- City of Brunswick
- Glynn County

U.S. Department of the Interior
U.S. Geological Survey

Cover Illustrations:

Photograph of wellhead of TW-26, on Colonels Island, near Brunswick, Georgia, 1999.
Before the widespread use of pressure transducers to measure artesian water levels,
a tower was necessary to measure the water level at TW-26;
the tower was removed in 2000.

Photograph by Alan M. Cressler, U.S. Geological Survey

Acoustic televiewer images from TW-26 showing:
(1) smooth-sided solution cavities in the lower water-bearing zone
of the Upper Floridan aquifer (depth interval 940–970 feet); and
(2) fractures and cavernous zones in the Fernandina permeable zone
of the Lower Floridan aquifer (depth interval 2,460–2,490 feet).

Hydrogeology and Water Quality (1978) of the Floridan Aquifer System at U.S. Geological Survey Test Well 26, on Colonels Island, near Brunswick, Georgia

By L. Elliott Jones, David C. Prowell, and Morris L. Maslia

U.S. Geological Survey

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Prepared in cooperation with the

City of Brunswick and

Glynn County

Atlanta, Georgia
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND VERTICAL AND HORIZONTAL DATUMS

CONVERSION FACTORS

Factors for converting inch-pound units to the International System (SI) of units are given below:

Multiply	By	To obtain
	Length	
foot (ft)	.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)

HORIZONTAL AND VERTICAL DATUMS

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Historical data collected and stored as National Geodetic Vertical Datum of 1929 have been converted to NAVD 88 for this publication.

SEA LEVEL

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.

HYDROGEOLOGY AND WATER QUALITY (1978) OF THE FLORIDAN AQUIFER SYSTEM AT U.S. GEOLOGICAL SURVEY TEST WELL 26, ON COLONELS ISLAND, NEAR BRUNSWICK, GEORGIA

by L. Elliott Jones[1], David C. Prowell[1] and Morris L. Maslia[2]

ABSTRACT

In 1978, the U.S. Geological Survey drilled a 2,727-foot-deep test well (TW-26) on Colonels Island in Glynn County about 3 miles west-southwest of downtown Brunswick, Georgia. The well was constructed to gain a better understanding of the hydrogeology and geochemistry of the carbonate Floridan aquifer system, which is comprised of the Upper and Lower Floridan aquifers, each of which is divided further into multiple water-bearing zones. At least since the 1940's, some of the shallower water-bearing zones of the Floridan aquifer system have been contaminated by saltwater. Analytical methods included examination of cuttings and core sections, geophysical logging, and collection of water-quality samples during construction and after completion.

Lithologic and paleontological data from TW-26 indicate strata ranging in geologic age from Late Cretaceous to Tertiary. Structural interpretations using geophysical logs suggest that these strata may be locally affected by faulting. Acoustic-televiewer and caliper logs reveal numerous layers within the carbonate Floridan aquifer system that have sizable dissolution cavities that commonly are adjacent to layers of relatively non-porous limestone or dolomite. Dissolution may increase as ground water fills openings caused by fracturing of brittle, non-porous carbonate rocks, and probably provides conduits for the circulation of large quantities of ground water. At a depth near 2,475 feet (ft), large dissolution cavities were observed near features that appear to be high-angle fault and/or fracture zones. These zones may allow upward migration of saline water to shallower water-bearing zones where hydraulic head has been reduced by pumping.

Chloride-concentration data from TW-26 indicate wide variation in salinity of ground-water in the Floridan aquifer system, including sharp increases and decreases in salinity (interfaces) with increasing depth, and long intervals of consistent salinity. During drilling, the first interface of increased salinity in the system was in the lower water-bearing zone of the Upper Floridan aquifer (955–960 ft, chloride concentration in the drilling fluid increased from 20 to 100 milligrams per liter (mg/L)). Salinity increased gradually through the lower-water bearing zone, the middle semiconfining unit, and the uppermost water-bearing zone of the Lower Floridan aquifer (chloride concentration in the drilling fluid had a local maximum of 604 mg/L at 1,245 ft). The interval 1,245–1,660 ft has low salinity—five bailer samples collected from 1,260 to 1,515 ft, during a period of free flow when the well had a temporary open interval of 598–1,528 ft, had chloride concentration ranging from 20 to 37 mg/L. Chloride concentration in drilling fluid decreased gradually from 1,260 to 1,520 ft; and during the next phase of drilling, chloride concentration in drilling-fluid samples remained generally less than 30 mg/L until 1,665 ft. The second interface of increased salinity during drilling was in the middle of the Lower Floridan aquifer (1,660–1,675 ft, from 24 to 580 mg/L), followed by an interval of almost 500 ft having moderate variation in salinity (1,675–2,145 ft, from 108 to 660 mg/L). A third interface of increased salinity was near the top of the Fernandina permeable zone in the lower part of the Lower Floridan aquifer (2,145–2,320 ft, from 282 to 16,500 mg/L). A bailer sample from the Fernandina permeable zone near the bottom of the well (2,710 ft) after completion had a chloride concentration of 33,000 mg/L, much greater than that of modern seawater (19,000 mg/L).

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Because ground water in the Fernandina permeable zone is much more saline than a high-chloride plume in the Upper Floridan aquifer at Brunswick (maximum sample chloride concentration 3,040 mg/L in 1970 and 1975), the Fernandina permeable zone is thought to be the source of the high-chloride water in the Upper Floridan aquifer at Brunswick. However, one sample from a shallower depth interval (1,612–1,712 ft) had a chloride concentration of 2,400 mg/L, suggesting there may be water-bearing zones above the Fernandina permeable zone that supply high-chloride water to the Upper Floridan aquifer in Brunswick. Comparison of sample chloride concentrations and specific conductances at various depths indicate a change in water type between ground water above and below a depth of about 1,500 ft.

Graphical analysis of the relative content of major cations and anions indicates that high-chloride water from TW-26 is not a simple mixture of freshwater from the Upper Floridan aquifer and modern seawater. Dissimilarities include: the percentage of dissolved calcium in all samples was higher than seawater and lower than freshwater; all samples had a markedly lower percentage of dissolved bicarbonate than freshwater; and three samples contained percentages of sodium-plus-potassium and/or chloride that lie beyond percentages of the freshwater and seawater end points.

INTRODUCTION

The Upper Floridan aquifer is the major source of water supply for industrial, irrigation, and municipal use in southeast Georgia. Until the 1940's, the Upper Floridan aquifer consistently produced fresh ground water of excellent quality in the Brunswick area. At that time, however, high-chloride water was first detected in the aquifer in downtown Brunswick. By the mid 1970's, the plume had spread northward toward pumping centers in north Brunswick. In 1999, the plume extended over about a 2.5-square-mile area and had a maximum chloride concentration of about 2,600 milligrams per liter (mg/L), more than ten times the secondary standard (formerly known as the Secondary Maximum Contaminant Level or SMCL) for chloride (250 mg/L; U.S. Environmental Protection Agency, 2000).

In the mid 1970's, water-resource investigations in the Brunswick, Ga., area suggested that saltwater contaminating the aquifer was entering the aquifer from a more deeply buried, more saline water-bearing zone. Data from wells completed below the Upper Floridan aquifer indicate a high-chloride water-bearing zone in the uppermost part of the Lower Floridan aquifer, and another freshwater zone below that. Although data from the Lower Floridan aquifer were sparse, at that time it was generally believed that the upper part of the Lower Floridan aquifer was the source of the saltwater entering the Upper Floridan aquifer (Gregg and Zimmerman, 1974).

Considering the importance of the Upper Floridan aquifer as a source of water supply, water resources managers needed to determine the source of the high-chloride water in order to develop a long-term water-management plan. In 1978, in cooperation with the Georgia Department of Natural Resources (GaDNR), Geologic and Water-Resources Division—which has been replaced in part by the GaDNR, Environmental Protection Division (GaEPD), Georgia Geologic Survey—the U.S. Geological Survey (USGS) drilled a deep test well (TW-26) on Colonels Island, in Glynn County, Ga., near Brunswick (fig. 1). Construction began in January 1978 and was completed in October 1978. Objectives of TW-26 were to: (1) identify the primary source of saltwater entering the Upper Floridan aquifer; and (2) determine the quality and vertical flow patterns of water entering the aquifer. A drilling site was chosen away from the plume of high-chloride water in the Upper Floridan aquifer. The well was to penetrate the entire thickness of the Tertiary carbonate sediments and the freshwater-bearing Upper Floridan aquifer was to be cased off and grouted before the saltwater zones were penetrated. The reverse-air rotary drilling method was chosen to allow collection of cuttings, water-level measurements, and discharge samples during drilling. The chloride concentration of discharge sampled every 5 to 10 feet (ft) would indicate saltwater zones and dictate the final construction of the well. TW-26 ultimately was intended to be a monitoring well of the deeper saltwater zone(s).

Since the late 1970's, the USGS and the City of Brunswick have maintained a cooperative agreement that provides for monitoring of water levels and water quality of the Floridan aquifer system and analysis of data collected. Another project between the USGS and the GaEPD, called the Coastal Sound-Science Initiative, includes the drilling of several deep test wells into the Lower Floridan aquifer in coastal Georgia and ground-water flow and solute-transport modeling of the Floridan aquifer system in the Glynn County area. In support of these projects, the USGS compiled and analyzed all available data from TW-26, and summarized the findings in this report.

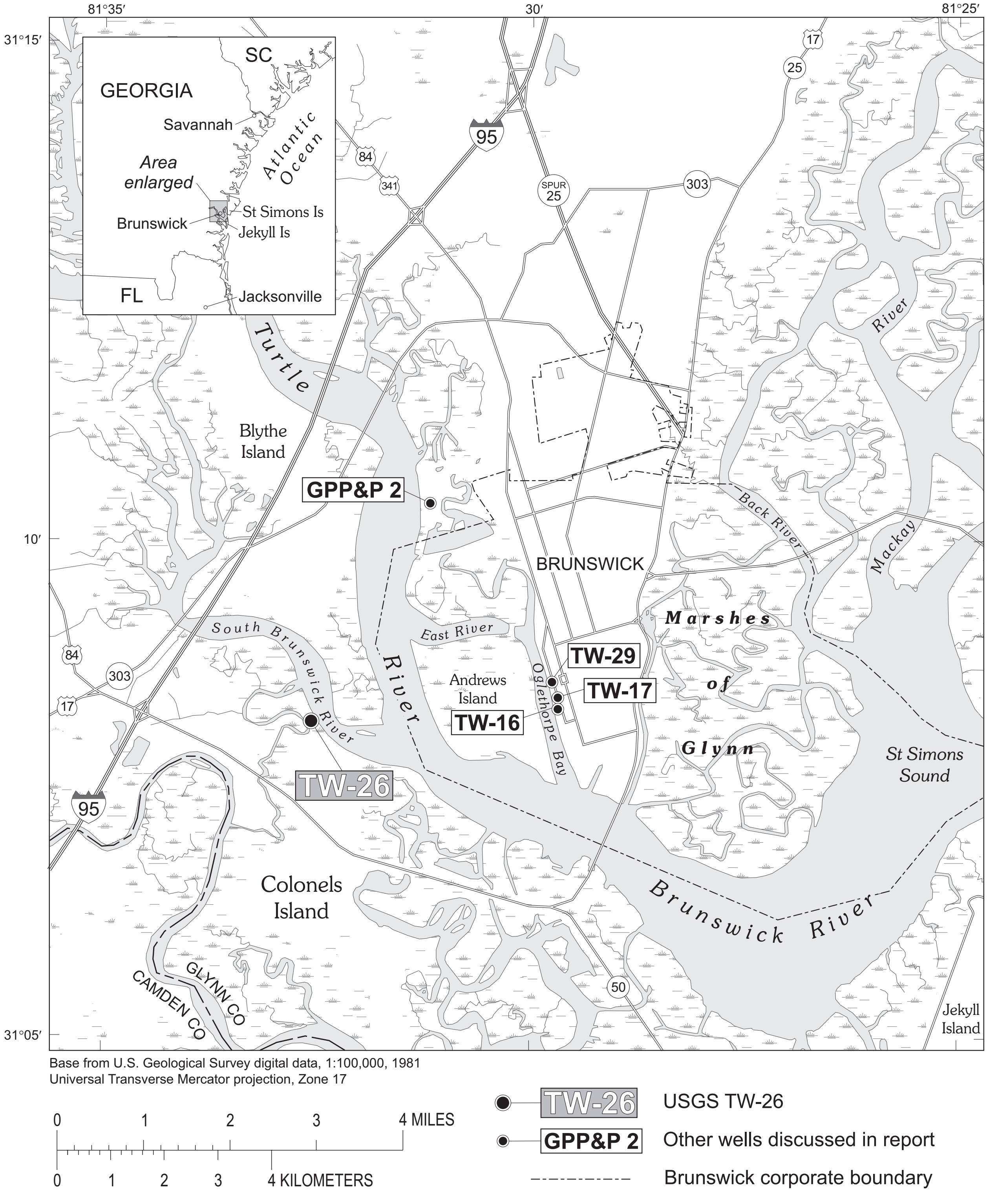

Figure 1. Location of TW-26 and other wells, near Brunswick, Georgia.

Purpose and Scope

This report characterizes the hydrogeology and water quality of the Floridan aquifer system at TW-26 through analysis of data on geologic and geophysical properties and ground-water quality from land surface to the bottom of the well bore at 2,720 ft below land surface. Of particular interest is the change in chloride concentration of ground water with increasing depth in relation to saltwater contamination in the Upper Floridan aquifer in the Brunswick area. This report summarizes testing at TW-26, including: litho-logic description of cuttings; coring of selected intervals for lithologic and paleontological analysis; geophysical logging (caliper, natural-gamma, neutron, spontaneous-potential, long- and short-normal resistivity, and acoustic televiewer); sampling of the drilling fluid for chloride concentration (every 5–10 ft from 645 ft to bottom of well); sampling of ground water at selected depths for ionic-content analysis; periodic composite sampling from the open interval of the completed well since 1978; and semi-continuous recording of ground-water level in the completed well since 1978.

Location of TW-26

TW-26 is on Colonels Island in Glynn County near Brunswick, Ga. (fig. 1). The site is near the Atlantic Coast about 87 miles (mi) north of Jacksonville, Fla., and about 80 mi south of Savannah, Ga. Downtown Brunswick is located on a peninsula extending southward from the mainland, west of the barrier islands, St Simons and Jekyll. The peninsula is bordered on the east by the estuarine Marshes of Glynn and associated waterways, and on the west and south by the Brunswick River and tributaries. TW-26 is about 3 mi west-southwest of downtown Brunswick, across the Turtle and South Brunswick Rivers. Location and other selected data for TW-26 and four other wells discussed in this report are in table 1. Continuous water-level data from TW-16 and water-quality data from TW-17 and GPP&P 2 are compared to data from TW-26; and TW-29 drilled in Brunswick in 2001 also penetrated the primary freshwater/saltwater interface.

Table 1. Location and other selected data for TW-26 and four other wells in this report

Site name	Other identifier	Site identification number	Latitude[1]	Longitude[1]	Depth, in feet below land surface		Land-surface altitude[2], in feet
					Casing	Well	
33H188	TW-26	310810081323501	31° 08'10"N	81° 32'34"W	2,138	2,727	8.32
34H391	TW-16	310818081294201	31° 08'19"N	81° 29'41"W	1,070	1,158	6.12
34H495	TW-29	310835081294501	31° 08'35"N	81° 29'45"W	2,084	2,720	13
34H393	TW-17	310825081294201	31° 08'26"N	81° 29'41"W	615	723	5.94
33H109	GPP&P 2	311023081311201	31° 10'24"N	81° 31'11"W	488	849	9

[1]Locations of all wells except TW-29 were determined from plotted locations on 7½-minute topographic maps, stored referenced to the North American Datum (NAD) of 1927, and converted to the NAD of 1983 (NAD 83). Location of TW-29 was determined by the Global Positioning System, and stored referenced to NAD 83.

[2]Land-surface altitudes reported to the nearest 0.01 feet were determined by leveling and are accurate to 0.01 feet; others were estimated from 7½-minute topographic maps and are accurate to 2.5 feet. All altitudes were collected and stored referenced to the National Geodetic Vertical Datum of 1929, and were converted to the North American Vertical Datum of 1988.

Previous Investigations

The surficial geology of Glynn County has been described in reports by Stephenson and Veatch (1915) and Cooke (1943). Herrick (1961) listed logs of wells in Glynn County in a report of well logs for the Coastal Plain of Georgia. Structure-contour and thickness maps of formations in the Coastal Plain area were presented by Herrick and Vorhis (1963). Wait (1965), Wait and Gregg (1973), Gregg and Zimmerman (1974), and Wait and Davis (1986) provided data on the geology of Glynn County in interpretive reports that dealt mostly with the problem of high-chloride water entering the Upper Floridan aquifer at Brunswick. Recent investigations of the geology of Glynn County, relying primarily on subsurface data, are described in reports by Miller (1986) and Krause and Randolph (1989). Miller (1986) described the generalized hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama; and Krause and Randolph (1989) provided a detailed description of the geology of the Georgia Coastal Plain including Glynn County.

The first published evidence of saltwater contamination of the Floridan aquifer system was in Warren (1944, p. 136), who discussed the occurrence of brackish water in a 1,000-foot city well in downtown Brunswick and the possibility of saltwater encroachment in Glynn County. Wait (1962; 1965), Wait and Gregg (1973), and Gregg and Zimmerman (1974) presented hydrologic and water-chemistry data in attempts to refine the understanding of the occurrence of high-chloride water in the Brunswick area. Gregg and Zimmerman (1974, plate 2) constructed a structure-contour map of the surface of the Oligocene sediments, showing probable and hypothetical faults that could allow deeper saline water to migrate into the Upper Floridan aquifer; and also suggested two primary locations of upward migration of deeper saline water into the Upper Floridan aquifer. Gill and Mitchell (1979) used results from TW-26 to conclude that the freshwater-saltwater interface occurs in a series of cavernous intervals in the lower part of the Floridan aquifer system (later called the Fernandina permeable zone), and that this cavernous zone is probably the primary source of saltwater entering the Upper Floridan aquifer.

Bush and Johnston (1988) provided a general summary of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama. The overall water quality of the Floridan aquifer system is discussed in detail in Sprinkle (1989). Krause and Randolph (1989) discussed the freshwater-saltwater interface at TW-26 in terms of the Hubbert relation (Hubbert, 1940) and density stratification of freshwater and saltwater; and also provided additional evidence that conduits caused by nearly vertical faulting are the mechanisms that permit the upward movement of saltwater from the Fernandina permeable zone to the Upper Floridan aquifer. Maslia and Prowell (1990) further developed a conceptual model of subsurface flow in the Glynn County area that includes a mapping of four inferred primary, and numerous inferred accessory faults. Using analyses of anisotropic aquifer properties, Maslia and Prowell (1990) also offered support for the notion that faulting and/or fracturing controls ground-water flow. More than 40 years of chloride-concentration data from nearly 100 wells in Brunswick are tabulated and graphed in Jones and Maslia (1994). Jones (1997) described how fault and fracture zones of the Upper Floridan aquifer in the Brunswick area were incorporated in a finite-element ground-water flow model which allows simulation of upward leakage from deeper water-bearing zones within the Floridan aquifer system. Jones (2000) presented preliminary results of analyses that are described in more detail herein. Jones (2001) illustrated a conceptual model of ground-water flow and chloride movement in the upper and lower water-bearing zones of the Upper Floridan aquifer at Brunswick.

Well Construction

TW-26 was drilled by the reverse-air rotary method in three sections. The upper section was intended to penetrate and case off the repetitive clastic-carbonate sequences of Miocene and post-Miocene rocks; the middle section was intended to penetrate and case off the carbonate Upper Floridan aquifer; and the lower section was intended to penetrate the principal saltwater zone(s) of the Lower Floridan aquifer. Table 2 summarizes major activities at TW-26 during the drilling and testing period from January 1978 through logging of the completed well in January 1980. A schematic diagram of the completed well is given as figure 2.

Data Collection

Numerous types of hydrogeologic data were collected during and after the construction of TW-26, based on physical observations, sampling of core and water, and measurements using a variety of devices. The primary data-collection methods and instruments used at TW-26 are described below, with respect to their utility in providing hydrogeologic information pertaining to the Colonels Island area.

Table 2. Major drilling and testing activities at TW-26, near Brunswick, Georgia

Date	Activity (depths, in feet below land surface)
01/27/1978	Began drilling upper section ($9^7/_8$-inch bit).
02/02–03/1978	Completed upper section 0–600 ft. Logged 0–600 ft: caliper, natural gamma, electric (spontaneous potential, long-, and short-normal resistivity).
02/10/1978	Set 25-inch surface casing 0–30 ft.
02/13/1978	Completed reaming 0–600 ft (21-inch reaming bit).
02/16–17/1978	Set and welded 16-inch casing 0–598 ft, cemented annular space.
02/21/1978	Began drilling middle section ($9^7/_8$-inch bit) 600–605 ft.
02/24/1978	Cored 605–626 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole, continued drilling ($9^7/_8$-inch bit). Collected samples of drilling fluid every 5–10 ft during drilling.
03/17–18/1978	Completed drilling middle section ($9^7/_8$-inch bit) 626–1,528 ft. Logged 600–1,500 ft: caliper, natural gamma, electric (spontaneous potential, long-, and short-normal resistivity).
04/11/1978	Completed reaming middle section to 1,528 ft ($15^7/_8$-inch bit). Logged: neutron porosity (0–1,528 ft), acoustic televiewer (598–1,520 ft). Collected water samples of flowing borehole (open interval 598–1,528 ft) using a bailer at 11 depths (700, 900, 960, 980, 1,000, 1,200, 1,260, 1,360, 1,400, 1,460, and 1,515 ft)
04/25/1978	Set 10-inch casing 0–1,525 ft.
05/16/1978	Completed cementing of annular space 0–1,525 ft.
05/22/1978	Began drilling lower section ($9^7/_8$-inch bit) 1,528–1,575 ft. Pumped water for drilling from Brunswick River.
05/23/1978	Cored 1,575–1,595 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole, continued drilling ($9^7/_8$-inch bit) to 1,800 ft, well flowing. Collected samples of drilling fluid every 5–10 ft during drilling.
06/07/1978	Cored 1,800–1,820 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole, continued drilling ($9^7/_8$-inch bit) and sampling drilling fluid to 2,000 ft.
06/20/1978	Cored 2,000–2,020 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole, continued drilling ($9^7/_8$-inch bit) and sampling drilling fluid to 2,200 ft.
06/27/1978	Cored 2,200–2,220 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole, continued drilling ($9^7/_8$-inch bit) and sampling drilling fluid to 2,557 ft.
07/13–15/1978	Cored 2,557–2,580 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole ($9^7/_8$-inch bit) and sampled drilling fluid. Logged: neutron porosity (1,500–2,580 ft), acoustic televiewer (1,520–2,500).
07/27–08/03/1978	Cored 2,580–2,640 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole ($9^7/_8$-inch bit) and sampled drilling fluid.
08/14–23/1978	Cored 2,640–2,720 ft (4-inch-diameter, 20-ft core barrel). Reamed corehole ($9^7/_8$-inch bit), continued drilling and sampling drilling fluid to 2,727 ft.
08/23–24/1978	Logged: caliper (1,525–2,702 ft), acoustic televiewer (2,500–2,717 ft), electric (1,525–2,720 ft; spontaneous potential, long-, and short-normal resistivity).
09/05–16/1978	Packed off intervals 2,530–2,580 ft, 2,120–2,220 ft, 1,832–1,942 ft, and 1,612–1,712 ft. Collected various samples with a bailer from above, within, and below packed intervals
09/20/1978	Suspended 6-inch casing 1,300–2,138 ft.
10/08/1978	Completed cementing of annular space 1,300–2,138 ft.
01/07/1980	Logged: natural gamma (0–2,700 ft).

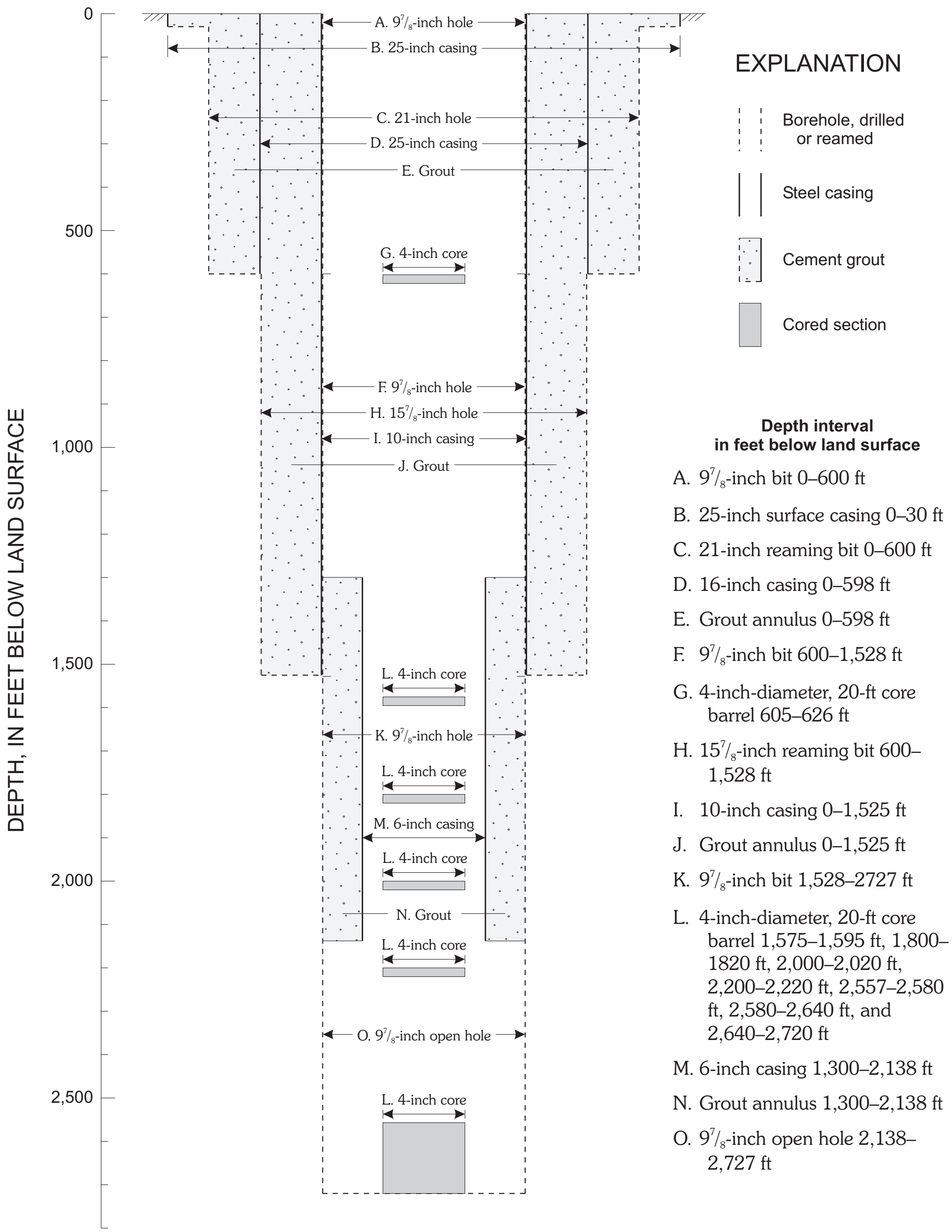

Figure 2. Schematic construction diagram of TW-26, near Brunswick,Georgia.

Lithologic description and paleontologic sampling

During the drilling of TW-26, drill cuttings were collected about every 5 ft and their lithology was described in field notes recorded at that time (Gail D. Mitchell, USGS, written commun., 1978). Because reverse-air rotary drilling method produces pulverized rock samples, the descriptions provide a general identification of rock type, but do not provide adequate paleontologic samples for reliable age dating. Consequently, the entire description of the cuttings is not replicated here, but a generalized lithologic column and a brief summary of the geologic properties of each geologic unit are given on plate 1, and some general lithologic descriptions are included in the Geologic Units section.

Several intervals of TW-26 were cored for geologic control. Using a 20-ft-long, 4-inch-diameter core barrel, two 20-ft-long sections near each of five depths (about 600, 1,600, 1,800, 2,000, and 2,200 ft; see table 1, figure 2, and plate 1), and the last 170 ft of the well (2,557–2,727 ft) were cored. In addition to providing information on the physical characteristics of the rock (texture, grain size, *etc*.), paleontologic samples from the core were examined to establish age control.

Geophysical logs and video images

Geophysical surveys were conducted in TW-26 after the completion of each section. The following brief descriptions of several types of geophysical logs as applied to the test well, were modified from previous publications (Keys and MacCary, 1971; Keys, 1988; and Johnson and others, 1999). More detailed descriptions of geophysical logging techniques are available therein.

Caliper logs provide a profile of the borehole diameter. Borehole enlargements generally are related to bedding planes and fractures, but also can be caused by changes in lithology, well construction, and dissolution. Cavities frequently are apparent on caliper logs of TW-26—some enlargements may be larger than the 18-inch caliper diameter.

Natural-gamma logs are a record of natural-gamma radiation (in counts per second) emitted from the formation surrounding a borehole. Natural-gamma logs were used in this investigation to supplement lithologic information. Generally, fine-grained sediments that contain abundant clay tend to be more radioactive than quartz sand and carbonate rocks. A notable exception occurs when carbonate or clastic rocks contain phosphate, which can be highly radioactive.

Neutron tools consist of a source of neutron radiation and a detector. High-energy neutrons are emitted from the source, pass through the fluid column and casing, and into the formation. Neutrons logs are used to estimate water content and porosity for saturated sediments. If the formation contains a relatively large quantity of water, more neutrons will be moderated and captured by the hydrogen atoms in the water, and fewer neutrons will be reflected back to the detector. Thus, the greater reflected neutron radiation, the lower the water content and the lower the porosity of the formation. For a particular rock type and tool, a relation between detected radiation and porosity can be developed. For the tool used (helium 3 detector, 16-inch spacing), an approximate scale of equivalent limestone porosity, in percent, is shown at the bottom of the neutron log on plate 1.

Acoustic televiewer (ATV) logs are produced by acoustic signals reflected off the inside wall of the well bore and electronically converted to visual images. In this investigation, variations in rock texture, layering, and foliation appear in ATV images as shades of lighter gray; whereas voids, solution openings, and fracture openings appear as areas of darker gray to black. A non-horizontal planar opening appears roughly as one period of a sine curve on rectangular ATV images, which depict depth on one axis and compass direction on the other axis. The dip azimuth of the plane is the compass direction of the minimum point of the sine curve, and the tangent of the dip angle is the amplitude of the sine curve divided by the diameter of the well bore.

A submersible video camera was also lowered down the lower part of the borehole of TW-26 (below 1,525 ft) after the 10-inch-diameter casing had been set. The camera lens was pointed downward at the apex of a conical mirror; thus, continuous, radial images of the borehole wall were recorded on video cassettes. Video images show rock type and other rock features such as fractures, bedding planes, and solution cavities; also, some fluid properties can be discerned by changes in turbidity and the motion of particles relative to the camera.

Water-Quality Sampling and Water-Level Monitoring

Beginning at a depth of 645 ft, water discharging from the well bore of TW-26 was sampled every 5 to 10 ft of depth drilled and analyzed for chloride concentration and specific conductance. Chloride concentration in drilling-fluid samples was determined by field titration with silver nitrate ($AgNO_3$) using potassium chromate (KCr) as an indicator; specific conductance was determined using a conductivity meter. After the middle section was drilled and reamed, 11 samples were collected using a bailer at selected depths within the temporary open interval 598–1,528 ft. Before the final casing was set, when the open-hole depth interval was 1,525–2,727 ft, attempts were made to isolate four selected intervals for aquifer testing, using a pair of 4-ft-long, inflatable packers, which were set over intervals of 1,612–1,712 ft, 1,832–1,942 ft, 2,120–2,220 ft, and 2,530–2,580 ft. The aquifer tests were inconclusive, probably due to leakage around the packers (H.E. Gill, USGS retired, oral commun., 2000), but during the tests, seven water samples of pumped discharge were collected from intervals either above, within, or below the packers. In 1980 and 1981, six samples were collected using a bailer at selected depths within the open interval of the completed well (2,138–2,727 ft). Periodically since 1981, 14 composite water samples were collected from the entire open interval of the completed well for analysis of chloride concentration, most recently in June 1999. At the USGS Water-Quality Laboratory in Ocala, Fla., analyses of major ionic concentrations and other constituents were performed on all bailer, packed-interval, and open-interval samples, and on one drilling-fluid sample from 1,522 ft.

The well was equipped with a continuous water-level recorder after completion, and except for two gaps totalling about 3¼ years (November 1985–February 1988, and January 1993–January 1994), water levels have been recorded on an hourly or half-hourly basis to the present (2002).

Acknowledgments

The drilling project described herein was conducted in 1978 by the USGS in cooperation with the Georgia Department of Natural Resources (Georgia DNR), Geologic and Water-Resources Division. Data compilation and analyses for this report were conducted by the USGS in cooperation with the City of Brunswick and Glynn County, Georgia. Some of the data used in this report were collected as part of the cooperative program between the USGS and the City of Brunswick and Glynn County. The cooperation of city and county officials in assisting with data collection is gratefully acknowledged.

Thanks are also extended to former USGS employees Harold E. Gill, who planned and was in charge of the drilling project in 1978, Gail D. Mitchell, who sat the drilling operations and described the cuttings, and Gerald E. Idler, who performed the geophysical logging. Messrs. Gill and Idler were consulted during preparation of this report.

HYDROGEOLOGY

Based on data collected from TW-26 and other nearby sites, geologic age and hydrogeologic units at TW-26 were identified (fig. 3, plate 1). Paleontological analyses of several selected core sections indicate geologic age from Late Cretaceous to Tertiary (table 3). Lithology and other geologic properties of the stratigraphic units are summarized on plate 1. In addition, drilling-time, caliper, natural-gamma, neutron, electric and ATV logs were used to identify stratigraphic units, water-bearing zones and confining units. Drilling-time and geophysical logs are shown on plate 1, and ATV images of strata in the Floridan aquifer system are compared to caliper and neutron logs in figures 4 through 10 (in back of report), which also indicate geologic age and hydrogeologic units.

Geologic Units

Brunswick, Ga., is located in the lower part of the Coastal Plain physiographic province within a regional depositional basin known as the Southeast Georgia Embayment (Owens and Gohn, 1985; Miller, 1986). In the study area, sedimentary rocks of Cretaceous and younger age were deposited over Paleozoic(?) metavolcanic rocks during subsidence of the Continental Margin. The subsidence of the Continental Margin and the episodic rise and fall of sea level have resulted in the deposition of many geologic formations in the outer Coastal Plain. These deposits are approximately 5,000-ft thick in Glynn County (Wait and Davis, 1986) and thin toward the basin edges. A more detailed description of the regional geology is given in Miller (1986).

The subsurface geology of the Brunswick area has never been described in great detail due to the sparsity of representative geologic samples such as cores. TW-26 is one of the few wells in the area for which definitive geologic samples (intermittent cores and cuttings) and geologic logs are available. Depth intervals of six cored sections are given in table 2 and in figure 2. The first five cored sections were examined for calcareous nannofossils and dinoflagellates, and the last cored section was examined for fossil bivalve molds. A summary of the paleontological analyses, including the depth of the paleontological samples, is given in table 3, and geophysical logs are shown on plate 1. Paleontological data and geophysical logs were used to differentiate geologic units, which are described in chronological order below.

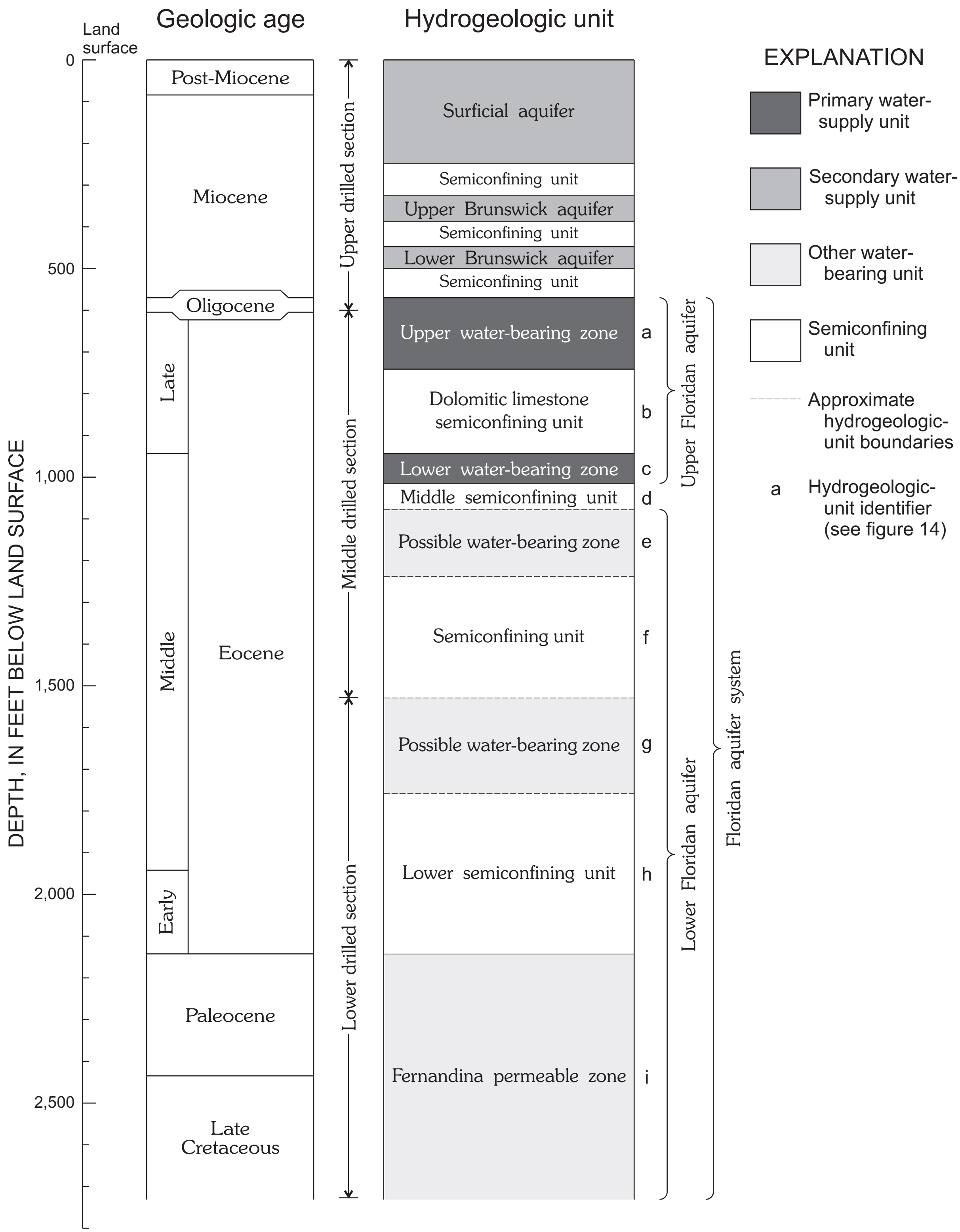

Figure 3. Geologic age and hydrogeologic units at TW-26, near Brunswick, Georgia (modified from Jones and Maslia, 1994).

Table 3. Summary of paleontologic analyses of core samples from TW-26, near Brunswick, Georgia

Depth[1] (in feet below land surface)	Fossils found	Geologic age
608	Calcareous nannofossils; rare, poorly preserved: *Reticulofenestra floridana*[2]	Eocene or Oligocene
608	Dinoflagellates; few, non diagnostic[3]	latest Oligocene(?) or early Miocene(?)
626	Calcareous nannofossils; frequent, poorly preserved: *Coccolithus pelagicus,* and *Reticulofenestra floridana*[2]	Eocene or Oligocene
626	Dinoflagellates: *Cordosphaerdium cantharellus, Gonyaulacysta* sp.*, Hystrichokolpoma rigaudiae, Lingulodinium machaerophorum, Nematosphaeropsis* sp.*, Operculocinium centrocarpum, Pediastrum* (freshwater algae)*, Pentadinium laticinctum, Polysphaeridium zoharyi, Spiniferites* sp.*, Tuberculodimium vancampoae*[3]	latest Eocene or early Miocene
1,575	Calcareous nannofossils; frequent: *Blackites spinosus*, *Coccolithus pelagicus, Cyclococcolithus formosus, Reticulofenestra floridana,* and *Sphenolithus morformis*[2]	Eocene or Oligocene
1,575–1,595	Dinoflagellate: *Enneadocysta arcuatum*[4]	middle Eocene to early Oligocene
1,595	Calcareous nannofossils; frequent, poorly preserved: *Coccolithus pelagicus* and *Reticulofenestra floridana*[2]	Eocene or Oligocene
1,800	Calcareous nannofossils; common, poorly preserved: *Coccolithus pelagicus, Cyclococcolithus formosus, Discolithina* sp.*, Reticulofenestra floridana,* and *Reticulofenestra umbilica*[2]	middle to late Eocene(?), or Oligocene(?)
1,800	Dinoflagellates: *Muratodinium fimbriatum*, *Operculodinium centrocarpum*, *Pentadinium laticinctum*, and *Polysphaeridium zoharyi*[3]	middle Eocene
1,820	Calcareous nannofossils; frequent, poorly preserved, non diagnostic[2]	unknown
1,820	Dinoflagellates; few, non diagnostic[3]	unknown
2,000	Calcareous nannofossils; frequent: *Campylosphaera dela*, *Chiasmolithus* unsplit X, *Coccolithus pelagicus*, *Sphenolithus* sp., and *Toweius craticulus*(?)[2]	early Eocene(?)
2,000	Dinoflagellates: *Achomosphaera alcicornu*, *Adnatosphaeridium multispinosum*, *Apteodinium australiense*, *Fibrocysta axialis*, *Muratodinium fimbriatum*, *Polysphaeridium zoharyi*, and *Wetzeliella* sp.[3]	early(?) Eocene
2,020	No calcareous nannofossils[2]	unknown
2,200	do.	do.
2,220	do.	do.
2,020	No dinoflagellates[3]	unknown
2,200	do.	do.
2,220	do.	do.
2,632	Molds of echinoids and pectins[5]	Late Cretaceous
2,659	do.	do.
2,663	do.	do.

[1]See Generalized lithology and fossil samples column on plate 1.
[2]Laurel M. Bybell, U.S. Geological Survey, written commun., 1983.
[3]Lucy E. Edwards, U.S. Geological Survey, written commun., 1982.
[4]Lucy E. Edwards, U.S. Geological Survey, written commun., 1999.
[5]Norman F. Sohl, U.S. Geological Survey, written commun., 1978

Upper Cretaceous strata

The basal Coastal Plain strata in Glynn County are clastic and carbonate rocks of Late Cretaceous age (66–100 million years old) having a total thickness of about 1,000 ft (Miller, 1986). The basal cores from TW-26 (2,557–2,727 ft) are from the uppermost beds of the Upper Cretaceous (fig. 3, plate 1). The limestone in this section is locally called the Lawson Limestone (Miller, 1986), but the calcareous mudstone at the very bottom of the core may represent an older formation. The Lawson Limestone probably was deposited as fine-grained, sandy limestone and shelly limestone, and subsequently recrystallized in part to tan to pale-orange dolostone and dolomitic sandstone. The original limestone matrix largely has been replaced by very fine rhombic crystals of dolomite, although shell ghosts and patches of less altered limestone remain. Secondary calcite and other unidentified minerals are present in small solution channels and irregular voids, indicating several stages of dissolution and recrystallization. Fossil molds of echinoids and pectins from 2,632, 2,659, and 2,663 ft in the core of TW-26 indicate Late Cretaceous age (middle to late Maastrichtian) for this stratigraphic section (Norman F. Sohl, USGS, written commun., 1978; see table 3).

Numerous openings or voids appear as darker areas in ATV images of the TW-26 borehole (fig. 10, in back of report). Most of the dark-appearing openings, such as those at 2,441 and 2,454 ft, are nearly horizontal and parallel to bedding planes. The horizontal openings range in thickness from less than 1 inch to several feet, and probably are attributed to dissolution of limestone that originally was more permeable than the adjacent strata. It is likely that when these rocks were near land surface, their higher permeability allowed circulation of slightly acidic ground water, which was the dissolution agent. Some of these horizontal voids also may be softer zones that were knocked loose and washed out during drilling, but the lateral extent of many of the openings probably is too large for them to have been caused by drilling. The caliper log correlated to the ATV images in figure 10 (in back of report) indicates that many of the horizontal solution openings extend beyond the diameter of the drill bit ($9^7/_8$ inches) to the extent of the caliper tool (about 18 inches). Drilling rods were reported to have dropped at least twice while drilling in Upper Cretaceous strata (4 ft at 2,496 ft and about 3 ft at 2,561 ft; Gail D. Mitchell, USGS, written commun., 1978). After the final cored sections were completed, a 9-ft discrepancy was indicated between a caliper log and the driller's log. The final cored sections probably began at 2,557 ft rather than 2,548 ft as recorded by the driller, due to a large cavern at this depth (fig. 10, in back of report). A 10-ft gap appears on the drilling-time record at this depth (plate 1), below which reported depths were adjusted from field notes to account for the discrepancy.

In TW-26, one prominent, steeply inclined, planar opening is present at about 2,473–2,478 ft, and several other, non-horizontal, planar openings are discernible at 2,534–2,547 ft (fig. 11). Using the relation described in the Introduction section, the dip azimuth of the prominent planar opening at about 2,473–2,478 ft (see sine curve in fig. 11) is roughly north-northeast, and the dip angle is: $tan^{-1}(60 \text{ inches} \div 9.875 \text{ inches}) \approx 81°$. These non-horizontal openings are interpreted as fractures and probably indicate post-depositional structural alteration of the limestone. The fracture openings may be the result of jointing in the hardened limestone or may be related to movement along steeply dipping fault planes. If the openings were the result of jointing in the limestone, they would be expected in other limestone and dolostone units in TW-26. However, ATV images from 2,400–2,700 ft (fig. 10, in back of report) indicate that the steeply inclined openings are largely confined to the lower part of the borehole, about 2,400–2,600 ft, and are best developed at about 2,480–2,550 ft. The localization of these features implies that they were not formed by uniformly distributed regional jointing. Therefore, the openings probably are attributable to fault movement, which may be formed either by solution-opening roof collapse or regional tectonism (Vernon, 1951; Prowell, 1988; Maslia and Prowell, 1990).

The fractures not only differ in orientation from horizontal solution openings associated with bedding planes, but in physical character as well. Horizontal solution openings, such as those at 2,441 and 2,454 ft (fig. 10, in back of report), are smooth-sided and uniform, suggesting that discrete depositional layers have been dissolved. The steeply inclined (fracture) openings, however, contain or are bordered by angular rock fragments, such as those at 2,535–2,542 ft (fig. 11).

Paleocene strata

Interbedded limestone, dolomitic limestone, and dolostone unconformably overlie Cretaceous strata in the Brunswick area. A large solution opening at 2,424–2,427 ft is assumed to be the approximate depth of the top of the Upper Cretaceous strata in TW-26 (fig. 10, in back of report). An increased response in the natural-gamma log above this opening (plate 1) also is suggestive of a depositional boundary. The overlying Paleocene section consists of gray to cream-colored, slightly to very porous, fossiliferous limestone bounded above and below by alternating beds of

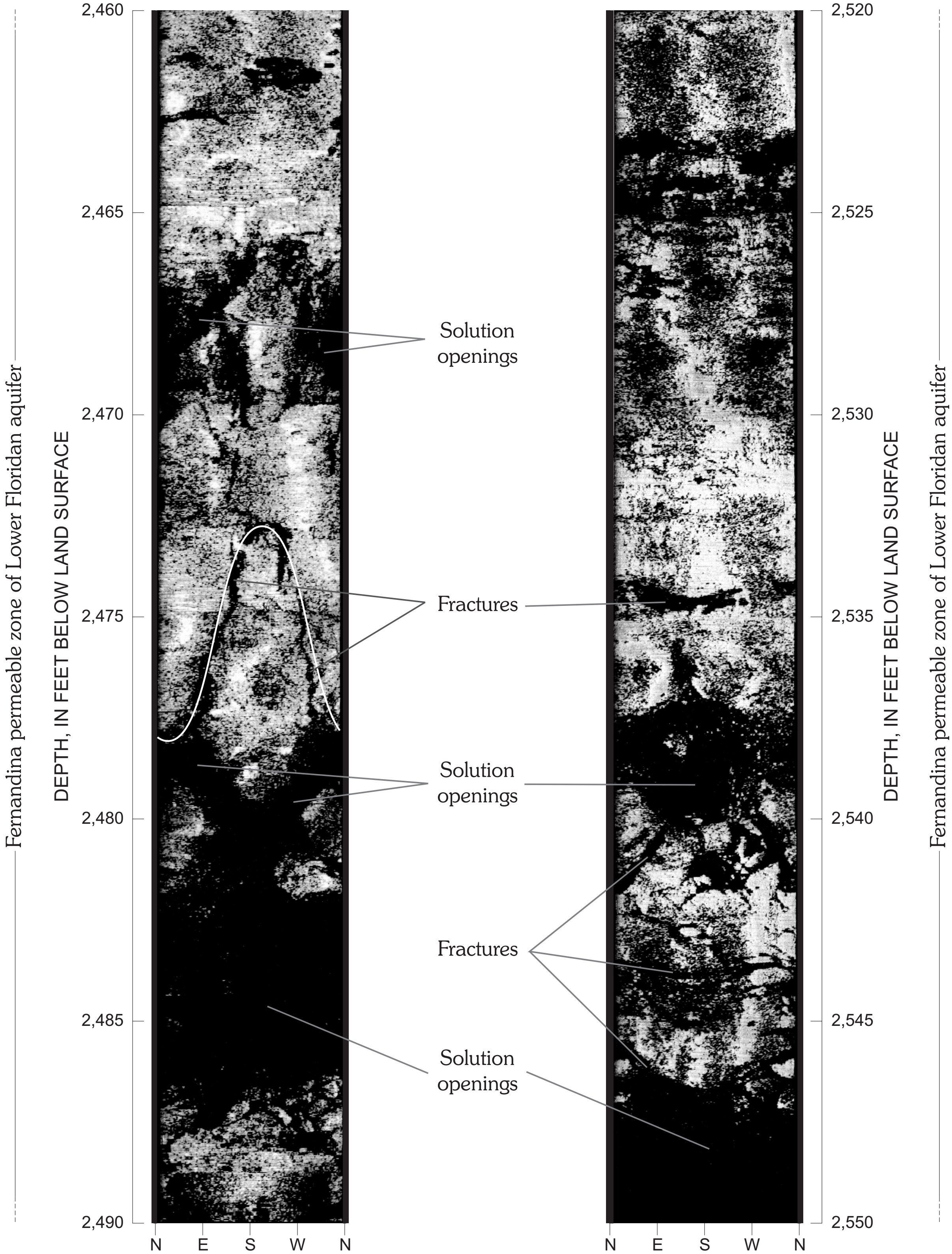

Figure 11. Acoustic-televiewer images from TW-26, near Brunswick, Georgia, showing hydrogeologic units, depth intervals 2,460–2,490 feet and 2,520–2,550 feet. Letters at bottom of images are compass directions (modified from Maslia and Prowell, 1990).

dolostone and dolomitic limestone. The dolomitic strata generally are non-porous, aphanitic, and tan, gray, or brown. Patches of chalky limestone are present within the dolomitized intervals and are associated with semi-recrystallized masses of megafossils. Like the Cretaceous strata, these rocks probably were deposited as shelly limestone that later was dolomitized. No age determinations were obtained from core samples of presumed Paleocene strata at TW-26, but Miller (1986) included these rocks as Midwayan (stage) Cedar Keys Formation of the Paleocene.

In the upper part of the Paleocene strata, numerous, irregular, near-horizontal vugs and solution cavities, as much as about 3 ft in height, are apparent on ATV images and caliper logs at about 2,142–2,197 ft (fig. 9, in back of report). In contrast to the large, angular, fracture openings in the Cretaceous strata, these openings are relatively smooth-sided, suggesting dissolution as the probable causative agent. Other near-horizontal solution openings appear on ATV images within the Paleocene strata (figs. 9 and 10, in back of report) over the interval 2,287–2,298 ft (several openings) and smaller discrete openings at 2,373 and 2,390 ft. These discrete, near-horizontal, solution openings usually are adjacent to intervals of relatively non-porous carbonate, where more reflected radiation is indicated on neutron logs. Other examples of similar correlations are discussed in the section on lower and middle Eocene strata, and in corresponding sections on Hydrogeologic Units.

Lower and middle Eocene strata

Muddy, fossiliferous limestone and dolostone unconformably overlie Paleocene rocks in the study area. Below about 2,141 ft in TW-26, the upper 50-55 ft of the Paleocene strata has numerous openings, apparent on the caliper log (plate 1) and in ATV images (fig. 9, in back of report); whereas, above about 2,141 ft, the lower part of the Eocene strata has fewer openings. A tentative pick between the lower and middle Eocene at about 1,941 ft is based on a conspicuous response on gamma-radiation logs (plate 1). The limestone in these units typically is light gray and some beds are highly fossiliferous and non-porous to porous. Most of the limestone is muddy and finely crystalline, but sparry calcite is present in irregular patches. Glauconite is common in the lowermost beds. The dolostone and dolomitic limestone layers are characteristically gray or brown, aphanitic, and non-porous. The original limestone texture and porosity generally have been removed by dolomitization, but the degree of alteration of the limestone can vary considerably over short intervals. The dolomitized strata typically are dense, and only in the upper few hundred feet of the unit does the dolomitized rock have substantial porosity. Thin beds of highly carbonaceous, calcareous mudstone and greenish-black, massive chert also are found in this section in TW-26, but the origin of these thin beds is uncertain. Some other beds also contain minor gypsum and/or anhydrite.

Dinoflagellate and calcareous nannofossil samples were analyzed from cores taken at 1,575, 1,595, 1,800, and 2,000 ft in TW-26, and were found to contain diagnostic species ranging in age from early Eocene to middle Eocene (Lucy E. Edwards, USGS, written commun., 1982; 1999; Laurel M. Bybell, USGS, written commun., 1983; see table 3). These age determinations, in conjunction with regional correlations by Miller (1986), indicate that this section is equivalent to the Oldsmar and Avon Park Formations in northern Florida. Although the samples in TW-26 provide no reliable lithologic criteria to differentiate these units, a tentative contact between units has been placed at a prominent spike (marker) on the gamma radiation logs at 1,930 ft (plate 1). This marker probably represents a bed of radioactive minerals that accumulated at the top of the early Eocene strata during a depositional hiatus.

Numerous irregular vugs and solution cavities appear on ATV images at about 943–1,015 ft (fig. 5, in back of report). Similar to those in the upper part of the Paleocene section discussed earlier, these openings are smooth-sided and suggest dissolution as a causative agent. A similar, but thinner, interval (about 1,217–1,237 ft) also appears to have numerous solution openings (fig. 6, in back of report).

Another notable feature in this sequence is the close juxtaposition of intervals of relatively non-porous carbonate—where more reflected radiation is indicated on neutron logs—and discrete, near-horizontal, solution openings discernible on the ATV images and caliper logs (figs. 5–7, in back of report). Examples of this juxtaposition are present in at least seven depth intervals: 944–973 ft, 1,078–1,083 ft; 1,102–1,107 ft; 1,367–1,372 ft; 1,460–1,468 ft; 1,665–1,674 ft; and 1,718–1,733 ft (figs. 5–7, in back of report). Other examples of similar correlations are discussed in the section on Paleocene strata, and in corresponding sections on Hydrogeologic Units. The intervals of non-porous carbonate in these units apparently are very hard, often requiring increased drilling time (plate 1). Within two larger intervals (about 1,080–1,125 ft and about 1,670–1,760 ft), drilling time is strongly proportional to the inverse of porosity, as indicated by the neutron log (plate 1).

Upper Eocene strata

White, tan, or light gray, fossiliferous limestone and fossil hash characterize upper Eocene units at TW-26. The contact is obscured by dolomitization, but has been tentatively placed at 925 ft on the basis of electric-log characteristics (plate 1). Thin calcareous sandstone layers interbedded with lime mudstone mark the upper limit of dolomitization near the center of the upper Eocene unit. The upper part of the unit is characterized by an abundance of whole or broken fossils, including foraminifera, bryozoans, mollusks, and echinoids. Muddy limestone and lime mudstone partially fill the voids in the shell-rich beds, but these layers still are porous. The upper part of the unit has a relatively low response on the natural gamma log; at shallower depth, the point directly below an increase in gamma radiation reflects the top of the upper Eocene unit, and is identified by a “D” on the natural-gamma log at 590 ft (plate 1).

A sample of muddy limestone from 626 ft yielded dinoflagellates and calcareous nannofossils that suggest an Eocene or Oligocene age (Laurel M. Bybell, USGS, written commun., 1982; Lucy E. Edwards, USGS, written commun., 1983; see table 3). Regional correlations by Miller (1986) and fossil identifications from samples in nearby wells (Herrick, 1961) suggest that the unit is the late Eocene-age Ocala Limestone.

Oligocene strata

A 20-ft-thick bed of white to light gray, nodular, locally calcitized, fossiliferous sandy limestone overlies the upper Eocene Ocala Limestone at TW-26. The base of the unit is identified by radioactive phosphate in a transgressive rubble bed just above the contact with the Eocene Ocala Limestone. Above this contact (D marker, plate 1), phosphatic limestone of Oligocene age produces a distinctive response on the natural-gamma log. The sandy limestone typically contains fragments of bryozoans and mollusk shells, whereas the upper Eocene calcitized beds are unfossiliferous and dense.

No paleontological data were obtained from this unit at TW-26, but Herrick (1961) identified foraminifera from this unit in nearby wells that suggest an Oligocene age. Regional correlations by Miller (1986) assigned these rocks to the Suwannee Limestone, suggesting they are the stratigraphic equivalent of the Ashley Member of the Cooper Marl in South Carolina (Ward and others, 1979).

Miocene strata

Unconformably overlying the Oligocene limestone in Glynn County is a 400-ft-thick sequence of phosphatic quartz sand, gravel, clay, marl, limestone, and dolomitic limestone. The sand is moderately sorted, fine to coarse quartz containing sparse small, well-rounded gravels and sand to pebble grains of phosphate in trace to moderate amounts. The clay and marl layers typically are dark-green, sandy to silty, and commonly phosphatic. Herrick (1961) also reported beds of light brown, sandy, locally phosphatic, saccharoidal dolomitic limestone in this unit; however, these were not observed in the cuttings from TW-26. Shell fragments are common in limestone layers and some sand layers, but no fossils have been identified from this unit in TW-26 or in wells examined by Herrick (1961). The age of this unit is based on stratigraphic position and on regional extrapolations by Herrick (1961) and Miller (1986). In the Glynn County area, this unit generally is placed in the Hawthorn Group of Miocene age, and may contain the Parachucla and Marks Head Formations in the lower part of the section and possibly the Berryville Clay, the Ebenezer, and(or) the Charlton Members of the Coosawhatchee Formation in the upper part (Huddleston, 1988).

Three beds within the Miocene strata typically are rich in radioactive elements (mainly phosphate minerals) in the Glynn County area, and have characteristic responses on natural-gamma geophysical logs. The deepest of these beds, informally called the C marker (labeled with a “C” on plate 1), is present at or near the contact between Miocene strata and the underlying Oligocene limestone, which is at 575 ft in TW-26. This contact probably represents a depositional hiatus (unconformity) of considerable time, because such a hiatus in an open marine environment is commonly marked by a bed of phosphatic debris. An intermediate B marker and an uppermost A marker (labeled “B” and “A”, respectively, on plate 1) mark similar contacts. Wait (1962) first identified the D marker (Oligocene/Eocene) and the C, B, and A markers (Miocene) on natural-gamma logs from the Glynn County area. Clarke and others (1990) informally named discrete geologic units C, B, and A within the Miocene strata in coastal Georgia, corresponding to the sediments above each of the C, B, and A markers.

Post-Miocene strata

The upper 80 ft of strata penetrated by TW-26 is characterized by fine, micaceous quartz sand and minor amounts of rounded gravel. Within the sand are grains of phosphate and numerous shell fragments. Thin beds of interbedded lignitic clay and silt, marl, and limestone also are present, but the thick marine clay beds that characterize the underlying Miocene unit are absent. The absence of these clay beds probably accounts for the low natural radioactivity as determined from natural-gamma geophysical logs. Although some beds are rich in macrofossils, no paleontological determinations are available to accurately establish the age of the strata. These post-Miocene strata are considered to be some combination of beds of Pliocene, Pleistocene, and(or) Holocene age and are undifferentiated at TW-26. Possible stratigraphic equivalents are the Raysor Formation, the Duplin Formation, and(or) the Waccamaw Formation of South Carolina in the lower part of the section. The upper part of the section probably contains the more local Cypress Head and Satilla Formations (Huddleston, 1988).

Hydrogeologic Units

The Floridan aquifer system is the dominant subsurface hydrogeologic unit in Glynn County and along the Georgia coast. The system underlies all of Florida, most of the Coastal Plain physiographic province of Georgia, and parts of the Coastal Plain of South Carolina and Alabama. The Floridan aquifer system is one of the most productive in the United States, and is the principal source of potable water in coastal Georgia. Throughout southeast Georgia, the Floridan aquifer system is divided into the Upper and Lower Floridan aquifers, which contain several distinct water-bearing subdivisions that are hydraulically connected in varying degrees (Miller, 1986). In the Glynn County area, in addition to a shallow surficial aquifer system, confined to semiconfined water-bearing zones also have been identified above the Floridan aquifer system (Clarke and others, 1990). These shallower aquifers are a secondary source of potable and non-potable water.

Few data were collected from TW-26 directly pertaining to the aquifer properties of the various water-bearing units, all of which, except for the deepest unit, were cased off and grouted in the completed well. Depths and thicknesses of hydrogeologic units were estimated based on previous investigations in the area, geologic data, water-quality data, and interpretation of geophysical logs (plate 1) and ATV images (in back of report) from the test well. However, due to the lack of data such as results of reliable flow metering or aquifer testing, the depths and thicknesses of the hydrogeologic units are approximate, and local aquifer properties are unknown. For more detailed information on the subsurface hydrogeologic framework and aquifer properties within Glynn County and in the Glynn County region, refer to Wait (1965), Wait and Gregg (1973), Gregg and Zimmerman (1974), Miller (1986), Krause and Randolph (1989), Clarke and others (1990), and Jones and Maslia (1994).

General descriptions of the major hydrogeologic units of the Floridan aquifer system penetrated by TW-26 are presented below. Brief descriptions of shallower hydrogeologic units also are included for completeness, but are not the subject of this report. Semiconfining units that confine or partially confine an underlying aquifer are discussed in the sections on the underlying aquifers. Some semiconfining units lie between individual water-bearing units of an aquifer.

Surficial aquifer

The surficial aquifer in the Glynn County area (fig. 3, plate 1) includes one or more water-bearing zones and consists of sandy layers in undifferentiated upper Miocene and post-Miocene strata. The surficial aquifer is a secondary source of water supply in the Glynn County area. The uppermost water-bearing zone is under water-table conditions. Based on information from shallow wells throughout the Glynn County area, deeper water-bearing zones are under confined or semiconfined conditions due to the presence of clay confining units within the aquifer (Clarke and others, 1990). Electric logs suggest that the aquifer extends to about 250 ft at TW-26 (plate 1).

Upper and lower Brunswick aquifers

Two relatively low-yielding water-bearing zones in Miocene rocks in the Glynn County and surrounding areas have been named the upper and lower Brunswick aquifers (Clarke and others, 1990; fig. 3, plate 1). The Brunswick aquifers probably were at one time an integral part of ground-water supply in the Glynn County area. However, as water demand increased, the preferred source of water supply became the well-consolidated Ocala Limestone of the Upper Floridan aquifer, which yielded more water and was less susceptible to well failure due to caving than the less consolidated sediments of the Brunswick aquifers. As drillers recognized this, longer casing strings usually were installed to exclude the Brunswick aquifers, which became secondary in importance for water supply. In 1997, due to chloride contamination of the Upper Floridan aquifer at Brunswick, the GaEPD capped pumpage from the Upper Floridan aquifer at 1997 permitted levels, prompting renewed usage of the upper and lower Brunswick aquifers as an alternative source of water.

The Brunswick aquifers are overlain by a semiconfining unit composed of dense, phosphatic limestone and(or) dolomite, and phosphatic, silty clay of Miocene age (the Berryville Clay). The tops of the Brunswick aquifers are defined by the upper two thin layers that produce prominent spikes on natural-gamma logs, the “A” and “B” markers (discussed in the section on Miocene strata). Electric logs shown on plate 1 suggest that the upper Brunswick aquifer extends from the “A” marker at about 326 ft to about 387 ft (about 61-ft thick), and the lower Brunswick aquifer extends from the “B” marker at about 448 ft to about 500 ft (about 52-ft thick).

Upper Floridan aquifer

In the Brunswick area, the Upper Floridan aquifer provides nearly all municipal and most industrial water supply; in Glynn County, pumpage from the aquifer was 65 million gallons per day (Mgal/d) in 1997 (Fanning, 1999). Due to chloride contamination of the Upper Floridan aquifer in Brunswick, in 1997 the GaEPD capped usage of the aquifer in Glynn County at 1997 permitted levels.

Continuous beds of low-permeability clay within lower Miocene sediments probably provide partial to complete confinement of the Upper Floridan aquifer. The top of the Upper Floridan aquifer is defined as the top of the Oligocene limestone (at about 575 ft in TW-26), and the aquifer includes the Oligocene limestone and limestone and dolomite in upper Eocene sediments. In the Glynn County area, the Upper Floridan aquifer has two primary permeable zones—the upper and lower water-bearing zones—which are separated by a dolomitic limestone semiconfining unit. The high permeability of the sediments that make up the upper and lower water-bearing zones is commonly the result of solution openings, which are evident in selected ATV images (fig. 12). ATV images and the caliper log (figs. 4 and 5, in back of report) clearly indicate the solution cavities and the extent of water-bearing zones, and suggest that in TW-26, the upper water-bearing zone of the Upper Floridan aquifer extends from about 575–741 ft (about 166-feet thick), and the lower water-bearing zone extends from about 944–1,015 ft (about 71-feet thick). In the upper part of the lower water bearing zone (about 944–973 ft), large solution cavities have formed in sediments adjacent to a very non-porous layer several feet thick, centered at about 955 ft (as indicated by high counts per second on neutron log in figure 5, in back of report). Dissolution may increase as ground water fills openings caused by fracturing of brittle, non-porous carbonates, and probably provides conduits for the movement of large volumes of ground water.

Lower Floridan aquifer

The lower part of the Floridan aquifer system, called the Lower Floridan aquifer, is less well defined than the Upper Floridan aquifer in the Glynn County area due to the scarcity of wells deep enough to penetrate it. Only a few wells open to the uppermost part of the Lower Floridan aquifer are used for water supply. In the Brunswick area, the Lower Floridan aquifer probably consists of at least three water-bearing zones—two unnamed zones are tentatively identified in the upper and middle parts of the aquifer, and the Fernandina permeable zone is in the lower part of the aquifer. ATV images and the caliper log from TW-26 also suggest one water-bearing zone in the interval about 1,078–1,238 ft (figs. 5 and 6, in back of report), and a second in the interval about 1,529–1,758 ft (fig. 7, in back of report). Gregg and Zimmerman (1974) also identified two water-bearing zones in the upper and middle parts of the Lower Floridan aquifer in Brunswick, which they called the “brackish-water zone” and the “deep freshwater zone,” respectively, based on the quality of water from the zones. Water-quality data, discussed later, indicate the two zones identified by Gregg and Zimmerman (1974) probably correspond to the two water-bearing zones identified above.

The Lower Floridan aquifer is confined by overlying middle Eocene dolomite and dolomitic limestone called the middle semiconfining unit. The base of the Lower Floridan aquifer and the Floridan aquifer system, which Miller (1986) estimated to be at a depth of more than 3,000 ft in the southern Glynn County, was not penetrated by TW-26.

As in the lower water-bearing zone of the Upper Floridan aquifer, several other examples of solution cavities (ATV images and caliper log) that have formed adjacent to non-porous dolomite layers (more counts per second on neutron log) occur in the upper part of the Lower Floridan aquifer (figs. 5–7, in back of report). The most prominent of these occurrences are near 1,081, 1,103, 1,123, 1,220, 1,368, 1,463, 1,672, and 1,730 ft. Most of the occurrences are within one of the two possible water-bearing zones. The two occurrences that are not within the possible water-bearing zones (near 1,368 and 1,463 ft) are isolated from the others

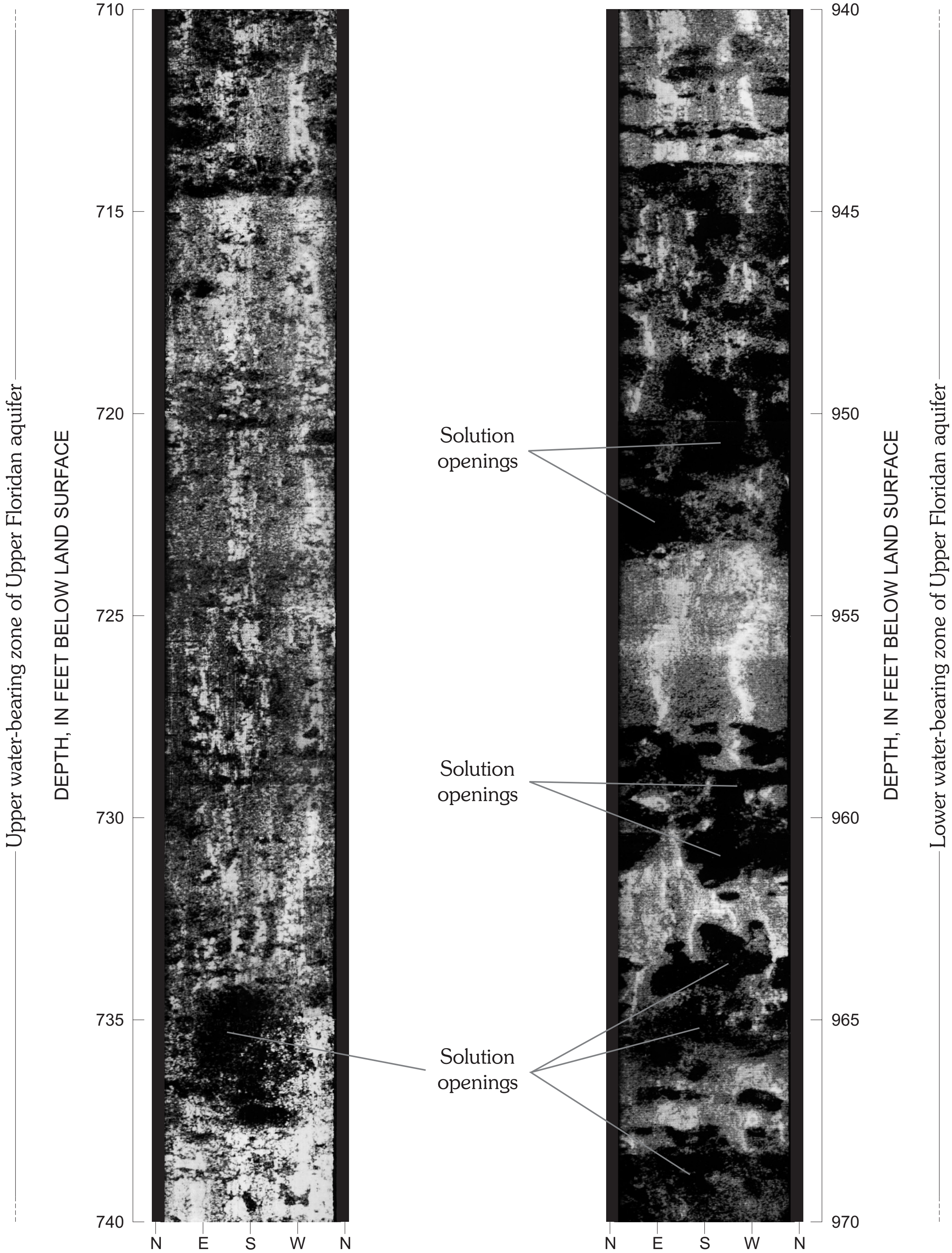

Figure 12. Acoustic-televiewer images from TW-26, near Brunswick, Georgia, showing hydrogeologic units, depth intervals 710–740 feet and 940–970 feet. Letters at bottom of images are compass directions.

by about 100 ft or more of sediments that do not appear to have substantial solution cavities, and probably transmit smaller volumes of water. Below the lower of the two possible water-bearing zones are nearly 400 ft of sediments (about 1,758–2,143 ft) that do not appear to have substantial solution cavities, and have been called the lower semiconfining unit.

The deepest known water-bearing unit of the Lower Floridan aquifer is the Fernandina permeable zone, which was first penetrated by a 2,130-ft-deep test well at Fernandina Beach, Fla., in 1945. In Glynn County, the zone is deeper and consists of Paleocene and Upper Cretaceous limestone and dolomite, which have extremely high permeability and are locally cavernous (Krause and Randolph, 1989). Large voids in this zone are clearly apparent in ATV (figs. 9 and 10, in back of report) and video images, and the drilling rods reportedly dropped about 4 ft at about 2,496 ft and about 3 ft at about 2,561 ft (Gail D. Mitchell, USGS, written commun., 1978). Also, a 9-ft-deep cavern was probably encountered at 2,248–2,257 ft (see discussion in section on Upper Cretaceous). Video images indicate these openings transmit large quantities of ground water. ATV images, caliper and neutron logs, and chloride-concentration data indicate the Fernandina permeable zone occurs from about 2,143 ft to at least the bottom of TW-26 at 2,727 ft (figs. 9 and 10, in back of report; plate 1).

The water level in completed TW-26 (open interval 2,138–2,727 ft in the Fernandina permeable zone) has been monitored intermittently using a continuous water-level recorder from 1978 to the present (2002). In figure 13, available monthly mean water levels in TW-26 are compared to monthly mean water levels in a well in Brunswick open to the upper part of the Lower Floridan aquifer (TW-16; fig. 1, table 1). Water levels in both wells generally fluctuate around an annual cycle of lows in summer to early fall, and highs in the winter to early spring. A typical annual water-level change is about 3–4 ft. Apparent long-term water-level trends, over multiple years, include: 1978–1981, a gradual decline; 1981–1983, a rapid rise related to industrial conservation measures; 1983–1990, a moderate decline; 1990–1995, a moderate rise (reduced industrial pumpage); and finally, 1995–2000, a gradual decline. Except for wells located close to pumping centers, these same general trends are apparent in water-level records for most wells open to any of the water-bearing zones in the Floridan aquifer system in the Brunswick area.

On two occasions, the water level in TW-26 decreased several feet within a month, March–April, 1984 (6.55 ft) and November–December, 1994 (4.30 ft). Original well records of water levels at TW-26 do not indicate any irregularities; data from an automatic water-level recorder were verified by field-measured water levels. However, a large decrease in water level would not be expected in a

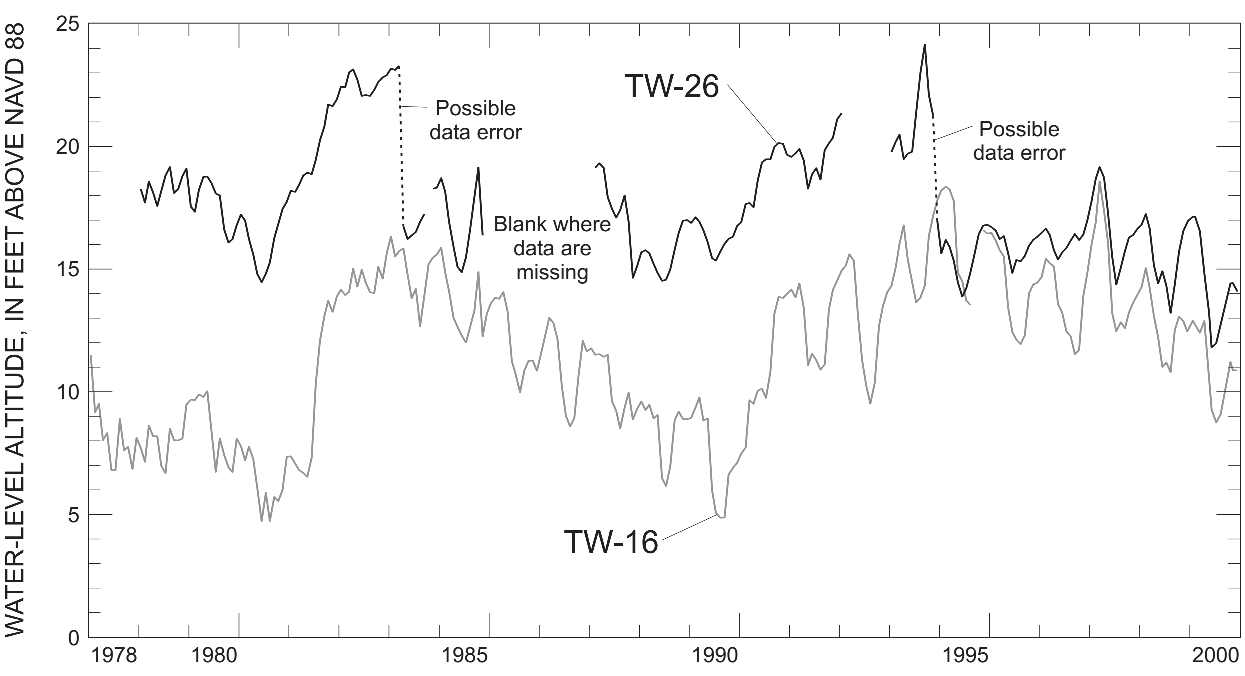

Figure 13. Water level in TW-26, near Brunswick, Georgia, and in TW-16 in south Brunswick, Georgia (modified from Cressler and others, 2001; see figure 1 and table 1 for well locations).

water-bearing zone that is not stressed by pumpage, and similar decreases were not documented in any other wells during these two 1-month periods. Reported decreases on these two occasions could be the result of measurement error and(or) unexpected effects of pumping the well.

GROUND-WATER QUALITY

The primary objective of constructing TW-26—to determine the distribution of high-chloride water in the Floridan aquifer system—was addressed by sampling ground water at many points within the Floridan aquifer system. Ground-water samples were collected: from borehole discharge every 5-10 ft during drilling of the middle and lower sections; from bailing at various open-hole depths; from pumped-interval discharge during packer tests; and from discharge from the completed well. Variation in chloride concentration in the samples (fig. 14) provides information on the depths and salinity of saltwater-bearing zones at TW-26, and comparing chloride concentration in and specific conductance of samples indicates indirectly a change in water type at different depths. Relative ionic content of samples from various depths and depth intervals (table 4) also indicates water type, and is compared graphically to typical modern seawater and to freshwater from the Upper Floridan aquifer at Brunswick to help determine origin and movement of saltwater through the Floridan aquifer system in the Brunswick area. Water types of samples from TW-26 (including a typical sample from the upper water-bearing zone of the Upper Floridan aquifer in Brunswick, unavailable at TW-26), ranged from a calcium/magnesium-sulfate/bicarbonate type in the upper part of the Upper Floridan aquifer, to a calcium/magnesium-sulfate type in the middle part of the Lower Floridan aquifer, to a sodium-chloride type in the Fernandina permeable zone in the lower part of the Lower Floridan aquifer. Major ionic-concentration ranges of samples (including a typical upper water-bearing zone sample) were: calcium (43–1,800 mg/L), magnesium (25–1,000 mg/L), potassium (negligible to 300 mg/L), sodium (15–22,000 mg/L), bicarbonate (44–150 mg/L), chloride (17–33,000 mg/L), and sulfate (94–4,400 mg/L); and total dissolved solids ranged from about 300 mg/L to about 60,000 mg/L.

The state of well construction and conditions under which ground-water samples were collected are important considerations in interpreting water-quality data from TW-26. The Floridan aquifer system was penetrated by the middle (598–1,525 ft) and lower (1,525–2,727 ft) drilled sections (fig. 2). After drilling, the middle section was completely cased and the lower section was partly cased (to 2,138 ft). Thus, the open-hole interval available to contribute water for sampling varied considerably over the sampling period, and all open-hole samples are subject to uneven mixing due to differences in pressure between water-producing zones within the open hole. During drilling, water from the formation was entering the borehole over the interval from the bottom of the casing to the depth of the drill bit. Water from the various open zones was mixed and drawn downward in the borehole annular space, through the drill bit, and then upward through the drilling column. The resulting drilling-fluid discharge contains drill cuttings suspended in water that is a variable mixture of waters from all water-producing zones in the available open interval; but, the water mixture probably better represents water-producing zones near the drill bit. Bailer samples were collected at varying depths within the available open hole when the well was flowing freely, not stressed by drilling or pumping. Bailer samples may represent the formation water at the sampling depth if that part of the borehole water column was relatively stagnant, or may represent a mixture of waters from available water-producing zones if the borehole water is moving under a pressure gradient between water-bearing zones and(or) the atmosphere. Pumped-interval samples represent a mixture of waters from all water-producing zones within the pumped interval, and samples from the completed well are a mixture of waters from water-producing zones within the Fernandina permeable zone.

Chloride Concentration and Specific Conductance

Field-measured chloride-concentration and specific-conductance data from the drilling discharge of TW-26 over the depth interval 645–2,720 ft and hydrogeologic units are shown in figure 14. Using a logarithmic scale, abrupt relative increases and decreases in chloride concentration and specific conductance are discernible within water-bearing zones and semiconfining units of the Floridan aquifer system. Although discharge samples may represent a mixture of water entering the entire open interval, sharp increases in chloride concentration are possible only where a zone of more saline water is present. Chloride-concentration data also are plotted on plate 1 for comparison to geophysical logs and geologic and hydrogeologic units. For reference, figure 14 also shows three chloride concentrations: (1) the secondary standard (formerly known as the Secondary Maximum Contaminant Level or SMCL) for drinking water (250 mg/L, U.S. Environmental Protection Agency, 2000); (2) the maximum yet detected in the Upper Floridan aquifer in Brunswick

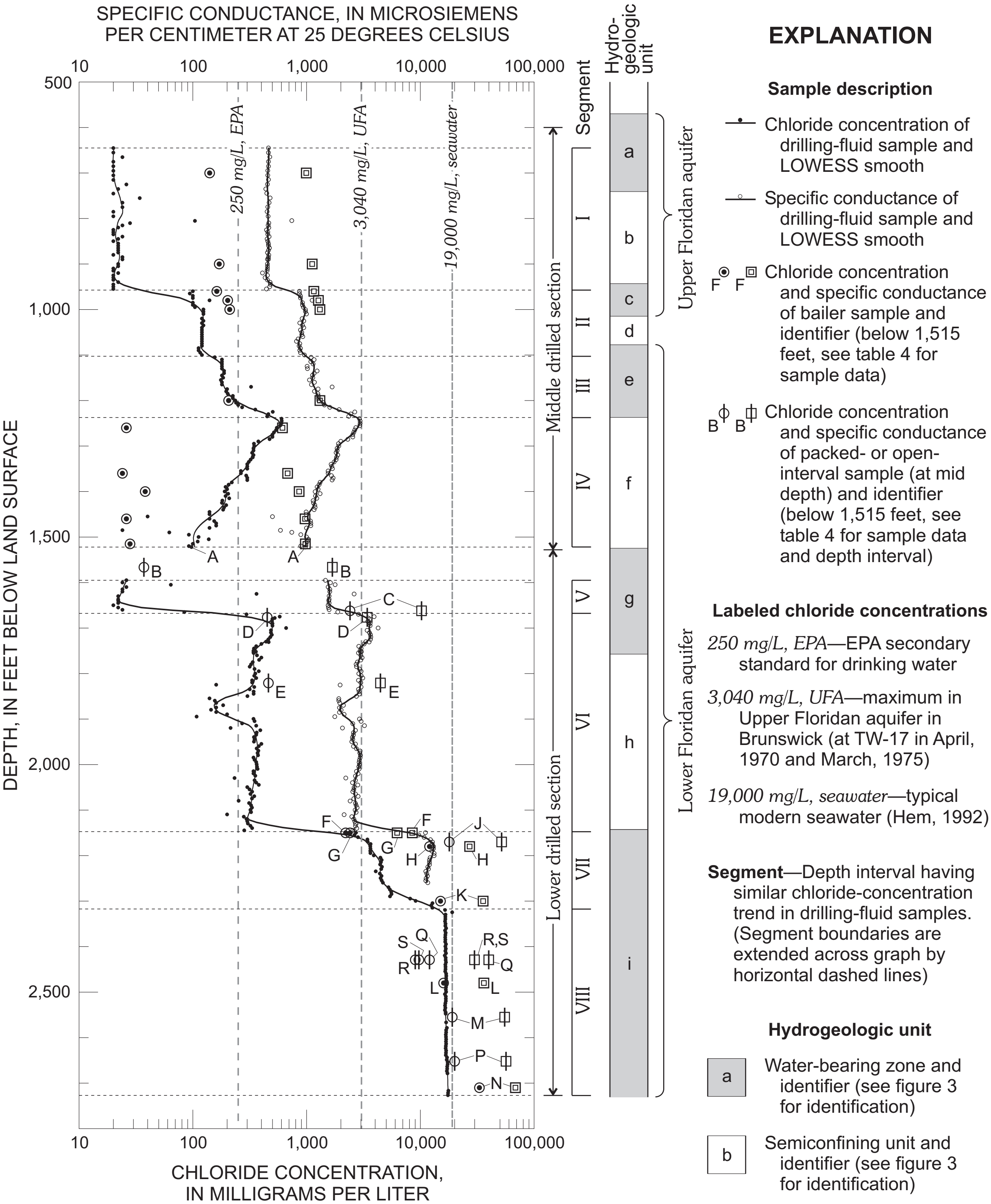

Figure 14. Chloride concentration, specific conductance, and depth of water samples from TW-26, near Brunswick, Georgia, and segments of similar chloride-concentration trend.

Table 4. Physical properties, ionic and other constituent concentrations of a water sample from well GPP&P 2 at Brunswick, Georgia, water samples from TW-26, near Brunswick, and modern seawater

[Sample identifier shown in figure 14; na, not applicable; µS/cm, microSiemens per centimeter; —, data not available; ° C, degrees Celsius; mg/L, milligrams per liter; <, less than; µg/L, micrograms per liter; nd, not detected]

Constituent, in units	Well GPP&P 2	Identifier for water samples from TW-26								
		A	B	C	D	E	F	G	H	J
Sampling date	04/10/68	03/17/78	09/16/78	09/16/78	09/14/78	09/09/78	01/10/80	08/24/81	08/25/81	09/12/78
Sampling depth or depth interval, in feet	448–849	1,522	1,525–1,608	1,612– 1,712	1,525–1,828	1,525–2,116	2,150	2,150	2,180	2,120–2,220
Sampling method or sampling location	open interval	drilling fluid	above packers[1/]	within packers	above packers[2]	above packers[3]	bailer	bailer	bailer	within packers
Physical properties and constituents										
pH, standard units	7.4	—	7.5	7.3	7.4	7.5	—	7.3	7.2	7.6
Specific conductance, µS/cm at 25 ° C	455	972	1,680	10,200	3,400	4,450	8,500	6,250	27,100	51,800
Temperature[5], ° C	—	27.0	28.5	32.5	29.0	22.0	21.0	25.0	24.5	27
Hardness as $CaCO_3$										
Total, mg/L	210	380	1,100	2,800	1,600	1,500	—	2,700	—	3,600
Noncarbonate, mg/L	93	270	950	2,600	1,500	1,400	—	2,600	—	3,500
Cations										
Calcium, mg/L	43	71	190	510	280	260	—	470	—	1,100
Magnesium, mg/L	25	49	140	360	210	200	—	370	1,000	200
Potassium, mg/L	2	3	10	27	11	10	—	29	<0.1	300
Sodium, mg/L	15	60	33	1,500	300	300	—	1,700	7,200	11,000
Alkalinity										
Alkalinity, mg/L as $CaCO_3$	118	110	110	120	110	110	—	100	110	120
Bicarbonate, mg/L	140	130	130	150	140	140	—	[6/]120	[6/]130	150
Carbonate, mg/L	0	0	0	0	0	0	—	—	—	0
Carbon dioxide, dissolved, mg/L	9.1	—	6.5	12.0	8.9	7.0	—	—	—	6.0
Anions										
Chloride, mg/L	17	97	37	2,400	450	460	2,200	2,400	12,000	18,000
Fluoride, mg/L	0.7	0.8	1.5	2.8	1.8	1.7	—	1.6	1.9	3.2
Sulfate, mg/L	94	260	910	2,100	1,300	1,200	—	2,000	2,600	3,500
Bromide, mg/L	—	—	0.2	—	2.7	—	14	11	69	86
Iodide, mg/L	—	—	0.11	—	0.22	—	0.03	0.50	0.39	0.74

See footnotes on page 24.

Table 4. Physical properties, ionic and other constituent concentrations of a water sample from well GPP&P 2 at Brunswick, Georgia, water samples from TW-26, near Brunswick, and modern seawater—Continued

[Sample identifier shown in figure 14; na, not applicable; µS/cm, microSiemens per centimeter; —, data not available; ° C, degrees Celsius; mg/L, milligrams per liter; <, less than; µg/L, micrograms per liter; nd, not detected]

Identifier for samples from TW-26								Seawater (Hem, 1992)	Constituent, in units
K	L	M	N	P	Q	R	S		
08/25/81	08/25/81	09/6/78	08/25/81	09/06/78	10/16/78	01/25/80	07/21/99	na	Sampling date
2,300	2,480	2,530–2,580	2,710	2,584–2,720	2,138–2,720	2,138–2,720	2,138–2,720	na	Sampling depth or depth interval, in feet
bailer	bailer	within packers	bailer	below packers[4]	open interval	open interval	open interval	na	Sampling method or sampling location
Physical properties and constituents									
7.1	7.0	7.3	7.5	7.0	7.0	—	7.3	—	pH, standard units
35,600	36,200	55,100	68,600	56,600	39,900	29,900	29,900	—	Specific conductance, µS/cm at 25 ° C
25.5	25.5	19.0	26.0	20.0	34.0	32.5	33.5	—	Temperature[5], ° C
									Hardness as $CaCO_3$
5,900	6,500	7,000	7,500	6,900	5,200	3,100	4,600	—	Total, mg/L
5,700	6,400	6,900	7,400	6,800	5,200	3,000	—	—	Noncarbonate, mg/L
Cations									
1,000	1,100	1,300	1,800	1,300	940	310	820	410	Calcium, mg/L
810	910	900	710	880	720	570	610	1,350	Magnesium, mg/L
<0.1	<0.1	300	0.0	300	21	150	120	390	Potassium, mg/L
8,200	8,900	11,000	22,000	11,000	7,000	5,000	5,700	10,500	Sodium, mg/L
Alkalinity									
120	120	98	36	98	110	120	120	—	Alkalinity, mg/L as $CaCO_3$
[6/]150	[6/]150	120	[6/]44	120	140	[6/]150	[6/]150	142	Bicarbonate, mg/L
—	—	0	—	0	0	—	—	—	Carbonate, mg/L
—	—	9.6	—	19.0	22.0	—	—	—	Carbon dioxide, dissolved, mg/L
Anions									
15,000	16,000	19,000	33,000	20,000	12,000	9,000	9,700	19,000	Chloride, mg/L
2.0	1.6	2.6	1.3	3.4	2.0	2.8	1.6	1.3	Fluoride, mg/L
3,000	2,700	4,200	3,200	4,400	2,900	2,700	2,900	2,700	Sulfate, mg/L
80	80	90	130	90	—	—	31	67	Bromide, mg/L
0.50	0.35	0.76	0.44	0.86	—	—	—	0.06	Iodide, mg/L

Table 4. Physical properties, ionic and other constituent concentrations of a water sample from well GPP&P 2 at Brunswick, Georgia, water samples from TW-26, near Brunswick, and modern seawater—Continued

[Sample identifier shown in figure 14; na, not applicable; µS/cm, microSiemens per centimeter; —, data not available; ° C, degrees Celsius; mg/L, milligrams per liter; <, less than; µg/L, micrograms per liter; nd, not detected]

Constituent, in units	Well GPP&P 2	Identifier for samples from TW-26								
		A	B	C	D	E	F	G	H	J
Other constituents										
Silica, mg/L	33	35	3	25	30	29	—	19	16	15
Nitrogen, $NO_2^-+NO_3^-$, mg/L as N	0.1	<0.01	<0.01	1.40	0.01	<0.01	—	0.04	0.02	<0.01
Dissolved solids										
Residue at 180° C, mg/L	300	689	1,630	7,890	2,980	2,830	—	8,390	27,600	35,900
Sum of constituents, mg/L	301	640	1,400	7,020	2,660	2,540	—	7,070	—	34,300
Other elements										
Aluminum, µg/L	—	30	20	10	20	20	—	30	40	20
Arsenic, µg/L	—	<1	<1	<1	<1	<1	—	1	1	<1
Barium, µg/L	—	—	<100	<100	<100	<100	—	<50	<50	<100
Cadmium, µg/L	—	2.0	<2.0	<2.0	<2.0	<2.0	—	4.0	2.0	<2.0
Chromium, µg/L	—	<2	<2	<2	<2	<2	—	10	10	2
Cobalt, µg/L	—	—	2	<2	<2	2	—	3	3	<2
Copper, µg/L	—	nd	3	3	5	3	—	4	2	3
Iron, µg/L	—	70	1,300	2,400	700	260	—	—	300	18,000
Lead, µg/L	—	nd	4	20	6	3	—	1	2	8
Manganese, µg/L	—	<10	30	60	20	<10	—	—	—	160
Mercury, µg/L	—	<0.5	<0.5	<0.5	<0.5	<0.5	—	0.7	0.8	<0.5
Nickel, µg/L	—	—	2	nd	5	2	—	11	11	2
Selenium, µg/L	—	<1	<1	<1	<1	<1	—	<1	<1	<1
Strontium, µg/L	570	—	5,000	11,000	6,700	6,200	—	11,000	18,000	2,000
Zinc, µg/L	—	<20	nd	<20	nd	nd	—	110	480	20

[1]Packed interval, 1,612–1,712 ft.
[2]Packed interval, 1,832–1,942 ft.
[3]Packed interval, 2,120–2,220 ft.
[4]Packed interval, 2,530–2,580 ft.
[5]Sample temperature—not formation temperature.
[6]Calculated from alkalinity (Hem, 1992, p. 55).

Table 4. Physical properties, ionic and other constituent concentrations of a water sample from well GPP&P 2 at Brunswick, Georgia, water samples from TW-26, near Brunswick, and modern seawater—Continued

[Sample identifier shown in figure 14; na, not applicable; µS/cm, microSiemens per centimeter; —, data not available; ° C, degrees Celsius; mg/L, milligrams per liter; <, less than; µg/L, micrograms per liter; nd, not detected]

Identifier for samples from TW-26								Seawater (Hem, 1992)	Constituent, in units
K	L	M	N	P	Q	R	S		
Other constituents									
15	15	13	6.1	12	19	24	23	6.4	Silica, mg/L
0.04	<0.01	<0.01	0.02	0.01	0.03	0.01	<0.02	0.67	Nitrogen, NO_2^-+NO_3^-, mg/L as N
									Dissolved solids
34,200	34,600	36,100	59,000	36,600	25,600	—	20,000	—	Residue at 180° C, mg/L
28,200	29,800	36,900	60,900	38,100	23,700	17,800	19,900	34,600	Sum of constituents, mg/L
Other elements									
30	30	<100	40	<100	520	—	<10	1	Aluminum, µg/L
1	1	1	1	<1	<1	—	—	3	Arsenic, µg/L
<50	<50	<100	<50	<100	<100	—	40	20	Barium, µg/L
3.0	2.0	<2.0	2.0	nd	2.0	—	<10	0.11	Cadmium, µg/L
7	10	5	8	5	<2	—	<10	0.05	Chromium, µg/L
2	3	3	2	<2	<2	—	<10	0.4	Cobalt, µg/L
3	3	2	4	3	<2	—	<10	3	Copper, µg/L
—	—	18,000	—	18,000	130	—	310	3	Iron, µg/L
1	2	6	1	3	37	—	<10	0.03	Lead, µg/L
—	—	420	—	480	60	—	<10	2	Manganese, µg/L
0.7	0.7	<0.5	0.5	<0.5	<0.5	—	—	0.2	Mercury, µg/L
11	12	3	11	3	2	—	<10	7	Nickel, µg/L
<1	<1	<1	<1	<1	<1	—	—	0.09	Selenium, µg/L
17,000	18,000	21,000	34,000	21,000	15,000	—	16,000	8,000	Strontium, µg/L
500	540	30	850	20	<20	—	<10	10	Zinc, µg/L

(3,040 mg/L, in April 1970, and March 1975, at TW-17 (fig.1)); and (3) that of typical modern seawater (19,000 mg/L, Hem, 1992, p. 7).

The Floridan aquifer system at TW-26 was divided into eight depth intervals, designated segments, based on the similarity in trend of chloride concentration in and specific conductance of drilling-fluid samples (fig. 14). Samples in segments I–IV, within of the middle drilled section, represent a mixture of water entering the borehole from the bottom of the 16-inch casing (598 ft) to the indicated depth of the drill bit; and samples in segments V–VIII, within the lower drilled section, represent a mixture of water from the bottom of the 10-inch casing (1,525 ft) to the indicated depth (fig. 2). The following descriptions of these segments are based on general trends in drilling-fluid samples and isolated distant outliers are not included. LOWESS smooths of the chloride-concentration and specific-conductance data indicate general trends (fig. 14). LOWESS, or LOcally WEighted Scatterplot Smoothing (Cleveland, 1979), is a method for determining the central tendency along the *x*-axis of scattered *x-y* data by fitting successive weighted-least-squares equations. The regression-equation weights are a function of both the distance from *x* and the magnitude of the residual from the previous regression (Helsel and Hirsch, 1992); thus, isolated distant outliers have little affect on a LOWESS smooth.

Middle drilled section (segments I–IV)—598–1,528 feet

Throughout segment I (645–965 ft, fig. 14), chloride concentration in drilling-fluid samples was generally very low (20–34 mg/L), suggesting segment I represents uncontaminated water from the upper water-bearing zone of the Upper Floridan aquifer. Near the top of the lower water-bearing zone of the Upper Floridan aquifer (970 ft), chloride concentration in drilling-fluid samples increased sharply (the first interface) to about 100 mg/L and remains nearly constant (94–124 mg/L) over the interval 970–1,100 ft, designated segment II. Segment II includes almost all of the lower water-bearing zone, the middle semiconfining unit, and the uppermost part of the unnamed, water-bearing zone at the top of the Lower Floridan aquifer. Near the top of this unnamed zone (1,105 ft), the chloride concentration in drilling-fluid samples increased to 156 mg/L, which is defined as the top of segment III. In drilling-fluid samples from the upper part of segment III, chloride concentration remained relatively constant, but began increasing with increasing depth in the lower part, exceeding the secondary standard (250 mg/L) first at 1,170 ft, and continuing to increase to 602 mg/L at 1,240 ft. This saline zone probably corresponds to the “brackish-water zone” of Gregg and Zimmerman (1974). Segment IV (1,245–1,522 ft) has generally decreasing chloride concentration in drilling-fluid samples to about 100 mg/L at 1,522 ft, near the bottom of the middle drilled section. Decreasing chloride concentration in drilling-fluid samples at increasing depth is a less reliable indicator of the formation water quality than increasing concentration, because if the formation at the drill bit produces small quantities of freshwater, the drilling fluid will be mixed with possibly more saline water entering the well bore from above the drill bit. Chloride concentration in drilling fluid samples from the lower part of segment IV (1,450–1,520 ft) varies widely, from 20–160 mg/L, which is probably a result of variable mixing of the drilling fluid. The actual chloride concentration of formation water throughout segment IV is probably lower than is indicated by the drilling-fluid samples.

After the middle section had been drilled and reamed using a $15^{7}/_{8}$-inch bit and before setting the 10-inch casing, the temporary open interval (598–1,528 ft), which provided artesian water flow, was sampled 11 times using a bailer (fig. 14). The first five bailer samples, from within the Upper Floridan aquifer in segments I and II (600–1,000 ft), had much higher chloride concentrations than drilling-fluid samples from similar depth. These samples probably represent mixtures of waters from the upper and lower water-bearing zones of the Upper Floridan aquifer and from the unnamed water-bearing zone at the top of the Lower Floridan aquifer. Based on the drilling-fluid data, the lower part of this unnamed water-bearing zone, near the bottom of segment III (1,170–1,240 ft), is the first depth interval penetrated yielding water that had chloride concentration higher than the bailer sample from 1,000 ft, indicating that this zone produced enough water to contribute a large portion of the upward-flowing discharge from the temporary open interval 598–1,528 ft. Another bailer sample from 1,200 ft had chloride concentration similar to a same-depth drilling-fluid sample. Five bailer samples taken from within segment IV (1,260–1,515 ft), however, had much lower chloride concentrations (similar to freshwater in the upper water-bearing zone of the Upper Floridan aquifer) than in same-depth drilling-fluid samples. Segment IV (1,245–1,525 ft) probably corresponds to a semiconfining unit that contributed little water to the temporary open-hole discharge, and there was little or no vertical flow or mixing of the borehole water when the bailer samples were collected. Thus, the low-chloride bailer samples are probably more representative of water in the low-permeability semiconfining unit, than the drilling-fluid samples. Water in the semiconfining unit may have remained fresh because the unit transmits water too slowly to have become contaminated by more saline water entering from water-bearing zones above and below. Also, the expected low yield of the semiconfining unit explains the decrease in chloride concentration of the drilling-fluid samples at increasing depth; as the drill bit moved farther from the saline water-bearing zone in segment III, gradually more water drawn up the drill stem was from the low-yielding, low-chloride semiconfining unit. Segment IV probably corresponds to the "deep freshwater zone" of Gregg and Zimmerman (1974).

Lower drilled section (segments V–VIII)—1,528–2,727 feet

During drilling of the first 50 ft below the 10-inch-diameter casing (1,525–1,575), there was not enough ground water yielded from the formation for reverse-rotary drilling, and water was pumped into the well bore from the nearby Turtle River. Only after a 20-ft-long section was cored (to 1,295 ft) was there enough ground water for drilling. Chloride concentration in drilling-fluid samples was very low over the interval 1,595–1,660, designated segment V (fig. 14). Although the chloride concentration in samples from segment V was similar to that in bailer samples in segment IV, segment V probably represents a more productive water-bearing zone than does segment IV, as indicated by acoustic televiewer images (fig. 7, in back of report) and the inception of artesian flow. Within this unnamed water-bearing zone in the middle of the Lower Floridan aquifer (about 1,528–1,758 ft), a large increase in chloride concentration of drilling-fluid samples (24–580 mg/L) occurs over 1,660–1,675 ft (the second interface). Below that to a depth of 2,145 ft, chloride concentration in drilling-fluid samples remains relatively stable (340–660 mg/L), except for a few samples that have chloride concentrations less than 250 mg/L in the interval 1,855–1,895 ft and at isolated other depths. Sample C, pumped from within the packed interval 1,612–1,712, which includes parts of segment V and VI, has chloride concentration (2,400 mg/L) much greater than drilling fluid samples from the same depth range. There apparently is a water-bearing zone in this interval that yields high-chloride water when isolated, but the drilling-fluid samples are mixtures that contain a larger portion of low-chloride water from productive freshwater zones in segment V. Segment VI (1,660–2,145 ft) includes the lower part of the possible water-bearing zones in the middle of the Lower Floridan aquifer, and the lower semiconfining unit.

In the interval 2,145–2,150 ft, at the top of the Fernandina permeable zone, chloride concentrations in drilling-fluid samples increased markedly (282–2,716 mg/L, the third interface); and at 2,165 ft (3,420 mg/L), chloride concentrations first exceeded the maximum detected in the Upper Floridan aquifer in downtown Brunswick (3,040 mg/L). Below this interface, chloride concentrations in drilling-fluid samples increased progressively at increasing depth to 16,500 mg/L at 2,320 ft. Relatively freshwater from above and more saline water from the formation probably are mixed in the interval 2,145–2,320 ft, designated segment VII, which is the upper part of the Fernandina permeable zone. From 2,320 ft to the bottom of the borehole at 2,727 ft, designated segment VIII, chloride concentrations in drilling-fluid samples remained fairly steady (16,440–19,040 mg/L), which is similar to the chloride concentration in typical modern seawater (19,000 mg/L, Hem, 1992, p. 7). Wells open to the Lower Floridan aquifer in other parts of coastal Georgia have a record of elevated chloride concentration (above 250 mg/L, the standard maximum for drinking water), most notably in Chatham County (Clarke and others, 1990); but the salinity of samples from these wells is substantially less than that of seawater. The interface within the interval 2,145–2,320 ft in TW-26, below which chloride concentration in ground water is similar to that of seawater, has been detected in Georgia only in the Brunswick area. In this report, this interface in TW-26 and in the Brunswick area is called the primary freshwater/saltwater interface. In 2001, the primary interface was penetrated by a new test well (TW-29; fig. 1) in southwest Brunswick about 2.5 mi northeast of TW-26 (W.F. Falls, USGS, written commun., 2001).

Chloride concentration in laboratory-measured samples A through S (table 4) were compared to field-measured chloride concentration in drilling-fluid samples from TW-26 (fig. 14). The bailer and packed- and open-interval samples (B through S) may be more representative of the actual formation water at the indicated depths and depth intervals than the drilling-fluid samples, which are a mixture of formation waters entering the borehole over the available open interval. A few of the bailer and interval samples have chloride concentrations notably greater than the drilling-discharge samples from the corresponding depth or depth interval (samples C, H, J, and N, fig. 14). Sample C (within packers 1,612–1,712 ft), had chloride concentration of 2,400 mg/L, much greater than same-depth drilling-discharge samples. Within this packed interval, there may be a zone of high-salinity water that did not contribute to the drilling-discharge samples, but yielded water when the packed interval was pumped, or the lower packer may have failed, allowing high-chloride water from below to mix with water from the packed interval. If the packers were effective, sample C suggests that there may be water-bearing zones above the Fernandina permeable zone that have chloride concentration high enough to be the source of high-chloride water in the Upper Floridan aquifer in Brunswick. The chloride concentrations of bailer sample H (12,000 mg/L at 2,180 ft) and interval sample J (18,000 mg/L, within packers 2,120–2,220 ft) probably are greater because the drilling-discharge samples were a mixture of formation waters over a larger interval. Samples H and J are probably more representative of the formation water in the upper part of the Fernandina permeable zone. Sample N, a bailer sample at a depth of 2,710 ft, is particularly notable because it has the highest chloride concentration of all samples (33,000 mg/L), which is substantially higher than the chloride concentration of typical modern seawater (19,000 mg/L, Hem, 1992, p. 7). Sample N suggests that the modern sea is not the direct or single source of water in the Fernandina permeable zone; rather, the water may be mixed with older, relict brines that have increased salinity due to evaporation, stratification, or other natural processes.

Discharge from TW-26 has been sampled for chloride-concentration analysis 14 times since completion, most recently in July 1999. Discharge from TW-26 is from the completed open interval 2,138–2,727 ft, which is open only to the Fernandina permeable zone. Available chloride-concentration data for bulk discharge samples from completed TW-26 (fig. 15) indicate little change in water quality of the Fernandina permeable zone over the sampling history. The moderate range of chloride concentration over time (range 6,545–10,000 mg/L) is probably due to variable mixing of ground water from water-bearing zones in the open interval.

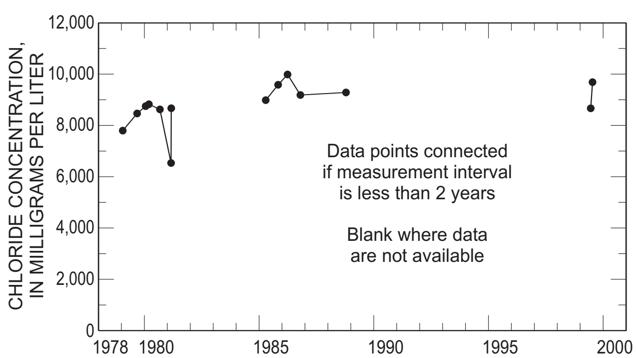

Figure 15. Chloride concentration in water samples from completed TW-26, near Brunswick, Georgia.

Relation between chloride concentration and specific conductance

A noticeable change in the relation between chloride concentration in and specific conductance of drilling-fluid samples occurs between the middle (segments I–IV) and lower (segments V–VIII) drilled sections of TW-26. Between the drilled sections there is a gap in drilling-fluid samples (1,525–1,595 ft), because the well did not produce enough water to drill at the start of the lower section and water had to be pumped into the well bore from the Turtle River. From above to below the gap, chloride concentration in samples decreases and specific conductance increases (fig. 14). Data from the field-measured drilling-fluid samples is confirmed by data from laboratory-measured samples A, B, and D, which were collected near the data gap. The relation between chloride concentration and specific conductance is further illustrated by a cartesian plot of the two variables in figure 16. The drilling-fluid data from the middle drilled section (segments I–IV) plot very closely to one linear-regression line ($y = 4.306x + 385.5$; $r^2 = 0.993$), and data from the upper part of the lower section (segments V and VI) plot almost as closely to a nearly parallel linear-regression line that has a distinctly higher *y*-axis intercept ($y = 4.192x + 1{,}390.0$; $r^2 = 0.934$). These data indicate that a change occurs in ground-water type between the middle and lower drilled section; in the lower section prominent ion(s) other than chloride probably contribute to the specific conductance of the ground water.

The precise depth interval where the change in ground-water type occurs cannot be determined from drilling-fluid data, because saline water from above probably is mixing across segment VI (1,245–1,522), and data are not available in the interval 1,522–1,595. However, the bailer samples collected before setting the 10-inch-diameter casing indicate that ground-water in segments I–III (sample depths 600–1,200 ft) is the type that plots along the lower regression line (fig. 16), and ground-water in segment IV (sample depths 1,260–1,515 ft) gradually changes from that type to the type that plots along the upper regression line. Unfortunately, bailer samples from the interval 600–1,515 ft were not analyzed for ionic concentrations other than chloride, prohibiting further interpretation and understanding of the observed change in ground-water type.

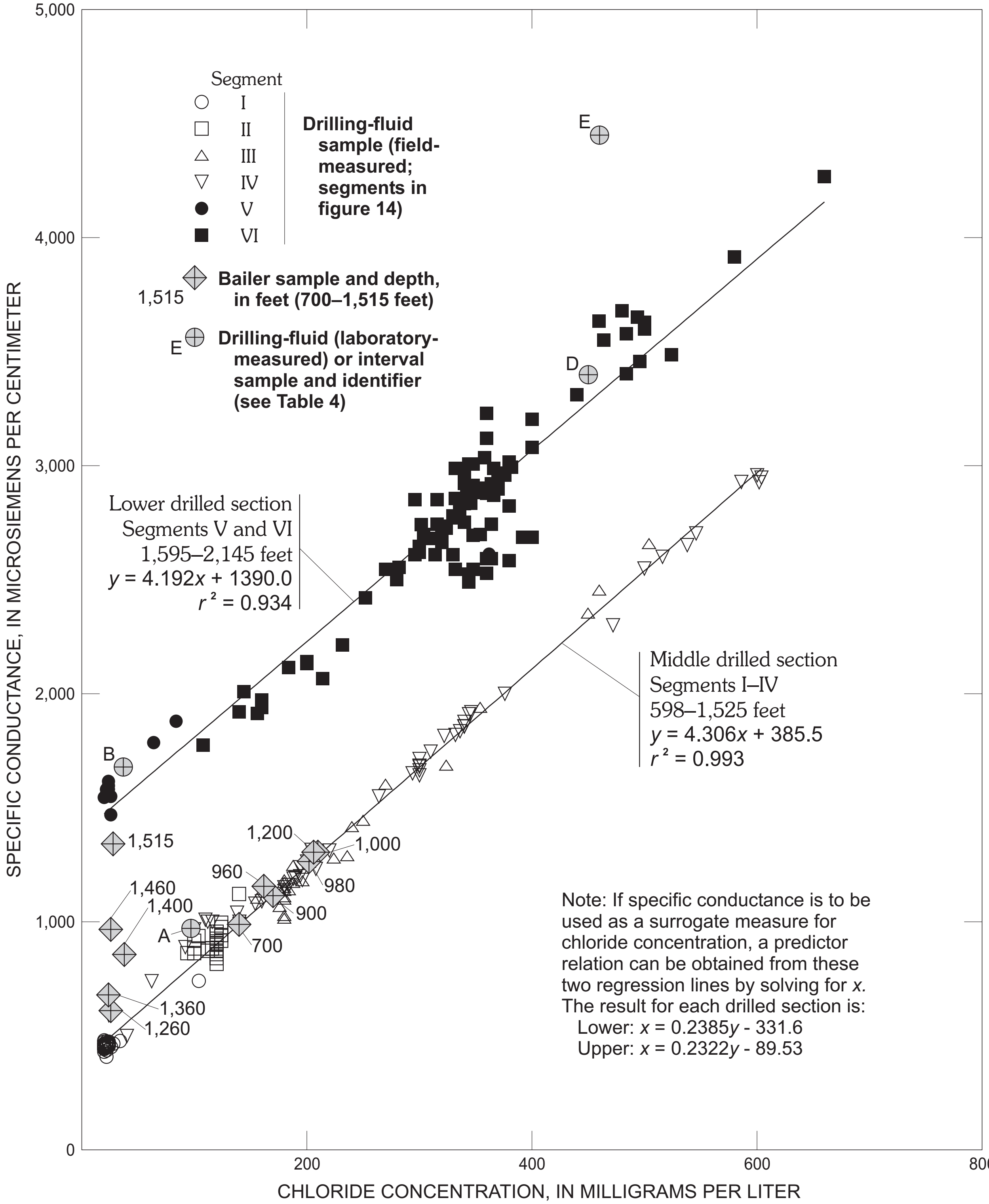

Figure 16. Relation between chloride concentration and specific conductance of water samples from TW-26, near Brunswick, Georgia, by segments of similar chloride-concentration trend, and linear-regression lines for samples in segments I–IV and in segments V and VI.

Ionic Content

Laboratory analyses of major ionic concentrations were performed on 17 samples from TW-26 (table 4), which are identified as samples A through S (I and O not used). One sample (A) was of the drilling-fluid discharge near the completion of the middle section; seven samples (B, C, D, E, J, M, and P) were collected during four attempted packer tests in September 1978, over the temporary open-hole depth interval 1,525–2727 ft, from intervals either above, within, or below a pair of inflated packers; six samples (F, G, H, K, L, and N) were bailer samples collected at specified depths within the open interval of the completed well 2,138–2,727 ft in 1980 and 1981; and three samples (Q, R, S) were collected from the completed well discharge after a period of free flow and are a mixture of water from the entire open interval of the completed well. In addition to chloride concentration, and other field-measured properties and constituents, water-quality data determined in the laboratory for each identified sample (A–S) included concentrations of cations, anions, and other constituents and elements (table 4). Some detection limits change from sample to sample.

Graphical analyses were used to characterize the ionic content of water samples from TW-26 (table 4) as they compare to typical, modern seawater (Hem, 1992, p. 7) and an uncontaminated, freshwater sample from the Upper Floridan aquifer at Brunswick (well GPP&P 2; table 1; fig. 1). Graphical procedures provide a means of comparing ionic content of samples, and help detect mixtures of waters of different compositions (Hem, 1992, p. 173). In this report, the object of graphical analysis is to observe changes in composition of ground water with increasing depth in TW-26, determine how similar ground water in the Fernandina permeable zone is to modern seawater, and evaluate the possibility that ground water sampled from zones between the Fernandina permeable zone and the Upper Floridan aquifer is a simple mixture of waters from the two aquifers. No samples were taken from the Upper Floridan aquifer at TW-26 before it was cased off, but uncontaminated samples from the Upper Floridan aquifer in the Glynn County area have very low ionic content and do not vary appreciably in comparison to the variability of samples from TW-26. Analyses of a freshwater sample collected on April 10, 1968, from an Upper Floridan aquifer well in the Georgia-Pacific Corporation well field (GPP&P 2) about 2.5 miles north-northeast of TW-26 in Brunswick, were used for comparison. Ionic concentrations for the Upper Floridan sample and a typical, modern seawater sample are given in table 4.

Ionic-content graphing methods represent simultaneously the total solute concentration and the proportions (in milliequivalents per liter) assigned to each of the major cations and anions in water samples (Hem, 1992, p. 173). Chosen on the basis of relative abundance in the samples, the three major cations and cation group were calcium (Ca), magnesium (Mg), and sodium-plus-potassium (Na+K), and the three major anions were chloride (Cl), sulfate (SO_4), and bicarbonate (HCO_3). Two methods were used to compare content of major cations and anions in samples from TW-26.

The first ionic-content graphing method used a system of patterns (similar to Stiff, 1951) that have three parallel horizontal axes, which represent major cations on the left of zero and major anions on the right (fig. 17). The combined widths of the axes is proportional to total ionic content, and connecting the axes results in distinctive, irregular polygonal patterns that illustrate water-composition differences and similarities (Hem, 1992, p. 175). Because total ionic content of the samples varied widely, patterns for samples having low ionic content were too narrow to be compared to patterns for samples having high ionic content. To provide broader-range comparison, patterns also were constructed on a logarithmic scale. (It should be noted that the combined widths of the axes in log-scale patterns are not proportional to total ionic content.)

The second ionic-content graphing method used a trilinear diagram (similar to Piper, 1944) that plots relative percentages of the three cations on a triangle on the left, relative percentages of the three anions on a triangle on the right, and projects those percentages onto a diamond above (fig. 18). Concentration of total dissolved solids (table 4) is indicated by point patterns and shading. Trilinear diagrams are useful in determining whether a sample is a simple mixture of waters for which analyses are available (Hem, 1992, p. 178). One or more ionic concentrations in samples F and H were unavailable, and these samples were not used in the graphical analyses.

Patterns in figure 17 illustrate differences in ionic content of the samples from TW-26, freshwater from the Upper Floridan aquifer in Brunswick, and modern seawater. Generally, samples from above the primary freshwater/saltwater interface at the top of the Fernandina permeable zone (A through E) have small, narrow patterns that are similar to the pattern for freshwater (Upper Floridan aquifer), and the patterns of samples from below the primary interface within the Fernandina permeable zone (G through S) are similar to the pattern for seawater. Exceptions to that general rule are sample C, which has higher chloride concentration (fig. 14) and greater overall ionic content (fig. 17) than other samples from above the primary interface, and sample G, which has lower ionic content than other samples from the Fernandina permeable zone. Sample C indicates that there may be zones above the Fernandina permeable zone that have salinity greater than is indicated by the drilling-fluid samples (fig. 14). Sample G, which is from near the primary freshwater/saltwater interface, is probably a mixture of water from above and below the interface.

There is one notable general difference between the patterns showing ionic content (fig. 17) of samples from within the Fernandina permeable zone (samples G through S) and the pattern for seawater, the relative ionic content of Ca to Mg. Samples from the Fernandina permeable zone have similar content of Ca and Mg, which results in patterns having a nearly vertical line from the middle to the bottom of the left side. Seawater has a markedly lower content of Ca than Mg, which results in a sloping line from the middle to the bottom of the left side. Assuming that the water in the Fernandina permeable zone is seawater that was trapped in Paleocene and Cretaceous sediments and remained there for an indefinite period of time, there are several factors that may explain the difference in relative ionic content of water from the Fernandina permeable zone and seawater, including: (1) seawater was trapped during a geologic time when typical seawater had a different relative ionic content than today; (2) seawater that was trapped was atypical with respect to relative ionic content; (3) after entrapment, relative ionic content of the seawater changed due to natural interaction with the limestone and dolomite sediments, which are calcium and magnesium carbonates; and(or) (4) after entrapment, seawater mixed with other non-marine water that has a different relative ionic content.

The trilinear diagram (fig. 18) illustrates differences in relative proportions of major cations and anions in ground water from TW-26, modern seawater, and freshwater from the Upper Floridan aquifer in the Brunswick area. The three plots indicate two general types of samples based on dominant cations and anions; samples A, B, D, and E are calcium/magnesium-sulfate (Ca/Mg-SO_4) type, and samples J through S and seawater are sodium-chloride (Na-Cl) type. Samples C and G have similar proportions of cations and anions, although sample C was collected from above the primary freshwater/saltwater interface and sample G from within the Fernandina permeable zone. Samples C and G are mixtures of Ca/Mg-SO_4 and Na-Cl types. The sample from well GPP&P 2, which is open to the Upper Floridan aquifer in Brunswick (sample UF), is similar to the Ca/Mg-SO_4 type samples; but, unlike those samples, HCO_3 is dominant in sample UF (anion triangle in fig. 18). Sample UF also has a slightly higher percentage of Ca than all samples (cation triangle in fig.18). Modern seawater (SW) has a lower percentage of Ca than all samples from TW-26, and a slightly higher percentage of Mg than the Na-Cl type samples. Although not dominant in any of the samples from TW-26, HCO_3 content is greater in the Ca/Mg-SO_4 type samples and samples G and C than in the Na-Cl type samples and seawater.

Differences between the composition of ground water in TW-26 and a mixture of modern seawater and freshwater from the Upper Floridan aquifer in the Brunswick area also are illustrated by the trilinear diagram (fig. 18). A straight line between two points in any sector of a trilinear diagram indicates the ionic proportions of all possible simple mixtures of waters represented by the two points. In figure 18, the dashed line connecting the points for seawater (SW) and freshwater from the Upper Floridan aquifer (UF) represents all possible mixtures of freshwater and seawater (called UF/SW mixtures); a dashed line connecting the extreme samples from TW-26 (B and N) is used to compare the samples from TW-26 to UF/SW mixtures. Continuing with the basic assumption that water in the Fernandina permeable zone is derived from modern seawater, it was further postulated that this saline ground water migrates upward to the pumping centers in the Upper Floridan aquifer, and, thus, all ground water between the two zones is an UF/SW mixture. Sample points from TW-26 that depart from UF/SW mixture line (fig. 18) have ionic proportions that contradict this expanded basic assumption. In the cation triangle, samples C, G, and the Na-Cl type samples have a lower percentage of Mg and a higher percentage of Ca than a UF/SW mixture, and the Ca/Mg-SO_4 type samples have a higher percentage of Mg and a lower percentage of Ca than a UF/SW mixture. Sample B has a Na+K percentage less than the UF endpoint, and samples N and J have a Na+K percentages greater than the SW endpoint. In the anion triangle, nearly all samples have a lower percentage of HCO_3 and a higher percentage of SO_4 than a UF/SW mixture; samples C, G, and the Ca/Mg-SO_4 type samples depart widely from the UF/SW line for these anions. Sample B has a Cl percentage less than the UF endpoint and sample N has a Cl percentage greater than the SW endpoint. Figure 18 clearly indicates that the expanded basic assumption is false—ground water from TW-26 is not similar to a mixture of freshwater and modern seawater. Ground water in the TW-26 may be mixed with relict brines that have an ionic proportion different from modern seawater due to evaporation, stratification, or other natural processes.

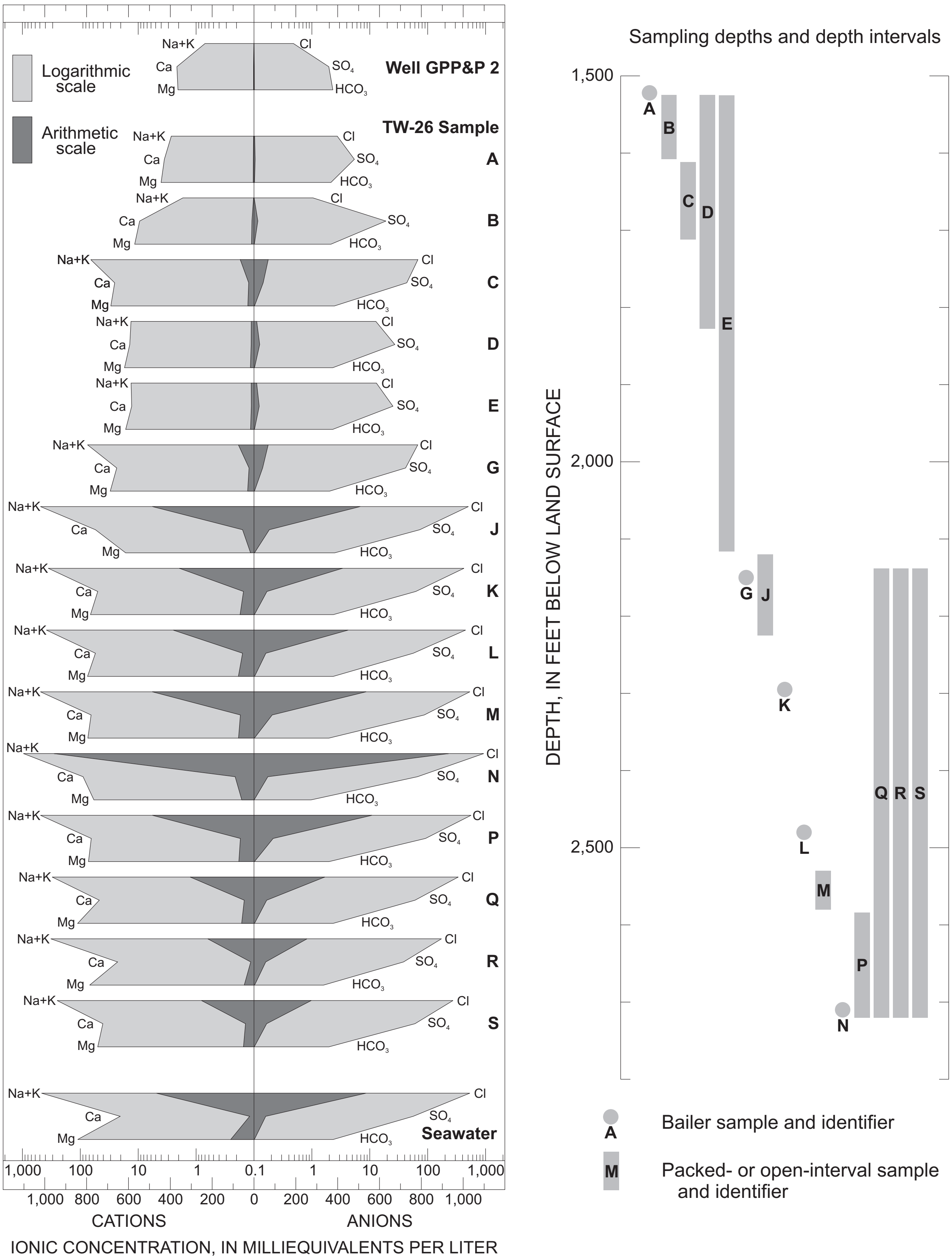

Figure 17. Patterns showing ionic content of a water sample from GPP&P 2 at Brunswick, Georgia, selected water samples from well TW-26, near Brunswick, and modern seawater; and sampling depths and depth intervals.

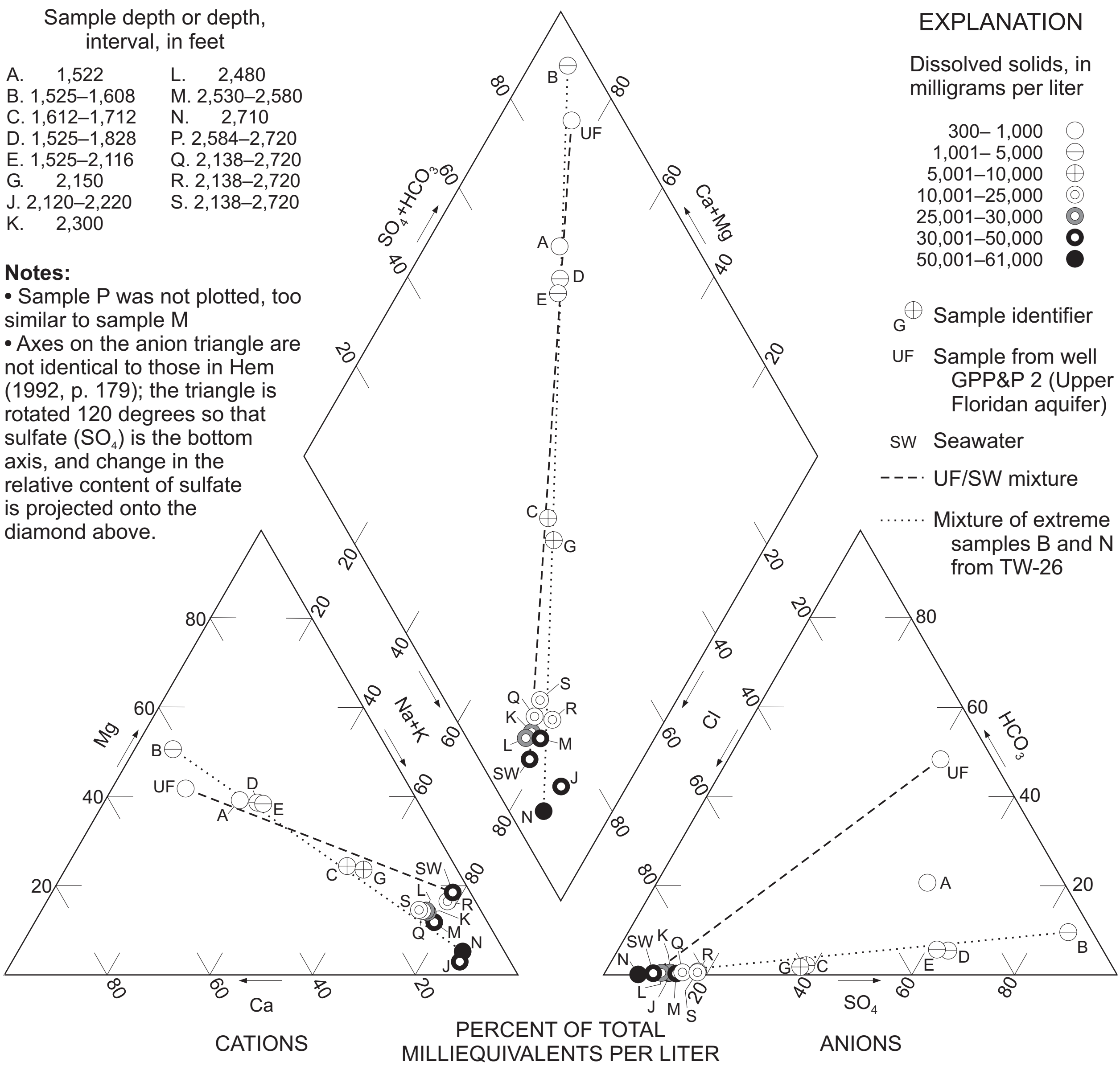

Figure 18. Trilinear diagram of relative ionic content of a water sample from well GPP&P 2 at Brunswick, Georgia, selected water samples from TW-26, near Brunswick, Georgia, and modern seawater.

SUMMARY

In summary, conclusions derived from this study include: (1) an improved estimate of the depth of a primary freshwater/saltwater interface at the top of the Fernandina permeable zone and better understanding of the distribution of saltwater in zones above the Fernandina permeable zone; (2) improved estimates of the depths of boundaries of geologic and hydrogeologic units based on paleontological analysis, geologic properties, geophysical-log and water-quality data analysis; (3) a better understanding of the distribution and magnitude of solution openings in carbonate rocks of Oligocene age and older, based on ATV images and neutron, caliper and drilling-time logs—comparing these data indicates solution openings commonly are adjacent to intervals of non-porous carbonates; (4) evidence of the presence of fractures and fracture zones that may result in large voids and very high permeability in the Fernandina permeable zone; (5) evidence that modern seawater is not the direct source of saltwater in the Floridan aquifer system based on (a) graphical analysis of water-quality data, which suggests that water sampled from the Lower Floridan aquifer is not a simple mixture of modern seawater and freshwater from the Upper Floridan aquifer in Brunswick, and (b) a single bailer sample near the bottom of TW-26, which had a chloride concentration much greater than that of modern seawater; and (6) chloride-concentration and specific-conductance data from drilling-fluid samples from TW-26 indicate a change in water type between the middle drilled (605–1,528 ft) and the lower drilled sections (1,528–2,272 ft).

Chloride-concentration data from TW-26 establishes the depth of a freshwater/saltwater interface near the top of the Fernandina permeable zone (2,145–2,320 ft), below which ground water has a chloride concentration similar to seawater. Except for TW-29 in nearby Brunswick, which was completed in 2001, no other onshore test well in the coastal Georgia area has provided data to determine the depth of this interface. However, because the primary freshwater/saltwater interface of the Floridan aquifer system is a three-dimensional surface, which probably has been disturbed by ground-water withdrawal, the depths of the primary interface at TW-26 and TW-29 are merely single points on an unsteady surface. Other zones above the Fernandina permeable zone yielded high-chloride water at TW-26, suggesting that shallower water-bearing zones may also contain relict, high-chloride ground water, or that pumping stresses may have caused the upward migration of saltwater from the Fernandina permeable zone into other water-bearing zones. A zone of moderately elevated chloride (250–602 mg/L) was detected in the upper part of the Lower Floridan aquifer (1,170–1,240 ft) and may correspond to the "brackish-water zone" previously identified at Brunswick; and a zone of relatively fresh ground water was detected below (1,240–1,660 ft) that may correspond to the "deep freshwater zone" previously identified at Brunswick. More information is needed to fully characterize the nature and interaction of freshwater and saltwater in the flow system of the Floridan aquifer system in the Glynn County area.

The depths and thicknesses of geologic and hydrogeologic units at TW-26 were estimated using paleontological analyses of core samples, lithologic descriptions of drill cuttings, geophysical logs and water-quality analyses. Core samples containing calcareous nannofossils, dinoflagellates, and molds of echinoids and pectins, suggested that geologic age of sediments within the Floridan aquifer system ranges from Late Cretaceous to Oligocene. Drill cuttings show that carbonate minerals (primarily limestone and dolomite) comprise most of the sediments within the Floridan aquifer system. Geophysical logs were used to help locate unconformities between sediments of differing age. Change in chloride-concentration in water samples was used to establish depths of water-bearing zones containing high-chloride ground water.

ATV images from TW-16 reveal openings over a broad range of depths within carbonate sediments from Upper Cretaceous to Oligocene. The size and texture of the openings, apparent in the images, indicate that some are bordered by angular rock fragments (especially in Upper Cretaceous sediments), which suggest these openings may have been formed during drilling or due to fracturing. Most openings, however, are nearly horizontal, smooth-sided and uniform (especially in Paleocene to middle-Eocene sediments), and probably are the result of dissolution of the sediments. Comparing ATV images to caliper, neutron and drilling-time logs revealed that several of the near horizontal solution openings are in close juxtaposition to intervals of relatively non-porous limestone and dolomite.

Openings bordered by angular rock fragments in Upper Cretaceous sediments usually are non-horizontal, and may be interpreted as fractures, probably indicating post-depositional structural alteration. Some of the angular fracture openings, which are as large as several feet in diameter, may have been formed or enlarged during drilling. However, in the depth interval 2,473–2,478 ft, one of the angular openings appears on ATV images as a non-horizontal planar opening (shaped like a sine curve) characteristic of a steeply dipping fracture (dip azimuth roughly north-northeast, dip angle about 81°). Video images indicate that these openings transmit large quantities of ground water.

Water-quality data from TW-26 were analyzed to determine whether modern seawater is the source of saltwater in the Floridan aquifer system in the Glynn County area. Samples from varying depths and depth intervals within TW-26 were collected during the last phase of construction (drilled section from 1,528–2,727 ft). Ionic-content data from these samples were plotted on a trilinear diagram, which illustrates water type and the ionic content of simple mixtures of samples. By also plotting the ionic content of modern seawater and freshwater from the Upper Floridan aquifer at Brunswick, water samples from TW-26 were shown to be dissimilar to a simple mixture of modern seawater and freshwater from the Upper Floridan aquifer. Also, one sample collected from near the bottom of TW-26 had a chloride concentration (33,000 mg/L) substantially greater than modern seawater, strengthening the argument that saltwater in the Fernandina permeable zone probably is mixed with relict brines that have higher salinity due to evaporation, stratification, and(or) other natural processes.

Chloride-concentration and specific-conductance data from drilling-fluid samples collected every 5–10 ft were graphically compared. For mixtures of water of the same ionic type, the relation between these two properties is typically linear. However, the linear relation between these two properties changed from the middle drilled section (605–1,528 ft) to the lower drilled section (1,528–2,727 ft), which indicates the water in the two sections are of different type. Although the unavailability of complete ionic analyses of samples taken from the middle drilled section precludes a better understanding of this water-type difference, ground water from the lower drilled section probably contains a higher proportion of sulfate (SO_4) than ground water from the middle drilled section.

SELECTED REFERENCES

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida, and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p.

Clarke, J.S., Hacke, C.M., and Peck, M.F., 1990, Geology and ground-water resources of the coastal area of Georgia: Georgia Geologic Survey Bulletin 113, 106 p.

Cleveland, W.S., 1979, Robust locally weighted regression and smoothing scatterplots: Journal of the American Statistical Association 74, p. 829–836.

Cooke, C.W., 1943, Geology of the Coastal Plain of Georgia: U.S. Geological Survey Bulletin 941, 121 p.

Cressler, A.M., Blackburn, D.K., and McSwain, K.B., 2001, Ground-water conditions in Georgia, 2000: U.S. Geological Survey Open-File Report 01-220, 182 p.

Fanning, J.L., 1999, Water use in coastal Georgia by county and source, 1997; and water-use trends, 1980–1997: Georgia Geologic Survey Information Circular 104, 37 p.

Gill, H.E., and Mitchell, G.D., 1979, Results of Colonels Island deep hydrologic test well, Appendix C *of* Georgia Geologic Survey, Investigations of alternative sources of ground water in the coastal area of Georgia: Georgia Department of Natural Resources Open File Report 80-3, p. C1–C13.

Gregg, D.O., and Zimmerman, E.A., 1974, Geologic and hydrologic control of chloride contamination in aquifers at Brunswick, Glynn County, Georgia: U.S. Geological Survey Water-Supply Paper 2029-D, 44 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Elsevier, Amsterdam, 529 p.

Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 3rd ed., 263 p.

Herrick, S.M., 1961, Well logs of the Coastal Plain of Georgia: Georgia Geological Survey Bulletin 70, 462 p.

Herrick, S.M., and Vorhis, R.C., 1963, Subsurface geology of the Georgia Coastal Plain: Georgia Geological Survey Information Circular 25, 80 p.

Hubbert, M.K., 1940, The theory of ground-water motion: Journal of Geology, vol. 48, no. 8, pt. 1, p. 785–944.

Huddleston, P.F., 1988, A revision of the lithostratigraphic units of the Coastal Plain of Georgia, the Miocene through Holocene, Georgia Geologic Survey Bulletin 104, 162 p.

Johnson, C.D., Dunstan, A.H., Mack, T.J., and Lane, J.W., Jr., 1999, Borehole-geophysical characterization of a fractured-bedrock aquifer, Rye, New Hampshire, U.S. Geological Survey Open-File Report 98-558, 61 p.

Jones, L.E., 1997, Ground-water management in coastal Georgia and adjacent parts of South Carolina and Florida—numerical ground-water modeling *in* Hatcher, K.J., *ed.*, 1997 Georgia Water Resources Conference, Athens, Georgia, March 20–22, 1997: Athens, Ga., The University of Georgia, Institute of Ecology, p. 440–443.

___ 2000, Hydrogeology and geochemistry of the Floridan aquifer system at U.S. Geological Survey test well 26, on Colonels Island, near Brunswick, Georgia (*abs.*): Geological Society of America Abstracts with Programs, v. 32, no. 2, p. A-28.

SELECTED REFERENCES—Continued

___ 2001, Saltwater contamination in the Upper Floridan aquifer at Brunswick, Georgia: Proceedings of the 2001 Georgia Water Resources Conference, held March 26-27, 2001, at the University of Georgia, Kathryn J. Hatcher, *ed.*, Institute of Ecology, University of Georgia, Athens, Georgia, p. 644–647.

Jones, L.E., and Maslia, M.L., 1994, Selected ground-water data and results of aquifer tests for the Upper Floridan aquifer, Brunswick, Glynn County, Georgia, area: U.S. Geological Survey Open-File Report 94-520, 107 p.

Keys, W.S., 1988, Borehole geophysics applied to ground-water hydrology: U.S. Geological Survey Open-File Report 87-539, 305 p.

Keys, W.S., and MacCary, L.M., 1971, Application of borehole geophysics to water-resource investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E1, 126 p.

Krause, R.E., and Randolph, R.B., 1989, Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina: U.S. Geological Survey Professional Paper 1403-D, 65 p.

Maslia, M.L., and Prowell, D.C., 1990, Effect of faults on fluid flow and chloride contamination in a carbonate aquifer system: Journal of Hydrology, v. 115, p. 1–49.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.

Owens, J.P., and Gohn, G.S., 1985, Depositional history of the Cretaceous Series in the U.S. Atlantic Coastal Plain; stratigraphy, paleoenvironments, and tectonic controls of sedimentation, *in* Poag, C.W., ed., Geologic Evolution of the United States Atlantic Margin: New York, Van Nostrand Reinhold, p. 25–86.

Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water-analyses: American Geophysical Union Transactions, v. 25, p. 914–923.

Prowell, D.C., 1988, Cretaceous and Cenozoic tectonism on the Atlantic Coastal Margin: *in* Sheridan, R.E. and Grow, J.A., *eds*., Geological Society of America, The Geology of North America, The Atlantic Continental Margin, U.S., v. I-2, p. 557–564.

Sprinkle, C.L., 1989, Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-I, 105 p.

Stephenson, L.W., and Veatch, J.O., 1915, Underground waters of the Coastal Plain of Georgia, and a *discussion* of the quality of the waters by R.B. Dole: U.S. Geological Survey Water-Supply Paper 341, 539 p.

Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, no. 10, p. 15–17.

Trent, V.P., Fanning, J.L., and Doonan, G.A., 1990, Water use in Georgia by county for 1987: Georgia Geologic Survey Information Circular 85, 111 p.

U.S. Environmental Protection Agency, 2000, Maximum contaminant levels (Part 143, National Secondary Drinking-water Regulations): U.S. Code of Federal Regulations, Title 40, parts 100–149, r*evised* as of July 1, 2000, p. 612–614.

Vernon, R.O., 1951, Geology of Citrus and Levy Counties, Florida: Florida Geological Survey Bulletin no. 33, 256 p.

Wait, R.L., 1962, Interim report on test drilling and water sampling in the Brunswick area, Glynn County, Georgia: Georgia Geological Survey Information Circular 23, 46 p.

____1965, Geology and occurrence of fresh and brackish water in Glynn County, Georgia: U.S. Geological Survey Water-Supply Paper 1613-E, 94 p.

Wait, R.L., and Davis, M.E., 1986, Configuration and hydrology of the pre-Cretaceous rocks underlying the Southeastern Coastal Plain aquifer system: U.S. Geological Survey Water-Resources Investigations Report 86-4010, 1 plate.

Wait, R.L., and Gregg, D.O., 1973, Hydrology and chloride contamination of the principal artesian aquifer in Glynn County, Georgia: Georgia Department of Natural Resources Hydrologic Report 1, 93 p.

Ward, L.W., Blackwelder, B.W., Gohn, G.S., and Poore, R.Z., 1979, Stratigraphic revision of Eocene, Oligocene, and lower Miocene formations of South Carolina: South Carolina Division of Geology Geologic Notes, v. 23, no. 1, p. 2–32.

Warren, M.A., 1944, Artesian water in southeastern Georgia, with special reference to the coastal area: Georgia Geological Survey Bulletin 49, 140 p.

FIGURES 4 THROUGH 10

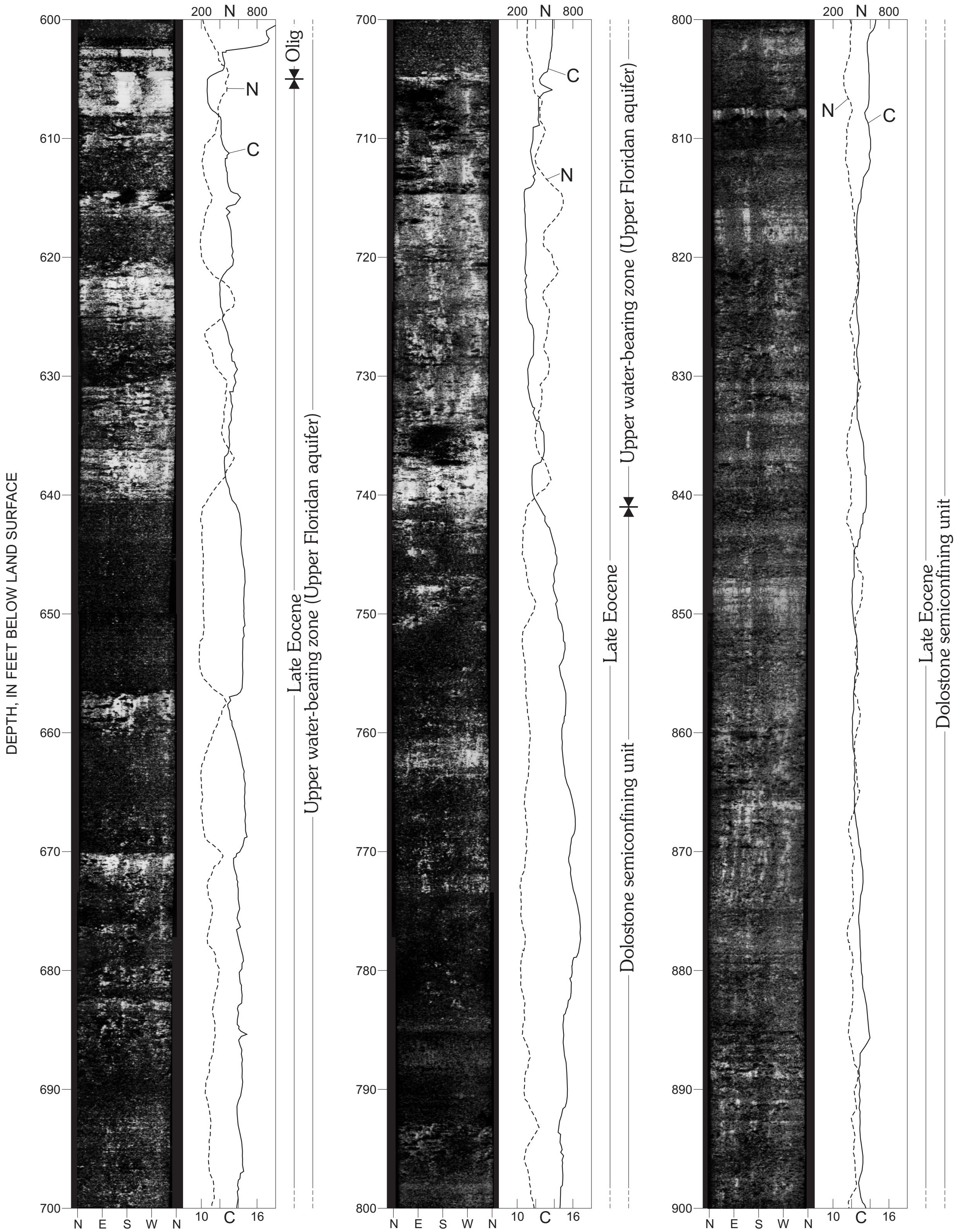

Figure 4. Acoustic-televiewer images, caliper and neutron logs from TW-26, near Brunswick, Georgia, showing geologic age and hydrogeologic units, depth interval 600–900 feet (C, caliper, in inches; N, neutron, in counts per second; Olig, Oligocene).

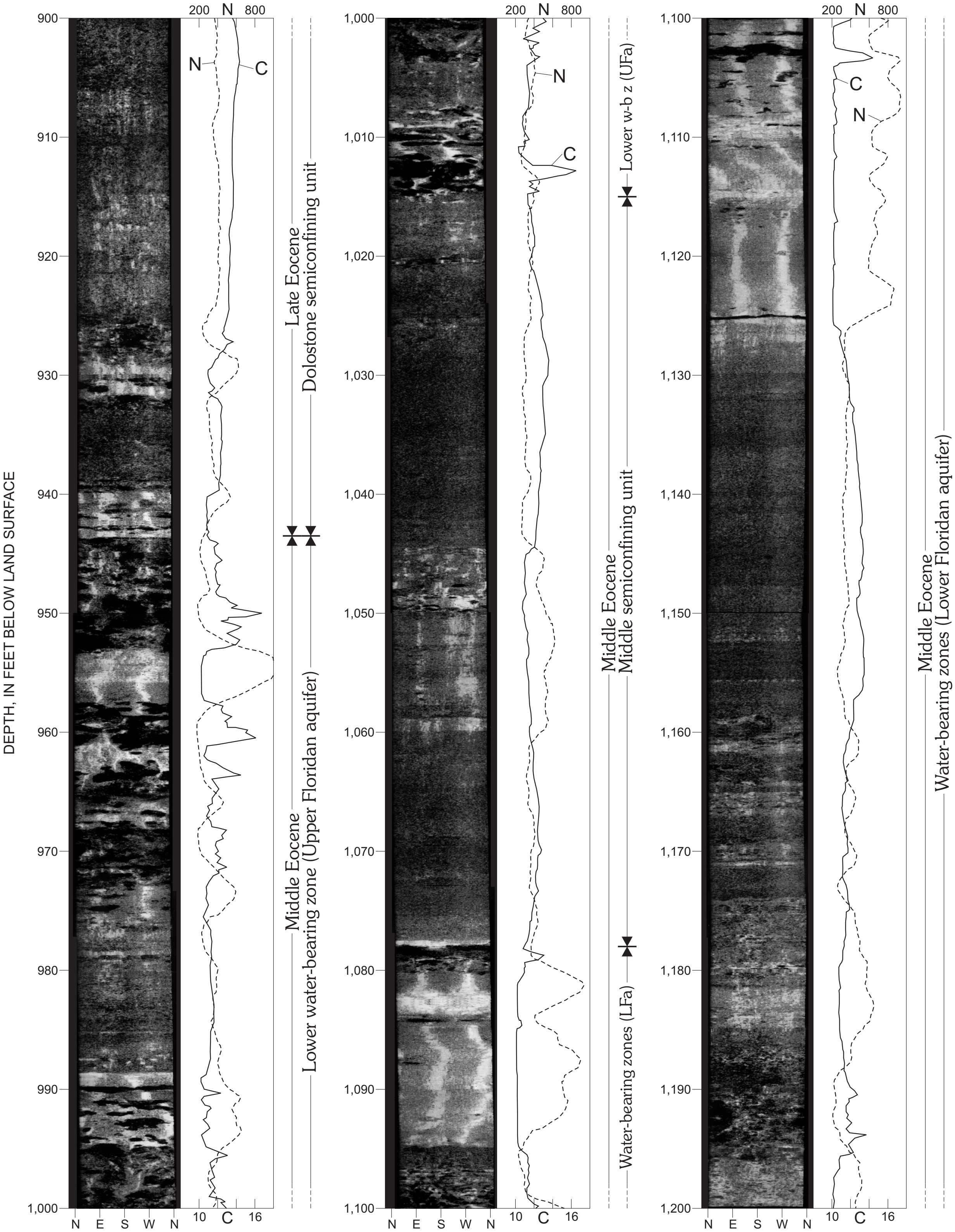

Figure 5. Acoustic-televiewer images, caliper and neutron logs from TW-26, near Brunswick, Georgia, showing geologic age and hydrogeologic units, depth interval 900–1,200 feet (C, caliper, in inches; N, neutron, in counts per second; w-b z, water-bearing zone; UFa, Upper Floridan aquifer; LFa, Lower Floridan aquifer).

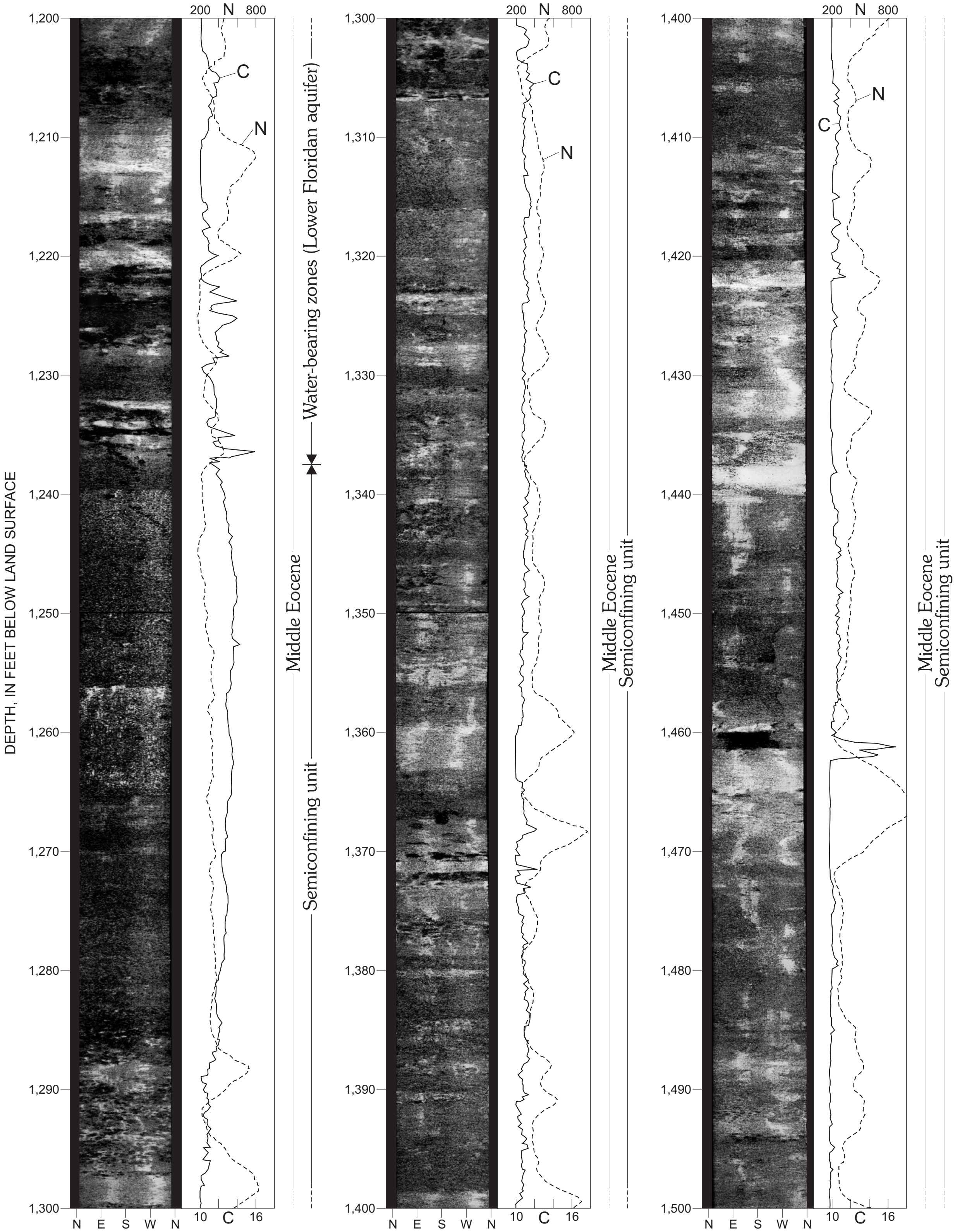

Figure 6. Acoustic-televiewer images, caliper and neutron logs from TW-26, near Brunswick, Georgia, showing geologic age and hydrogeologic units, depth interval 1,200–1,500 feet (C, caliper, in inches; N, neutron, in counts per second).

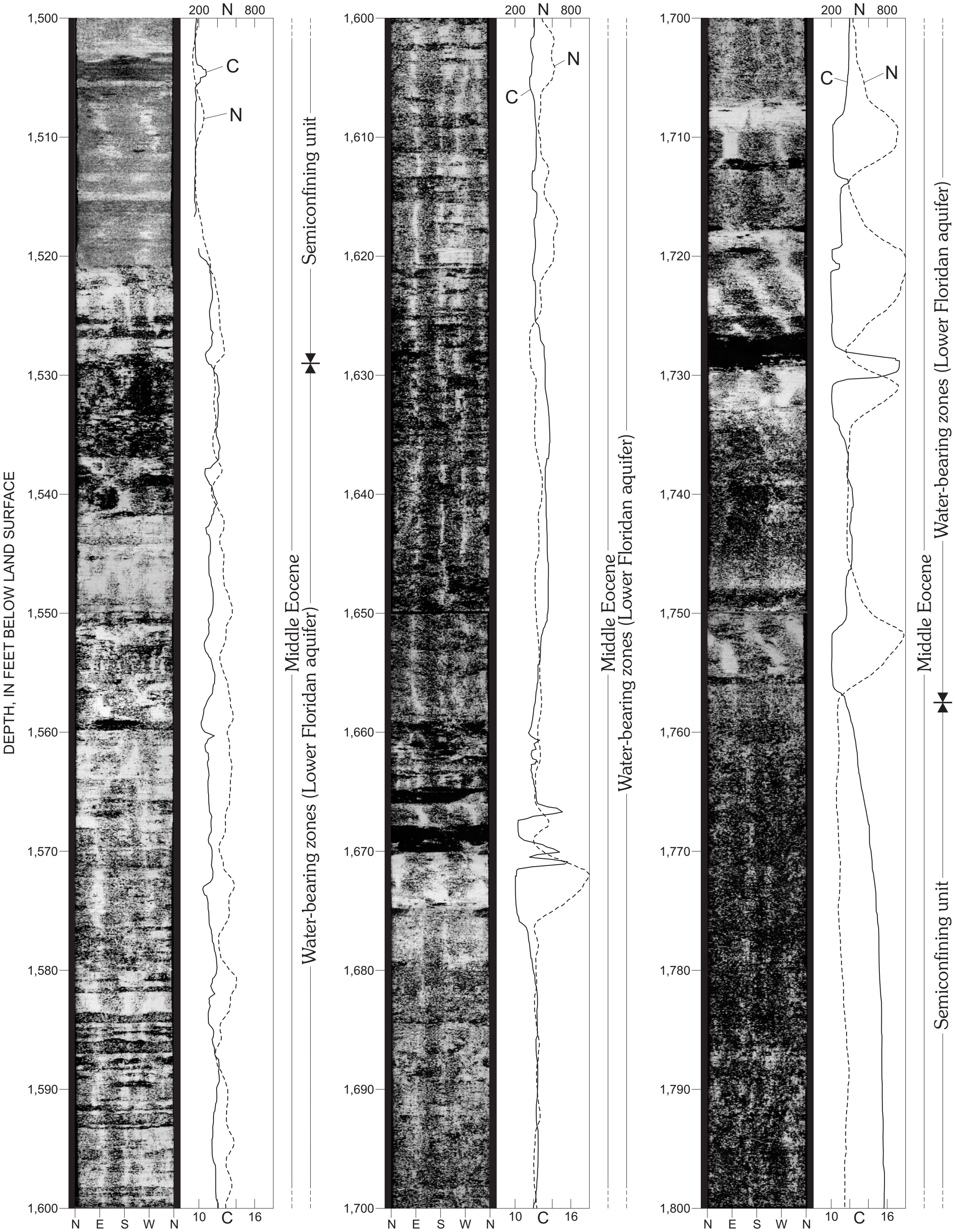

Figure 7. Acoustic-televiewer images, caliper and neutron logs from TW-26, near Brunswick, Georgia, showing geologic age and hydrogeologic units, depth interval 1,500–1,800 feet (C, caliper, in inches; N, neutron, in counts per second).

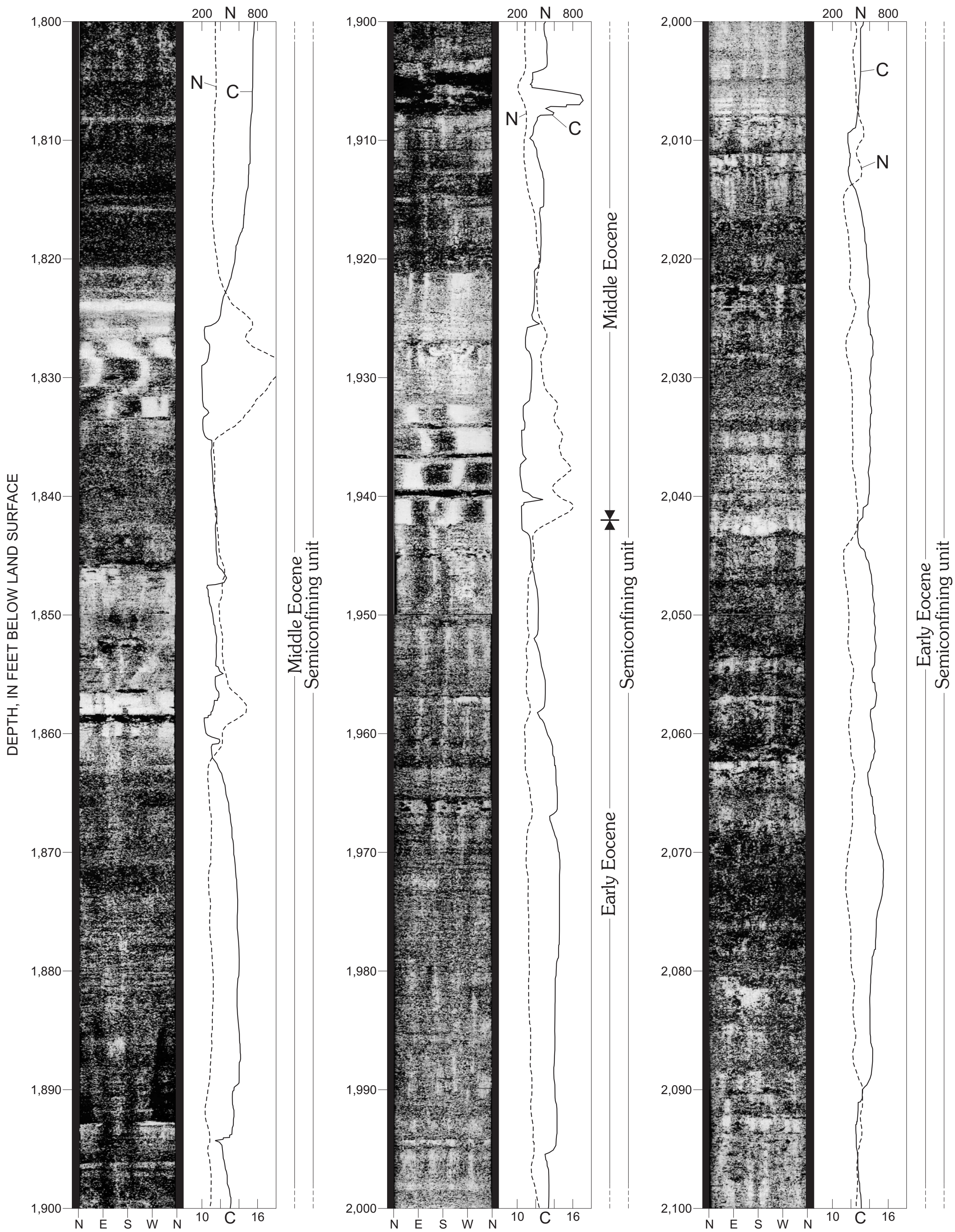

Figure 8. Acoustic-televiewer images, caliper and neutron logs from TW-26, near Brunswick, Georgia, showing geologic age and hydrogeologic units, depth interval 1,800–2,100 feet (C, caliper, in inches; N, neutron, in counts per second).

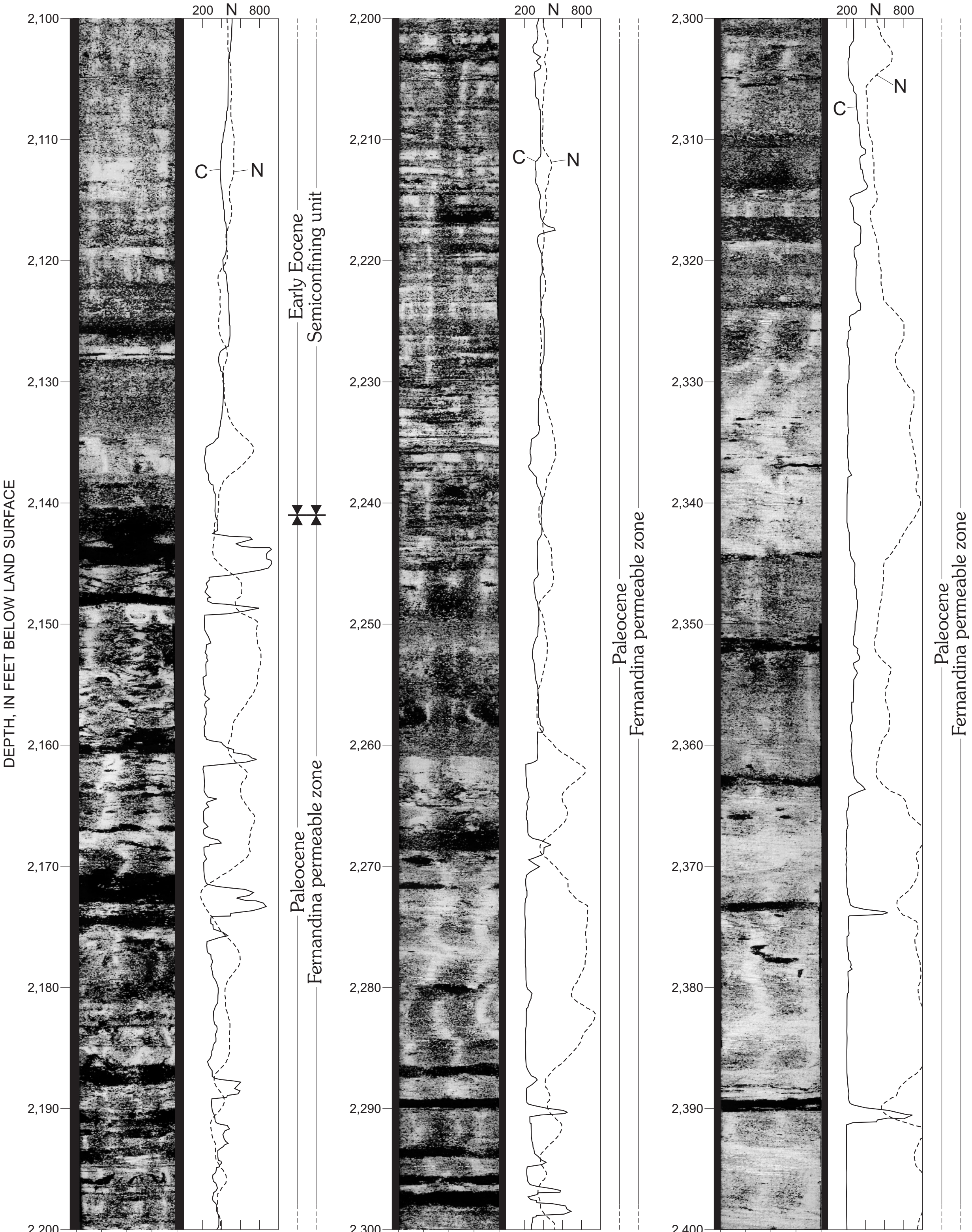

Figure 9. Acoustic-televiewer images, caliper and neutron logs from TW-26, near Brunswick, Georgia, showing geologic age and hydrogeologic units, depth interval 2,100–2,400 feet (C, caliper, in inches; N, neutron, in counts per second).

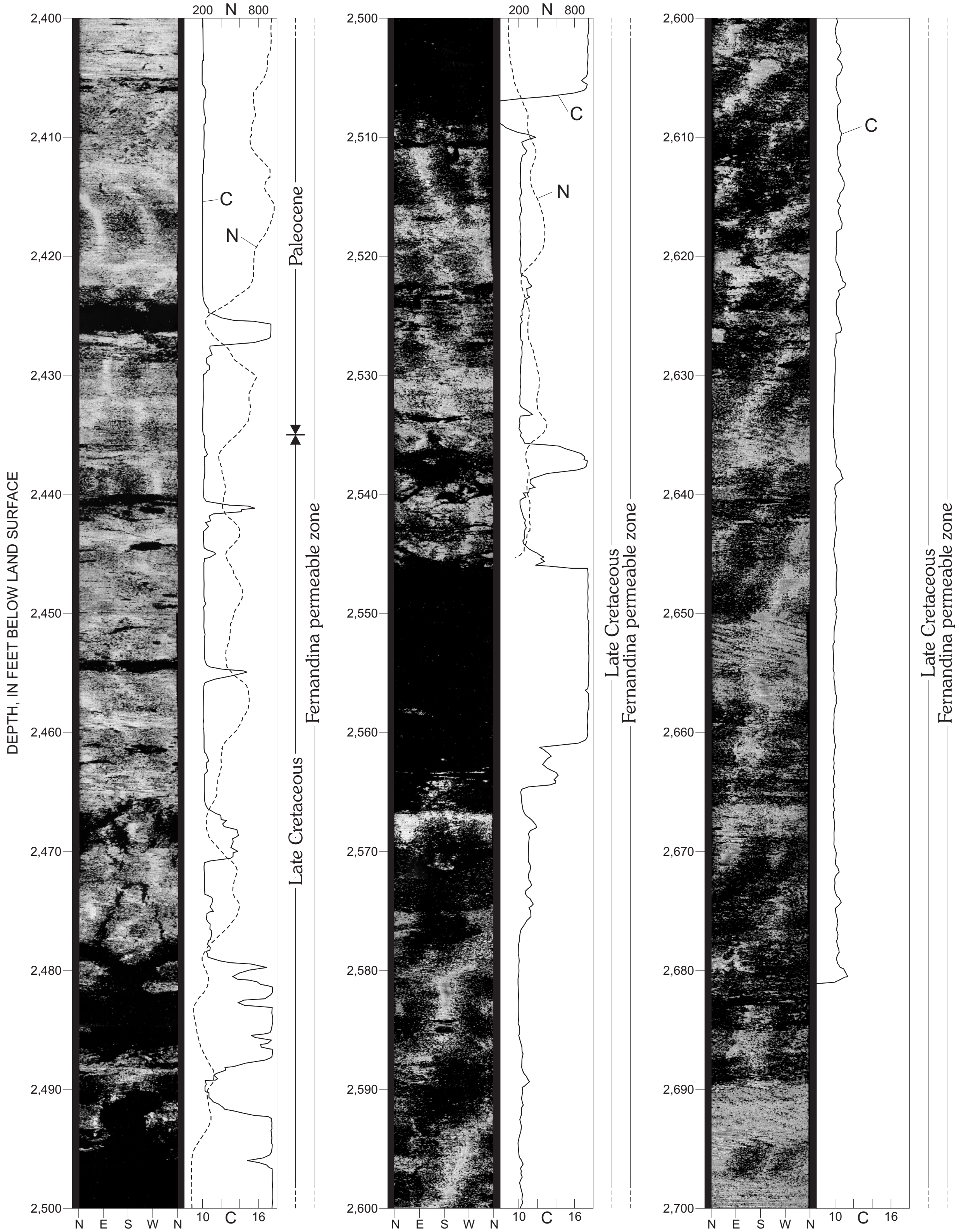

Figure 10. Acoustic-televiewer images, caliper and neutron logs from TW-26, near Brunswick, Georgia, showing geologic age and hydrogeologic units, depth interval 2,400–2,700 feet (C, caliper, in inches; N, neutron, in counts per second).