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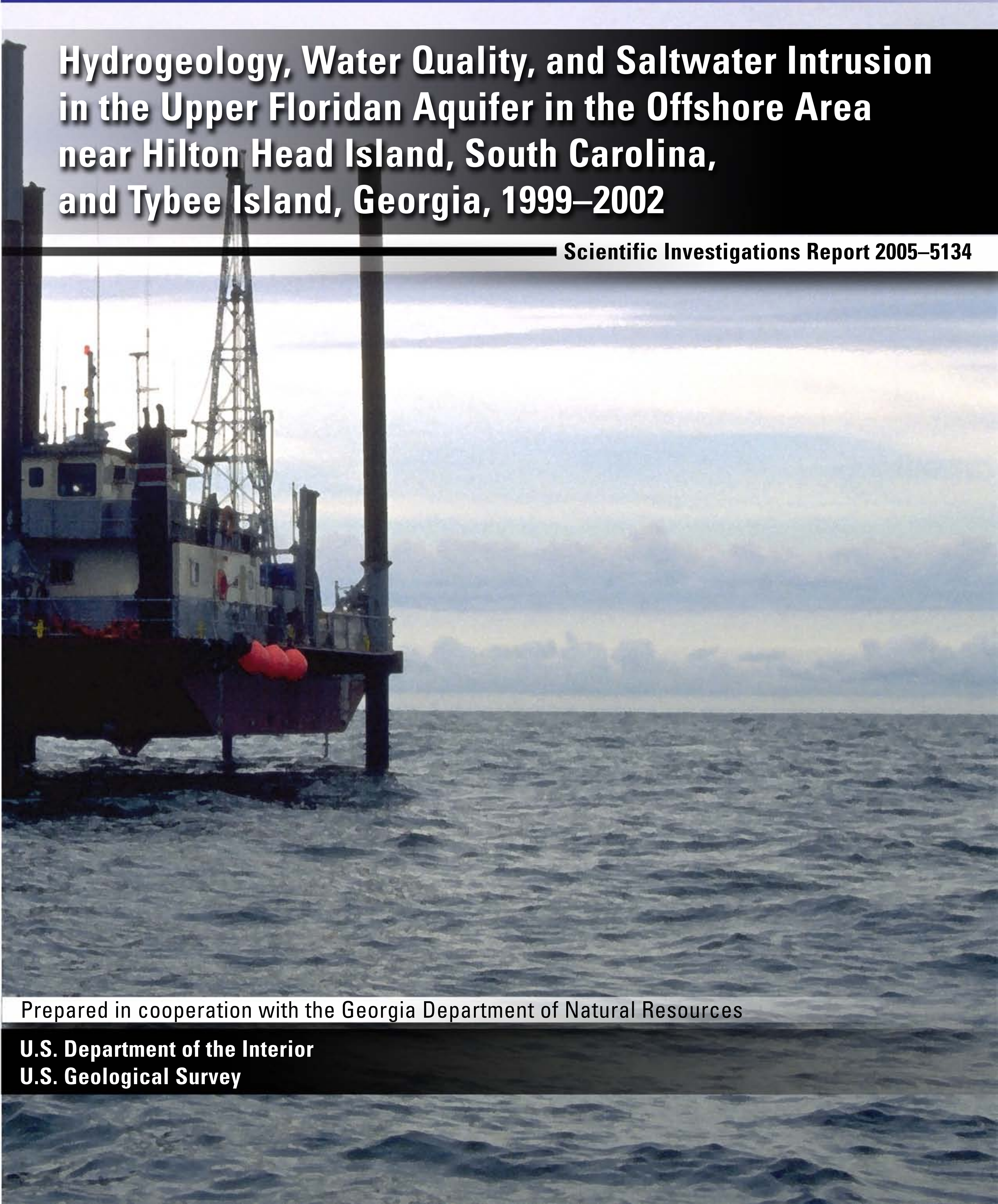
Hydrogeology, Water Quality, and Saltwater Intrusion in the Upper Floridan Aquifer in the Offshore Area near Hilton Head Island, South Carolina, and Tybee Island, Georgia, 1999–2002

Scientific Investigations Report 2005–5134



Prepared in cooperation with the Georgia Department of Natural Resources

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

Cover Image:
Drilling platform at the 10-mile site,
off Hilton Head Island, South Carolina, June 2000.
Photography:
W. Fred Falls, U.S. Geological Survey
Design:
James R. Douglas, U.S. Geological Survey

Hydrogeology, Water Quality, and Saltwater Intrusion in the Upper Floridan Aquifer in the Offshore Area near Hilton Head Island, South Carolina, and Tybee Island, Georgia, 1999–2002

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2005

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Suggested citation:
Falls, W.F., Ransom, Camille, Landmeyer, J.E., Reuber, E.J., and Edwards, L.E., 2005, Hydrogeology, water quality, and saltwater intrusion in the Upper Florida aquifer in the offshore area near Hilton Head Island, South Carolina, and Tybee Island, Georgia, 1999–2002: U.S. Geological Survey Scientific Investigations Report 2005–5134, 48 p.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow	
gallon per day (gal/d)	0.00379	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) unless otherwise noted; horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

In this report, altitude refers to distance above and below NAVD 88.

Acronyms and Abbreviations

$CaCO_3$	calcium carbonate
cps	counts per second
CSSI	Coastal Sound Science Initiative
DIC	dissolved inorganic carbon
FAS	Floridan aquifer system
FPZ	Fernandina permeable zone
GA	Georgia
GaEPD	Georgia Environmental Protection Division
g/cm^3	gram per cubic centimeter
GWSI	Ground-Water Site Inventory
LFA	Lower Floridan aquifer
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligram per liter
Mgal/d	million gallons per day
PDB	Peedee Belemnite
pmc	percent modern carbon
SC	South Carolina
SCDHEC	South Carolina Department of Health and Environmental Control
SJRWMD	St Johns River Water Management District
TDS	total dissolved solids
TU	tritium unit
UFA	Upper Floridan aquifer
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
V-SMOW	Vienna-Standard Mean Ocean Water

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Abstract

To assess the hydrogeology, water quality, and the potential for saltwater intrusion in the offshore Upper Floridan aquifer, a scientific investigation was conducted near Tybee Island, Georgia, and Hilton Head Island, South Carolina. Four temporary wells were drilled at 7, 8, 10, and 15 miles to the northeast of Tybee Island, and one temporary well was drilled in Calibogue Sound west of Hilton Head Island.

The Upper Floridan aquifer at the offshore and Calibogue sites includes the unconsolidated calcareous quartz sand, calcareous quartz sandstone, and sandy limestone of the Oligocene Lazaretto Creek and Tiger Leap Formations, and the limestone of the late Eocene Ocala Limestone and middle Avon Park Formation. At the 7-, 10-, and 15-mile sites, the upper confining unit between the Upper Floridan and surficial aquifers correlates to the Miocene Marks Head Formation. Paleochannel incisions have completely removed the upper confining unit at the Calibogue site and all but a 0.8-foot-thick interval of the confining unit at the 8-mile site, raising concern about the potential for saltwater intrusion through the paleochannel-fill sediments at these two sites. The paleochannel incisions at the Calibogue and 8-mile sites are filled with fine- and coarse-grained sediments, respectively.

The hydrogeologic setting and the vertical hydraulic gradients at the 7- and 10-mile sites favored the absence of saltwater intrusion during predevelopment. After decades of onshore water use in Georgia and South Carolina, the 0-foot contour in the regional cone of depression of the Upper Floridan aquifer is estimated to have been at the general location of the 7- and 10-mile sites by the mid-1950s and at or past the 15-mile site by the 1980s. The upward vertical hydraulic gradient reversed, but the presence of more than 17 feet of upper confining unit impeded the downward movement of saltwater from the surficial aquifer to the Upper Floridan aquifer at the 7- and 10-mile sites.

At the 10-mile site, the chloride concentration in the Upper Floridan borehole-water sample and the pore-water samples from the Oligocene and Eocene strata support the conclusion of no noticeable modern saltwater intrusion in the Upper Floridan aquifer. The chloride concentration of 370 milligrams per liter in the borehole-water sample at the 7-mile site from the Upper Floridan aquifer at 78 to 135 feet below North American Vertical Datum of 1988 is considerably higher than the chloride concentration of 25 milligrams per liter measured at the 10-mile site. The higher concentration probably is the result of downward leakage of saltwater through the confining unit at the 7-mile site or could reflect downward leakage of saltwater through an even thinner layer of the upper confining unit beneath the paleochannel to the northeast and lateral movement (encroachment) from the paleochannel to the 7-mile site. Carbon-14 concentrations at both sites, however, are low and indicate that most of the water is relict fresh ground water.

The hydrogeology at the 15-mile site includes 17 feet of the upper confining unit. The chloride concentration in the Upper Floridan aquifer is 6,800 milligrams per liter. The setting for the Upper Floridan aquifer beneath the 15-mile site is interpreted as a transitional mixing zone between relict freshwater and relict saltwater.

At the Calibogue site, 35 feet of fine-grained paleochannel-fill sediments overlies the Oligocene strata of the Upper Floridan aquifer. The vertical hydraulic conductivity of the paleochannel fill at this site is similar to the upper confining unit and effectively replaces the missing upper confining unit. Chloride concentrations and low carbon-14 and tritium concentrations in borehole water from the Upper Floridan aquifer, and low chloride concentrations in pore water from the upper confining unit indicate relict freshwater confined in the Upper Floridan aquifer at the Calibogue site.

The coarse-grained paleochannel-fill sediments at the 8-mile site along with the downward hydraulic gradient that began in the 1950s potentially created a pathway for

downward leakage of saline water from the surficial aquifer to the Upper Floridan aquifer. The presence of very saline water in the Oligocene strata of the Upper Floridan aquifer at the 8-mile site supports the occurrence of saltwater intrusion or encroachment. Beneath the Oligocene strata, pore-water chloride concentration decreases to less than 500 milligrams per liter in the Eocene part of the Upper Floridan aquifer. The water in the Oligocene strata at the 8-mile site has a carbon-14 concentration of 2.3 percent modern carbon; however, this site has the highest tritium concentration (4 tritium units) of all the temporary wells. The calculated freshwater/modern saltwater mixing of the water at the 8-mile site is 55/45 percent. Therefore, the carbon-14 and tritium concentrations do not support the concept of relatively modern saline water mixing with relict freshwater in the Upper Floridan aquifer at the 8-mile site. Instead, the carbon-14 and tritium results indicate that the intruding water predominantly is relict saline water from the surficial aquifer with only a minor component of modern saltwater.

Introduction

Since the 1880s, the development and the economic growth of Chatham County, Georgia (GA), and most of Beaufort County, South Carolina (SC), have depended on the availability of freshwater in the Floridan aquifer system, formerly known as the principal artesian aquifer and Tertiary limestone aquifer (Warren, 1944; Hazen and Sawyer, 1956; Siple, 1956; Counts and Donsky, 1963; McCollum and Counts, 1964; Hayes, 1979). Since 1903, saltwater contamination of wells has been documented in Beaufort County, SC. Previous studies attributed saltwater contamination to the local hydrogeologic setting and to the effect that water use in Beaufort and Chatham Counties had on the regional ground-water flow potential.

The same conditions that favor saltwater contamination in Beaufort County, SC, also exist in the area seaward of Hilton Head Island and west of Hilton Head Island in Calibogue Sound (fig. 1). Given enough time, potential saltwater intrusion in these areas could affect the freshwater resources in the Upper Floridan aquifer beneath developing coastal communities on Hilton Head and Daufuskie Islands, SC, and Tybee Island, GA.

Onshore hydrologic investigations in Beaufort and Chatham Counties, and in Port Royal Sound, SC, documenting saltwater contamination have benefited from the abundance of subsurface data from water-supply and monitoring wells. In contrast, data for the Upper Floridan aquifer offshore have been limited to a few deep stratigraphic test holes drilled seaward of the Inner Continental Shelf and a few geotechnical borings and temporary wells in the Inner Continental Shelf near Hilton Head and Tybee Islands (Furlow, 1969; Hathaway and others, 1979; Scholle, 1979; Burt and others, 1987; U.S. Army Corps of Engineers, 1998). Much of what is hypothesized about the position of the freshwater/saltwater interface, the potentiometric surface, and the hydrogeology of the Floridan aquifer system in the offshore area and inland waterways near Hilton Head Island, with the exception of Port Royal Sound, has been extrapolated from onshore and nearshore data.

To address the issue of saltwater contamination, the Georgia Environmental Protection Division (GaEPD) implemented the Coastal Sound Science Initiative (CSSI) and coordinated with the South Carolina Department of Health and Environmental Control (SCDHEC) in a series of scientific and feasibility studies to support the development of Georgia's Final Water-Management Strategy for mitigating saltwater intrusion in the Atlantic coastal counties of Georgia and adjacent areas in South Carolina and Florida (Georgia Environmental Protection Division, 1997). The U.S. Geological Survey (USGS) in cooperation with the State of Georgia and as part of the CSSI, assessed the hydrogeology, water quality, and potential for saltwater intrusion of the Upper Floridan aquifer in the area seaward of Hilton Head Island and in Calibogue Sound (fig. 1).

The results of this study provide GaEPD, SCDHEC, and other area water managers with field verification of the hydrology and water quality of the Upper Floridan aquifer and the overlying upper confining unit in the offshore area. The results also support ground-water flow and solute-transport modeling of this area by the USGS, which will be used to help develop Georgia's Final Water-Management Strategy for coastal Georgia. Additionally, this investigation makes an important contribution to the understanding of coastal-zone issues of water use and saltwater intrusion that affect water resources in Georgia and elsewhere in the Nation (U.S. Geological Survey, 1999).

Purpose and Scope

The purpose of this report is to document the hydrogeologic and water-quality results of a field investigation in the offshore area near Hilton Head Island and in Calibogue Sound west of Hilton Head Island conducted during the summers of 1999, 2000, and 2001 (figs. 1, 2). Data from temporary test wells drilled by the U.S. Army Corps of Engineers (USACE) are presented for one site in Calibogue Sound and four offshore sites located 7, 8, 10, and 15 miles to the east-northeast of the northern end of Tybee Island, GA (fig. 1). Included in this report are interpretations of the hydrogeologic framework and water quality of the Upper Floridan aquifer, the overlying confining unit, and the surficial aquifer. These interpretations are based on the descriptions and analyses of cores, cuttings, and water samples collected during the drilling of the temporary test wells at the five drill sites.

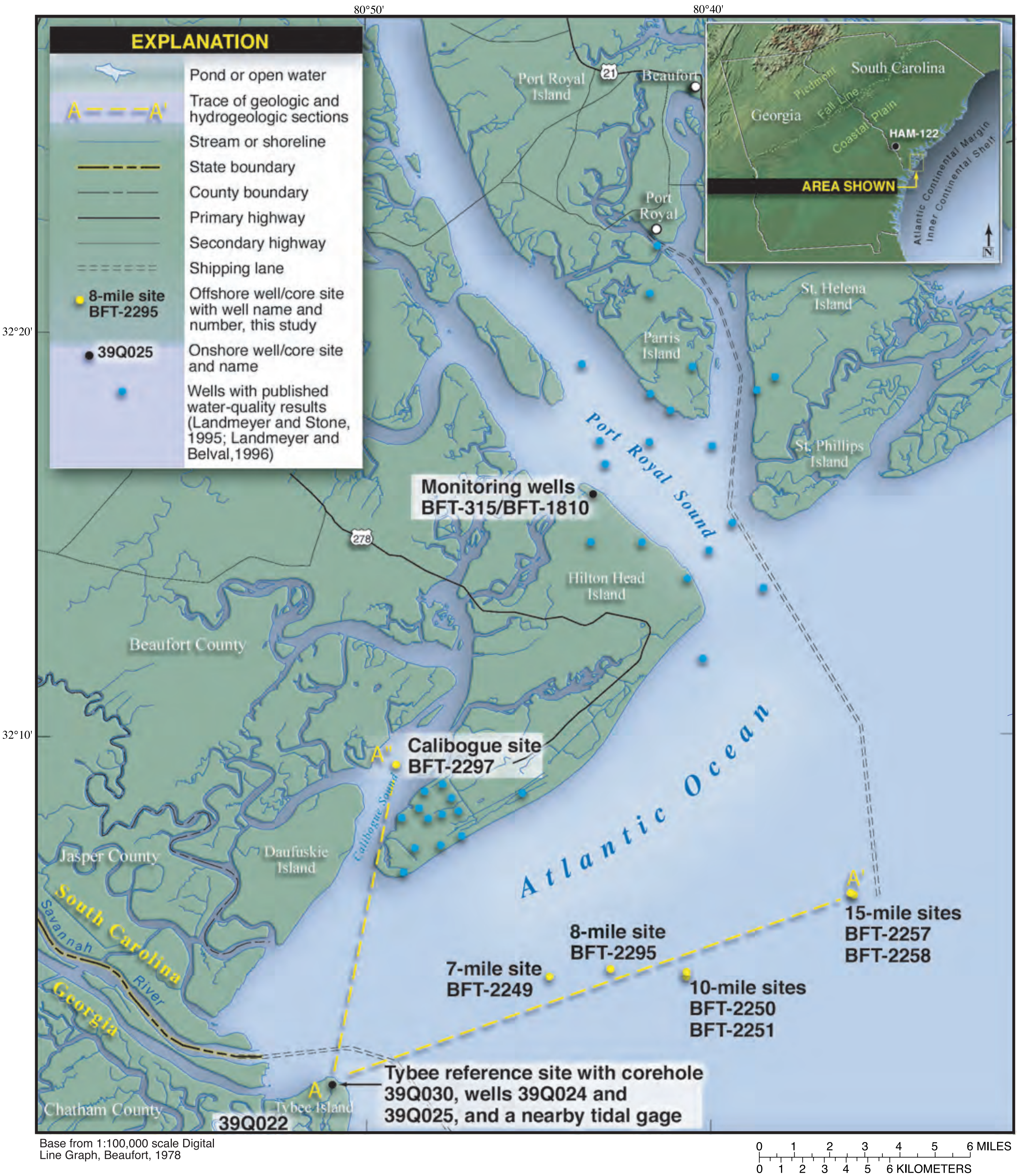


Figure 1. Location of the study area, onshore and offshore wells, and traces of cross sections A-A' and A-A'' near Hilton Head Island, South Carolina, and Tybee Island, Georgia.

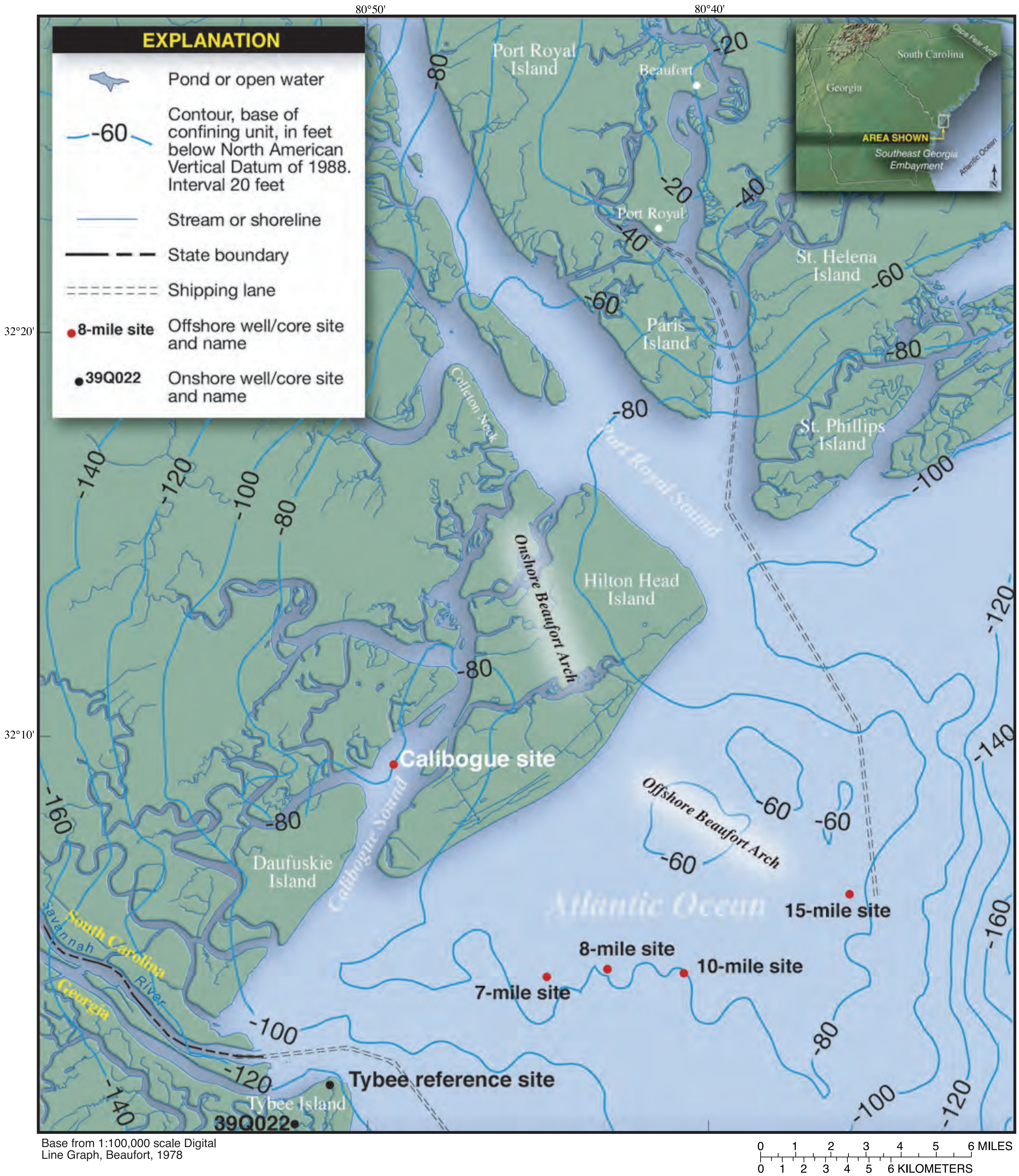


Figure 2. Altitude of the base of the upper (Miocene) confining unit near Hilton Head Island, South Carolina, and Tybee Island, Georgia (modified from Foyle and others, 2001).

Location of the Study Area

The study area extends along the Atlantic continental margin of the Southeastern United States from Chatham and Beaufort Counties along the eastern margin of the Atlantic Coastal Plain Physiographic Province to the Inner Continental Shelf of the Atlantic Ocean (fig. 1). The study area specifically includes the area from Tybee Island, GA, to Calibogue Sound west of Hilton Head Island, SC, and to the Beaufort Arch seaward of Hilton Head Island (fig. 2).

Previous Investigations

Several regional studies have been conducted to document the geology, hydrology, hydraulic properties, water quality, and water-supply potential of the Floridan aquifer system (Miller, 1986; Bush and Johnston, 1988; Krause and Randolph, 1989; Sprinkle, 1989, Clarke and others, 1990; Garza and Krause, 1996). The abundance of water-supply and monitoring wells and geotechnical borings in Beaufort and Jasper Counties, SC, and Chatham County, GA, provided ample data for detailed investigations of the geology, hydrology, and distribution of chloride in the Upper Floridan aquifer beneath onshore areas, Port Royal Sound, the nearshore area at the mouth of Port Royal Sound, and the Savannah River (Warren, 1944; Counts and Donsky, 1963; McCollum and Counts, 1964; Siple, 1965; Hayes, 1979; Hassen, 1985; Burt and others, 1987; Smith, 1988, 1993; Hughes and others, 1989; Clarke and others, 1990; Burt, 1993; Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998; Ransom and White, 1999). The stratigraphy of the Eocene through Holocene strata from Chatham County, GA, north to Port Royal Sound, SC, is relevant to the hydrogeology of the upper permeable zone of the Upper Floridan aquifer, the upper confining unit, and the surficial aquifer beneath the offshore Beaufort Arch and Calibogue Sound, SC (Huddlestun and Hetrick, 1985; Huddlestun, 1988, 1993; Weems and Edwards, 2001). Marine seismic surveys also have been conducted to study the distribution and absence of the confining unit in areas of concern beneath Port Royal Sound, the Savannah River, and estuarine and offshore areas surrounding Hilton Head Island (Duncan, 1972; Kellam and Henry, 1986; Henry and Kellam, 1988; Foyle and others, 2001; Ocean Surveys, Inc., 2004).

Well-Identification System

In this report, names of the offshore drilling sites seaward of Hilton Head Island, SC, are based on their approximate distances, in miles, from corehole 39Q030 and wells 39Q024 and 39Q025 at the northern end of Tybee Island, GA (fig. 1). This site is used as an onshore stratigraphic and hydrogeologic reference site and is referred to as the Tybee reference site in this report (fig. 1; table 1). Therefore, the offshore well sites are named the 7-, 8-, 10-, and 15-mile sites to the northeast of the Tybee reference site. The drill site in Calibogue Sound is simply named the Calibogue site.

In addition to these well names, each well was assigned a county well-inventory number by the SCDHEC and a 15-digit well-site identification number by the USGS (app. 1). The county numbering system is based on the county abbreviation with a sequential inventory number. All of the wells drilled in this project were assigned to the Beaufort County well inventory. Therefore, well BFT-2249, the 7-mile well, was the 2,249th well inventoried in Beaufort County by the State of South Carolina. The 15-digit well-site identification number is based on the 6-digit latitude and 7-digit longitude, in degrees, minutes, and seconds, for each well site, and a 2-digit sequential well number for each well drilled at the same latitude and longitude. For example, the 7-mile well, drilled at latitude 32°04'02" N. and longitude 080°44'41" W., was the first and only well drilled at this location and was assigned well-site identification number 320402080444101 in the USGS Ground-Water Site Inventory (GWSI) database.

Acknowledgments

The authors thank Dr. William H. McLemore of the Georgia Geologic Survey; H. Cardwell Smith of the U.S. Army Corps of Engineers, Savannah (GA) District; and Drs. Anthony M. Foyle and V. James Henry of Southern Applied Coastal Research Laboratory, Georgia Southern University, for their guidance in the planning of this scientific investigation. H. Cardwell Smith and the drill crew, boat crew, and onshore-support personnel of the U.S. Army Corps of Engineers, Savannah District, were responsible for drilling and well installation, and provided all necessary assistance to the authors to complete the field component of this investigation. The authors also thank Dr. Jean M. Self-Trail of the USGS, Reston, Virginia, for examining and interpreting the calcareous nannofossils in a sediment sample from the 15-mile site.

Offshore Drilling and Methods

To obtain data on the geologic, hydraulic, and water-quality characteristics of the offshore hydrogeologic units, temporary wells were installed at one site in Calibogue Sound west of Hilton Head Island and at four sites seaward of Hilton Head Island by the USACE using the Explorer, a self-propelled, self-elevated drilling barge. The drilling barge can operate in water as deep as 40 feet (ft) below the bottom of the barge. Tides, wave height, and storm swells, however, were considered when selecting drill sites in order to maintain adequate clearance between the bottom of the barge and the surface of the ocean. Water depths at all selected sites were

Table 1. Location, construction, and hydrogeology of temporary wells open to the Upper Floridan aquifer at the Calibogue and offshore sites, South Carolina, and the Tybee reference site, Georgia.

[NAVD 88, North American Vertical Datum of 1988; BFT, Beaufort County, South Carolina]

Well number/ site name (fig. 1)	Latitude	Longitude	6-inch casing top/ bottom (in feet above or below NAVD 88)	Bottom of open borehole in Upper Floridan aquifer (in feet below NAVD 88)	Top of surficial aquifer, Pleistocene/ Holocene (in feet below NAVD 88)	Altitudes of hydrogeologic tops (in feet below NAVD 88)			
						Top of paleo-channel-fill sediment	Top of upper confining unit, Miocene	Top of Upper Floridan aquifer, Oligocene	Top of Upper Floridan aquifer, Eocene
BFT-2257, BFT-2258/ 15-mile site	32°06'04.69"	080°35'54.50"	17.7 / 88.3	154.3	27.4	absent	62.5	79.8	not penetrated
BFT-2250, BFT-2251/ 10-mile site	32°04'07.09"	080°40'42.12"	16.8 / 91.5	698.2	22.1	absent	55.1	87.1	169.2
BFT-2295/ 8-mile site	32°04'14.29"	080°42'55.05"	16.6 / 98.4	207.4	31.6	58	77.7	78.5	147.4
BFT-2249/ 7-mile site	32°04'02.36"	080°44'41.27"	19.3 / 77.5	134.7	29.5	absent	57.2	74.2	120.7
BFT-2297/ Calibogue site	32°09'17.46"	080°49'07.56"	20.3 / 95.7	120.7	27.7	44.2	absent	79.2	126.6
Core 39Q030 (wells 39Q024, 39Q025)/ Tybee reference site	32°01'28" (32°01'27")	080°51'10" (080°51'12")	(9 / 831, 9 / 116)	(879, 136)	9[a]	absent	45.0	114.4	180.0

[a]In feet above NAVD 88 for Tybee reference site.

less than 30 ft below mean low water, or approximately 33 ft below the North American Vertical Datum of 1988 (NAVD 88), based on results of depth finders on the barge and charted depth soundings (U.S. Department of Commerce, 1997).

Each well was constructed in three stages (app. 1). In the first stage, the bottom edge of a 10-inch-diameter steel casing was lowered through the deck of the drilling barge to the sea floor and driven into the sediments of the surficial aquifer. The surface casing was not grouted into place. Total penetration of the surficial aquifer by the surface casing was as little as 12.9 ft at the 15-mile site and as much as 23.3 ft at the 8-mile site. In the second stage, a 4-inch-diameter borehole was cored from the sea floor to the base of the upper confining unit using mud-rotary wireline coring techniques and, for selected core intervals, split-spoon coring techniques. After collection of cores, the borehole was reamed with a 9.875-inch-diameter rotary bit and cased with 6-inch (inner diameter) steel casing that was grouted into place. The design of the 6-inch casing included a reverse-threaded joint at a depth of 3 to 5 ft below the sea floor. After grouting the 6-inch casing, the 10-inch surface casing was extracted. In the third stage, a borehole was drilled with a 5.5-inch-diameter mud-rotary bit and(or) a continuous mud-rotary wireline-coring barrel. Following sample collection, the open borehole was filled with sand and the casing was filled with grout. The 6-inch casing then was turned to detach it at the reverse-threaded joint and retrieved to the deck of the drilling barge; the remainder of the 6-inch casing was buried 3 to 5 ft below the sea floor, leaving no obstruction to navigation or fishing.

The total depth of each well depended on site-specific conditions, including well construction, borehole stability, and weather. All wells, with the exception of the 15-mile site, penetrated the top of the Eocene limestone (table 1). The 15-mile site included two wells drilled approximately 200 ft apart, including one to the top of the Oligocene (well BFT-2257) and one into the Oligocene (well BFT-2258). The 10-mile site included two wells drilled approximately 140 ft apart. At the 10-mile site, well BFT-2250 was drilled to the base of the upper confining unit and was abandoned because of problems with the installation of the 6-inch casing. Well BFT-2251 at the 10-mile site was drilled to a total depth of 698 ft below NAVD 88 and was the only well drilled below the base of the Upper Floridan aquifer in this investigation. All drilling fluids were prepared with potable freshwater carried aboard the drilling barge or supplied by support vessels.

Guided by maps of seismic stratigraphic units prepared by the Georgia Southern Applied Coastal Research Laboratory and later published in Foyle and others (2001), the data from the 7-, 10-, and 15-mile sites were used to confirm the hydrogeology and water quality of the Upper Floridan aquifer in offshore areas where the upper confining unit was interpreted to be intact (fig. 3). Wells drilled at the Calibogue and 8-mile sites specifically targeted areas interpreted by Foyle and others (2001) as “no Miocene” sites to assess the potential for saltwater intrusion in association with the paleochannels. The geologic interpretation of the Tybee Island corehole 39Q030 by Weems and Edwards (2001) and geophysical logs of well 39Q024, both at the same site on the northern end of Tybee Island, were used to correlate the geologic and hydrogeologic units of the offshore and Calibogue sites to onshore units in Chatham County, GA (figs. 1, 4). Water levels from a tidal gage near the Tybee reference site (fig. 1) were compared with ground-water levels measured for the Upper Floridan aquifer at well 39Q024 to analyze tidal effects on ground-water levels.

Samples were collected from the cored intervals for analysis of lithology, paleontology, confining-unit hydraulic conductivity, and pore-water chemistry. Cuttings also were collected for lithologic descriptions from intervals that were not cored. Samples of cores and cuttings were described with reflected-light microscopy for texture, mineralogy, and fossils. Selected core samples were processed, described, and interpreted for age-diagnostic microfossils, including dinoflagellates and calcareous nannofossils, by USGS paleontologists in Reston, Virginia, and were reported relative to the dinoflagellate zonation of de Verteuil and Norris (1996; app. 2). The lithologies and paleontology at the offshore and Calibogue sites were compared with the strata described at the Tybee reference site on the northern end of Tybee Island, GA (fig. 4).

Selected core samples from the upper confining unit and the paleochannel-fill sediments were analyzed for grain size by sieve and hydrometer analysis, and for vertical hydraulic conductivity by falling-head permeameter analysis (American Society for Testing and Materials, 1990, 2002; table 2). Pore water was extracted from selected cores and analyzed to determine the dissolved-chloride concentration in the surficial aquifer, the upper confining unit, the paleochannel-fill sediments, and the limestone of the Upper Floridan aquifer. Generally, fine-grained sediment samples were collected to minimize infiltration of drilling fluids and squeezed to extrude pore water for analysis (Manheim, 1966).

Water samples were collected from open borehole intervals in the Upper Floridan aquifer using a submersible pump for analysis of ion chemistry, carbon-14, tritium, and stable oxygen, hydrogen, and carbon isotopes (app. 3). Wells were developed with air-surge methods prior to installation of a submersible pump. Water was pumped from the wells to the deck of the drilling barge using a closed pump system and was monitored until field water-quality properties stabilized before collecting samples. Sample bottles for tritium and carbon-14 were filled from the bottom of the bottle by placing the outflow hose into the bottle and allowing the discharge water to overflow for several minutes to flush all atmospheric contamination from the bottle. Concentrations of total dissolved solids in the water samples were computed from the ion results.

Geophysical logs were obtained after the installation of each well and before development and water sampling. The types of logs recorded in the open borehole interval depended on the availability and diameter of the logging tools (sondes) and the stability of the borehole. With the exception of the 7-mile site, caliper logs were not collected because of borehole instability in the Oligocene strata. Logs of the open borehole include all or some of the following: natural gamma, borehole fluid resistivity and temperature, and several formation-resistivity logs. In the cased intervals, only natural gamma logs were collected.

Hydrogeology

The strata beneath the Coastal Plain and the Continental Shelf of South Carolina and Georgia generally have a southwesterly regional dip along the Atlantic Coast from a structural high on the Cape Fear Arch in North Carolina to a structural low in the Southeast Georgia Embayment and a southeasterly regional dip from the Fall Line to the Inner Continental Shelf (figs. 1, 2). In addition to the regional structure, the Beaufort Arch, known locally and alternately as the Burton High, the Tybee High or the Hilton Head High, is a local structural feature that is present onshore and offshore near Hilton Head Island (Siple, 1960; Colquhoun, 1969; Furlow, 1969; Hayes, 1979; Hughes and others, 1989; Foyle and others, 2001). This local structural high affects the geology and hydrogeology of onshore Beaufort County, part of northeastern Chatham County, and the offshore area (fig. 2).

Individual geologic units are depositionally and erosionally thin and, in a few places, pinch out near the crest of the Beaufort Arch. The thinning and truncation of geologic units are particularly noticeable in the Oligocene and Miocene sediments of onshore and offshore Chatham and Beaufort Counties (Foyle and others, 2001; Weems and Edwards, 2001). The total thickness, however, of sedimentary strata near the crest of the Beaufort Arch beneath Hilton Head Island exceeds 3,800 ft and includes Cretaceous to Holocene

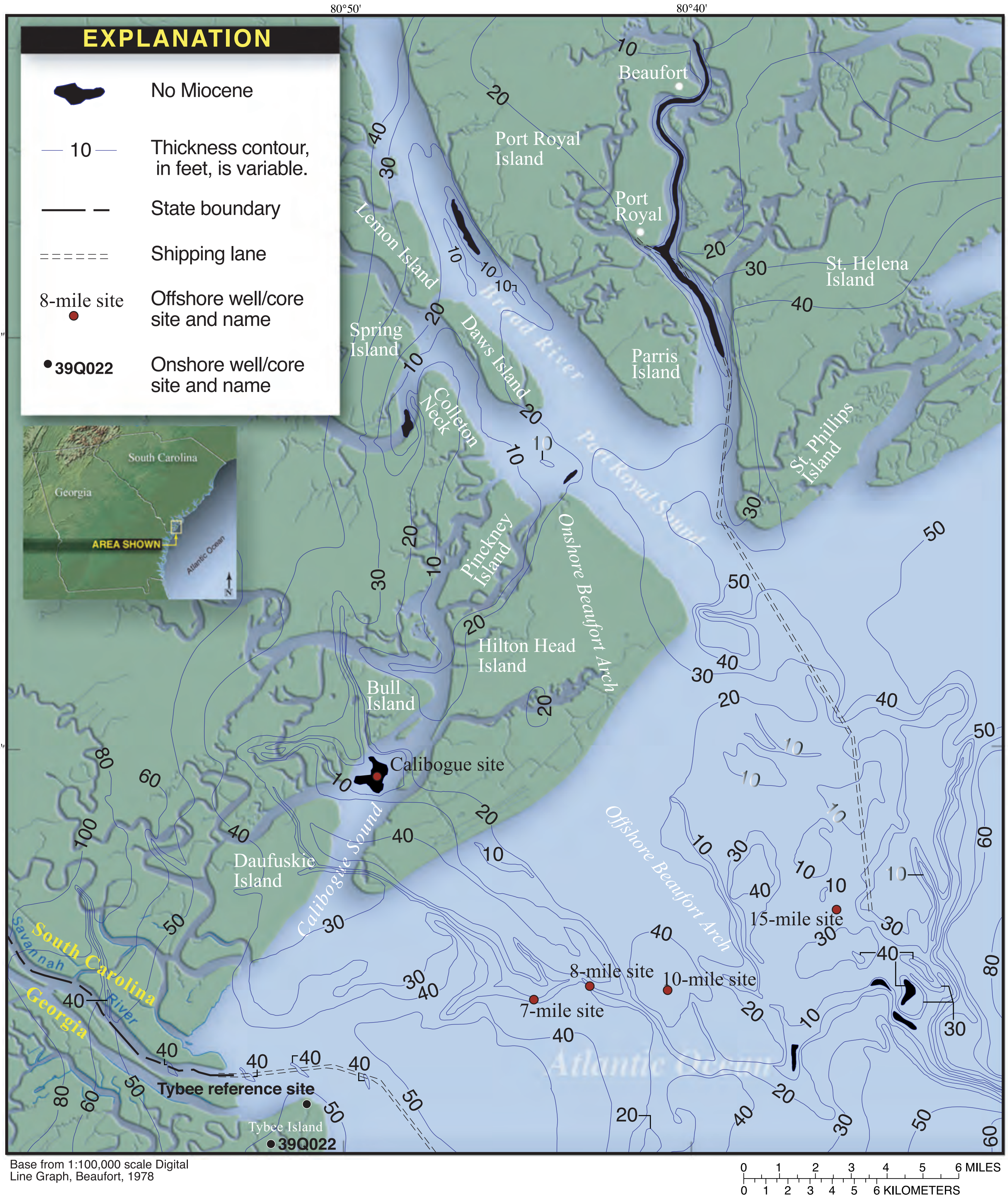


Figure 3. Thickness of the upper (Miocene) confining unit and location of onshore and offshore sites, and core 39Q022, Georgia (modified from Foyle and others, 2001).

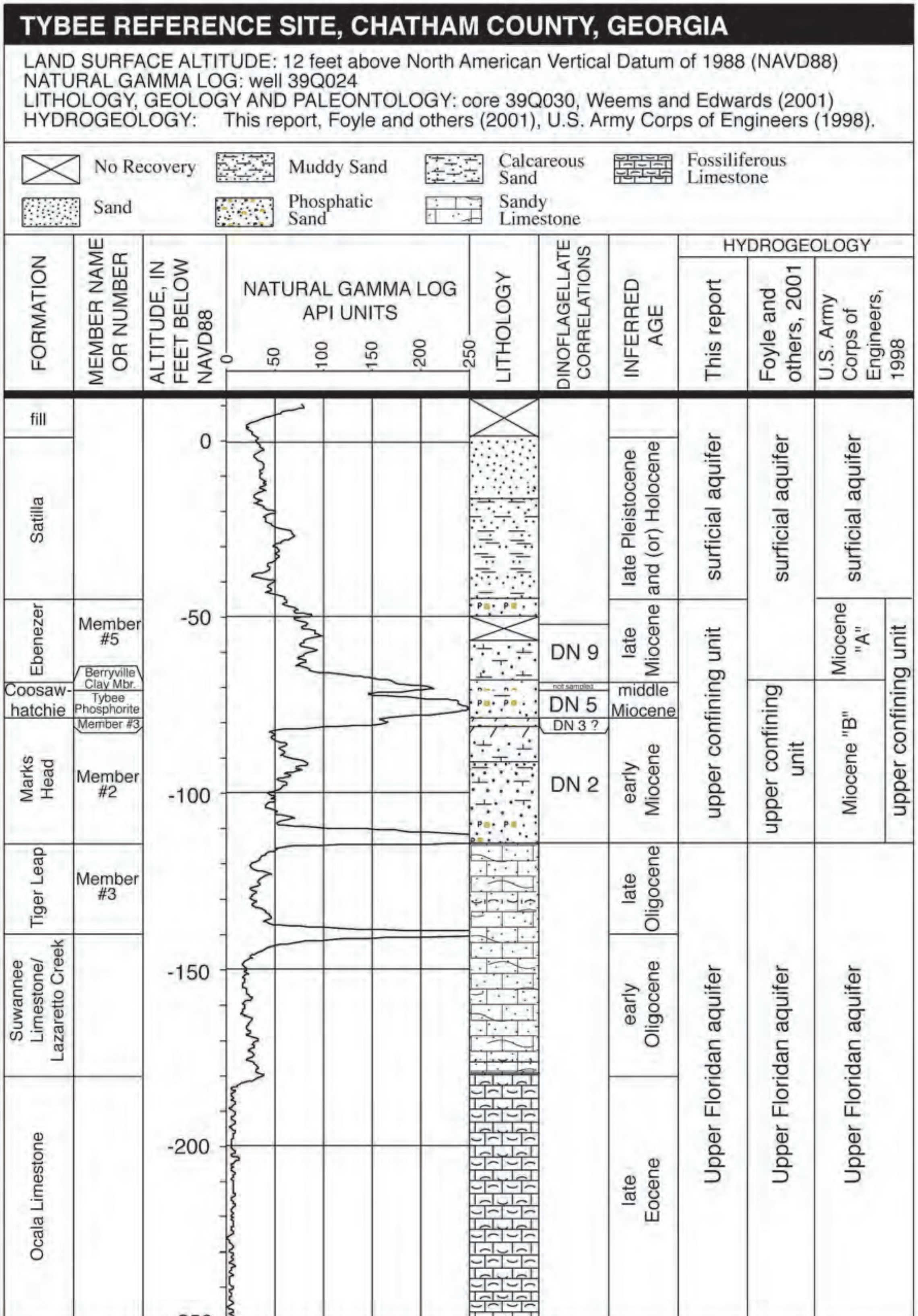


Figure 4. Geology and hydrogeology of the Tybee reference site (core 39Q030 and well 39Q024) at the northern end of Tybee Island, Georgia (modified from Weems and Edwards, 2001).

Table 2. Results of sieve and falling-head permeameter testing of core samples collected at the Calibogue, 7-mile, 8-mile, and 10-mile sites, South Carolina.

[NAVD 88, North American Vertical Datum of 1988; BFT, Beaufort County, South Carolina; hydraulic properties were determined by Geotechnics, East Pittsburgh, Pennsylvania]

Well number/ site name (fig. 1)	Date collected	Date analyzed	Hydrogeologic unit	Altitude (in feet below NAVD 88)	Gravel / sand / silt / clay (in percent)	Porosity (in percent volume)	Vertical hydraulic conductivity (in feet per day)
BFT-2251/ 10-mile site	6/20/2000	8/31/2000	Upper confining unit	81.6–82.1	0 / 57 / 24 / 19	63	2.5×10^{-4}
BFT-2295/ 8-mile site	5/31/2001	8/15/2001	Surficial aquifer	46.4–46.8	5 / 86 / 2 / 7	44	6.5×10^{-3}
BFT-2249/ 7-mile site	6/10/2000	8/25/2000	Upper confining unit	55.9–56.3	2 / 52 / 21 / 25	65	2.5×10^{-4}
BFT-2249/ 7-mile site	6/10/2000	8/25/2000	Upper confining unit	71–71.5	0 / 28 / 55 / 17	60	2.3×10^{-4}
BFT-2297/ Calibogue site	7/16/2001	8/15/2001	Surficial aquifer	39.2–39.7	19 / 77 / 0 / 4	40	4.8×10^{-1}
BFT-2297/ Calibogue site	7/17/2001	8/15/2001	Fine-grained paleochannel fill	59.7–60.2	2 / 22 / 39 / 37	68	5.4×10^{-4}
BFT-2297/ Calibogue site	7/17/2001	8/17/2001	Fine-grained paleochannel fill	75.2–75.7	0 / 19 / 39 / 42	73	4.5×10^{-4}

rocks and sediments (Atlanta Testing and Engineering, 1992; Temples and Engelhardt, 1997).

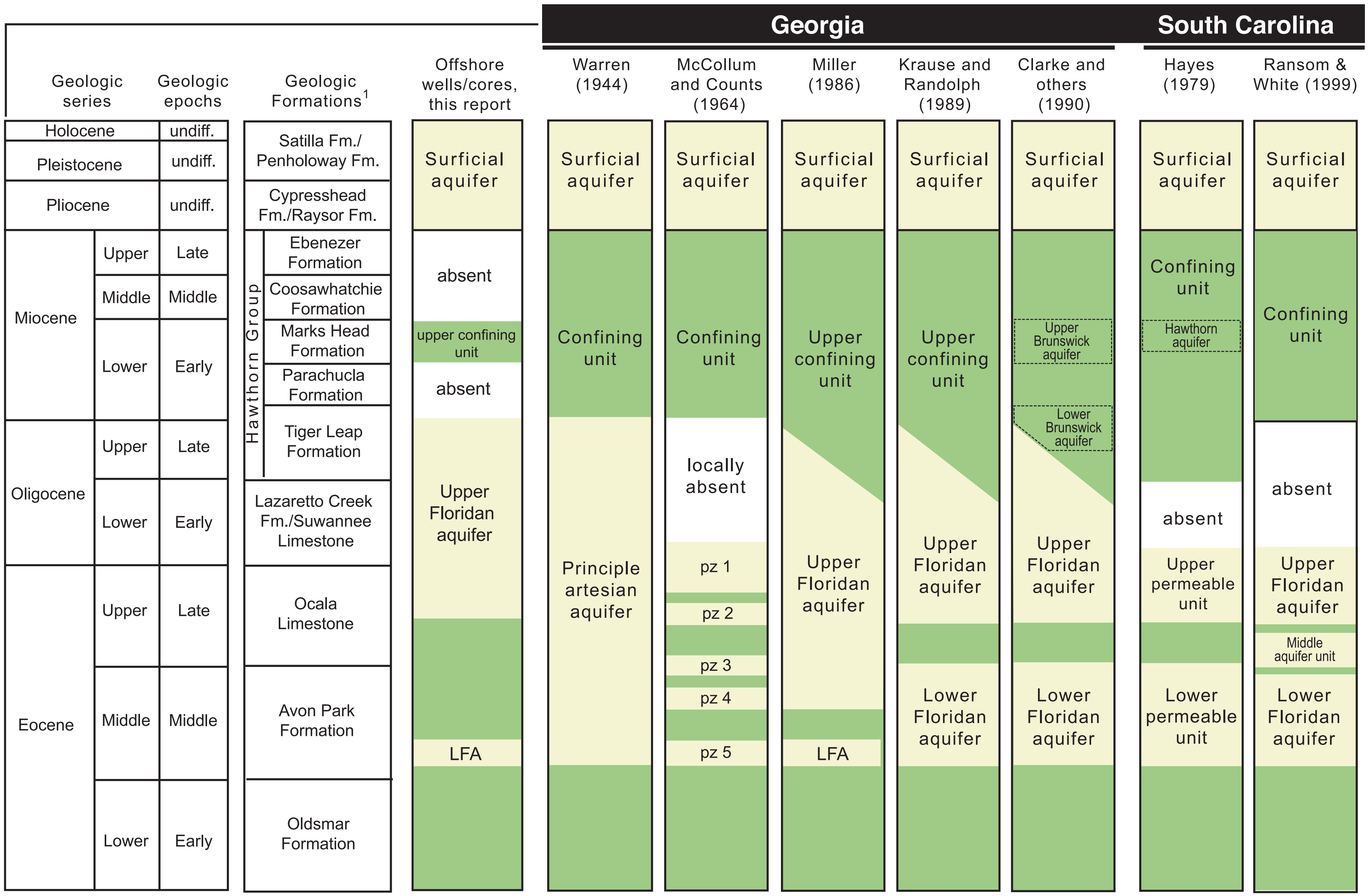
Hydrogeologic Setting

The hydrogeologic units of the Tertiary and Quaternary strata beneath the study area include, in descending order, the surficial aquifer, the upper confining unit, and the Upper and Lower Floridan aquifers, which form the Floridan aquifer system (Miller, 1986; figs. 4, 5). Underlying aquifers in the Cretaceous strata are not discussed in this report.

The surficial aquifer generally consists of Pleistocene and Holocene formations of sand and clay that overlie the Floridan aquifer system in Chatham County, GA, and Beaufort County, SC, (Krause and Randolph, 1989; Clarke and others, 1990). The aquifer is unconfined and includes the unsaturated zone and the water table in the study area. In parts of coastal Georgia, the surficial aquifer is divided into the unconfined water table and a lower semiconfined permeable zone (Clarke and others, 1990; Leeth and others, 2003). Water quality in the surficial aquifer varies from saline water in the Inner Continental Shelf and nearshore areas, and beneath sounds, estuaries, and salt marshes; and freshwater beneath landmasses, including most coastal barrier islands (Siple, 1960; Hayes, 1979).

The upper confining unit, as mapped in most of the study area, consists of Miocene strata of sand, silt, and clay with interbedded limestone and dolomite (Miller, 1986; fig. 4). Although not recognized in this report, the upper confining unit includes permeable zones used locally for onshore water supply, only with considerably less freshwater yield than the Upper Floridan aquifer (Hayes, 1979; Clarke and others, 1990). Among these permeable zones are the upper and lower Brunswick aquifers, as they are known in Georgia, which are used as an alternative water supply to the Upper Floridan aquifer in the southern coastal counties of Georgia. The upper and lower Brunswick aquifers are not well defined, however, and typically are not used in the northern coastal counties of Georgia because of their low yield (Clarke and others, 1990). In South Carolina, the Hawthorn aquifer is a low-yield permeable zone in the thin interval of Miocene strata composing the upper confining unit (Hayes, 1979). In addition to low yields, the potential for saltwater encroachment locally restricts use of these aquifers in coastal Georgia and South Carolina (Hayes, 1979; Clarke and others, 1990; Krause and Clarke, 2001).

The top of the Floridan aquifer system is the top of the continuous section of carbonate strata that include the Eocene strata and all or part of the Oligocene strata in Chatham County, GA (Miller, 1986; Clarke and others, 1990). The Oligocene strata are thin to the north of the Savannah River in South Carolina and pinch out to the north and the northwest of Hilton Head Island where the top of the Upper Floridan aquifer is the top of the late Eocene Ocala Limestone (Foyle and others, 2001). The Floridan aquifer system predominantly



[1] Oligocene through Holocene stratigraphy from Weems and Edwards (2001). Eocene stratigraphy based on Miller (1986).

[undiff., undifferentiated epochs; Fm, formation; pz, permeable zone; LFA, Lower Floridan aquifer; , aquifers recognized in the upper confining unit; , confining and semiconfining units]

Figure 5. Generalized geology and hydrogeology of the surficial aquifer, upper confining unit, and Floridan aquifer system in the offshore study area, and in Chatham County, Georgia, and Beaufort and Jasper Counties, South Carolina.

consists of limestone with minor layers of dolomite in the study area and can include Late Cretaceous to late Oligocene geologic formations, depending on locality.

The permeable zones of the Floridan aquifer system are divided into the Upper and Lower Floridan aquifers in Chatham County, GA, and Beaufort County, SC (fig. 5). The Upper Floridan aquifer beneath Chatham County consists of the permeable zones in the upper part of the Avon Park Formation, the Ocala Limestone, and the overlying Oligocene carbonates and non-carbonates, and contains freshwater with a concentration of total dissolved solids (TDS) less than 1,000 milligrams per liter (mg/L; McCollum and Counts, 1964; Krause and Randolph, 1989; Clarke and others, 1990; fig. 5). One permeable zone near the top of the Ocala Limestone is the dominant source of freshwater beneath Beaufort County and is simply referred to as the upper permeable zone of the Floridan aquifer system (Hayes, 1979; Hughes and others, 1989; Ransom and White, 1999). The Lower Floridan aquifer consists of a permeable zone toward the base of the middle Eocene Avon Park Formation, and generally contains saline water with a TDS concentration greater than 1,000 mg/L in Chatham and Beaufort Counties (U.S. Army Corps of Engineers, 1998; Falls and others, 2001). The top of the Lower Floridan aquifer is approximately 700 ft below NAVD 88 in the vicinity of the Tybee reference site, and correlates with the lowermost zone of the five permeable zones correlated in Chatham County (McCollum and Counts, 1964; Miller, 1986; fig. 5).

Details of the hydrogeology of the offshore and some of the onshore waterways near Hilton Head Island have been interpreted from seismic-reflection data (Henry and Kellam, 1988; Foyle and others, 2001; figs. 2, 3). The upper confining unit in the onshore and offshore area near Hilton Head Island is thinner across the Beaufort Arch (Colquhoun, 1969; Siple, 1969; Foyle and others, 2001). This feature caused the Miocene sediments of the upper confining unit and the top of the limestone of the Upper Floridan aquifer to be structurally higher in the subsurface (less than 100 ft below NAVD 88) of the offshore area near Hilton Head Island, relative to the offshore area near Tybee Island, and the rest of the Inner Continental Shelf seaward of Georgia (figs. 2, 3).

The interpretation of the seismic stratigraphy also identified several sites beneath the Atlantic Ocean seaward of Hilton Head Island and beneath eastern Beaufort County where the Miocene sediments of the upper confining unit generally are thin and, in several places, completely removed by incision of paleoriver channels (fig. 3). In the late Miocene, Pliocene, and Pleistocene, several low stands in sea level (lower than present-day sea level) occurred when the Inner Continental Shelf was subaerially exposed (Haq and others, 1987). During these low stands, rivers flowed across the Coastal Plain and the exposed Inner Continental Shelf and scoured into and, in some areas, completely through the underlying Miocene sediments of the upper confining unit (Foyle and others, 2001). After the low stand, sea level rose and the river channels and their valleys were backfilled with sediments of varying permeability. In this report, these features and the sediments in these features are referred to as paleochannels and paleochannel-fill sediments. In the study area, sites interpreted as having complete or nearly complete removal of the Miocene sediments on the offshore Beaufort Arch near Hilton Head Island were identified by Foyle and others (2001) as "no Miocene" sites and were discussed as potential saltwater-intrusion sites.

Although the outlines of the paleochannels were clearly identifiable in the seismic-reflection data, the texture and hydraulic properties of the paleochannel-fill sediments and the water quality of the Upper Floridan aquifer beneath the "no Miocene" sites could not be determined from the seismic-reflection data (Foyle and others, 2001). In a separate investigation, small paleochannels were interpreted from seismic-reflection surveys of the lower Savannah River and were drilled to determine the texture and vertical permeability of the paleochannel-fill and Miocene sediments (U.S. Army Corps of Engineers, 1998; Ocean Surveys, Inc., 2004). These small paleochannels were filled with silty sand and silt that had an average vertical permeability similar to that of the Miocene units sampled beneath the Savannah River. Depending on the permeability of the paleochannel fill at each "no Miocene" site, these paleochannels could provide local pathways for water movement between the surficial and Upper Floridan aquifers or act as a substitute for missing confining units, as appears likely at the lower Savannah River drill sites.

Ground-Water Supply and Saltwater Contamination

The Upper Floridan aquifer is the principal source of fresh ground-water supply in coastal Georgia and southern South Carolina. Withdrawal from the aquifer has changed over the years because of increased demand and changes in water quality.

Ground water from the Upper Floridan aquifer replaced surface water from the Savannah River as the primary source of public supply for Savannah in Chatham County, GA, in 1887. By 1888, Savannah was pumping ground water at the rate of 5.8 million gallons per day (Mgal/d) (Dole, 1915; Counts and Donsky, 1963). In the late 1890s, wells in the city of Beaufort and on Parris Island in Beaufort County, SC, also tapped the Upper Floridan aquifer. While the wells in the city of Beaufort continued to pump freshwater for several decades before water-quality problems ensued, the wells at Parris Island were taken out of production in 1903 because of elevated chloride levels (Counts and Donsky, 1963).

Ground-water use in Beaufort County, SC, and Chatham County, GA, near Savannah, steadily increased from 1887 to the late 1980s with increasing populations and commerce, and this increasing trend locally affected ground-water levels.

Municipal and industrial ground-water use by the city of Savannah and nearby industries increased from 5.8 Mgal/d in 1888 to approximately 20 Mgal/d in 1937 (Counts and Donsky, 1963). From 1937 to 1957, total water use in the Savannah area increased sharply from 20 to 62 Mgal/d, primarily in response to industrial water use. A regional cone of depression, centered on an industrial area northwest of downtown Savannah, developed in the potentiometric surface of the Upper Floridan aquifer (fig. 6). Although saltwater intrusion has not been detected in the Upper Floridan aquifer wells at Tybee Island, GA (Leeth and others, 2003), water-quality monitoring of the Upper Floridan aquifer on the northern end of Hilton Head Island, SC, recorded a progressive increase in chloride concentrations in well BFT-315 from less than 100 mg/L in 1974 to greater than 600 mg/L in 1983 (figs. 1, 7). Specific conductance in well BFT-1810 also increased from less than 4,000 to greater than 14,000 microsiemens per centimeter at 25 degrees Celsius (µS/cm) from 1987 to 2003 (fig. 7).

In an effort to protect the freshwater resource of the Upper Floridan aquifer and to mitigate the effects of saltwater intrusion, ground-water withdrawals from the Upper Floridan aquifer in Beaufort County, SC, and Chatham County, GA, are regulated, respectively, by the SCDHEC, as part of the Low

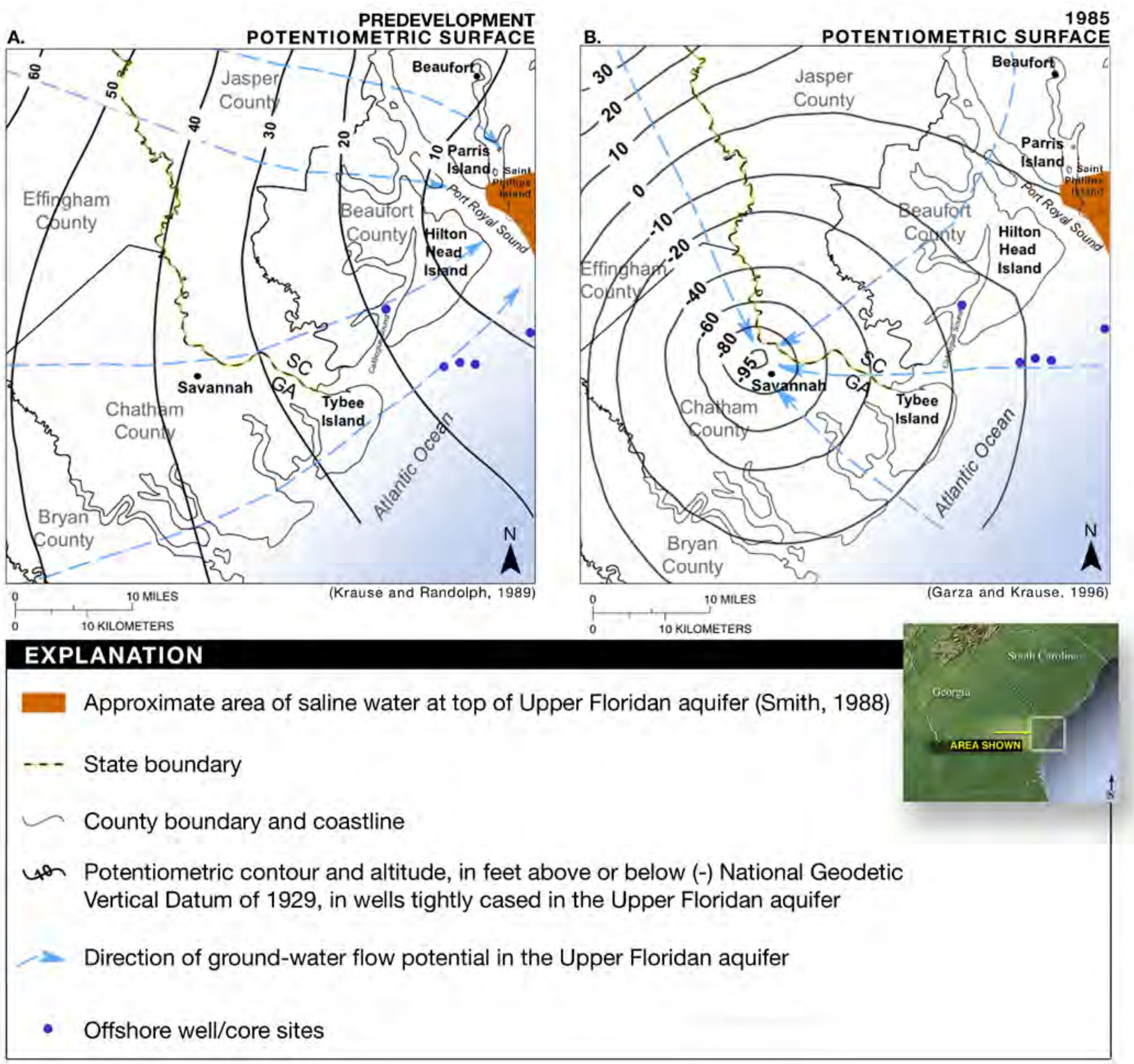


Figure 6. Altitudes of (A) predevelopment potentiometric surface (Krause and Randolph, 1989) and (B) 1985 potentiometric surface (Garza and Krause, 1996) of the Upper Floridan aquifer in the area of Savannah, Georgia.

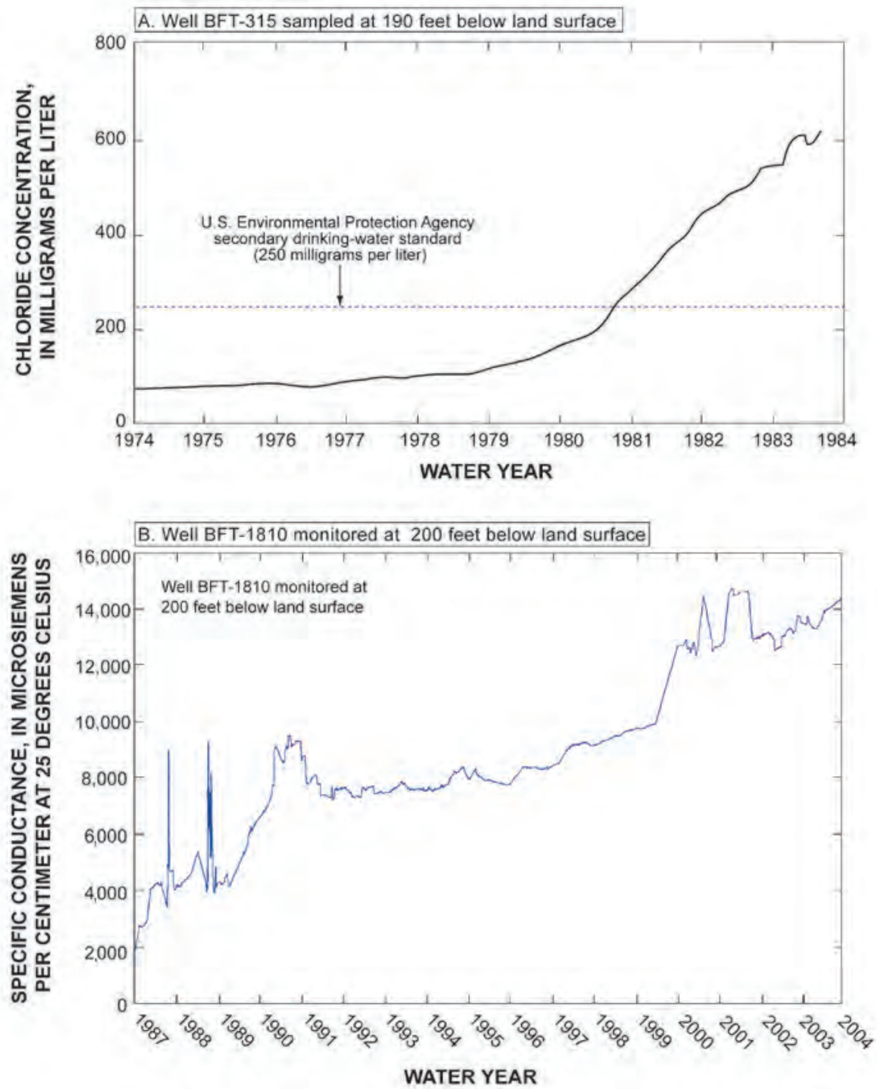


Figure 7. Monitoring results for (A) chloride concentration at well BFT-315 and (B) specific conductance at well BFT-1810 in the Upper Floridan aquifer on the northern end of Hilton Head Island, South Carolina. Chloride concentration at well BFT-1810 in 2003 exceeded 1,700 milligrams per liter.

Country Capacity Use Area, and by the GaEPD, as part of the Georgia Interim Strategy for managing saltwater intrusion (South Carolina Water Resources Commission, 1981; Georgia Environmental Protection Division, 1997). The SCDHEC requires permitting of all Upper Floridan aquifer wells with a pumping capacity of 100,000 gallons per day (gal/d), and monitors water quality in the Upper Floridan aquifer for saltwater intrusion. Efforts by the GaEPD to mitigate the potential for saltwater intrusion in the vicinity of Savannah have included the implementation of the Georgia Interim Strategy, which limits withdrawals from the Upper Floridan aquifer to 1997 water-use rates in parts of coastal Georgia, including Chatham County.

Ground-Water Flow and Potential for Saltwater Intrusion

Prior to the onshore withdrawal of freshwater from the Upper Floridan aquifer in the 1880s, the horizontal flow gradient was from west to east beneath Chatham and Beaufort Counties, and ground water moved from onshore to offshore along the coast (fig. 6). The freshwater was bounded along the eastern margin by saltwater in the confined Upper Floridan aquifer near the southern end of St. Phillips Island and adjacent parts of Port Royal Sound, SC (Smith, 1988). Southeast of Port Royal Sound, the freshwater/saltwater interface in the confined Upper Floridan aquifer was held further seaward of the coastline by the freshwater head of the Floridan aquifer system. Water levels in the Upper Floridan aquifer prior to development were greater than water levels in the overlying surficial aquifer in the onshore and offshore areas of Chatham and Beaufort Counties, which created a flow potential for upward leakage of freshwater from the confined Upper Floridan aquifer to the unconfined surficial aquifer. The potential for upward leakage of freshwater from the Upper Floridan aquifer precluded the downward leakage of saline water from surface water and the surficial aquifer in the study area, except in areas where the vertical hydraulic gradient approached 0 ft, and was of particular importance in areas where the confining unit was absent beneath Beaufort County (onshore) and the Beaufort Arch (offshore).

With onshore development of the freshwater resource of the Upper Floridan aquifer, water levels in Savannah declined from a predevelopment high of approximately 35 ft above NAVD 88 (25 ft above land surface) to more than 95 ft below NAVD 88 (105 ft below land surface) near the center of municipal and industrial withdrawals (Krause and Randolph, 1989; Garza and Krause, 1996). By 1998, the resulting cone of depression in the potentiometric surface of the Upper Floridan aquifer extended along the coastline as far north as Port Royal Sound, SC, and into the offshore areas near Hilton Head Island, SC, and Tybee Island, GA (fig. 6). Along coastal areas of Chatham and Beaufort Counties within the cone of depression, the horizontal hydraulic gradient in the Upper Floridan aquifer has changed, and currently (2005), ground water moves from offshore to onshore, a reversal of the predevelopment hydraulic gradient. The predevelopment direction of the vertical flow potential from the Upper Floridan aquifer to the surficial aquifer also has reversed to create a downward leakage potential through the upper confining unit and the paleochannel incisions in the upper confining unit.

Geologic and Hydraulic Characteristics of Hydrogeologic Units

The geology and hydrogeology observed at the four offshore sites and the Calibogue site were correlated to the stratigraphy and the hydrogeology of the Tybee reference site at the northern end of Tybee Island, and are illustrated in two geologic and two hydrogeologic cross sections (figs. 8–11; table 1). The cross sections are drawn along traces from the Tybee reference site to the 15-mile site (section A-A') and from the Tybee reference site to the Calibogue site (section A-A''; fig. 1). The biostratigraphic framework for the correlation of geologic units in this report is based primarily on the identification of dinoflagellates from selected core samples (fig. 4; app. 2).

Surficial Aquifer

In this report, the surficial aquifer correlates to the Satilla Formation (figs. 4, 8, 11). As reintroduced by Huddlestun (1988), the Satilla Formation includes the coastal barrier-island and marine inner-shelf deposits of the late Pleistocene and Holocene. The Satilla Formation at the Tybee reference site is predominantly fine- to medium-grained sand and silty sand with thin clay layers and sparse shell fragments; it is interpreted as barrier-island and near-shore deposits (Weems and Edwards, 2001).

The top of the surficial aquifer is land surface at the Tybee reference site and the sediment/water interface of the sea floor at the four offshore sites and at the Calibogue site (figs. 9, 11; table 1). The surficial aquifer is 54 ft thick at the Tybee reference site compared with 16.5 ft at the Calibogue site and 26.4 to 35.1 ft at the four offshore sites (figs. 9, 11). The differences in thickness of the surficial aquifer are largely a result of the relief along the top of the aquifer from the Tybee reference site to the offshore sites relative to the relief along the base of the aquifer. The base of the surficial aquifer is the contact of the base of the late Pleistocene Satilla Formation with the top of the late Miocene Ebenezer Formation at the Tybee reference site (fig. 4). The base of the surficial aquifer is the top of the upper confining unit at the 7-, 10-, and 15-mile sites and the top of channel-fill sediments at the Calibogue and 8-mile sites (figs. 9, 11).

At the four offshore sites, the installation of the surface casing disturbed the texture of the sediments in the upper 8.5 to 18.5 ft of the surficial aquifer. The cuttings and the disturbed sediment cores recovered from the surface casing consisted of very fine- to coarse-grained sand with shell fragments. Below the surface casing, the surficial aquifer consists of very fine- to fine-grained, well-sorted sand with minor amounts of phosphate (1 to 2 percent) and intergranular matrix of slightly calcareous clay and silt (5 to 10 percent).

Fossils in the Satilla Formation at the four offshore sites are abundant and diverse, as compared with the Satilla Formation at the Tybee reference site, and include shell fragments, echinoid spines, foraminifers, and small siliceous perforated tubules. Sediment samples from the 8- and 15-mile sites were processed and examined for microfossils and found to contain abundant pollen and sparse, commonly fragmented dinoflagellates, some of which are restricted to early Miocene and older ages. The sample at the 15-mile site collected near the base of the surficial aquifer contained Pleistocene calcareous nannofossils. Based on results at the 15-mile site, the age of the sediments of the surficial aquifer at the four offshore sites is interpreted as Pleistocene with reworked early Miocene dinoflagellates. Holocene sediments presumably are part of the sea floor deposits; however, a specific contact between the Pleistocene and Holocene was not determined. The Pleistocene sediments observed in the four offshore sites are open-marine, inner-shelf deposits of the Satilla Formation,

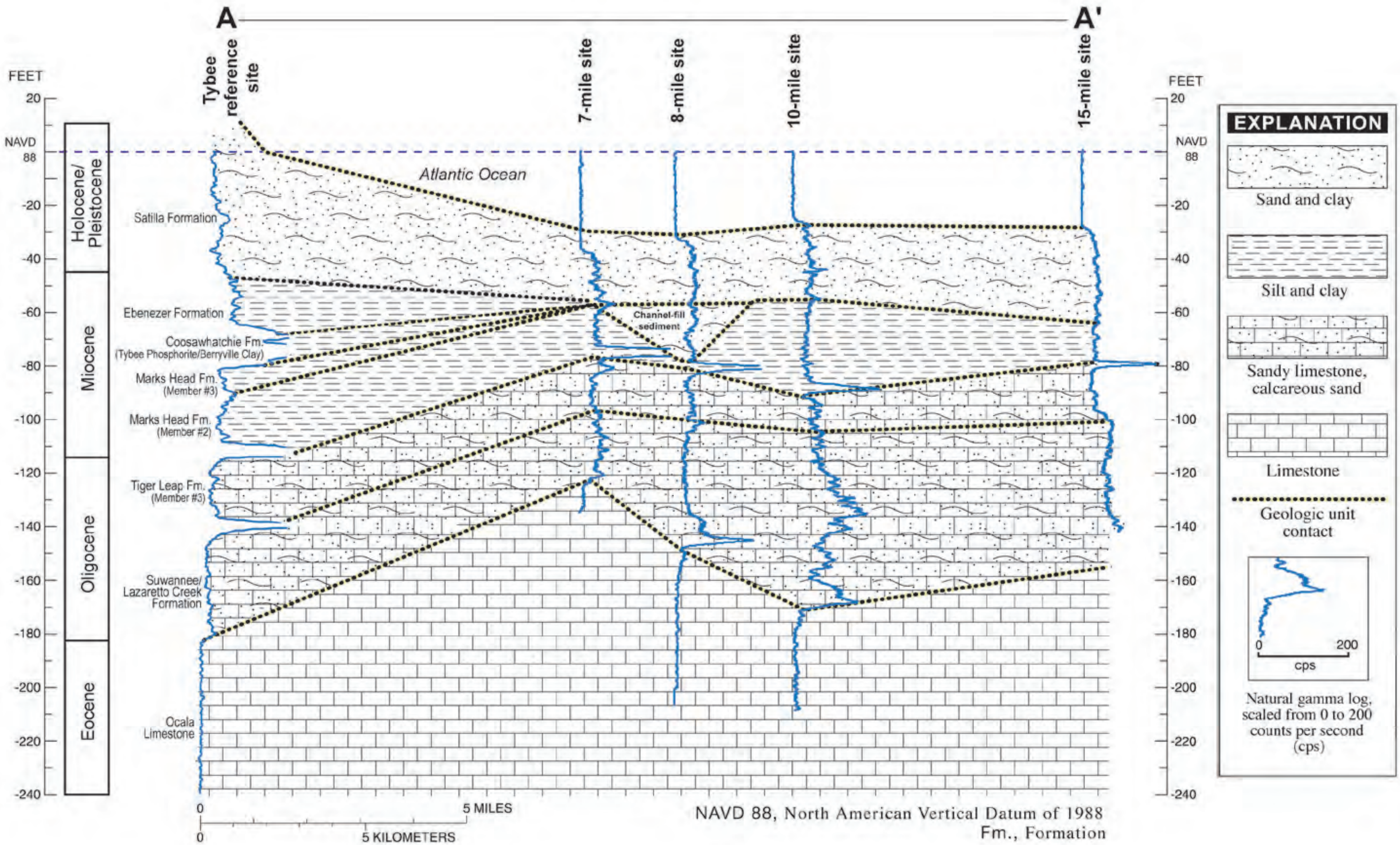


Figure 8. Geologic cross section A-A′ from the Tybee reference site at the northern end of Tybee Island, Georgia, to the 15-mile site on the Beaufort Arch seaward of Hilton Head Island, South Carolina (site locations are shown in figure 1).

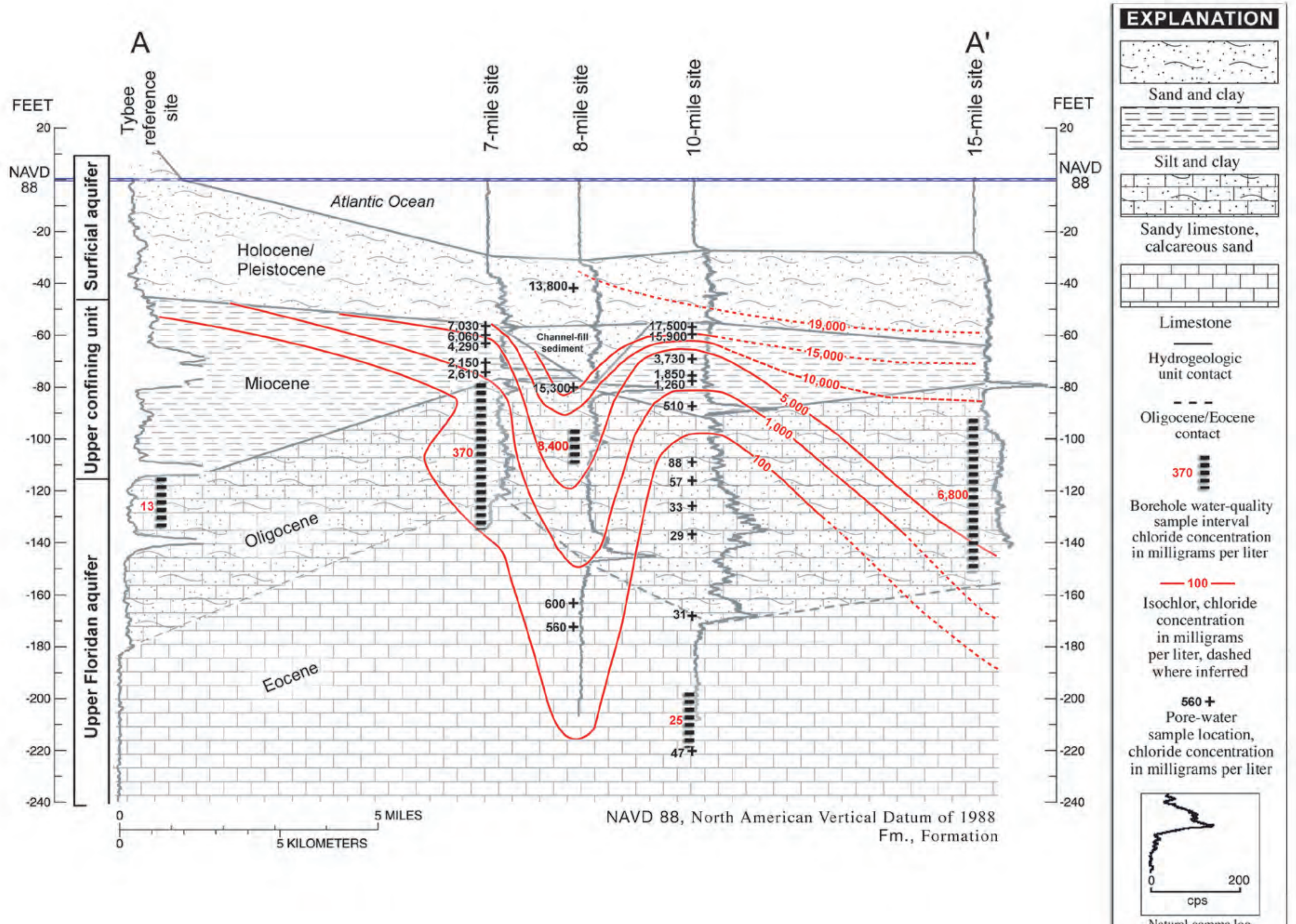


Figure 9. Hydrogeologic cross section A-A′ and chloride distribution from the Tybee reference site at the northern end of Tybee Island, Georgia, to the 15-mile site on the Beaufort Arch seaward of Hilton Head Island, South Carolina (site locations are shown in figure 1).

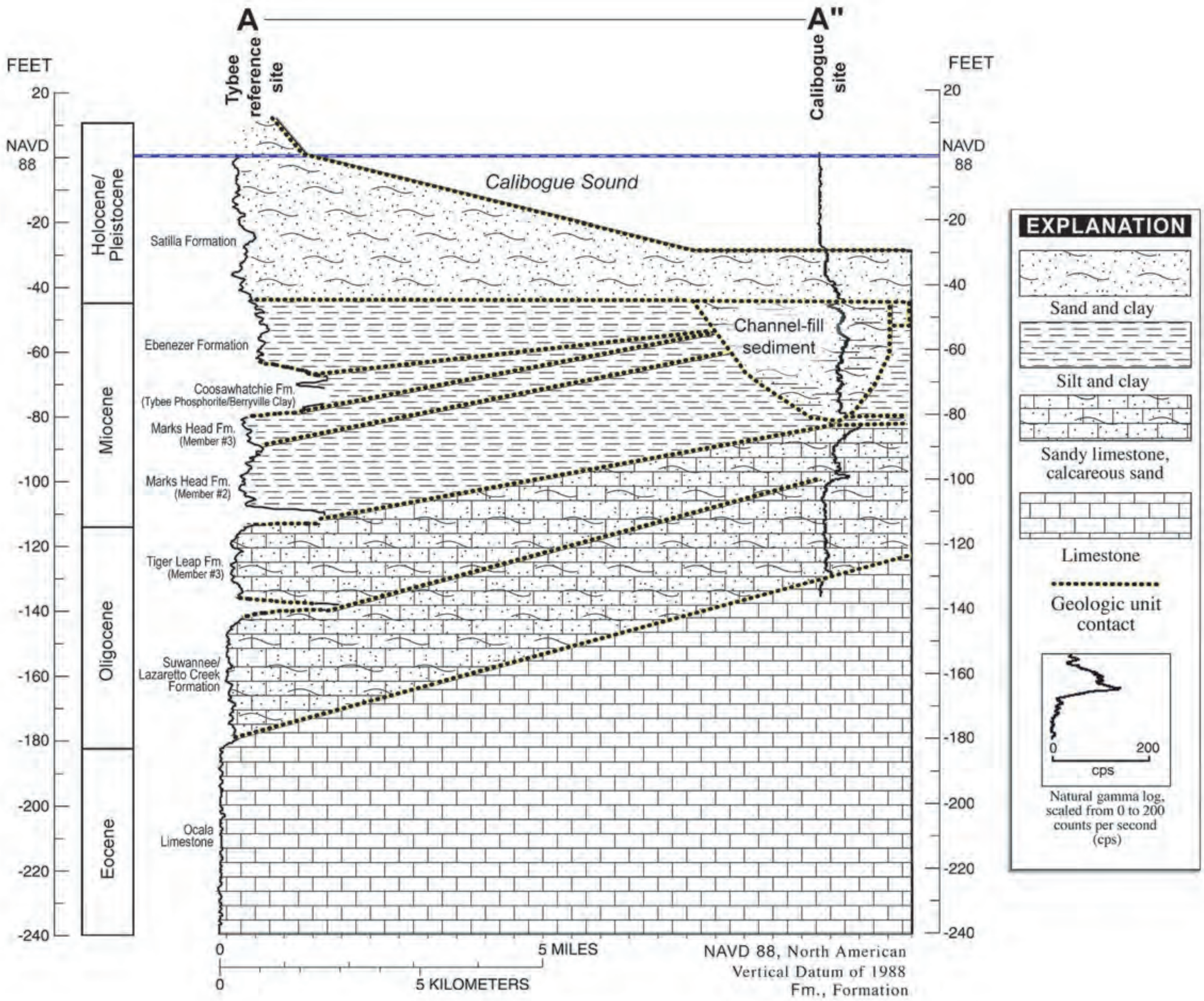


Figure 10. Geologic cross section A-A'' from the Tybee reference site at the northern end of Tybee Island, Georgia, to the Calibogue site west of Hilton Head Island, South Carolina (site locations are shown in figure 1).

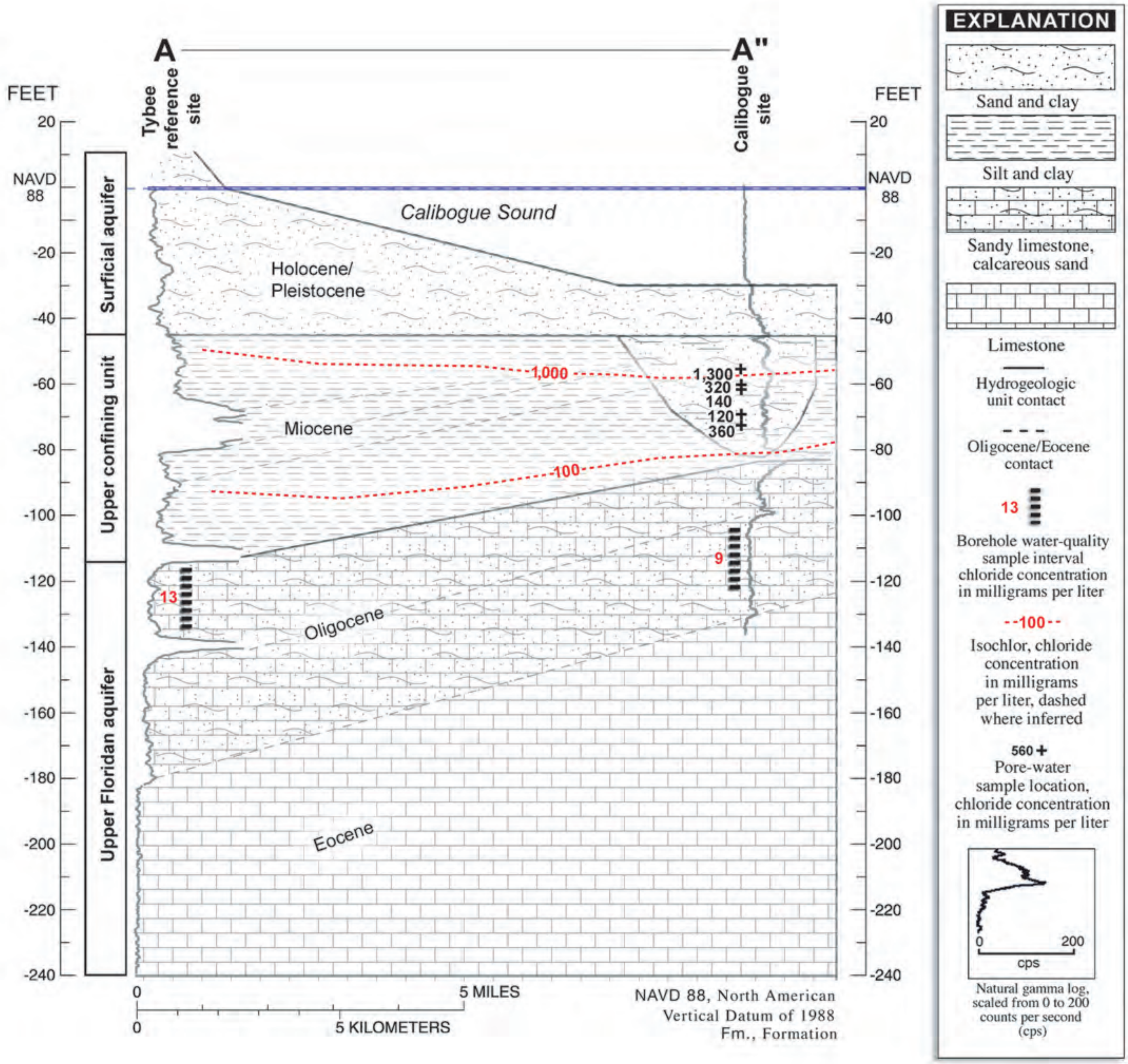


Figure 11. Hydrogeologic cross section A-A'' and chloride distribution from the Tybee reference site at the northern end of Tybee Island, Georgia, to the Calibogue site west of Hilton Head Island, South Carolina (site locations are shown in figure 1).

in contrast to the barrier-island and nearshore deposits at the onshore Tybee reference site.

At the Calibogue site, installation of the surface casing disturbed the sediments in the upper 8.5 ft of the surficial aquifer. The sediments of the surficial aquifer below the surface casing were sampled using a split-spoon coring technique, and included layers of medium- to very coarse-grained sand and fine- to medium-grained sand with clay matrix (generally less than 10 percent) and thin layers (less than 0.2 ft) of dark gray clay. Other components of the sediments include quartz granules and trace amounts (less than 1 percent) of phosphate and mica. Fossils include fragmented oysters, gastropods, and bryozoans. A sample processed for microfossils yielded plant debris, pollen, diatoms, and a few dinoflagellates. The dinoflagellates were not reworked and could only be identified as younger than Miocene. Therefore, the sediments from the sea floor to the top of the underlying paleochannel fill are interpreted as younger than Miocene and presumed to be Pleistocene and(or) Holocene marginal-marine deposits.

Two core samples from the surficial aquifer were analyzed for vertical hydraulic conductivity (figs. 9, 11). The sand sample from the Calibogue site had a hydraulic conductivity of 0.48 foot per day (ft/d; table 2). A clay layer sampled in the otherwise sand-dominated surficial aquifer at the 8-mile site had a hydraulic conductivity of 6.5×10^{-3} ft/d. Depending on the continuity and thickness of clay layers in the surficial aquifer, localized confining or semiconfining layers may be present in the surficial aquifer.

Paleochannel Fill

Paleochannel fill was found at the 8-mile and Calibogue sites beneath the surficial aquifer (figs. 9, 11). The sedimentary textures and the hydraulic conductivities of the sediments differ considerably at these two sites.

At the 8-mile site, the bit for the wire-line coring system rapidly penetrated the sediment from the sea floor to 76.7 ft below NAVD 88 with no noticeable difference in penetration rate. Core recovery for this interval was less than 25 percent. The interval from 76.7 to 80 ft below NAVD 88 was sampled using a split-spoon coring technique. The sediments in this interval included a lithologic contact at 77.7 ft below NAVD 88, which is interpreted as the base of the paleochannel-fill sand and the eroded top of the upper confining unit (fig. 9; table 1). A specific contact between the surficial aquifer and the paleochannel-fill sediments was not observed in the cores and was not detected in the drilling penetration rate. The top of the paleochannel fill is estimated to be approximately 58 ft below NAVD 88 on the basis of the textural differences between the fine- to medium-grained sand recovered above 58 ft, the poorly sorted, fine- to very coarse-grained sand below 58 ft, and a small spike in the natural gamma log at 58 ft (fig. 9). The estimated thickness of the paleochannel-fill sediments is 19.7 ft with only 2.5 ft of recovered sediment. The paleochannel-fill sediments are very poorly sorted and consist of fine- to very coarse-grained sand with quartz granules (5 to 10 percent), phosphate granules (1 to 2 percent), abundant shell fragments (10 to 25 percent), and only minor amounts of intergranular clay matrix (less than 10 percent). It is questionable whether the recovered sediments represent a true depositional texture or reflect a coring-disturbed texture. Samples were contaminated with drilling mud; therefore, the samples were not processed for microfossils or hydraulic properties. Based on the penetration rate, it is assumed that the sediments of the paleochannel fill are predominantly unlithified sand with more textural similarity to the sands of the surficial aquifer compared with the clay, silt, and silty sand of the upper confining unit.

At the Calibogue site, the core recovery was approximately 60 percent in the surficial aquifer and paleochannel-fill interval. Similar to the 8-mile site, the contact at the top of the paleochannel-fill sediments was not observed in a core but was estimated to be 44.2 ft below NAVD 88, and is correlated to a sudden change in drill-bit penetration rate and a small spike in the natural gamma log (figs. 10, 11; table 1). The sharp basal contact of the paleochannel fill with the underlying Oligocene limestone of the Tiger Leap Formation was observed at 79.2 ft below NAVD 88. The total thickness of the paleochannel fill is 35 ft. In contrast to the 8-mile site, the paleochannel-fill sediments at the Calibogue site are similar in texture to the fine-grained sediments of the upper confining unit and consist of sand- and matrix-dominated lithologies. The sand-dominated lithology consists of very fine- to fine-grained sand with an abundant matrix (20 to 50 percent) of silt, clay, and carbonate. The matrix completely fills the intergranular space between sand grains. The matrix-dominated lithology generally has a sand component of less than 25 percent, wavy-laminated to burrow-mottled textures, and includes sand-sized grains of phosphate (1 to 2 percent), mica, shell fragments (less than 5 percent), and shark teeth. The paleochannel fill has a basal layer of medium- to very coarse-grained sand with silt and clay matrix (20 to 30 percent) and rounded sand-sized grains and granules of phosphate (5 to 15 percent). The abundance of phosphate at the basal contact resulted in a large spike in the natural gamma log (figs. 10, 11). The phosphate in the basal sand interval probably was reworked from eroded Miocene sediments of the Marks Head Formation and the phosphatic upper contact of the underlying Oligocene limestone of the Tiger Leap Formation at 79.2 ft below NAVD 88.

Three sediment samples at 58, 69.2, and 75.7 ft below NAVD 88 were processed for microfossils; the samples contained relatively few dinoflagellates compared with samples from the upper confining unit. The samples included reworked dinoflagellate specimens of mostly early Miocene age and in-situ specimens of a younger than Miocene age, similar to the Pleistocene sediment sample from the surficial aquifer at this site. The samples collected higher in the paleochannel fill at 69.2 and 58 ft below NAVD 88 progressively had more in-situ dinoflagellate specimens of a younger than Miocene age and fewer reworked specimens relative to the sample at 75.7 ft below NAVD 88. The sample at 58 ft below NAVD 88 also contained abundant plant debris and diatoms. The age of the paleochannel-fill interval is interpreted as post-early Miocene, based on the reworking of early Miocene microfossils; however, the in-situ microfossils were not age-specific.

At the Calibogue site, the results for the vertical hydraulic conductivities of two samples from the paleochannel-fill sediments are 4.5×10^{-4} and 5.4×10^{-4} ft/d (table 2). These results are lower than results for the paleochannel-fill sediments and the late and middle Miocene sediments beneath the Savannah River (averages equal 7.7×10^{-3} and 9.9×10^{-3} ft/d, respectively) reported by the USACE (1998), but are similar to results for the early Miocene sediments (average equals 5.4×10^{-4} ft/d).

Upper Confining Unit

The upper confining unit at the Tybee reference site is 69.4 ft thick and includes two unnamed members of the early Miocene Marks Head Formation, the Tybee Phosphorite and Berryville Clay members of the middle Miocene Coosawhatchie Formation, and the late Miocene Ebenezer Formation (U.S. Army Corps of Engineers, 1998; Weems and Edwards, 2001; fig. 4). The top of the upper confining unit at the Tybee reference site is the top of the Ebenezer Formation at 45 ft below NAVD 88 (fig. 4; table 1). The basal contact with the Oligocene limestone of the Tiger Leap Formation is at 114.4 ft below NAVD 88. Foyle and others (2001) mapped the thickness of the upper confining unit as slightly more than 50 ft, and does not include more than 15 ft of sediments of the Ebenezer Formation (fig. 3).

At the Tybee reference site, the late Miocene Ebenezer Formation is a sand-dominated interval (fig. 4). The sand is very fine to medium grained and well sorted, and has more silt and clay matrix and a more diverse component of marine fossils relative to the overlying Satilla Formation. Lithologically, the Coosawhatchie Formation is distinguished from the late and early Miocene formations by the abundance of granular phosphate in the Tybee Phosphorite and Berryville Clay members, which equals as much as 80 and 20 percent of the two members, respectively. The phosphate emits gamma radiation from decaying uranium in its crystalline structure, which results in a strong spike (hundreds of gamma-ray counts per second) in the borehole natural gamma log, relative to the overlying Ebenezer and underlying Marks Head Formations (fig. 4). The upper member (member #3) of the Marks Head Formation consists of a thin (0.3 ft thick) dolomitic and sandy silt layer at its upper contact and a silty, medium to very coarse sand with a minor amount of phosphate. The lower member (member #2) of the Marks Head Formation consists of sand- and matrix-dominated lithologies, including silty dolomitic sand and sandstone, sandy silt, and silty clay. Lithologies in the Marks Head Formation have small amounts (typically 1 to 5 percent) of calcite, phosphate, and dolomite. The sand in the lower member of the Marks Head Formation is very fine to fine grained and well sorted, and has an abundant intergranular matrix of silty clay and dolomite.

With the absence of middle and late Miocene sediments, the upper confining unit consists of the lower member (member #2) of the early Miocene Marks Head Formation at the four offshore sites (figs. 8, 9). The top, the thickness, and the base of the upper confining unit at each of the four offshore sites agree to the seismic interpretation of the Miocene confining unit of Foyle and others (2001). The thickness of the confining unit is 17, 32 and 17.3 ft at the 7-, 10-, and 15-mile sites, respectively (figs. 8, 9). The paleochannel incisions completely removed the upper confining unit at the Calibogue site (fig. 10) and all but 0.8 ft of the confining unit at the 8-mile site (fig. 9).

At the 7-, 10-, and 15-mile sites, the Miocene sediments of the upper confining unit have more phosphate and a fine-grained matrix of silt, clay, and carbonate relative to the overlying surficial aquifer (figs. 8, 9). The sediments correlate with the lithologies of member #2 of the Marks Head Formation at the onshore Tybee reference site and vary from matrix- to sand-dominated; moreover, even the intergranular space in the sand is filled with a calcareous mix of clay and silt. The matrix also can include silt-size rhombic dolomite crystals, as much as 25 percent, and commonly has a subtle burrow-mottled texture. The sand generally is very fine to fine grained with some coarser-grained intervals present. The amount present of carbonate shell fragments and sand- and granule-sized grains of phosphate generally is less than 2 percent, but this composition is more common in a few small intervals.

Samples of the upper confining unit were processed for dinoflagellates at all four offshore sites. The dinoflagellates in all samples were well preserved with no indication of reworking, and were clearly diagnostic of the upper part of dinoflagellate zone DN2 or the early Burdigalian age of the early Miocene (de Verteuil and Norris, 1996). The abundance of pollen observed in the Pleistocene samples of the surficial aquifer was not observed in the Miocene samples, indicating that the depositional environment of the Miocene was probably farther from a terrigenous source (farther seaward from the coast) relative to the depositional environment of the Pleistocene at these sites.

Phosphatic sediments of the middle Miocene Coosawhatchie Formation and silty sand of the late Miocene Ebenezer Formation are absent at the Calibogue site and the four offshore sites (figs. 8, 10). This absence is attributed to non-deposition or post-depositional erosion near the crest of the Beaufort Arch. Because of the absence of the phosphatic members of the Coosawhatchie Formation, only a small spike was observed on the natural gamma logs in sediments above the top of the paleochannel-fill sediments at the 8-mile and Calibogue sites, and in sediments overlying the Marks Head Formation at the 7- and 10-mile sites. No spike was observed on the natural gamma log in these sediments at the 15-mile site. The small spike in the gamma-ray log is the result of a small amount (less than 3 percent) of phosphate in the basal lag of the Pleistocene sediments that was probably reworked from the underlying Miocene sediments.

Vertical hydraulic conductivity ranged from 2.3×10^{-4} to 2.5×10^{-4} ft/d for two samples from the upper confining unit at the 7-mile site and one sample from the 10-mile site (table 2). These results are similar to the average vertical hydraulic conductivity of 5.4×10^{-4} ft/d reported for 11 samples collected from the Marks Head Formation of the upper confining unit beneath the Savannah River near Tybee Island (U.S. Army Corps of Engineers, 1998).

Upper Floridan Aquifer

In this report, the Oligocene Tiger Leap Formation and the Suwannee Limestone/Lazaretto Creek Formation are included with the Eocene Ocala Limestone and Avon Park Formation to form the Upper Floridan aquifer (figs. 4, 5; table 1). The early Oligocene strata include carbonates of the Suwannee Limestone in most of Chatham County, GA, but are dominated by sand and clay lithologies of the Lazaretto Creek Formation along the coast of northeastern Chatham County and in the offshore study area (Huddlestun, 1993; Weems and Edwards, 2001). The sand- and clay-dominated lithologies of the Lazaretto Creek Formation at the onshore Tybee reference site, the Calibogue site, and the four offshore sites separate the carbonate of the Oligocene Tiger Leap Formation from the Eocene carbonates, and may serve locally as a confining unit between permeable zones in the Tiger Leap Formation and Ocala Limestone in the offshore study area. In the following discussion, the early Oligocene strata are discussed as the Lazaretto Creek Formation because of the dominance of sand and clay overlying carbonates at the offshore and Calibogue sites.

The cored interval at the Tybee reference site (39Q030 core) includes 6.9 ft of sandy Oligocene carbonate from the base of the Marks Head Formation at 114.4 ft below NAVD 88 to the termination of coring at 121.3 ft below NAVD 88 (Weems and Edwards, 2001; fig. 4). Descriptions of sediments and rock cuttings collected from the remainder of the Oligocene section at the Tybee reference site (well 39Q024) and from corehole 39Q022 drilled by the Georgia Geologic Survey on Tybee Island, include mixed lithologies of unconsolidated calcareous quartz sand, calcareous quartz sandstone, and sandy limestone (Huddlestun, 1993). The Oligocene section is 70 ft thick in the 39Q022 core and is the type section for the Oligocene Lazaretto Creek Formation (Huddleston, 1993). Weems and Edwards (2001) used a spike on the natural gamma log associated with phosphate in the 39Q022 core as evidence of an unconformity, and divided the Oligocene into the early Oligocene Lazaretto Creek Formation and the late Oligocene Tiger Leap Formation. A similar spike occurred on the natural gamma log for well 39Q024 at the Tybee reference site, and was correlated with the phosphatic upper contacts of the Lazaretto Creek Formation (fig. 4). The Tiger Leap Formation is dominated by calcareous sandstone and sandy limestone relative to the unconsolidated calcareous sand that dominates the Lazaretto Creek Formation. In addition to intergranular porosity, the sandy limestone and calcareous sandstone in both formations have moldic porosity, ranging from a few percent to as much as 20 percent, that is the product of selective dissolution of carbonate shells (Huddlestun, 1993; Weems and Edwards, 2001).

The Eocene strata at the Tybee reference site include the late Eocene Ocala Limestone and the middle Eocene Avon Park Formation; both are lithologically distinctive from the overlying Oligocene Suwannee Limestone/Lazaretto Creek Formation by the near absence of quartz sand (fig. 4). The Ocala Limestone and Avon Park Formation contain marine fossils, including bryozoans, foraminifers, pelecypods, and echinoids, and generally have interparticle porosity (0 to 20 percent) associated with the depositional texture of the limestone.

At all four offshore drill sites and the Calibogue site, the top of the Upper Floridan aquifer, as mapped by Foyle and others (2001), closely approximates the contact between the base of the Marks Head Formation of the upper confining unit and the top of the sediment and rock units of the underlying Oligocene (figs. 2, 8–11; table 1). With the exception of the 15-mile site, each of the offshore sites and the Calibogue site penetrated the Oligocene strata and terminated in the Eocene. At the 15-mile site, drilling terminated in the Oligocene. The top of the Oligocene Tiger Leap Formation is easily recognized by a strong spike in the natural gamma log at the phosphatic, dolomitic upper contact with the Miocene Marks Head Formation at the four offshore sites and with paleochannel fill at the Calibogue site (figs. 8, 10). The effects of erosional and depositional thinning in the Oligocene strata are evident when comparing the slightly thinner and structurally higher strata at the 7-mile and Calibogue sites relative to the Tybee reference site. The 8- and 10-mile sites are progressively thicker and structurally lower on the flank of the offshore extension of the Beaufort Arch, relative to the 7-mile site. Likewise, the top of the Eocene strata is higher at the 7-mile and Calibogue sites relative to the Tybee reference site and progressively lower at the 8- and 10-mile sites relative to the 7-mile site. Because the top of the Eocene strata was not penetrated at the 15-mile site, the thickness of the Oligocene strata was not determined at this location.

The Tiger Leap Formation at the four offshore sites and the Calibogue site is lithologically similar to the Tiger Leap Formation at the Tybee reference site, and contains limestone with 5- to 25-percent quartz sand, calcareous quartz sandstone, and unconsolidated calcareous quartz sand. The quartz sand generally is medium to coarse grained. The unconsolidated sediments include calcareous sand and are less common than the hardened rock lithologies at the offshore and Calibogue sites, with the exception of the 10-mile site. Recovered cores at the 10-mile site include thin intervals of sandy limestone near the top of the Oligocene, but are dominated by unconsolidated fine- to very coarse-grained quartz sand with carbonate and clay matrix (10 to 25 percent).

The Lazaretto Creek Formation at the offshore and Calibogue sites is dominated by unconsolidated medium- to coarse-grained quartz sand with clay and carbonate matrix. The formation includes minor amounts of sand-sized phosphate and subtle laminated and burrow-mottled textures.

Samples processed for dinoflagellates yielded sparse and poorly preserved specimens in the sections interpreted as the Tiger Leap Formation at the 7-, 10-, and 15-mile sites and abundant, diverse specimens of early Oligocene age in the section interpreted as the Lazaretto Creek Formation at the 10-mile site. The dinoflagellates in the Tiger Leap Formation were not clearly age specific and could represent reworked and in-situ specimens. Both formations are interpreted as open, shallow marine environments.

Offshore Water Levels in the Upper Floridan Aquifer

To better define ground-water flow in the study area, head measurements in the Upper Floridan aquifer were made in the offshore and Calibogue wells. The water levels were used to verify estimated and simulated water levels in potentiometric maps (Krause and Randolph, 1989; Garza and Krause, 1996; Ransom and White, 1999; fig. 6).

According to the potentiometric map by Warren (1944), predevelopment (1888) water levels for the Upper Floridan aquifer were estimated to be approximately 15 ft above NAVD 88 at the Calibogue site, 10 ft above NAVD 88 at the 7-, 8- and 10-mile sites, and less than 10 ft above NAVD 88 at the 15-mile site. The potentiometric map by Counts and Donsky (1963) indicates that by December 1957, water levels declined to 5 ft below NAVD 88 at the Calibogue site, and approximately 0 ft at the 7-, 8-, and 10-mile sites. The area inside the 0-ft contour for the Upper Floridan potentiometric surface included the southern half of Hilton Head Island, the 7-, 8-, and 10-mile offshore sites by December 1957, and all of Hilton Head Island, most of Port Royal Sound, and the 15-mile site during the 1980s and 1990s (Krause and Randolph, 1989; Garza and Krause, 1996; Ransom and White, 1999; fig. 6).

Continuous monitoring of water levels in the temporary wells was not conducted because of the cost and time constraints of the offshore drilling program. Instead, water levels were determined with an electric measuring tape after the development of the open borehole intervals in the Oligocene and Eocene sediments of the Upper Floridan aquifer. Water levels were measured at each well before and after water-quality sampling (generally several hours apart) and were averaged as an approximation of the water level in the Upper Floridan aquifer relative to NAVD 88. The measured water levels were corrected for the effects of water density and tidal loading before they were compared with potentiometric maps representing freshwater head.

The density of saline water is a function of the quantity of TDS, which reduces the altitude to which water rises in a well cased in a confined aquifer relative to an equivalent freshwater head. The relation is described by Cooper and others (1964) using the following formula:

$$l_f = p_s l_s / p_f ,$$

where:

- l is the length of the water column measured above the bottom of the casing;
- p is the density of the water in the casing; and
- f and s refer to freshwater and saline water, respectively.

For example, the water level in a well with a 100-ft-long column of saline water in a well casing would have an equivalent freshwater head that is 2.4 ft higher, assuming densities of 1 gram per cubic centimeter (g/cm^3) for freshwater and 1.024 g/cm^3 for saline water equivalent to modern seawater.

Water density for each well in this study was calculated by using the software program WATEQ4F to sum the dissolved-constituent concentrations from laboratory analyses of the water samples collected from the Upper Floridan aquifer (Ball and Nordestrom, 1991). The water samples collected at the 8-mile and 15-mile sites had TDS concentrations greater than 1,000 mg/L and calculated densities of 1.009 and 1.008 g/cm^3, respectively. All other water samples collected from the Upper Floridan aquifer had TDS concentrations of less than 1,000 mg/L and calculated densities between 1.0 and 1.001 g/cm^3. Density corrections for these freshwater samples were less than 0.02 ft and were not applied. Density corrections of 0.9 and 0.8 ft were applied to the reported daily mean water levels for the saline samples collected at the 8-mile and 15-mile sites (app. 1).

Tides in the study area rise and fall twice daily in the inland estuaries and open-ocean environments. The magnitude of the tidal range can exceed 9 ft near the mouth of the Savannah River. The hydrostatic pressure change associated with tidal loading and unloading along the coast also results in twice-daily highs and lows in ground-water levels in the confined Upper Floridan aquifer (Gawne, 1997). Ground-water levels in onshore wells in the Upper Floridan aquifer near Hilton Head Island have a tidal-loading effect of as much as 70 percent of the tidal range, or 6.3 ft. The actual magnitude of the tidal effect on the water level in any single well depends on the thickness and competency of the confining unit and the depth to the top of the confined aquifer (Landmeyer, 1996). For instance, the daily magnitude of water levels in the Upper Floridan aquifer well, 39Q025, on the northern end of Tybee Island varied from approximately 1.7 to 3.5 ft during September 1999 (fig. 12). An approximate 1-hour lag was observed between the surface-water high tides and the high ground-water levels in well 39Q025.

The density-corrected mean water level in the Upper Floridan aquifer was 2.3 ft above NAVD 88 at the 15-mile site in September 1999 and 11.5 ft below NAVD 88 at the 8-mile site in June 2001 (app. 1). The mean water level was 17.7 ft in July 2001 at the Calibogue site, 17.4 ft in June 2000

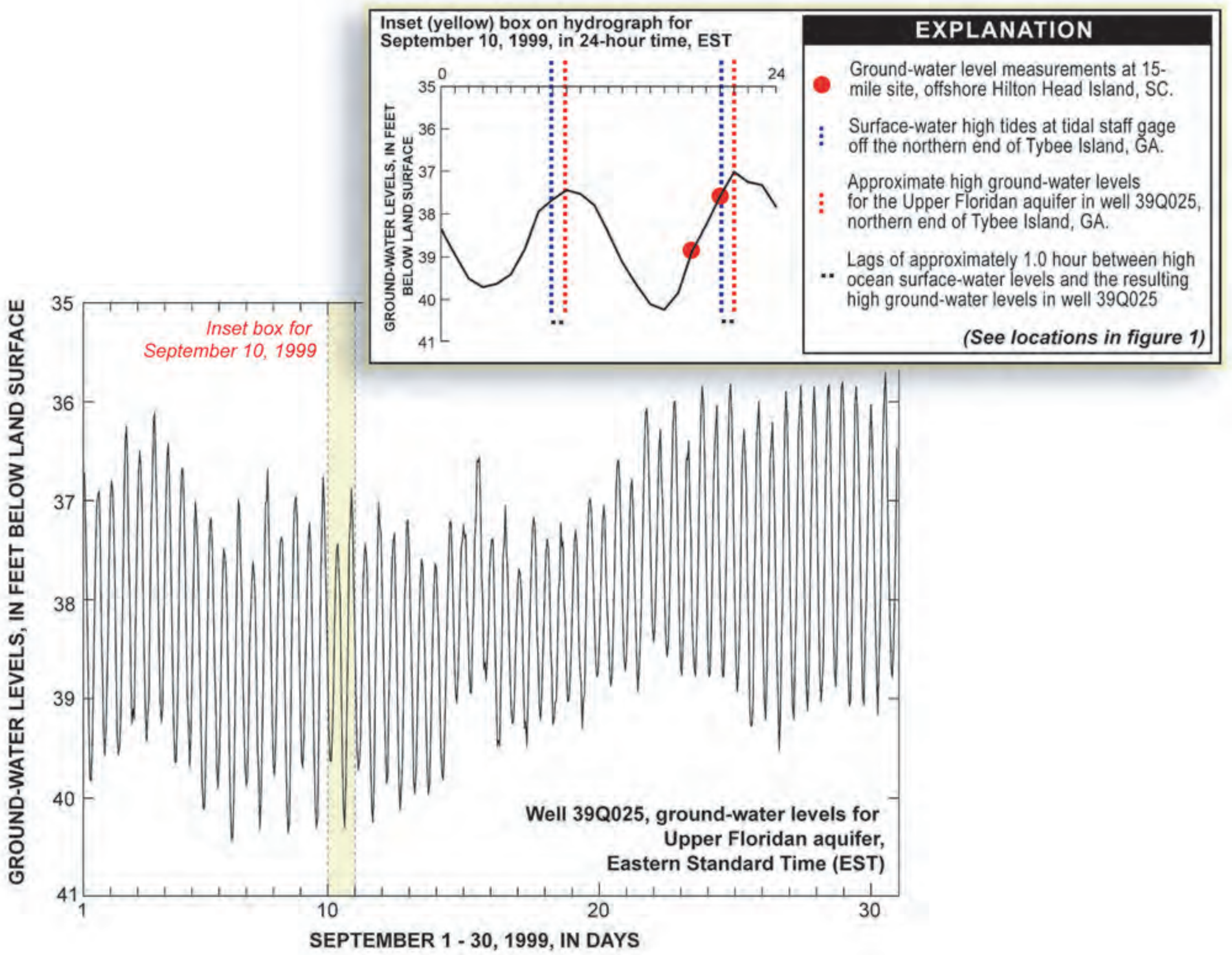


Figure 12. Hourly water levels, in feet below land surface, in the Upper Floridan aquifer in well 39Q025 at the northern end of Tybee Island, Georgia, for September 1999.

at the 7-mile site, and 13.1 ft in June 2000 at the 10-mile site, all below NAVD 88. With the exception of the 15-mile site, all water levels basically matched the 1985 and later Upper Floridan potentiometric surfaces of Garza and Krause (1996) and Ransom and White (1999).

The density-corrected water levels used to calculate the mean water level for the 15-mile site were 1.0 and 3.6 ft above NAVD 88, and were measured at approximately high tide and 2 hours after high tide, respectively. The time lag between the surface-water high tide and the recorded high in the ground-water hydrograph at the Tybee reference site is approximately 1 hour (fig. 12). Assuming a similar time lag at the 15-mile site, the two water levels of 1.0 and 3.6 ft above NAVD 88 were measured on the rising limb of the ground-water hydrograph, and are assumed to approximate the mean and high ground-water levels. Therefore, an average daily mean water level at the 15-mile site probably would approximate 1 ft above NAVD 88. This water level requires that the 0-ft contour be at or just west of the 15-mile site, in contrast to published maps that show the 0-ft contour east of the 15-mile site (Krause and Randolph, 1989; Garza and Krause, 1996; Ransom and White, 1999; fig. 6). This interpretation is not meant to imply that the 1999 water levels measured at the 15-mile site are higher than 1985 water levels at this site, which would suggest recovery of water levels in the Upper Floridan aquifer. The 1985 model simulations simply underestimated the water level at the seaward edge of the cone of depression and projected the 0-ft contour too far to the east.

Water Quality

Water samples from the Upper Floridan aquifer were collected with a submersible pump from boreholes opened to the Oligocene strata (Calibogue, 7-mile, 8-mile, and 15-mile sites) and the Eocene strata (10-mile site); results of the borehole-water samples are given in appendix 3. Depth intervals for these samples are shown in the hydrogeologic cross sections in figures 9 and 11.

A borehole-water sample also was collected at the 10-mile site after the borehole was drilled to 698 ft below NAVD 88. This sample was collected with the submersible pump set at 586 ft below NAVD 88 in a borehole open from the top of the Upper Floridan aquifer to near the top of the Lower Floridan aquifer. Given the large open-borehole interval and the potential for borehole mixing of waters from several depth intervals, results for the deep 10-mile sample probably are not representative of a depth-specific sample. The results for this sample, however, are included in this report as evidence that the TDS concentration in the Floridan aquifer system increases with depth. The sample interval for this sample is not presented on the offshore hydrogeologic cross section in figure 9.

Water-quality results from this study are compared with published results for water samples collected from Upper Floridan aquifer wells in Beaufort County, a well near the Upper Floridan recharge area in Hampton County, SC (HAM-122), an Upper Floridan well (39Q025) at the onshore Tybee reference site, and a seawater sample (Hem, 1989; Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998; Phelps, 2001; fig. 1). The published results for seawater discussed in this report are those for the ion chemistry reported in Hem (1989) and the isotopic results reported in Phelps (2001).

In addition to open-borehole samples, pore water was extracted and analyzed to determine dissolved-chloride concentrations in core samples from the Calibogue site and the 7-, 8-, and 10-mile sites. To minimize the potential for contamination of pore-water samples with drilling fluids, samples of fine-grained clays, silts, and limestone generally were collected from the central part of the unbroken core. Core samples were wiped clean of drilling mud and sealed in paraffin until the pore waters could be extracted in the laboratory.

For this report, freshwater and saline waters are classified according to TDS concentrations (Robinove and others, 1958). Freshwater has a TDS concentration of less than 1,000 mg/L. Saline water varies from slightly saline (TDS concentrations of 1,000 to 3,000 mg/L), to moderately saline (TDS concentrations of 3,000 to 10,000 mg/L), to very saline (TDS concentrations of 10,000 to 35,000 mg/L).

Seawater has TDS concentrations of approximately 35,000 mg/L (Hem, 1989). Seawater also has concentrations of 19,000 mg/L for chloride, 2,700 mg/L for sulfate, 67 mg/L for bromide, and 8 mg/L for strontium (app. 3). In contrast, freshwater from the Upper Floridan aquifer typically has chloride and sulfate concentrations less than 500 mg/L, and strontium and bromide concentrations less than 1.5 mg/L (Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998).

Stable hydrogen and oxygen isotopes, commonly used as conservative environmental tracers to determine source, movement, and proportional mixing of water masses, were used in this study to interpret proportional mixing of freshwater in the Upper Floridan aquifer with modern seawater. Stable carbon isotopes commonly are used as environmental tracers of carbon sources contributing to the dissolved inorganic carbon (DIC) in water and the geochemical processes that affect water chemistry. The stable isotopic results are reported by the laboratory in delta notation, which is defined as the per mil (parts per thousand) difference between the isotopic ratio of the sample relative to the isotopic ratio of a standard (Faure, 1977). The isotopic ratios used are oxygen-18/oxygen-16 of water, deuterium/hydrogen of water, and carbon-13/carbon-12 of DIC in water. Therefore, sample results are more positive or more negative when the sample is more enriched or more depleted, respectively, in the heavier isotope in each ratio. The standards are Peedee Belemnite (PDB) for stable carbon isotopes of DIC in water and Vienna-Standard Mean Ocean Water (V-SMOW) for the stable hydrogen and oxygen isotopes of water (Gonfiantini, 1984; Coplen, 1994). The 2-sigma (two standard deviations) analytical precision of the laboratory is 0.2 per mil for oxygen, 1.5 per mil for deuterium, and 0.2 per mil for carbon isotopes.

Most of the temporary wells in this study were sampled for tritium and carbon-14 (app. 3). In previous studies, carbon-14, tritium, and the stable carbon isotopic compositions of the DIC in water samples have been presented and used to interpret the relative and absolute ages of water samples collected from the Upper Floridan aquifer beneath coastal Chatham and Beaufort Counties, and Port Royal Sound (Plummer, 1993; Landmeyer and Stone, 1995; Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998). Tritium and carbon-14 are reported in tritium units and percent modern carbon, respectively. One tritium unit (TU) equals 3.19 picocuries per liter or 1 atom of tritium for every 10^{18} atoms of hydrogen (Faure, 1977). Analytical precisions for tritium and carbon-14 results are 0.3 TU and less than 0.1 percent modern carbon (pmc), respectively.

In the hydrologic cycle, the natural source of tritium and carbon-14 isotopes is the atmosphere. The DIC in recharge water is assumed to be in equilibrium with the atmospheric reservoir of carbon-14 (approximately 100 pmc) and to have a stable carbon isotopic composition in equilibrium with carbon dioxide from the soil zone, respiration of plants, and oxidation of organic matter (approximately -25 per mil). Recharge water also is assumed to be in equilibrium with atmospheric tritium and the stable oxygen and hydrogen isotopic composition of atmospheric moisture. As recharge water flows from the recharge area to the confined ground-water system, it becomes isolated from the atmospheric source of carbon-14 and tritium. Concentrations of carbon-14 and tritium decrease in the confined ground-water flow system by radioactive decay, mixing with older waters, and in the case of carbon-14, dilution with “radioactively dead” carbon derived from the dissolution of carbonate minerals and reduction of organic carbon in the aquifer.

Radioactive decay of tritium and carbon-14 provides an indication of the residence time of ground water in an aquifer.

The concentrations of tritium and carbon-14 in the aquifer are used in this report to estimate the relative age of ground water. The half life of tritium is 12.3 years, and the half life of carbon-14 is 5,730 years. Therefore, the presence of tritium in excess of 1 TU and high concentrations (50 to 100 pmc) of carbon-14 indicate that relatively modern water, freshwater or saltwater, has recharged the aquifer. Conversely, low concentrations of carbon-14 (less than 5 percent) indicate long residence time and geochemical conditions that favor dilution of the carbon-14 in the relict water of the aquifer.

The possibility of sample contamination also has to be considered when discussing tritium and carbon-14 results. For both isotopes, contamination of aquifer samples with modern water results in an increase in tritium and carbon-14 concentrations. Wells were developed using air-surge techniques and a submersible pump prior to sampling; however, the potential exists for samples to be contaminated as water is collected in bottles. The potential for contamination is discussed, based on the results of specific samples.

Borehole-Water Samples

The Upper Floridan aquifer at the Hampton County well (HAM-122), Tybee reference well, and Calibogue well contained freshwater with chloride and TDS concentrations less than 15 and 200 mg/L, respectively (app. 3). The freshwater at these sites is a calcium-magnesium-sodium-bicarbonate water type (fig. 13). The confined Upper Floridan aquifer at the offshore 10-mile site contained freshwater in the sample collected from the Eocene strata in the interval from 198 to 220 ft below NAVD 88; however, the same sample had a high dissolved sulfate concentration of 100 mg/L compared with concentrations of less than 15 mg/L at the Calibogue, Tybee reference, and HAM-122 wells (app. 3). Water from the 10-mile site is a calcium-magnesium-sodium-sulfate-bicarbonate water type. The water sample collected from the Upper Floridan aquifer at the 7-mile site also was freshwater; however, compared with the previous four freshwater samples, the sample from the 7-mile site had higher chloride and TDS concentrations of 370 and 887 mg/L, respectively; the water is a sodium-chloride water type at the 7-mile site. These five freshwater samples in the Upper Floridan aquifer had concentrations equal to or less than 1.3 mg/L for dissolved strontium and for dissolved bromide.

In contrast to the freshwater samples, water from the Upper Floridan aquifer at the 8- and 15-mile sites contained a sodium-chloride water type and was very saline with TDS concentrations of 14,900 and 13,000 mg/L, respectively, and chloride concentrations of 8,400 and 6,800 mg/L, respectively (fig. 13; app. 3). The 8-mile and 15-mile samples had higher concentrations of 9.6 and 4.5 mg/L for dissolved strontium and 32 and 23 mg/L for dissolved bromide, respectively, relative to the freshwater samples. The relative ion proportions of these two samples plot close to the ion proportion of modern seawater.

The 8- and 15-mile sites also had higher concentrations of dissolved sulfate (990 and 1,200 mg/L) and total organic carbon (1.0 and 2.9 mg/L), relative to the freshwater samples, but the relative proportion of sulfate was low compared with the relative proportion of chloride (fig. 13). At the offshore and Calibogue sites and at the Tybee reference site, water from the Upper Floridan aquifer had dissolved-oxygen concentrations below detection (less than 0.2 mg/L). Given the absence of oxygen (anaerobic conditions) in the aquifer, microbial reduction of dissolved sulfate in the aquifer produced hydrogen sulfide concentrations of 6 and 30 mg/L at the 8- and 15-mile sites, respectively (app. 3). Sulfate reduction also was apparent in the saline water of the Upper Floridan aquifer reported beneath and adjacent to Port Royal Sound where dissolved sulfate and organic carbon concentrations also were high relative to the freshwater of the onshore Upper Floridan aquifer (Landmeyer and Belval, 1996). Sulfate reduction also may have occurred in the offshore and Calibogue wells containing freshwater, but hydrogen sulfide was not detected in concentrations greater than the minimum laboratory-reporting limit of 0.5 mg/L in any of these wells.

Alkalinities in the Upper Floridan aquifer generally exceeded 180 mg/L as calcium carbonate ($CaCO_3$) in areas of saline water as was present beneath Port Royal Sound and adjacent areas of Beaufort County, SC (Landmeyer and Belval, 1996). Alkalinity in the very saline water sample at the 15-mile site was 244 mg/L as $CaCO_3$ (app. 3). Conversely, the alkalinity of the very saline water at the 8-mile site was 127 mg/L as $CaCO_3$. Freshwater in the Upper Floridan aquifer, as in the Calibogue, 7-mile, and 10-mile wells of this study and in onshore wells in previous studies, generally had alkalinity concentrations ranging from 110 to 140 mg/L as $CaCO_3$ (Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998).

The water sample collected at 586 ft below NAVD 88 in the 10-mile well also is a slightly saline, sodium-sulfate-chloride water type with a TDS concentration of 2,320 mg/L (fig. 13). This sample, however, had a chloride concentration of 740 mg/L, which is an order of magnitude lower than the very saline water samples from the Upper Floridan aquifer at the 8- and 15-mile sites (app. 3). The sample at the 10-mile site had a concentration of 9.4 mg/L for dissolved strontium, which was similar to the very saline water of the 8-mile site (9.6 mg/L), and a concentration of 2.6 mg/L for dissolved bromide, which was not similar to the very saline water samples at the 8- and 15-mile sites (32 and 23 mg/L, respectively). Even with the pump set at 586 ft, the open-borehole interval from which the sample was collected ranged from 698 ft to the top of the Upper Floridan aquifer, which leaves the potential for this water sample to represent mixed waters from permeable zones at several depths in the borehole, rather than a discreet sample depth. The results confirm that, with depth below the Upper Floridan aquifer, salinity increases in the Floridan aquifer system.

The presence of very saline water in the Upper Floridan aquifer at the 8- and 15-mile sites indicates mixing of relict

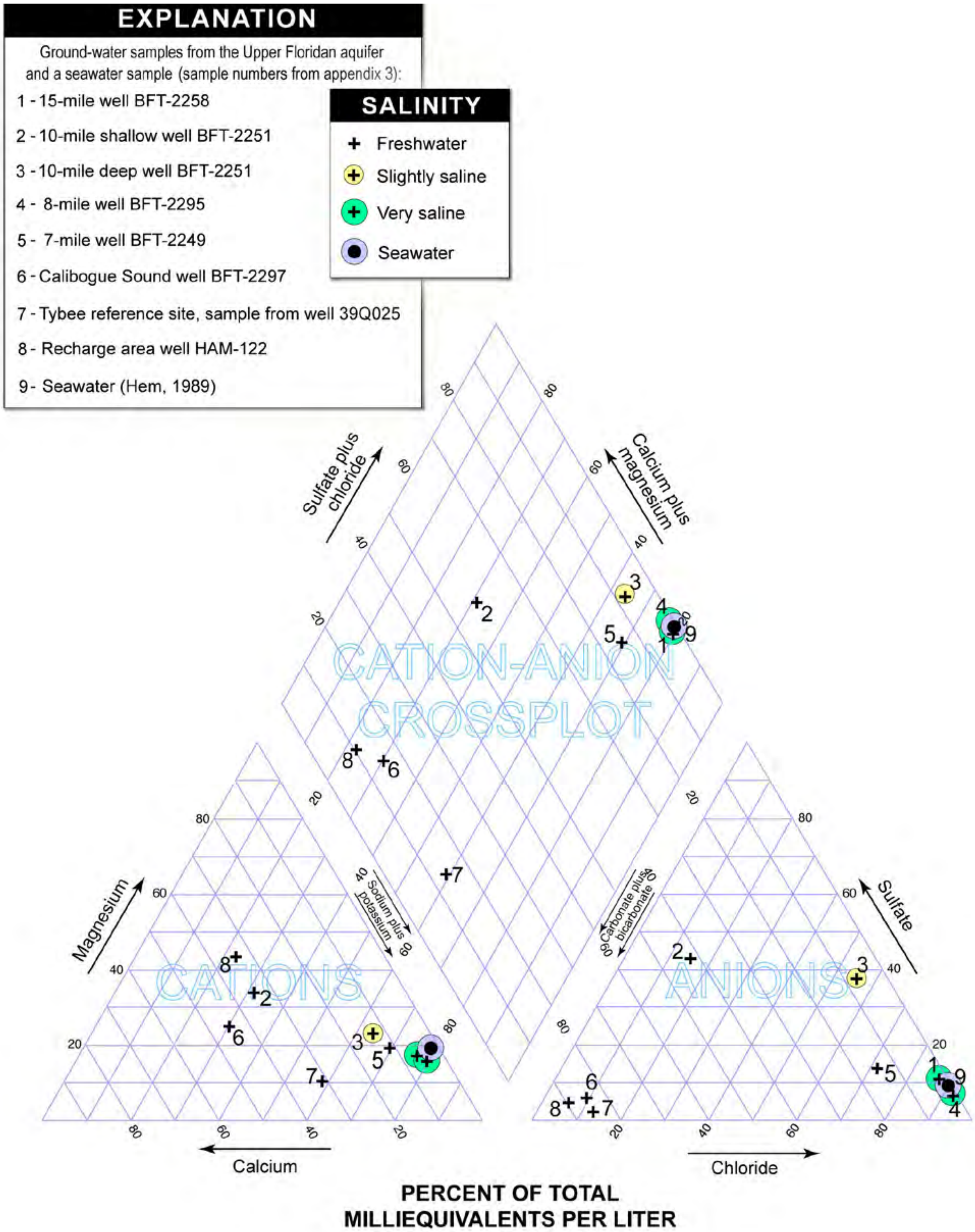


Figure 13. Major cation and anion compositions of a freshwater sample from the Upper Floridan recharge area in Hampton County well HAM-122, South Carolina, well 39Q025 in Chatham County, Georgia, the offshore wells, and a modern seawater sample (Hem, 1989).

freshwater in the Upper Floridan aquifer with a saltwater source. Relative to the freshwater contribution to the mixture, saltwater introduced higher concentrations of chloride, TDS, bromide, sulfate and total organic carbon as well as higher concentrations of major cations (app. 3). If the two very saline waters were the result of modern seawater mixing with freshwater having a composition similar to the shallow Upper Floridan aquifer sample at the 10-mile site, then the average freshwater/seawater mixing proportions would be 55/45 percent at the 8-mile site and 63/37 percent at the 15-mile site (table 3). Concentrations of TDS, chloride, and bromide for modern seawater are used in this example to calculate the mixing proportions. The chloride-to-bromide ratios of samples from the 8- and 15-mile sites are 263 and 296, respectively, compared with 284 for modern seawater (app. 3). It cannot be concluded, however, from the ion chemistry or the chloride-to-bromide ratios of the samples from the 8- and 15-mile sites that the saltwater source is modern seawater, as opposed to relict saltwater of similar composition in the surficial aquifer.

Stable Oxygen and Hydrogen Isotopes

The very saline water at the 8- and 15-mile sites had similar stable isotopic compositions of about -2 and -9 per mil for stable oxygen and hydrogen isotopes, respectively (fig. 14). In contrast, freshwater samples at the Calibogue, 7-mile, and 10-mile sites had compositions of -4 and -19 per mil for stable oxygen and hydrogen isotopes, respectively. In comparison, the modern seawater sample collected from the Atlantic Ocean near the study area in 1998 as part of another USGS investigation had stable oxygen and hydrogen isotopic compositions of 0.7 and 6.2 per mil, respectively (Phelps, 2001).

The stable oxygen and hydrogen isotopic compositions of freshwater in the Upper Floridan aquifer at the 10-mile site, very saline waters in the Upper Floridan aquifer at the 8-mile and 15-mile sites, and modern seawater also were used to calculate freshwater/modern seawater mixing proportions at the 8- and 15-mile sites (table 3). The mixing proportions calculated with the stable isotopic compositions were approximately the same as the proportions calculated with the TDS, chloride, and bromide concentrations (table 3). The average percentages for freshwater/modern seawater mixing proportions were 55/45 percent at the 8-mile site and 63/37 percent at the 15-mile site (table 3). As with the ion chemistry, it cannot be concluded from the stable oxygen and hydrogen isotopic compositions of the samples from the 8- and 15-mile sites whether the saltwater source is modern seawater, or whether the source is relict saltwater in the surficial aquifer; however, these results are consistent with a modern saltwater source.

Carbon Isotopes

Water samples for stable carbon isotopic compositions of the DIC were collected at the Calibogue site and all four

Table 3. Calculation of freshwater/seawater mixing at the 8-mile and 15-mile sites using analyses of water samples collected from the Upper Floridan aquifer at the 8-mile, 10-mile and 15-mile sites, and published water-quality results for seawater (Hem, 1989; Phelps, 2001).

[mg/L, milligrams per liter; $\delta^{18}O$, delta oxygen-18; δD, delta deuterium; V-SMOW, Vienna-Standard Mean Ocean Water]

Water-quality constituent	Results for freshwater sample in Upper Floridan aquifer at 10-mile site	Results for saline-water sample at 8-mile site	Percent freshwater/seawater mixing at 8-mile site	Results for saline-water sample at 15-mile site	Percent freshwater/seawater mixing at 15-mile site	Results for seawater sample from Hem (1989) and Phelps (2001)
Total dissolved solids (mg/L)	305	14,900	57 / 43	13,000	63 / 37	35,000
Chloride, dissolved (mg/L)	25	8,400	56 / 44	6,800	64 / 36	19,000
Bromide, dissolved (mg/L)	0.1	32	52 / 48	23	66 / 34	67
$\delta^{18}O$ per mil V-SMOW	-4.1	-1.9	53 / 47	-2.1	59 / 41	0.7
δD per mil V-SMOW	-19.5	-8	56 / 44	-9.8	64 / 36	6.2
Average percent freshwater/seawater for all five estimates			55 / 45		63 / 37	

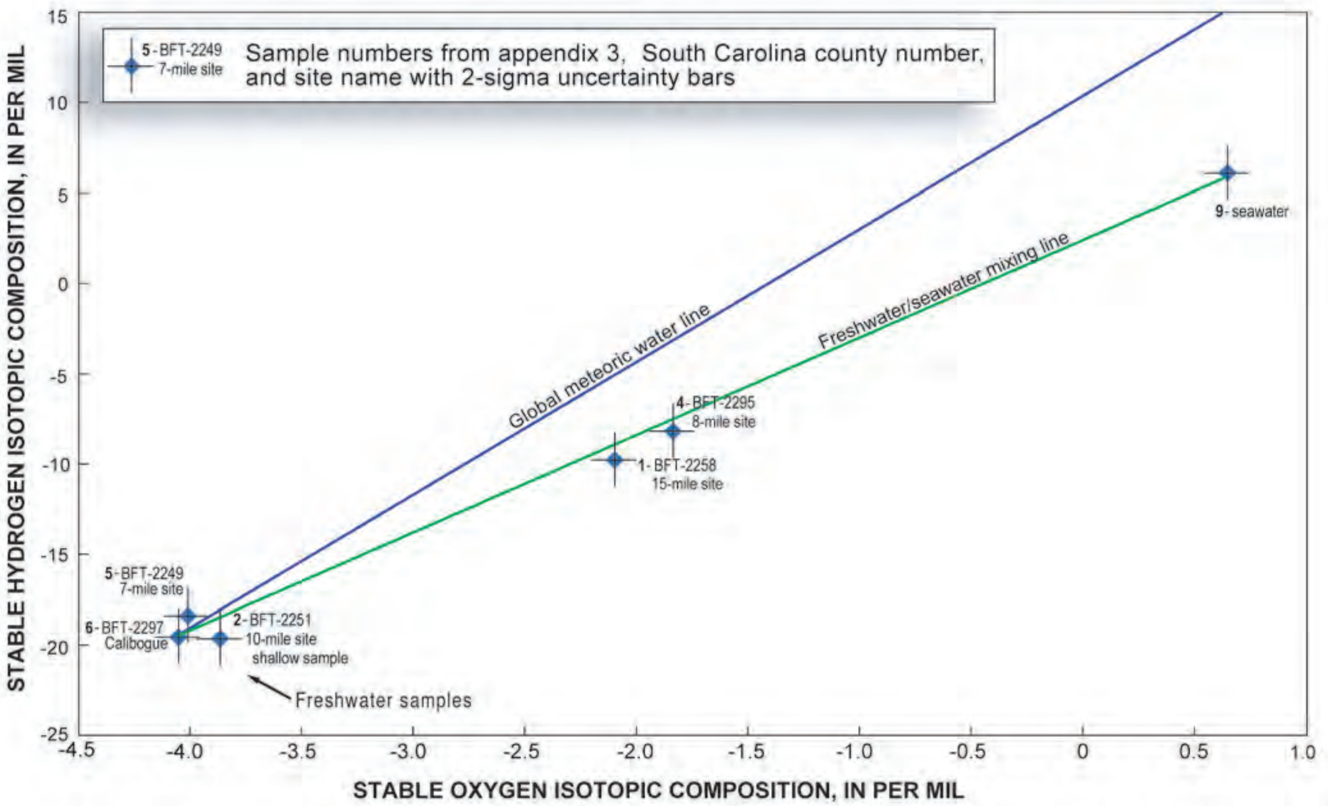


Figure 14. Stable oxygen and hydrogen isotopic compositions relative to Vienna-Standard Mean Ocean Water of borehole-water samples from the Upper Floridan aquifer in the offshore Coastal Sound Science Initiative wells and a modern seawater sample (Phelps, 2001).

offshore sites. Water samples for carbon-14 analysis were collected at all sites, except the 15-mile site.

The carbon-14 and stable carbon isotopic compositions reported for the seawater sample collected near the study area were 110 pmc and -1.8 per mil (Phelps, 2001; fig. 15). In published reports, freshwater samples from the Upper Floridan aquifer beneath the southern end of Hilton Head Island had carbon-14 concentrations ranging from 0.5 to 1.4 plus or minus 0.1 pmc and stable carbon isotopic compositions ranging from -2.3 to -2.8 per mil. Based on these results, samples were interpreted to be relict ground water isolated from the atmosphere (confined in the aquifer) for thousands to tens of thousands of years (Plummer, 1993; Landmeyer and Stone, 1995). At the northern end of Hilton Head Island and beneath Port Royal Sound, saline water in the Upper Floridan aquifer had carbon-14 concentrations ranging from 5 to 39.5 pmc and stable carbon isotopic compositions ranging from -7.4 to -12.2 per mil (Landmeyer and Belval, 1996; fig. 15). The saline water in the Upper Floridan aquifer beneath Port Royal Sound is influenced by recharge of modern seawater from Port Royal Sound that probably mixes with relict freshwater and relict saltwater in the Upper Floridan aquifer.

Freshwater samples from the Upper Floridan aquifer at the Calibogue site, and 7- and 10-mile sites had carbon-14 concentrations ranging from less than 0.9 to 3.2 pmc and stable carbon isotopic values ranging from -1.4 to -3.4 per mil (fig. 15; app. 3). These values are similar to the range in compositions reported for relict freshwater in the Upper Floridan aquifer beneath the southern end of Hilton Head Island and are typical of relict freshwater at the downgradient end of a predevelopment flow path (Plummer, 1993; Landmeyer and Belval, 1996; fig. 6).

The very saline water at the 8-mile site had a slightly positive stable carbon isotopic composition of 0.4 per mil and a carbon-14 concentration of 2.3 pmc (fig. 15). The very saline water at the 15-mile site had a positive stable carbon isotopic value of 2.2 per mil (app. 3). The low carbon-14 concentration at the 8-mile site was in the same range as the concentrations at the Tybee reference, Calibogue, and 7- and 10-mile sites and at the southern end of Hilton Head Island, and indicated that the very saline water was relict water. The stable carbon isotopic compositions at the 8- and 15-mile sites were enriched (more positive) in the carbon-13 isotope relative to the compositions of the relict water at the Tybee reference site, Calibogue site, and 7- and 10-mile sites, and beneath the southern end of Hilton Head Island. Considering

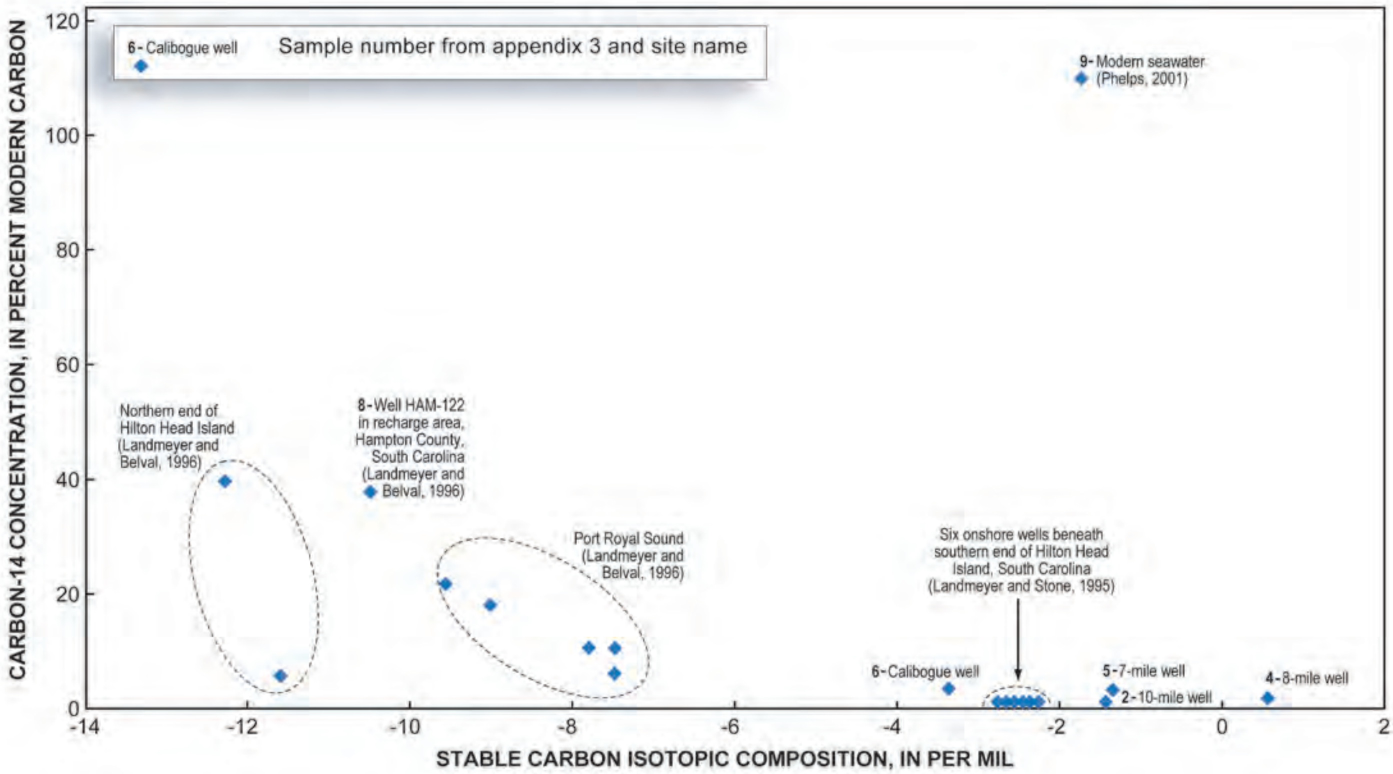


Figure 15. Stable carbon isotopic compositions of dissolved inorganic carbon relative to Peedee Belemnite and carbon-14 concentrations in water samples from offshore and Calibogue wells compared to results for modern sea water and water samples from wells near Hilton Head Island, South Carolina.

all of the wells in this study, water sampled from the Upper Floridan aquifer only at the 8- and 15-mile sites had detectable hydrogen sulfide concentrations of 6 and 30 mg/L, respectively, indicating active sulfate reduction at these sites. As a result, carbon dioxide concentrations produced during sulfate reduction would stimulate additional carbonate dissolution and shift the stable carbon isotopic compositions of the DIC in the water toward the stable isotopic composition of marine carbonate sediments in the Upper Floridan aquifer (0 to 2 per mil).

Tritium

Water samples from the Upper Floridan aquifer at the Calibogue and four offshore sites were analyzed for tritium. The water sample collected from the deep open-borehole interval at 586 ft below NAVD 88 at the 10-mile site was not analyzed for tritium.

The presence of tritium at concentrations less than 1 TU would be consistent with relict freshwater or saline water confined in the Upper Floridan aquifer for hundreds or thousands of years before present. Tritium concentrations greater than 1 TU in the Upper Floridan aquifer would be consistent with recharge of the Upper Floridan aquifer by a modern source of seawater or freshwater (intrusion). Tritium concentrations greater than 1 TU in the Upper Floridan aquifer also could be the result of contamination of the sample in the field or laboratory.

Water samples collected at the Calibogue and 15-mile sites had tritium concentrations less than 1 TU (app. 3), which indicate that these waters are relict freshwater and saline waters, respectively, and presumably have not been intruded by a modern source of tritium. The sample from the 8-mile site had the highest tritium concentration (4 TU) of the four offshore wells, which is consistent with the possibility of modern seawater intrusion through a breach in the confining unit at this site; however, the carbon-14 concentration at the 8-mile site is consistent with relict water, not modern water. The tritium concentrations of 2.2 and 3.2 TU for freshwaters at the 7- and 10-mile sites, respectively, also are above 1 TU, which is inconsistent with expected and observed results for water in the confined Upper Floridan aquifer (Landmeyer and Belval, 1996). Recharge by downward intrusion, if it occurred at the 7- and 10-mile sites, would consist of freshwater and saline water from the surficial aquifer and the confining unit, not modern freshwater. The slightly higher chloride and TDS concentrations at the 7-mile site, relative to the other offshore freshwater sites, indicate a minor component (less than

5 percent) of saline water mixing with the relict freshwater that could come from the paleochannel to the northeast of the 7-mile site and could introduce a minor amount of tritium from the surficial aquifer (fig. 2). This assumes that the intruding water has a modern water component. Freshwater in the Upper Floridan aquifer at the 10-mile site is confined and has water quality, stable oxygen and hydrogen isotopic compositions, and carbon-14 concentrations (less than 0.9 pmc) that are consistent with relict freshwater and inconsistent with the presence of modern seawater recharge (Landmeyer and Belval, 1996; U.S. Army Corps of Engineers, 1998). While the tritium results of less than 1 TU at the Calibogue and 15-mile sites are consistent with relict waters and the absence of recent downward intrusion, the tritium detections greater than 1 TU in water samples collected from the Upper Floridan aquifer at the 10-mile site raises suspicions about the possibility of contamination of samples collected at the 7- and 8-mile sites.

Pore-Water Samples

Chloride concentrations in pore water with depth at the Calibogue, 7-mile, 8-mile, and 10-mile sites indicate that concentrations generally decrease with increased depth from the base of the surficial aquifer to the Upper Floridan aquifer (figs. 9, 11). The highest chloride concentrations in the pore-water samples were collected from the surficial aquifer and the 0.8-ft-thick interval of the upper confining unit at the 8-mile site, and from the top 10 ft of the upper confining unit at the 10-mile site. The pore-water chloride concentrations ranged from 13,800 to 17,500 mg/L, approaching those of modern seawater (19,000 mg/L, fig. 9). The chloride concentration in a sample collected above the top of the upper confining unit at the 7-mile site was 7,030 mg/L.

Chloride concentrations at the 7- and 10-mile sites decreased to less than 3,000 mg/L and less than 1,000 mg/L, respectively, at the base of the upper confining unit. At the 10-mile site, chloride concentrations in pore-water samples collected from the Upper Floridan aquifer decreased to 29 mg/L in the Oligocene sediments and 47 mg/L in the Eocene sediments, approximating the chloride concentration of 25 mg/L in the borehole-water sample collected at the 10-mile site (fig. 9).

Pore-water samples collected from the Eocene strata at the 8-mile site had chloride concentrations of 560 and 600 mg/L. In contrast, the chloride concentration in the borehole sample collected from the overlying Oligocene strata of the Upper Floridan aquifer at the 8-mile site was 8,400 mg/L (fig. 9). Pore waters collected from the fine-grained paleochannel-fill sediments at the Calibogue site had chloride concentrations ranging from 120 to 1,300 mg/L (fig. 11).

Saltwater Intrusion

The hydrogeology and water-quality results for each of the five drill sites are discussed in this section as evidence for interpreting the occurrence of or potential for saltwater intrusion or encroachment in the Upper Floridan aquifer at each drill site. In this report, saltwater intrusion refers to the occurrence of or potential for downward leakage of saline water from the surficial aquifer to the Oligocene and Eocene strata of the Upper Floridan aquifer. Saltwater encroachment refers to lateral movement and mixing of saltwater with freshwater in the Upper Floridan aquifer. In a modern sense, saltwater intrusion and encroachment generally result from artificial stress on the aquifer as a result of pumping; however, water levels in the Upper Floridan aquifer beneath Port Royal Sound and in the general vicinity of the 15-mile site are approximately equal to sea level (NAVD 88). Therefore, tidal fluctuations in water level and inversion of water density with dense saltwater overlying less-dense freshwater also could drive downward leakage of saline water from the surficial aquifer to the Upper Floridan aquifer (Landmeyer and Belval, 1996).

The current distribution of freshwater and saline water in the surficial aquifer, the upper confining unit, and the Floridan aquifer system represents the long predevelopment and recent (since the 1880s) histories of water use and water-level decline in the study area (figs. 6, 16). As mentioned in the “Hydrogeologic Setting” section, the Coastal Plain and Inner Continental Shelf, including the study area, were subaerially exposed during the Pleistocene low stand in sea level 11,000 years ago. As sea level rose to its present (2005) position, the Inner Continental Shelf was inundated with seawater from the Atlantic Ocean. Seawater also infiltrated the surficial aquifer of the Inner Continental Shelf (figs. 1, 16).

Freshwater head in the Floridan aquifer system beneath the Coastal Plain from the period of the Pleistocene low stand to the 1880s created an eastward hydraulic gradient that was great enough to displace saltwater in the Floridan aquifer system to the offshore area of the Inner Continental Shelf (figs. 6, 16). The altitude of freshwater head in the confined Floridan aquifer system also varied from greater than (near shore) to equal to (offshore near the 0-ft contour) sea level (NAVD 88) in the study area and promoted upward leakage of freshwater from the Upper Floridan aquifer through the upper confining unit to the surficial aquifer (fig. 16).

During predevelopment, if the magnitude of the measured vertical hydraulic gradient between the Upper Floridan and surficial aquifers was great enough, less-dense freshwater from the Upper Floridan aquifer would discharge to the surficial aquifer to dilute saltwater in the surficial aquifer (fig. 16). If the magnitude of the measured vertical hydraulic gradient was close to or less than zero and, therefore, too small to displace the dense saltwater of the surficial aquifer, freshwater would not discharge to the surficial aquifer and dilute the saltwater. The chloride concentrations of 7,030 and 17,500 mg/L in

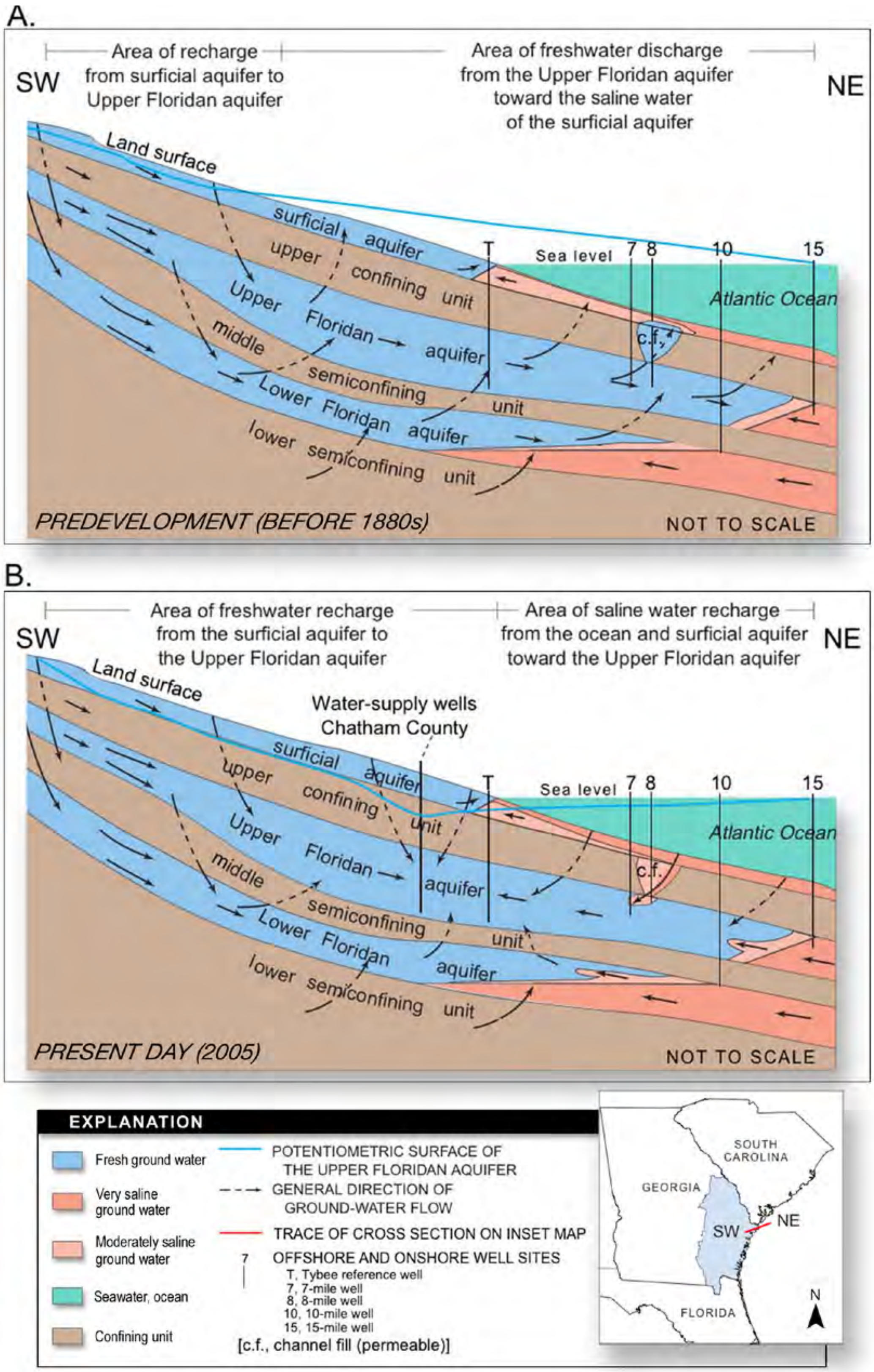


Figure 16. Conceptual models of (A) predevelopment and (B) present day (1999–2001) ground-water flow in the Floridan aquifer system beneath Chatham County, Georgia, and the offshore study area (modified from Krause and Randolph, 1989).

the pore-water samples collected from the top of the upper confining unit at the 7- and 10-mile sites, respectively, could partially reflect the chloride concentrations in the surficial aquifer at these two sites, which were established during the predevelopment period (figs. 9, 16). Therefore, the water of the surficial aquifer in the offshore study area could have chloride concentrations that range from very saline near the 0-ft contour to slightly saline water closer to shore. Since the water in the surficial aquifer, particularly near the contact with the upper confining unit, could have infiltrated the surficial aquifer hundreds to thousands of years before present and mixed with relict freshwater discharging during predevelopment, the water is considered to be relict ground water, not modern water.

Onshore development of the Upper Floridan aquifer, particularly for industrial- and municipal-water supply, resulted in a decline in the potentiometric surface of the Upper Floridan aquifer and a westward hydraulic gradient from the offshore study area toward the coast (figs. 1, 16). The decline in head also resulted in a downward vertical hydraulic gradient from the surficial aquifer to the Upper Floridan aquifer, which disturbed the dynamic equilibrium established during predevelopment between the freshwater discharge to and the dense saline water in the surficial aquifer. The low hydraulic conductivity of the upper confining unit, where present, retards the rate of downward leakage of saline water from the surficial aquifer to the Upper Floridan aquifer (fig. 16; table 2).

At sites where the upper confining unit is present, the effects of saltwater intrusion on the chloride concentrations of waters in the upper confining unit and the Upper Floridan aquifer also would depend on the chloride concentrations of the waters in the surficial aquifer and the magnitude of the downward vertical hydraulic gradient (figs. 9, 16). With a lower estimated vertical hydraulic gradient at the 10-mile site relative to the 7-mile site during predevelopment, there would have been less upward leakage of freshwater from the Upper Floridan aquifer through the confining unit and, therefore, water in the confining unit at the 10-mile site would have had a higher chloride concentration, relative to the 7-mile site. Following development, the potential for downward leakage could have been greater at sites of channel incision, relative to sites where the upper confining unit is present, depending on the hydraulic properties of the paleochannel-fill sediments.

The following discussion of the potential for saltwater intrusion at the five drill sites is based on the presence or absence of Miocene sediments of the upper confining unit and on water quality. The upper confining unit is present at the 7-, 10-, and 15-mile sites, whereas paleochannel incision has removed the upper confining unit and replaced it with coarse- and fine-grained channel-fill sediments at the 8-mile and Calibogue sites, respectively. The 15-mile site is discussed separately from the 7- and 10-mile sites because of the presence of saline water in the Upper Floridan aquifer.

The 7- and 10-Mile Sites

The hydrogeologic setting and vertical hydraulic gradients at the 7- and 10-mile sites precluded saltwater intrusion during predevelopment. The upper confining unit at the 7- and 10-mile sites is 17 and 32 ft thick, respectively, and consists of fine-grained sediments of the Marks Head Formation with vertical hydraulic conductivities of approximately 2.5×10^{-4} ft/d. The predevelopment freshwater head of the Upper Floridan aquifer was approximately 10 ft above NAVD 88 at the 7- and 10-mile sites, resulting in upward hydraulic gradients across the upper confining unit and potential for upward movement of freshwater from the Upper Floridan aquifer through the upper confining unit to offset density-driven downward diffusion of saltwater from the surficial aquifer (Warren, 1944; Garza and Krause, 1996; fig. 6). Assuming this upward flow potential existed for several thousand years or more prior to the development of the cone of depression, there would have been low concentrations of dissolved chloride in the confining unit between the Upper Floridan and surficial aquifers and in the surficial aquifer relative to saline water in the open ocean. If, however, vertical leakage of freshwater from the Upper Floridan aquifer were offset by the density of saline water in the surficial aquifer, then water in the surficial aquifer could have remained salty and could have had a long residence time in the surficial aquifer (fig. 16).

After decades of onshore water use in Georgia and South Carolina, the 0-ft contour in the regional cone of depression of the Upper Floridan aquifer spread northeastward to the vicinity of the offshore Beaufort Arch, and is estimated to have reached the general location of the 7- and 10-mile sites by the mid-1950s, and at or past the 15-mile site by the 1980s (Counts and Donsky, 1963; Garza and Krause, 1996; fig. 6). The predevelopment upward hydraulic gradient reversed, but the presence of greater than 17 ft of upper confining unit impeded the downward movement of saltwater from the surficial aquifer to the Upper Floridan aquifer at the 7- and 10 mile sites. The mean measured water levels in the Upper Floridan aquifer at the 7- and 10-mile sites were 17.4 and 13.0 ft below NAVD 88, respectively.

The chloride concentrations in pore-water samples at the 7- and 10-mile sites decreased from the top to the bottom of the confining unit and are assumed to reflect downward leakage of saline water from the surficial aquifer in response to the downward hydraulic gradient of the last 50 years (fig. 9). Pore-water chloride concentrations near the base of the confining unit are greater (2,010 mg/L) at the 7-mile site than at the 10-mile site (510 mg/L), and reflect differences in confining-unit thickness and subtle differences in the magnitude of the vertical hydraulic gradient at these two sites. At the 10-mile site, the chloride concentrations in the borehole-water sample from the Eocene strata (25 mg/L from a sampling interval of 198 to 220 ft below NAVD 88) and the pore-water samples from the Oligocene and Eocene strata (ranging from 29 to 88 mg/L) support the conclusion of no noticeable effects of modern saltwater intrusion in the Upper Floridan aquifer at the 10-mile site. The chloride concentration of 370 mg/L in the borehole-water sample from the Upper Floridan aquifer collected from 78 to 135 ft below NAVD 88 at the 7-mile site is considerably higher than in the pore-water samples at the 10-mile site, which ranged from 29 to 88 mg/L. This chloride concentration is probably the result of downward displacement of saltwater through the upper confining unit at the 7-mile site. The chloride concentration could reflect downward leakage of saltwater through a thin section of upper confining unit beneath the paleochannel to the northeast and lateral movement (encroachment) from the paleochannel to the 7-mile site (figs. 3, 16).

The carbon-14 concentrations at both sites are low and indicate that most of the water is relict fresh ground water. If saline water has intruded the Upper Floridan aquifer at the 7-mile site by downward leakage from the surficial aquifer or upper confining unit, or by encroachment from the nearby paleochannel-fill sediments, then the low carbon-14 concentration in the Upper Floridan sample at the 7-mile site seems to support the concept of intrusion of relict water from the surficial aquifer and confining unit.

The 15-Mile Site

The upper confining unit is 17 ft thick at the 15-mile site; however, saltwater intrusion and encroachment are still likely to occur, even during predevelopment, given the confining-unit thickness and the vertical hydraulic gradients in the vicinity of the 15-mile site. The upper confining unit is less than 10 ft thick in several areas north, east, and south of the 15-mile site and absent in a few areas south of the 15-mile site (fig. 3).

Based on the density- and tide-corrected water levels for the Upper Floridan aquifer at the 15-mile site, the daily mean water level at the 15-mile site is assumed to be approximately equal to or slightly greater than NAVD 88 (fig. 6). If the 0-ft contour of the potentiometric surface of the Upper Floridan aquifer also were near the 15-mile site during predevelopment, then the vertical hydraulic gradient between the Upper Floridan and surficial aquifers would be low to absent, and unlike the 7- and 10-mile sites, downward leakage of saline water into the Upper Floridan aquifer would not be impeded. Therefore, saline water from the surficial aquifer could have been dispersing through the relatively thin upper confining unit and into the underlying Upper Floridan aquifer in the vicinity of the 15-mile site for the past several thousand years and encroaching (lateral movement) on the 15-mile site.

The setting for the saline water in the Upper Floridan aquifer beneath the 15-mile site is interpreted as a transitional mixing zone between relict freshwater and relict saltwater in the Upper Floridan aquifer; however, intrusion of saline water from the surficial aquifer probably is still (2005) occurring in the area to the north, east, and south of the 15-mile site where the upper confining unit is thin to absent. The tritium concentration of less than 1 TU in the Upper Floridan water sample at this site confirms that intrusion has not introduced modern water or enough modern water to result in a detectable tritium concentration (app. 3).

The 8-Mile and Calibogue Sites

The 8-mile and Calibogue sites were identified as “no Miocene” sites by Foyle and others (2001) and were characterized as having the top of the Upper Floridan aquifer, instead of the upper confining unit, overlain by paleochannel-fill sediments. A previous study indicated variable permeability of paleochannel fill, which controls in part the degree of saltwater intrusion (U.S. Army Corps of Engineers, 1998). These paleochannels, incised in the Miocene beneath the Savannah River, also were identified by seismic-reflection surveys, were filled with predominantly silt and clay, and had vertical hydraulic conductivity of 5.4×10^{-4} ft/d, similar to the upper confining unit (U.S. Army Corps of Engineers, 1998; Ocean Surveys, Inc., 2004). If the hydraulic conductivity of the paleochannel-fill sediments is greater than the surrounding Miocene sediments, the “no Miocene” sites identified by Foyle and others (2001) on the offshore Beaufort Arch and in Calibogue Sound could provide localized pathways for downward leakage of saline water from the surficial aquifer to the Upper Floridan aquifer (fig. 2).

At the Calibogue site, 35 ft of fine-grained paleochannel-fill sediments overlie the Oligocene strata of the Upper Floridan aquifer. The vertical hydraulic conductivity of the paleochannel fill at this site is similar to the Marks Head Formation of the upper confining unit, and effectively replaces the missing low-hydraulic conductivity Miocene sediments of the upper confining unit. The mean water level in the Upper Floridan aquifer measured in the temporary well at this site was 17.7 ft below NAVD 88, indicating a downward hydraulic gradient. Despite the potential for saltwater intrusion, chloride concentrations in borehole water from the Upper Floridan aquifer and pore water from the upper confining unit indicate that no saltwater intrusion has occurred at the Calibogue site (figs. 11, 13). At this site, water from the Upper Floridan aquifer had an ion composition very similar to samples collected in well 39Q025 at the north end of Tybee Island and in well HAM-122 in Hampton County, SC (fig. 13; app. 3). The carbon-14 and tritium concentrations were low, indicating relict freshwater confined in the Upper Floridan aquifer (app. 3).

The 8-mile site has only 0.8 ft of fine-grained Marks Head Formation overlying the top of the Oligocene strata of the Upper Floridan aquifer. From examination of core samples, the overlying paleochannel-fill sediments are coarser grained relative to the fine-grained paleochannel fill at the Calibogue site, and presumably have a vertical hydraulic conductivity that is less like the upper confining unit and more like the sand of the surficial aquifer (app. 3). In comparison with the upper confining unit, the paleochannel-fill sediments at the 8-mile site potentially created a preferred pathway for freshwater discharge from the Upper Floridan aquifer to the surficial aquifer during predevelopment and with the reversal of flow potential beginning in the 1950s created a preferential pathway for downward leakage of saline water from the surficial aquifer to the Upper Floridan aquifer.

Ion water chemistry in the Upper Floridan aquifer at the 8-mile site seems to support the probable occurrence of saltwater intrusion or encroachment. The water sample from the Oligocene strata at the 8-mile site is very saline sodium-chloride water, with a chloride concentration of 8,400 mg/L (figs. 9, 13). Beneath the Oligocene, pore-water chloride concentrations decreased to 560 and 600 mg/L in the Eocene part of the Upper Floridan aquifer. Therefore, the effects of saltwater intrusion are evident in the Eocene strata of the Upper Floridan aquifer, but less so than in the Oligocene.

As for the occurrence of modern saltwater intrusion at the 8-mile site, the carbon-14 and tritium concentrations are problematic. The very saline water at the 8-mile site has a carbon-14 concentration of 2.3 pmc, similar to the confined relict freshwater from the Calibogue and 7-mile sites (2.4 and 3.2 pmc, respectively), and the published onshore results for the southern end of Hilton Head Island (0.5 to 1.4 pmc; Landmeyer and Stone, 1995); however, the 8-mile site has the highest tritium concentration (4 TU) of all the wells in this study (app. 3).

The calculated freshwater/saltwater mixing for the very saline water at the 8-mile site is 55/45 percent (table 3). If the very saline water were roughly 45 percent modern saltwater, the carbon-14 concentration would be closer to 45 pmc, assuming no other sources of dead carbon were present to dilute the carbon-14 concentration. Assuming, however, that the geochemistries of the saline water and freshwater are at steady state in the surficial and Upper Floridan aquifers, respectively, the mixing of freshwater and saline water during intrusion is likely to result in geochemical reactions that would result in dilution of the carbon-14 concentration with dead carbon sources.

The mixing of saline and freshwaters could result in ion-exchange reactions that would promote dissolution of calcium carbonate in the aquifer to dilute the carbon-14 concentration. The intrusion of saline water from the ocean or surficial aquifer to the Upper Floridan aquifer would introduce a substantial source of dissolved sulfate to the anaerobic environment in the Upper Floridan aquifer. Active sulfate reduction in the Upper Floridan aquifer at the 8-mile site, as is evident from the hydrogen sulfide concentration of 6 mg/L, would produce carbon dioxide with the consumption of organic carbon. The addition of carbon dioxide from sulfate reduction also would result in the dissolution of carbonate, as was evident from pelecypod-shaped moldic pores found in the upper 10 ft of the Oligocene limestone at this site. Therefore, sulfate reduction would introduce two sources of dead carbon—organic-derived carbon dioxide and carbonate-derived bicarbonate—to dilute the carbon-14 concentration.

One other probable cause of the low carbon-14 concentration is that intrusion has not introduced modern saltwater but has introduced relict saline water from the channel-fill sediments and the surficial aquifer to the relict freshwater of the Upper Floridan aquifer (fig. 16). The tritium concentration of 4 TU, however, indicates that modern water has intruded the Upper Floridan aquifer at the 8-mile site. Therefore, the combination of low carbon-14 and detectable tritium concentrations support the concept of downward intrusion of a multi-component water mixture, including a minor amount of relatively modern saltwater with relict saline water, through the channel-fill sediments to the Upper Floridan aquifer at the 8-mile site.

Summary

The same conditions that favor saltwater intrusion onshore in Beaufort County, South Carolina, also exist in the offshore area seaward of Hilton Head Island beneath the Atlantic Ocean and west of Hilton Head Island in Calibogue Sound. The U.S. Geological Survey, in cooperation with the State of Georgia and as part of the Coastal Sound Science Initiative, assessed the hydrogeology, water quality, and the potential for saltwater intrusion of the Upper Floridan aquifer in the offshore area seaward of Hilton Head Island and in Calibogue Sound by drilling and sampling temporary wells from 1999 to 2001.

The geology and hydrogeology of the four offshore sites and the Calibogue site were correlated to the stratigraphy and the hydrogeology defined at the northern end of Tybee Island, Georgia (core 39Q030 and well 39Q025), identified in this report as the Tybee reference site. Wells drilled as part of this investigation are 7, 8, 10, and 15 miles to the northeast of the Tybee reference site and in Calibogue Sound west of the southern end of Hilton Head Island.

In this report, the surficial aquifer correlates to the coastal barrier-island and marine inner-shelf deposits of Pleistocene and Holocene ages. The surficial aquifer consists of very fine- to fine-grained, well-sorted sand with minor amounts of phosphate and has a hydraulic conductivity of 0.48 feet per day.

Sediments of the paleochannel fill at the 8-mile site are predominantly unlithified sand with more textural similarity to the sands of the surficial aquifer, relative to the clay, silt, and silty sand of the upper confining unit underlying the surficial aquifer. Conversely, the paleochannel-fill sediments at the Calibogue site are similar in texture to the fine-grained sediments of the upper confining unit. The age of the paleochannel-fill intervals is interpreted as postdating the early Miocene, based on the presence of reworked early Miocene microfossils. At the Calibogue site, the vertical hydraulic conductivities of two samples of the paleochannel-fill sediments were 4.5×10^{-4} and 5.4×10^{-4} feet per day, greater than the late and middle Miocene sediments (averaging 7.7×10^{-3} and 9.9×10^{-3} feet per day, respectively) and similar to the early Miocene sediments (averaging 5.4×10^{-4} feet per day) of the upper confining unit in the study area.

The upper confining unit at the Tybee reference site is 69.4 feet thick and includes two unnamed members of the early Miocene Marks Head Formation, the Tybee Phosphorite and Berryville Clay members of the middle Miocene Coosawhatchie Formation, and the late Miocene Ebenezer Formation. At the 7-, 10-, and 15-mile sites, the Miocene sediments of the upper confining unit are similar to the lithologies of member #2 of the Marks Head Formation at the onshore reference site. Dinoflagellates present in all samples were well preserved with no indication of reworking and were clearly diagnostic of the upper part of dinoflagellate zone DN2 or the early Burdigalian stage of the early Miocene. The phosphatic sediments of the middle Miocene Coosawhatchie Formation and the silty sand of the late Miocene Ebenezer Formation were absent at the Calibogue site and the four offshore sites. The paleochannel incisions completely removed the upper confining unit at the Calibogue site and removed all but 0.8 feet of the upper confining unit at the 8-mile site, corroborating the results of published seismic data.

The top of the Upper Floridan aquifer, as mapped from seismic-reflection surveys, closely approximates the contact between the base of the Marks Head Formation of the upper confining unit and the top of the sediments and rock units of the underlying Oligocene, as seen in cores from the temporary wells. The Upper Floridan aquifer at the offshore and Calibogue sites includes unconsolidated calcareous quartz sand, calcareous quartz sandstone, and sandy limestone of the Oligocene Lazaretto Creek and Tiger Leap Formations, and limestone of the late Eocene Ocala Limestone and middle Eocene Avon Park Formation.

Mean water levels in the Upper Floridan aquifer, which were corrected for water density at the 8- and 15-mile sites, were 2.3 feet above NAVD 88 at the 15-mile site in September 1999 and 11.5 feet below NAVD 88 at the 8-mile site in June 2001 as equivalent freshwater head. The mean water level was 17.7 feet below NAVD 88 in July 2001 at the Calibogue site, 17.4 feet below NAVD 88 at the 7-mile site in June 2000, and 13.1 ft below NAVD 88 at the 10-mile site in June 2000.

The low ionic-strength freshwater at the Tybee reference and Calibogue sites is a calcium-magnesium-sodium-bicarbonate water type. The water at the 10-mile site had a dissolved sulfate concentration of 100 milligrams per liter, compared with concentrations of less than 15 milligrams per liter at the other three wells; the water is a calcium-magnesium-sodium-sulfate-bicarbonate water type. The sample collected at the 7-mile site also is freshwater; however, relative to the other freshwater samples in this study, the freshwater at the 7-mile site has higher chloride and total dissolved solids concentrations (370 and 887 milligrams per liter, respectively) and is a sodium-chloride water type.

The Upper Floridan aquifer at the 8- and 15-mile sites contains sodium-chloride water. The water is classified as very saline, with total dissolved solids concentrations of 14,900 and 13,000 milligrams per liter, respectively, and chloride concentrations of 8,400 and 6,800 milligrams per liter, respectively. The water samples at the 8- and 15-mile sites had the two highest concentrations of sulfate (990 and 1,200 milligrams per liter), hydrogen sulfide (6 and 30 milligrams per liter), and total organic carbon (1.0 and 2.9 milligrams per liter) respectively. In contrast, the freshwater in the Upper Floridan aquifer at the Tybee reference site, Calibogue site, and 7- and 10-mile sites had sulfate concentrations less than 100 milligrams per liter, hydrogen sulfide less than 0.1 milligram per liter, and total organic carbon less than 1 milligram per liter. A saltwater source mixing with freshwater at or near the 8- and 15-mile sites is introducing sulfate and organic carbon into the Upper Floridan aquifer. Alkalinity in the water sample at the 15-mile site was 244 milligrams per liter as calcium carbonate and, along with higher concentrations of hydrogen sulfide and organic carbon, distinguished the water at the 15-mile site from the water at the 8-mile site.

The freshwater/modern seawater mixing proportions for the very saline water in the Upper Floridan aquifer at the 8- and 15-mile sites were approximately 55/45 percent at the 8-mile site and 63/37 percent at the 15-mile site. Concentrations of total dissolved solids, bromide, and chloride, and the stable oxygen and hydrogen isotopic compositions of freshwater at the 10-mile site and modern seawater were used as end members to calculate the mixing proportions.

The freshwater in the Upper Floridan aquifer at the Tybee reference site, the Calibogue site, and the 7- and 10-mile sites had carbon-14 concentrations ranging from 0.9 to 3.2 percent modern carbon, and was interpreted to be relict freshwater. Very saline water at the 8-mile site had a similar concentration of carbon-14 (2.3 percent modern carbon) relative to the freshwater samples. The carbon-14 results do not support the concept of 55/45-percent proportional mixing of freshwater in the Upper Floridan aquifer with modern seawater without dilution of the carbon-14 by a dead-carbon source. Instead, the carbon-14 concentration supports the concept of intrusion by relict water from the surficial aquifer and the upper confining unit to the Upper Floridan aquifer.

The water sample collected at 586 feet below NAVD 88 in the 10-mile well is slightly saline and classified as a sodium-sulfate-chloride water type. This sample had a chloride concentration of 740 milligrams per liter and was slightly saline, with a total dissolved solids concentration of 2,320 milligrams per liter.

The chloride concentrations in pore-water samples at the 7- and 10-mile sites decreased from the top to the bottom of the upper confining unit and are assumed to reflect downward intrusion of saline water into the upper confining unit from the surficial aquifer. The high chloride concentration (370 milligrams per liter) in the borehole-water sample at the 7-mile site is probably the result of downward movement of saline water through the upper confining unit at this site or in the nearby paleochannel incisions to the north and east. Given the negligible vertical-flow potential and the presence of about 17 feet of upper confining unit, the water at the 15-mile site is assumed to be the product of mixing in the transitional zone between confined relict saline water and confined relict freshwater.

The pore-water chloride concentrations in the fine-grained paleochannel-fill sediments at the Calibogue site declined from approximately 1,300 milligrams per liter near the top of the upper confining unit to 120 milligrams per liter near the middle of the upper confining unit. The carbon-14 and chloride concentrations in the Upper Floridan water sample were low, indicating relict freshwater confined in the Upper Floridan aquifer with no noticeable saltwater intrusion at the Calibogue site.

The coarse-grained paleochannel-fill sediments at the 8-mile site could serve as a preferred pathway for downward leakage of saline water from the surficial aquifer to the Upper Floridan aquifer. Ion water chemistry in the Upper Floridan aquifer at the 8-mile site seems to support the probable occurrence of saltwater intrusion or encroachment. The water sample from the Oligocene strata at the 8-mile site is very saline and a sodium-chloride water type, with a chloride concentration of 8,400 milligrams per liter. Beneath the Oligocene strata, pore-water chloride concentration decreased to 560 milligrams per liter in the Eocene part of the Upper Floridan aquifer, which indicates less saltwater intrusion relative to the Oligocene strata.

Although the very saline water at the 8-mile site had a carbon-14 concentration of 2.3 percent modern carbon, similar to the confined relict freshwater from the Calibogue and 7-mile sites, it has the highest tritium concentration (4 tritium units) of all wells sampled during this investigation. The calculated freshwater/modern saltwater mixing at the 8-mile site is 55/45 percent. The carbon-14 and tritium concentrations do not support the mixing proportions of relatively modern seawater with relict freshwater in the Upper Floridan aquifer at the 8-mile site. Instead, the carbon-14 and tritium results indicate that the intruding water predominantly is relict saline water from the surficial aquifer with only a minor component of modern saltwater.

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Appendix 1. Identification, location, construction, and water-level data for one well site in Calibogue Sound and four offshore well sites southeast of Hilton Head Island, South Carolina.

[BFT, Beaufort County; USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; latitude and longitude in degrees, minutes, and seconds]

	Calibogue site	7-mile site	8-mile site
County well identification[1]	BFT-2297	BFT-2249	BFT-2295
USGS well-site identification	320918080490801	320402080444101	320414080425501
Drilling start date	July 16, 2001	June 9, 2000	May 30, 2001
Drilling end date	July 20, 2001	June 13, 2000	June 5, 2001
Latitude	320917.46	320402.36	320414.29
Longitude	0804907.56	0804441.27	0804255.05
Sea-floor altitude, in feet below NAVD 88	27.7	29.5	31.6
Altitude of top of 10-inch-diameter casing, in feet above NAVD 88	17.7	17.8	14.9
Length of 10-inch-diameter casing and penetration below sea floor, in feet	65 feet and 19.6 feet	65.9 feet and 18.6 feet	69.8 feet and 23.3 feet
Final bottom altitude of 10-inch-diameter casing, in feet below NAVD 88	47.3	48.1	52
Starting altitude of first core interval, in feet below NAVD 88	29.2	37.2	60.6
Bottom altitude of first core interval, in feet below NAVD 88	137.60	75.7	100.1
Bottom altitude of logging interval from top of 10-inch diameter casing, altitude in feet below NAVD 88	136.2	not logged	100.1
Altitude of top of drilling interval before 6-inch-diameter casing, in feet below NAVD 88 (bit size, in inches)	133.7 (9.875)	76.7 (9.875)	96.9 (9.875)
Altitude of top of 6-inch casing, in feet above NAVD 88	20.3	19.3	16.6
Length of 6-inch casing, in feet	116	96.8	115
Altitude of bottom of 6-inch casing, in feet below NAVD 88	95.7	77.5	98.4
Starting altitude of second core interval, in feet below NAVD 88	not cored	80.7	101.7
Bottom altitude of second core interval, in feet below NAVD 88	not cored	134.7	180.2
Altitude of top of drilling interval after 6-inch casing installed, in feet below NAVD 88, drilled with 5.5-inch bit	103.5	not drilled	180.2
Bottom altitude of drilling interval after 6-inch casing installed, in feet below NAVD 88	120.7	not drilled	207.4
Bottom altitude of logging interval, in feet below NAVD 88	not logged	134.7	206.2
Altitude of water level, in feet above (+) or below (-) NAVD 88 (density corrected altitude); date/24-hour time	-16.9; July 20, 2001 at 13:26	-16.1; June 13, 2000 at 07:01	-10.8 (-9.9); June 3, 2001 at 20:37
Altitude of water-level in feet above (+) or below (-) NAVD 88 (density corrected altitude); date/24-hour time	-18.5; July 20, 2001 at 16:25	-18.7; June 13, 2000 at 09:05	-14.0 (-13.1); June 5, 2001 at 04:51;

Appendix 1. Identification, location, construction, and water-level data for one well site in Calibogue Sound and four offshore well sites southeast of Hilton Head Island, South Carolina.—Continued

[BFT, Beaufort County; USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; latitude and longitude in degrees, minutes, and seconds]

	10-mile site	10-mile site	15-mile site	15-mile site
County well identification[1]	BFT-2250	BFT-2251	BFT-2257	BFT-2258
USGS well-site identification	320406080404200	320407080404201	320604080355200	320605080355500
Drilling start date	June 19, 2000	June 21, 2000	August 24, 1999	September 8, 1999
Drilling end date	June 21, 2000	June 28, 2000	August 26, 1999	September 10, 1999
Latitude	32045.78	320407.09	320603.77	320604.69
Longitude	0804042.12	0804042.12	0803552.42	0803554.50
Sea-floor altitude, in feet below NAVD 88	28.1	27	27.4	29.4
Altitude of top of 10-inch casing, in feet above NAVD 88	12.9	14.6	13.5	16.1
Length of 10-inch casing and penetration below sea floor, in feet	53.9 feet and 12.9 feet	54.9 feet and 20 feet	56 feet and 15.1feet	59.8 feet and 14.3 feet
Final bottom altitude of 10-inch casing, in feet below NAVD 88	41	40.3	42.5	43.7
Starting altitude of first core interval, in feet below NAVD 88	40.1	not cored	41	not cored
Bottom altitude of first core interval, in feet below NAVD 88	95.1	not cored	88	not cored
Bottom altitude of logging interval from top of 10-inch casing, altitude in feet below NAVD 88	95.1	not logged	not logged	not logged
Altitude of top of drilling interval before 6-inch casing, in feet below NAVD 88 (bit size, in inches)	95.1 (9.0)	91.9 (9.0)	not drilled	91.9 (9.0)
Altitude of top of 6-inch casing, in feet above NAVD 88	16.2	16.8	not cased	17.7
Length of 6-inch casing, in feet	108	108.3	not cased	106
Altitude of bottom of 6-inch casing, in feet below NAVD 88	91.8	91.5	not cased	88.3
Starting altitude of second core interval, in feet below NAVD 88	not cored	93.2	not cored	not cored
Bottom altitude of second core interval, in feet below NAVD 88	not cored	221.2	not cored	not cored
Altitude of top of drilling interval after 6-inch casing installed, in feet below NAVD 88, drilled with 5.5-inch bit	not drilled	207.2	not drilled	91.3
Bottom altitude of drilling interval after 6-inch casing installed, in feet below NAVD 88	not drilled	698.2	not drilled	154.3
Bottom altitude of logging interval, in feet below NAVD 88	not logged	698.2	not logged	154.3
Altitude of water level, in feet above (+) or below (-) NAVD 88 (density corrected altitude); date/24-hour time	not measured	-13.0; June 25, 2000 at 11:42	not measured	+0.2 (+1.0); September 10, 1999 at 18:05
Altitude of water-level in feet above (+) or below (-) NAVD 88 (density corrected altitude); date/24-hour time	not measured	-13.3; June 28, 2000 at 01:00	not measured	+2.8 (+3.6); September 10, 1999 at 20:11
Altitude of water-level in feet above (+) or below (-) NAVD 88; (density corrected altitude); date/24-hour time	not measured	-12.9; June 28, 2000 at 05:45	not measured	not measured

[1]County well inventory number assigned by South Carolina Department of Health and Environmental Control.

Appendix 2. Dinoflagellate taxa identified in core samples collected at the four offshore and Calibogue sites, and interpretation of age and geologic unit.

[BFT, Beaufort County, South Carolina; NAVD 88, North American Vertical Datum of 1988; ft, feet; sp., species; X, present; . , not observed; ?, questionable identification;

Well-site name:	7-mile site		8-mile site				10-mile site
Well number:	BFT-2249		BFT 2295		BFT-2251		
Elevation of top of sample, below NAVD 88:	-97.1 ft	-64.7 ft	-78.3 ft	-43.4 ft	-163.2 ft	-128.2 ft	-120.7 ft
Sample number:	R6123 B	R6123 A	R6198 A	R6198 B	R6125 C	R6125 B	R6125 A
Age of dinocyst assemblage:	Oligocene or earliest Miocene	Early Miocene DN2	Early Miocene DN2	Mixed	Latter part of early Oligocene	Oligocene	Late Oligocene
Geologic unit:	Tiger Leap Formation	Marks Head Formation	Marks Head Formation	Valley-fill sediments	Lazaretto Creek Formation	Tiger Leap Formation	
Achilleodinium biformoides	.	.	.	.	X	.	.
Apteodinium australiense	.	.	.	.	X	.	.
Apteodinium spiridoides	.	.	.	.	.	.	.
Apteodinium tectatum	.	X	X	.	.	.	.
Batiacasphaera hirsuta	.	X	.	.	.	.	.
Batiacasphaera sphaerica	.	.	.	.	.	.	X
Bitectatodinium tepikiense	.	.	.	.	.	.	.
Brigantedinium sp.							
Cerebrocysta satchelliae	.	X	.	.	.	.	.
Chiropteridium lobospinosum	X	.	.	.	X	X	X
Cleistosphaeridium placacanthum	.	X	X	.	.	.	.
Cordosphaeridium cantharellus	.	.	.	.	X	.	.
Cordosphaeridium fibrospinosum	.	.	.	.	.	X	.
Cordosphaeridium minimum	.	.	.	.	.	.	.
Cousteaudinium aubryae	.	?	X	.	.	.	.
Cribrosphaeridium tenuispinosum	X	.	.	.	.	.	.
Cribroperidinium sp.	.	.	.	.	.	.	.
Cyclopsiella sp.	.	.	.	.	X	.	.
Dapsilidinium pseudocolligerum	.	.	.	.	X	.	.
Deflandrea phosphoritica/heterophlycta	.	.	.	.	X	.	.
Dinopterygium cladoides sensu	.	.	.	.	X	.	.
Distatodinium paradoxum	.	.	X	.	.	.	.
Exochosphaeridium insigne	.	X	X	rw(M)	.	.	.
Fibrocysta? sp.	.	.	.	.	.	.	.
Heteraulacacysta sp.	.	X	X	.	X	.	.
Homotryblium plectilum	.	.	X	.	X	.	.
Hystrichokolpoma cinctum	.	.	.	.	.	.	.
Hystrichokolpoma rigaudiae	.	X	X	.	X	.	.
Hystrichokolpoma sp.	.	.	.	.	.	.	.
Hystrichosphaeropsis obscura	.	.	.	.	.	.	.
Impagidinium sphaericum	.	.	.	.	.	.	.
Impagidinium sp.	.	.	X	.	.	.	.
Lejeunecysta spp.	.	X	X	.	X	X	.

??, very questionable identification; re, reworked long-ranging; rw(O), reworked from the Oligocene; rw(M), reworked from the Miocene]

15-mile site						Calibogue site			
BFT-2250	BFT-2258		BFT-2257			BFT-2297			
-69.7 ft	-80.7 ft	-76.5 ft	-69.0 ft	-62.0 ft	-56.6 ft	-75.7 ft	-69.2 ft	-58.0 ft	-35.2 ft
R6124	R6056 AB	R6056 AA	R6056 A	R6056 B	R6056 C	R6199 A	R6199 B	R6199 C	R6199 D
Early Miocene DN2	Oligocene ?	Early Miocene	Early Miocene DN2	Mixed, includes Miocene		Mixed, includes Miocene		Younger than early Miocene	
Marks Head Formation	Tiger Leap Formation	Marks Head Formation		Satilla Formation		Valley-fill sediments			Satilla Formation
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
X	.	.	.	rw	.	.	.	.	.
X	X	X	X	.	.	.	.	.	.
X	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	X	.	.
				X					
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.	X	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	X	.	rw	.	rw	.	.
.	.	.	.	.	.	.	.	.	.
X	.	.	.	.	.	.	.	.	.
X	.	.	X	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
X	.	X	X	rw	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
X	.	.	X	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.
X	.	X	X	? rw(M)	.	rw(M)	rw(M)	.	.
.	.	.	.	rw	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	X	.	.	.	.	.	.
X	.	.	.	.	.	.	.	.	.
.	.	X	.	.	.	X	.	.	.
.	.	.	.	.	.	rw(M)	.	.	.
.	.	.	.	.	.	X	X	X	.
.	.	.	.	.	.	.	.	.	.
.	.	.	X	.	.	.	.	.	.

Appendix 2. Dinoflagellate taxa identified in core samples collected at the four offshore and Calibogue sites, and interpretation of age and geologic unit.—Continued

[BFT, Beaufort County, South Carolina; NAVD 88, North American Vertical Datum of 1988; ft, feet; sp., species; X, present; . , not observed; ?, questionable identification;

Well-site name:	7-mile site		8-mile site		10-mile site		
Well number:	BFT-2249		BFT 2295		BFT-2251		
Elevation of top of sample, below NAVD 88:	-97.1 ft	-64.7 ft	-78.3 ft	-43.4 ft	-163.2 ft	-128.2 ft	-120.7 ft
Sample number:	R6123 B	R6123 A	R6198 A	R6198 B	R6125 C	R6125 B	R6125 A
Age of dinocyst assemblage:	Oligocene or earliest Miocene	Early Miocene DN2	Early Miocene DN2	Mixed	Latter part of early Oligocene	Oligocene	Late Oligocene
Geologic unit:	Tiger Leap Formation	Marks Head Formation	Marks Head Formation	Valley-fill sediments	Lazaretto Creek Formation	Tiger Leap Formation	
Lingulodinium machaerophorum	.	X	X	.	X	.	.
Membranophoridium aspinatum	.	.	.	.	X	.	X
Nematosphaeropsis rigida	.	.	.	.	.	.	.
Operculodinium spp.	.	X	X	X	.	.	.
Pentadinium imaginatum	.	.	.	rw(O)	X	X	X
Pentadinium laticinctum (grano-vermiculate form)	X	.	.	.	X	.	.
Pentadinium sp. cf. P. laticinctum granulatum	.	.	.	.	.	.	.
Pentadinium group sp.	.	.	.	.	.	.	.
cysts of Polykrikos sp.	.	.	.	.	.	.	.
Polysphaeridium zoharyi	.	X	X	.	.	.	.
cysts of Protoperidinium spp.	.	.	.	.	.	.	.
Reticulatasphaera actinocoronata	.	.	.	.	.	.	.
Saturnodinium pansum	.	.	.	.	X	X	X
Selenopemphix nephroides	.	.	X	.	.	.	.
Selenopemphix quanta	.	.	X	.	X	.	.
Spiniferites mirabilis	.	.	.	.	.	.	.
Spiniferites pseudofurcatus	X	X	X	.	X	.	.
Spiniferites spp.	.	X	X	X	X	X	.
Sumatradinium hamulatum	.	.	X	.	.	.	.
Sumatradinium soucouyantiae	.	X	X	.	.	.	.
Sumatradinium spp.	.	.	.	.	.	.	.
Systematophora placacantha	.	.	.	.	.	.	.
Tectatodinium pellitum	.	X	.	.	X	.	.
Trinovantedinium papulum	.	.	.	.	.	.	.
Tuberculodinium vancampoae	.	X	X	X	??	.	.
miscellaneous areoligeracean forms	.	.	.	.	.	.	.
round, spinose forms	.	.	.	X	.	.	.
Preservation	poor	good	good	very few	fair	poor-fair	poor

??, very questionable identification; re, reworked long-ranging; rw(O), reworked from the Oligocene; rw(M), reworked from the Miocene]

15-mile site						Calibogue site			
BFT-2250	BFT-2258		BFT-2257			BFT-2297			
-69.7 ft	-80.7 ft	-76.5 ft	-69.0 ft	-62.0 ft	-56.6 ft	-75.7 ft	-69.2 ft	-58.0 ft	-35.2 ft
R6124	R6056 AB	R6056 AA	R6056 A	R6056 B	R6056 C	R6199 A	R6199 B	R6199 C	R6199 D
Early Miocene DN2	Oligocene ?	Early Miocene	Early Miocene DN2	Mixed, includes Miocene		Mixed, includes Miocene		Younger than early Miocene	
Marks Head Formation	Tiger Leap Formation	Marks Head Formation		Satilla Formation		Valley-fill sediments			Satilla Formation
X	.	.	X	.	X	?	?	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	sp.	.	.	X	.	X
X	.	.	X	X	X	?	X	X	?
.	?	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	rw(M)	.	.
.	.	.	.	.	.	.	.	X	.
X	.	.	.	.	.	.	.	.	.
X	X	.	.	.	X	X	X	.	.
.	.	.	.	.	.	X	X	X	.
.	.	.	X	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
X	.	.	.	.	.	.	.	.	.
.	.	.	.	X	.	.	.	.	.
.	.	.	.	X	X	.	.	.	.
X	.	.	X	.	rw	.	.	.	.
X	.	.	X	X	X	X	X	X	X
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	X	.	.	.	.	.	.
.	.	.	X	.	.	.	.	.	.
X	.	.	X	.	.	.	X	.	.
X	.	.	.	.	.	.	.	.	.
.	.	.	X	X	X	.	X	.	X
.	.	.	.	.	rw	rw	.	.	.
.	.	.	.	.	.	.	.	.	.
good	nearly barren	poor	good	poor	poor	good	fair-good	good	very few

Appendix 3. Field and laboratory analyses for water samples collected from the Calibogue and offshore wells, and well 39Q025 (fig. 1), well HAM-122 (Hampton, SC), and the Atlantic Ocean (Hem, 1989; Phelps, 2001).

[NAVD 88, North America Vertical Datum of 1988; °C, Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; g/cm^3, grams per cubic centimeter; BFT, Beaufort County; HAM, Hampton County; <, less than; —, no results; µg/L, micrograms per liter; $\delta^{18}O$, delta oxygen-18; δD, delta deuterium; $\delta^{13}C$, delta carbon-13; dissolved-oxygen concentrations less than 0.2 mg/L for all ground-water samples]

(Sample number) South Carolina county number or Georgia well name, site name	Aquifer	Depth, in feet below NAVD 88	Date and 24-hour time of sample collection	Temperature (°C)	Field specific conductance (µS/cm)	Total dissolved solids (mg/L)	Field pH, (standard units)	Hardness, total as calcium carbonate (mg/L)	Calculated density (g/cm^3)	Nitrogen, ammonia dissolved (mg/L)	Nitrogen, nitrite plus nitrate dissolved (mg/L)	Phosphorus, dissolved (mg/L)	Phosphorus, ortho dissolved (mg/L)
(1) BFT-2258, 15-mile site	Upper Floridan aquifer	91 to 154	9/10/1999 18:00	22.5	22,570	13,000	7.5	2,400	1.009	5.4	<0.02	0.05	0.06
(2) BFT-2251, 10-mile site	Upper Floridan aquifer	198 to 220	6/25/2000 13:30	22	472	305	7.9	180	<1.001	0.16	<0.02	<0.02	<0.01
(3) BFT-2251, 10-mile site	Upper/ Lower Floridan aquifer	93 to 698 (pump set at 586 feet)	6/28/2000 13:00	23.5	3,650	2,320	7.6	690	1.002	0.89	<0.02	<0.02	<0.01
(4) BFT-2295, 8-mile site	Upper Floridan aquifer	95.5 to 107	6/04/2001 03:00	21.5	25,800	14,900	7.6	2,900	1.010	1.48	<0.02	0.02	0.04
(5) BFT-2249, 7-mile site	Upper Floridan aquifer	78 to 135	6/13/2000 14:35	22	1,900	887	8.1	250	<1.001	0.12	0.02	<0.02	<0.01
(6) BFT-2297, Calibogue site	Upper Floridan aquifer	103 to 121	7/20/2001 22:00	21.8	231	199	9	98	<1.001	0.05	<0.02	<0.02	<0.01
(7) 39Q025, Tybee reference site, Georgia	Upper Floridan aquifer	115 to 135	8/19/1997 13:00	23.5	265	186	9.8	—	<1.001	—	<0.05	<0.02	—
(8) HAM-122, Hampton County, South Carolina	Upper Floridan aquifer	7 to 99	6/25/1985	20.5	285	132	7.3	—	<1.001	0.02	<0.01	0.06	0.05
(9) Seawater (Hem, 1989; Phelps, 2001)	—	—	—	—	—	35,000	—	—	1.024	—	—	0.09	—

Appendix 3. Field and laboratory analyses for water samples collected from the Calibogue and offshore wells, and well 39Q025 (fig. 1), well HAM-122 (Hampton, SC), and the Atlantic Ocean (Hem, 1989; Phelps, 2001).—Continued

[NAVD 88, North America Vertical Datum of 1988; °C, Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; g/cm^3, grams per cubic centimeter; BFT, Beaufort County; HAM, Hampton County; <, less than; —, no results; µg/L, micrograms per liter; $\delta^{18}O$, delta oxygen-18; δD, delta deuterium; $\delta^{13}C$, delta carbon-13; dissolved-oxygen concentrations less than 0.2 mg/L for all ground-water samples]

(Sample number) South Carolina county number or Georgia well name, site name	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Strontium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Alkalinity, as calcium carbonate (mg/L)	Hydrogen sulfide (mg/L)	Total organic carbon (mg/L)	Chloride-to-bromide ratio
(1) BFT-2258, 15-mile site	190	460	4,000	150	4.5	6,800	1,200	0.67	28	244	30	2.9	296
(2) BFT-2251, 10-mile site	36	21	33	4.3	1.3	25	100	0.68	35	98.5	<1.0	0.4	250
(3) BFT-2251, 10-mile site	100	104	530	29	9.4	740	700	2.4	34	132	<1.0	0.7	284
(4) BFT-2295, 8-mile site	280	540	4,400	97	9.6	8,400	990	0.2	27	127	6	1	263
(5) BFT-2249, 7-mile site	36	39	250	11	0.9	370	99	0.53	30	105	<1.0	0.4	285
(6) BFT-2297, Calibogue site	25	8.6	18	2.7	0.4	9.3	11	0.5	47	127	<1.0	0.5	186
(7) 39Q025, Tybee reference site, Georgia	18	4.1	30	11	0.7	13	5.5	0.65	32	120	—	0.6	433
(8) HAM-122, Hampton County, South Carolina	50	51	5.6	1.9	—	3.3	3.3	0.1	19	149	—	1.6	not calculated
(9) Seawater (Hem, 1989; Phelps, 2001)	410	1,350	10,500	390	8.0	19,000	2,700	1.3	6.4	116	—	0.1	284

Appendix 3. Field and laboratory analyses for water samples collected from the Calibogue and offshore wells, and well 39Q025 (fig. 1), well HAM-122 (Hampton, SC), and the Atlantic Ocean (Hem, 1989; Phelps, 2001).—Continued

[NAVD 88, North America Vertical Datum of 1988; °C, Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; g/cm^3, grams per cubic centimeter; BFT, Beaufort County; HAM, Hampton County; <, less than; —, no results; µg/L, micrograms per liter; $\delta^{18}O$, delta oxygen-18; δD, delta deuterium; $\delta^{13}C$, delta carbon-13; dissolved-oxygen concentrations less than 0.2 mg/L for all ground-water samples]

(Sample number) South Carolina county number or Georgia well name, site name	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Aluminum, dissolved (µg/L)	Barium, dissolved (µg/L)	Lithium, dissolved (µg/L)	Bromide, dissolved (mg/L)	$\delta^{18}O$ per mil (Vienna-Standard Mean Ocean Water)	δD per mil (Vienna-Standard Mean Ocean Water)	$\delta^{13}C$ per mil (Peedee Belemnite)	Carbon-14, (percent modern carbon)	Tritium (tritium units)
(1) BFT-2258, 15-mile site	70	25	31	9	110	23	-2.1	-9.8	2.2	—	0.6
(2) BFT-2251, 10-mile site	569	7.4	52	9	12	0.1	-4.1	-19.5	-1.5	0.9	3.2
(3) BFT-2251, 10-mile site	21	<5.0	27	8	64	2.6	-3.9	-19.8	—	—	—
(4) BFT-2295, 8-mile site	90	<5.0	17	160	96	32	-1.9	-8	0.4	2.3	4
(5) BFT-2249, 7-mile site	13	12	8.2	13	18	1.3	-3.9	-19.6	-1.4	3.2	2.2
(6) BFT-2297, Calibogue site	<2.0	<5.0	171	12	11	0.05	-4	-18.4	-3.4	2.4	<0.3
(7) 39Q025 Tybee reference site, Georgia	<3.0	<1.0	23	128	—	0.03	—	—	—	—	—
(8) HAM-122, Hampton County, South Carolina	570	52	10	—	10	—	-3.4	-16	-10.5	37.2	—
(9) Seawater (Hem, 1989; Phelps, 2001)	3	2	1	20	170	67	0.7	6.2	-1.75	110	—

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