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U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 98-4253

Prepared in cooperation with the
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

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By Ronald S. Reese

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Tallahassee, Florida
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Hydrogeology and the Distribution of Salinity in the Floridan Aquifer System, Southwestern Florida

By Ronald S. Reese

Abstract

A study was conducted to establish a detailed hydrogeologic framework in the complex Floridan aquifer system of southwestern Florida, and to evaluate and relate the distribution of salinity found in this system. The Floridan aquifer system consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer. The Upper Floridan aquifer extends into a basal unit of the Hawthorn Group; however, a regional unconformity present at the base of this unit generally marks the top of the Floridan aquifer system, as it does in the rest of southern Florida. The basal Hawthorn unit, which is defined at its top by a correlative marker unit, ranges in thickness from 120 to 460 feet. Paleotopography present prior to deposition of the basal Hawthorn unit, which resulted at least in part from erosion, is believed to have caused some of this variation in thickness. However, in some areas where the basal Hawthorn unit is thick, particularly in Lee County, depositional buildup created paleotopographic highs at the top of the unit. In these areas, permeable limestone zones are present in the unit, giving the unit a high transmissivity.

In most of the study area, the Floridan aquifer system can be divided into a brackish-water zone, a salinity transition zone, and a saline-water zone. The brackish-water zone contains water with a dissolved-solids concentration of less than 10,000 milligrams per liter. The saline-water zone has a dissolved-solids concentration of at least 35,000 milligrams per liter and a salinity similar to that of seawater. The salinity transition zone that separates these two zones is usually 150 feet or less in thickness. The altitude of the base of the brackish-water zone was mapped primarily using geophysical logs; it ranges from as shallow as 565 feet below sea level along the coast to almost 2,200 feet below sea level inland. This mapping indicated that the boundary represents a salinity interface, the depth of which is controlled by head in the brackish-water zone.

Chloride concentrations in the upper part of the brackish-water zone range from 400 to 4,000 milligrams per liter. A large area of relatively low salinity in north-central Collier County and to the northwest, as defined by a 1,200-milligram-per-liter chloride-concentration line, coincides with a high area on the basal contact of the Hawthorn Group. As this contact dips away from this high area to central Hendry and southwestern Collier Counties, chloride concentration increases to 2,000 milligrams per liter or greater. However, the increase in salinity in these areas occurs only in the basal Hawthorn unit or Suwannee Limestone, but not in deeper units. In central Hendry County, the increase occurs only in the basal Hawthorn unit in an area where the unit is well developed and thick. These areas of higher salinity could have resulted from the influx of seawater from southwestern Collier County into zones of higher permeability in the Upper Floridan aquifer during high sea-level stands. The influx may only have occurred in structurally low areas and may have experienced incomplete flushing subsequently by the modern freshwater flow system.

In an area in north-central Collier County, the altitude of the base of the brackish-water zone

is anomalously deep given the position of this area relative to the coast. In this area, the base extends as deep as 2,090 feet below sea level, and the salinity transition zone is not present or is poorly defined. The origin of this anomalous area is interpreted to be related to the development of a unit containing thick dolomite and evaporite beds high in the middle confining unit of the Floridan aquifer system. The top of this dolomite-evaporite unit, which probably has very low permeability, occurs at the base of the brackish-water zone in this area. The axis of a high area mapped at the top of the unit trends to the northwest from central Collier County into north-central Lee County. This axis parallels and lies just to the west of the anomalous area, and it could have acted as an impermeable sill, preventing saline water from moving in laterally from the coast to the southwest and up from the Lower Floridan aquifer. Locating a Floridan aquifer system well field in or near this anomalous area could be optimal because of the lack of a salinity interface at depth.

INTRODUCTION

Increasing demand for water from the surficial aquifer system in the highly populated coastal area of southern Florida has prompted a need to find supplemental sources of available water for both public and agricultural use. In 1995, nearly 456 Mgal/d (million gallons per day) were withdrawn from ground-water sources in Collier, Hendry, and Lee Counties (Marella, 1999). Of this amount, 60 percent was obtained from the surficial aquifer system, 38 percent from the intermediate aquifer system, and 2 percent from the Floridan aquifer system (Marella, 1999). Ground-water withdrawals in these three counties increased 107 percent between 1975 and 1995.

The virtually untapped, but well-developed Floridan aquifer system can be used to assist in the need to find supplemental water sources in southern Florida. Because of the generally brackish nature of this ground-water source, its use has been primarily for withdrawal for irrigation.

Two other methods for using the aquifer system are currently being explored: (1) the reverse-osmosis desalination method, and (2) the aquifer storage and retrieval (ASR) method. With the reverse-osmosis method, high pressure is applied to the water being treated, forcing it through a semipermeable membrane. This process removes the dissolved salts, thus producing pure water (freshwater). Because the salinity of water in the upper part of the Floridan aquifer system is only about 10 percent of that of seawater, the expense of the reverse-osmosis treatment is much less than desalting seawater.

With the ASR method, freshwater from the surface or the surficial aquifer system is temporarily stored in the upper part of the Floridan aquifer system and withdrawn when the water is needed. Before use of the Floridan aquifer system can be implemented on a large scale, its hydrogeologic framework and distribution of salinity in southern Florida need to be characterized and better understood.

To address these information needs, the U.S. Geological Survey (USGS), in cooperation with the South Florida Water Management District (SFWMD), conducted a study from October 1992 through September 1995 to: (1) describe the vertical and areal variations in water quality in the Floridan aquifer system, and (2) relate these variations in water quality to the local hydrogeologic framework of southern Florida. Emphasis in this study was placed on the upper part of the Floridan aquifer system in Collier, Hendry, and Lee Counties, and small parts of Charlotte and Glades Counties to the north; Palm Beach, Broward, and Dade Counties to the east; and Monroe County to the south (fig. 1). The study area is bounded by Lake Okeechobee on the northeast and the Gulf of Mexico on the west. Two similar studies were conducted, one in southeastern Florida encompassing mainly Dade and Broward Counties (Reese, 1994) and the other in Palm Beach County (Reese and Memberg, 1999).

Purpose and Scope

This report delineates the distribution of salinity in relation to the local hydrogeology of southwestern Florida, and assesses the potential processes that might control (or have affected) the distribution of salinity in the Floridan aquifer system. Hydrogeologic sections and maps were prepared showing the altitude of the top of a basal Hawthorn unit in the Hawthorn Group, the altitude of the basal contact of the Hawthorn Group, and the thickness of the basal Hawthorn unit. The basal contact of the Hawthorn Group approximately coincides with the top of the Floridan aquifer

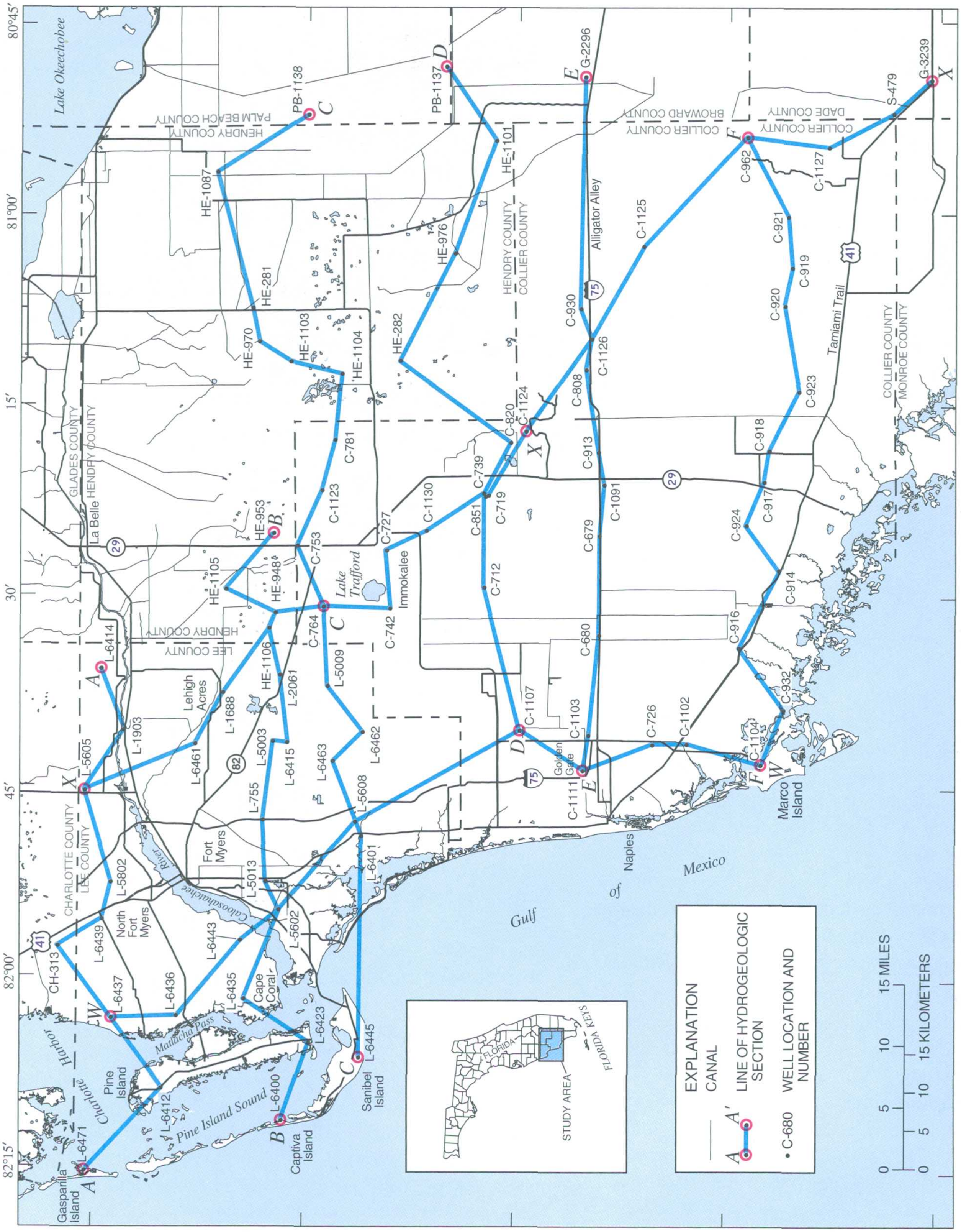


Figure 1. Study area and trace of hydrogeologic section lines.

system. The altitude of a thick dolomite evaporite unit in the middle confining unit of the Floridan aquifer system was also mapped. Lithologic descriptions and borehole geophysical logs were used to correlate geologic units between wells. The principal aquifer systems and their hydrogeologic units in southwestern Florida (the water-table aquifer, lower Tamiami aquifer, sandstone aquifer, mid-Hawthorn aquifer, Upper Floridan aquifer, middle confining unit, and the Lower Floridan aquifer) are described, including their thicknesses, relations to geologic units, and hydraulic properties.

Because the water-quality data available in the study area were not comprehensive enough for a complete water-quality analysis, the analysis in this report deals primarily with salinity (principally chloride and dissolved-solids concentrations). The water-quality data presented in this report consist of 137 analyses, 59 of which were collected and analyzed by the USGS. No water samples were collected specifically for this study.

Borehole geophysical logs, including porosity and resistivity logs, were used to evaluate ground-water (formation water) salinity. The depths of occurrence of threshold salinity values of interest in the Floridan aquifer system were approximated based on resistivity geophysical logs, and the average salinity of particular depth intervals was calculated for a number of wells. These geophysical logs were not run as part of this study, but were available for use. As part of this geophysical log evaluation, relations were developed between chloride and dissolved-solids concentrations, and between chloride concentration and specific conductance based on water-quality data from the Floridan aquifer system. Additionally, relations were developed between sonic log interval transit time and density log porosity, and between formation temperature and well depth.

The Floridan aquifer system has been divided into three salinity zones; in order of increasing depth, they are the brackish-water zone, a salinity transition zone, and the saline-water zone. The boundaries between these zones principally were determined based on borehole geophysical logs. However, they also were determined based on water-quality data, which were collected while drilling or from completed intervals. Maps were prepared that show the altitude of the base of the brackish-water zone and the distribution of chloride and sulfate concentrations in this zone in the study area. One plot was constructed that shows the distribution of chloride concentration in ground water relative to depth above and below the basal contact of the Hawthorn Group. A plot of chloride and sulfate concentrations in ground water was constructed for comparison with a pure water-seawater mixing line. The influence of gypsum dissolution and seawater mixing was evaluated by plotting the sulfate-to-chloride ratio against sulfate concentration in ground water from the Floridan aquifer system. The description and character of the brackish-water zone are emphasized in this report because of its potential use as a supplemental water-supply source. These maps and plots of the brackish-water zone were useful in determining processes that could control the thickness of the brackish-water zone and the distribution of salinity within it.

Classification and Characterization of Salinity

A classification scheme for water based on dissolved-solids concentrations was used to define salinity in the Floridan aquifer system in southwestern Florida. In this scheme, brackish water contains dissolved-solids concentrations that range from 1,000 to 10,000 mg/L (milligrams per liter), moderately saline water contains concentrations that range from 10,000 to 35,000 mg/L, and saline water contains concentrations from 35,000 to 100,000 mg/L. This scheme is similar to, but differs from, the one defined by Fetter (1988, p. 368) in which the moderately saline water portion does not exist, and saline water has dissolved-solids concentrations that range from 10,000 to 100,000 mg/L. Seawater has dissolved-solids concentrations of about 36,000 mg/L (Nordstrom and others, 1979). A well-defined relation between dissolved-solids and chloride concentrations in water produced from the Floridan aquifer system has been established for southeastern Florida (Reese, 1994), allowing for the interchanging of these constituents in the characterization of salinity. Chloride concentration was used in mapping the distribution of salinity in this report.

Water in the Upper Floridan aquifer in southern Florida is brackish with chloride and dissolved-solids concentrations generally greater than 1,000 mg/L (Sprinkle, 1989, pls. 6, 8). The Lower Floridan aquifer contains water with a salinity similar to that of seawater (Meyer, 1989, fig. 3). Parts of the Floridan aquifer system where water has dissolved-solids concentrations less than 10,000 mg/L are protected from contamination by injected wastewater through the Underground Injection Control Program of the Safe Drinking Water Act (Fetter, 1988, p. 459). Underground injection in Florida is regulated by the Florida Department of Environmental Protection (FDEP), formerly known as the Florida Department of Regulation (1982).

Inventory of Well Data

Data for all wells used in this study are presented in appendix I and include: local well number, other well identifier or owner, site identification number, latitude and longitude, land-net location, altitude of measuring point, well depth, bottom and diameter of casing, and date at end of well construction. The well locations are shown in figures 2 and 3. Data from all wells presented in this report are stored in the USGS Ground Water Site Inventory (GWSI) computer system. Some information on these wells beyond that given in appendix I, such as the drilling contractor's name and the top and bottom of the completed (open) intervals in a well, is stored in the GWSI. A completed interval in a well is defined in this report as an interval open to flow regardless of the type of openings in the interval. Completed intervals are generally isolated from each other and from other parts of the borehole through the use of casing and cement during construction of the well. Most completed intervals in the wells used in this report are open-hole completions. Additional data, including site use, geophysical logs run, and a representative water-quality analysis, are presented in a publication by Smith and others (1982).

Depth in a well, as used in this report, refers to feet below the measuring point. In most instances, the altitude of the measuring point is the same as the elevation of the land surface; however, in some instances, it is higher than the land surface, such as the top of a drilling floor, which can be a number of feet above the land surface. If measurement of a point in a well is referenced to sea level datum in this report, the phrase "altitude, in feet above sea level" or just "feet below sea level" is used.

Many of the wells used in this report were drilled for the purpose of oil exploration or production (67 wells), and several wells were drilled and completed at five wastewater injection system sites (table 1). The oil test wells, generally at least 11,000 ft (feet) deep, are located mostly in an area that extends from north-central Collier County, northwest into western Hendry County (fig. 3). Lithologic sample descriptions were produced and open-hole geophysical logs were run in many of the oil test wells. Although the lithologic descriptions are available, the quality of drill cutting samples from most of the oil test wells often is not good because of the large sampling depth interval and the use of the mud rotary method for drilling. The geophysical logs that were run in the oil test wells sometimes included both resistivity and porosity logs of good quality. Most of the water-quality data collected from the oil test wells in the study area was accomplished after setting an intermediate casing string and deepening the hole a short distance below the casing.

Nine wells (table 1) were drilled at the following wastewater injection system well sites:

- South States Utilities Marco Island Wastewater Treatment Plant (injection well C-1104 and monitor well C-1105),
- North County Regional Water Treatment Plant (injection well C-1107 and monitor well C-1108),
- Zemel Road Landfill (injection well CH-313 and monitor well CH-314),
- North Fort Myers Utility Wastewater Treatment Plant (injection well L-5802 and monitor well L-5803), and
- Gasparilla Island Wastewater Treatment Plant (injection well L-6471).

At four wastewater injection well sites, monitor wells were drilled adjacent to an injection well. The monitor wells at these sites are located less than 200 ft apart from their companion injection well. Thus, data collected from these wells drilled in close proximity at a site are considered as data collected from one well in this report.

Lithologic sample descriptions were produced and open-hole geophysical logs were run in the wastewater injection wells, as was the case for the oil test wells. The quality of drill cutting samples from these wells generally is good because of the small sampling depth interval (5 or 10 ft) and the use of the reverse-air rotary drilling method. A full suite of geophysical logs is usually run in these wells, including borehole television surveys of open-hole sections before emplacement of the casing. Whole-diameter cores of selected intervals in the Floridan aquifer system were taken and analyzed in a laboratory.

Seven wells used in the study area were continuously cored their entire depth, including: wells L-6400, L-6401, and L-6403 in Lee County; wells C-1090 and C-1091 in Collier County; and wells HE-1084 and HE-1085 in Hendry County (Green and others, 1990). In addition to a detailed lithologic description available for these wells, some geophysical logs were also run. In addition to the seven cored wells, well C-851 was almost continuously cored and had a total depth of 2,056 ft.

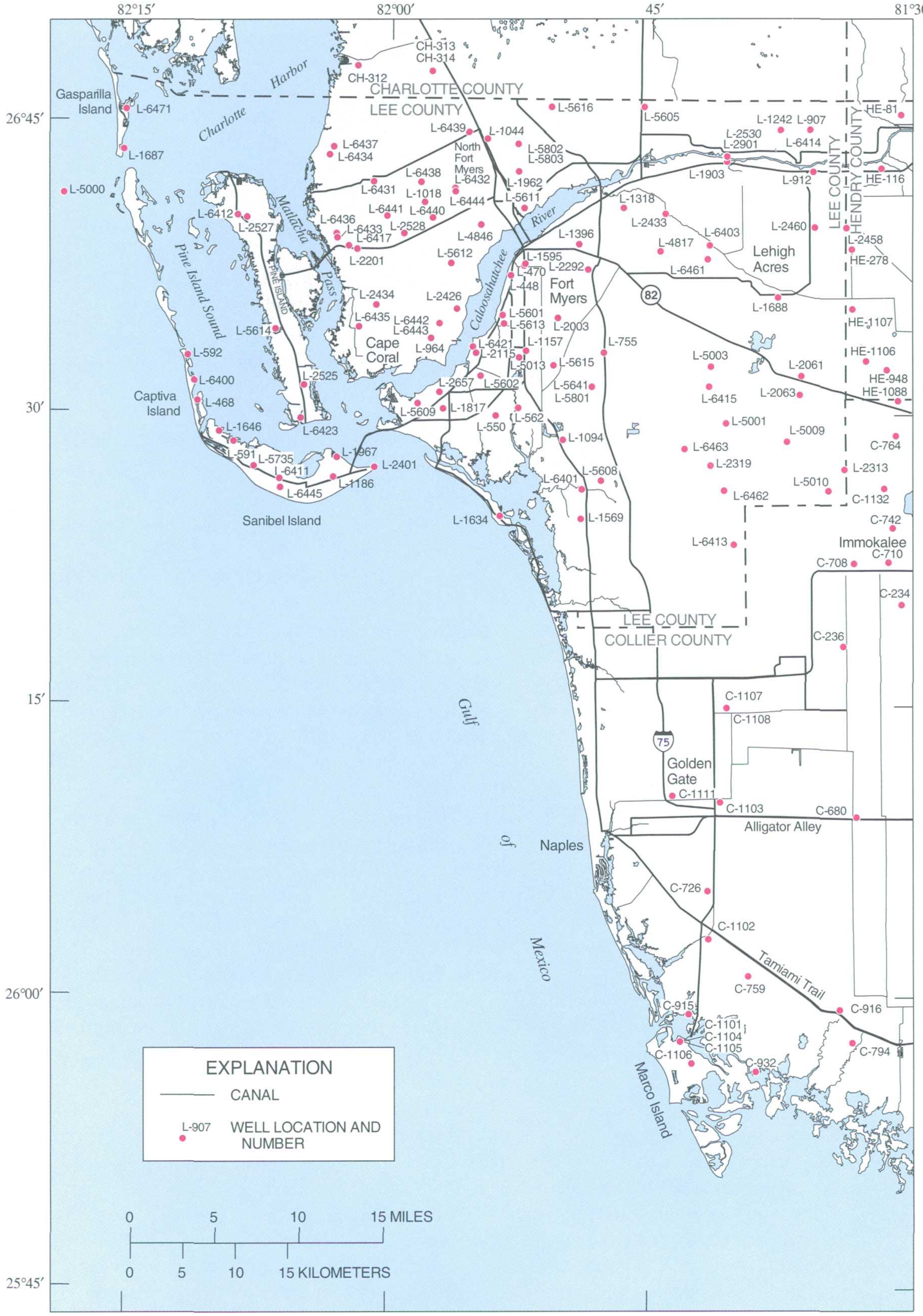


Figure 2. Location of wells used for the study in the western part of the study area.

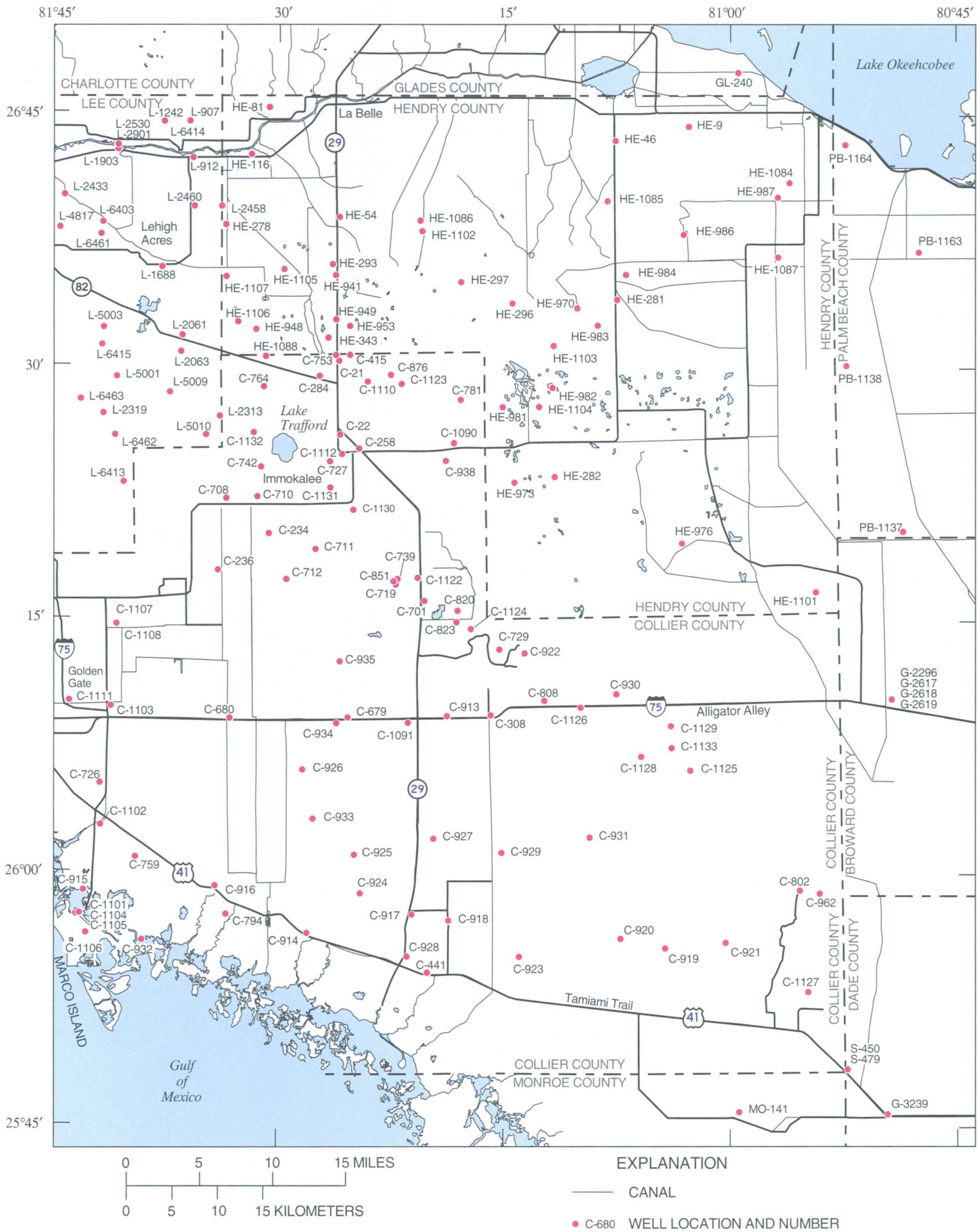


Figure 3. Location of wells used for the study in the eastern part of the study area.

Table 1. List of oil test wells and wastewater injection system wells used in the study

[WWI, wastewater injection well. Asterisk indicates monitor well at the same site as the preceding injection well]

Well number	Type of well	Well number	Type of well
C-324	Oil test	C-1133	Oil test
C-415	do.	CH-313	WWI
C-701	do.	CH-314*	WWI
C-708	do.	L-5000	Oil test
C-710	do.	L-5001	do.
C-711	do.	L-5003	do.
C-712	do.	L-5009	do.
C-719	do.	L-5010	do.
C-726	do.	L-5013	do.
C-727	do.	L-5802	WWI
C-729	do.	L-5803*	WWI
C-739	do.	L-6415	Oil test
C-742	do.	L-6461	do.
C-753	do.	L-6462	do.
C-759	do.	L-6463	do.
C-764	do.	L-6471	WWI
C-781	do.	G-3239	Oil test
C-794	do.	S-479	do.
C-802	do.	GL-240	do.
C-808	do.	HE-282	do.
C-820	do.	HE-343	do.
C-823	do.	HE-941	do.
C-962	do.	HE-948	do.
C-1104	WWI	HE-949	do.
C-1105*	WWI	HE-953	do.
C-1107	WWI	HE-970	do.
C-1108*	WWI	HE-973	do.
C-1122	Oil test	HE-976	do.
C-1123	do.	HE-1101	do.
C-1124	do.	HE-1102	do.
C-1125	do.	HE-1103	do.
C-1126	do.	HE-1104	do.
C-1127	do.	HE-1105	do.
C-1128	do.	HE-1106	do.
C-1129	do.	HE-1107	do.
C-1130	do.	MO-141	do.
C-1131	do.	PB-1137	do.
C-1132	do.	PB-1138	do.

Inventory and Collection of Water-Quality Data

Selected water-quality data from well sampling intervals in the intermediate and Floridan aquifer systems are presented in appendix II. Included in the appendix are 137 water analyses taken from 104 wells, with the analyses listed chronologically by local well identifier. Of the 137 samples, 103 were obtained from completed intervals, 25 were obtained from open-hole intervals by a packer test, and 9 were obtained by the reverse-air rotary method while drilling. Of the 103 samples that were from completed intervals, 15 were obtained as a result of a well-abandonment program conducted by the SFWMD. These water-quality data (along with other data including flow measurements and casing and open-hole condition) were collected from the SFWMD wells just before abandonment and are stored in an SFWMD data storage and retrieval computer system (DATAFLEX).

Of the 137 samples listed in appendix II, 59 were collected and analyzed by the USGS; however, no USGS water samples were collected specifically for this study. Sampling procedures and analytical methods used to determine the value of the constituents given in the appendix for the USGS samples are described by Brown and others (1970). The constituents in appendix II include chloride, sulfate, dissolved solids, and specific conductance. Most of the USGS data are stored in a USGS water-quality data storage and retrieval computer system (QWDATA). The other water samples in appendix II were collected and analyzed by the SFWMD (29 analyses) and private consultants (49 analyses).

Control of water sampling and testing methods for wastewater injection system wells (table 1) is overseen by the FDEP. According to FDEP rules (Florida Department of Environmental Regulation, 1982), the background water quality of the injection and monitoring zone(s) shall be established prior to injection. FDEP permits issued to construct and operate injection well systems include specific testing requirements, one of which is pumping at least three well volumes of fluid from a monitor well before sampling.

Open-hole packer test samples are often more contaminated than water samples from completed intervals due to the small volume of water produced before sampling occurs and the possibility of leakage of drilling fluid around packers. Barite-weighted bentonite drilling mud wafers, instead of saltwater slugs, are used occasionally to control artesian pressure in the Floridan aquifer system. The use of mud wafers reduces the potential for deep invasion of the formation by drilling fluid.

Wells are commonly drilled in the Floridan aquifer system in southern Florida with the reverse-air rotary method in which air is injected into the drill pipe at a variable depth. This air provides the lift needed to bring fluid and drill cuttings up the drill pipe to the surface (return flow). Water samples of this return flow are collected at regular intervals while drilling. A common problem with this method is that a change in salinity with depth might not be detected. This results if the permeability of the rock being drilled is low so that little of the return flow originates from the rock (formation) at or near the drill bit as expected. Rather, the flow continues to come from a permeable zone higher in the hole between the borehole wall and the drill pipe. For this reason, the top of the sampling interval in each of the nine samples collected by this method (app. II) is at the top of the open-hole section being drilled (base of the casing).

Previous Studies

The Regional Aquifer System Analysis (RASA) Program of the USGS provided background information for this report. Final interpretive results of the RASA Program, which began in 1978, are presented in a series of USGS Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. A series of studies on the Floridan aquifer system that were conducted as part of the RASA program (USGS Professional Paper 1403 series reports) were used for this report.

Meyer (1989) analyzed the hydrogeology, ground-water movement, and subsurface storage of liquid waste and freshwater in the Floridan aquifer system in southern Florida. Miller (1986), who studied the hydrogeologic framework of the Floridan aquifer system in the RASA study area (Florida and parts of Georgia, Alabama, and South Carolina), subdivided the aquifer system into chronostratigraphic units and constructed hydrogeologic sections, isopach maps, and structure maps. Additional studies of the same area were conducted by Bush and Johnston (1988) and Sprinkle (1989). Bush and Johnston (1988) described ground-water hydraulics, regional flow, and changes in the flow system as a result of ground-water development of the Floridan aquifer system. Sprinkle (1989) examined the geochemistry of the Floridan aquifer system and mapped the concentrations of selected constituents in water from the Upper Floridan aquifer. More recent work done by the USGS on the geochemistry of ground water in the Floridan aquifer system focuses on sources of sulfate in ground water found in the Upper Floridan aquifer in southwestern Florida (Sacks and Tihansky, 1996).

Chen (1965) studied the lithology and stratigraphy of Paleocene and Eocene strata in Florida and made paleogeographic interpretations. The Floridan aquifer system in southern Florida was mostly deposited during Eocene time (Miller, 1986). Puri and Winston (1974) mapped and described high transmissivity zones in southern Florida. Scott (1988) studied the Hawthorn Group, describing its lithologies, stratigraphy, and relation to subjacent and suprajacent units. Recent work on the Tertiary stratigraphy for the Florida Keys and the southern peninsula of Florida has been done by Cunningham and others (1998). This work has resulted in the definition of two new formations of upper Miocene to Pliocene age, and also includes analyses of previously defined formations as old as the Oligocene.

Detailed hydrogeologic mapping and descriptions of the intermediate aquifer system and the Upper Floridan aquifer were done in Lee County by Wedderburn and others (1982), whose work provided important groundwork for this study. Other useful SFWMD reports that deal with the geology, hydrogeology, or ground-water resources in the study area include those by Peacock (1983) covering southern Collier County, Knapp and others (1986) covering western Collier County, and Smith and Adams (1988) covering Hendry County.

Studies of saline ground-water resources and saline-water intrusion in Lee County were conducted by Boggess (1974) and Sproul and others (1972). Hydrogeologic sections of the surficial aquifer system and the upper part of the intermediate aquifer system in Lee County and adjacent areas were constructed by Boggess and others (1981). Missimer and Associates (1991a, b) conducted a hydrogeologic study in southwestern Collier County, which included the drilling of two deep test wells, and a detailed hydrogeologic study in the Cape Coral area of northwestern Lee County, which included water-quality mapping of the intermediate and Floridan aquifer systems.

Acknowledgments

Appreciation is extended to several organizations and individuals who contributed data and helpful suggestions during the course of this study. Invaluable input and data were provided by Robert Caughey of the Florida Geological Survey in Fort Myers, who has many years of experience working with oil test wells and the geology in the study area. George Winston, consulting geologist, provided lithologic descriptions of a number of wells that were used in the hydrogeologic sections as well as useful ideas concerning construction of the hydrogeologic sections. Charles "Buzz" Walker of Missimer International, Inc., was very helpful in providing data collected by Missimer and Associates or related consulting firms. Richard Orth of the FDEP in Fort Myers provided data on deep injection system wells collected by consulting firms. Michael Bennett of the SFWMD was instrumental in providing data collected from wells drilled by SFWMD during the course of this study and in having SFWMD digitize many of the geophysical logs used on the hydrogeologic sections.

A USGS colleague, Richard Kane, contributed much to this study, including some of the analysis of water-quality data and many of the calculations of salinity from geophysical logs. Other USGS colleagues and part-time students who helped with this study are Linda Powell, Michael Byrne, Isaac Segal, Robert Mooney, and Steven Memberg. The large effort involved in the construction of the hydrogeologic sections, including the digitizing of geophysical logs and construction and coding of the lithocolumns, would not have been possible without the help of these individuals. The final drafting of the hydrogeologic sections and the contour maps was all computer generated and produced by USGS scientific illustrator Kimberly Swidarski of the USGS Miami Subdistrict office.

HYDROGEOLOGY OF SOUTHWESTERN FLORIDA

Southern Florida is underlain by rocks of Cenozoic age to a depth of about 5,000 ft (Meyer, 1989, p. G5). These rocks are principally carbonates (limestone and dolostone), with minor amounts of evaporites (gypsum and anhydrite) in the lower part and clastics (sand and clay) in the upper part. The movement of ground water from inland areas to the ocean and the reverse occurs primarily through the carbonate rocks (Meyer, 1989, p. G5). This section of the report presents a detailed discussion of the geologic framework of the study area, including the lithology, stratigraphy, and structure. Also discussed are the principal aquifer systems and hydrogeologic units of southwestern Florida.

The Floridan aquifer system in southwestern Florida includes (from oldest to youngest) the upper part of the Cedar Keys Formation of Paleocene age, Oldsmar Formation of early Eocene age, Avon Park Formation of middle Eocene age, Ocala Limestone of late Eocene age, and the Suwannee Limestone of early Oligocene age (fig. 4). Overlying the Suwannee Limestone is the Hawthorn Group as defined by Scott (1988), and the lower part of this group is included in the Floridan aquifer system in this report. The Hawthorn Group, which is divided into the Peace River Formation in the upper part and the Arcadia Formation in the lower part, was thought to be all Miocene in age (Miller, 1986; Scott, 1988); however, age-dating of core taken from a well in southwestern Florida has shown that the lowermost part of the Arcadia Formation is as old as early Oligocene in age (Wingard and others, 1994).

To illustrate geologic and hydrologic boundaries and spatial relations in the study area, 10 hydrogeologic sections were constructed (pls. 1-10, in pocket). The locations of the east-west sections (pls. 1-7) and the northwest-southwest sections (pl. 8-10) are shown in figure 1. The depth of these hydrogeologic sections extends from 200 to 2,400 ft below sea level; however, some of the wells on the sections were not drilled as deep as 2,400 ft below sea level. Data presented for each well on the sections include geophysical logs (gamma ray or spontaneous potential and resistivity curves), lithology, and water-quality data. Geologic and salinity zone boundaries, as determined in this study, are also shown on the hydrogeologic sections.

Lithology and Stratigraphy

The Floridan aquifer system in southwestern Florida is composed predominantly of limestone with dolomitic limestone and dolomite being common in the lower part of the aquifer system (fig. 4). Delineation of the geologic units in the study area began with selected wells where the boundaries of the units were determined based on geophysical well logs and/or lithologic sample descriptions. The gamma-ray log was the most useful well log for determining geologic boundaries and making correlations between wells.

Series		Geologic Unit		Approximate thickness (feet)	Lithology
HOLOCENE TO PLIOCENE		UNDIFFERENTIATED		0-70	Quartz sand, silt, clay, and shell
HOLOCENE TO PLIOCENE		TAMIAMI FORMATION		0-175	Silt, sandy clay, micritic limestone, sandy, shelly limestone, calcereous sand-stone, and quartz sand
MIOCENE AND LATE OLIGOCENE		HAWTHORN GROUP	PEACE RIVER FORMATION	50-400	Interbedded sand, silt, gravel, clay, carbonate, and phosphatic sand
MIOCENE AND LATE OLIGOCENE		HAWTHORN GROUP	ARCADIA FORMATION	400-550	Sandy limestone, shell beds, dolomite, phosphatic sand and carbonate, sand, silt, and clay
EARLY OLIGOCENE		SUWANNEE LIMESTONE		0-600	Fossiliferous, calcarenitic limestone
EOCENE	LATE	OCALA LIMESTONE		0-400	Chalky to fossiliferous, calcarenitic limestone
EOCENE	MIDDLE	AVON PARK FORMATION		900-1,200	Fine-grained, micritic to fossiliferous limestone, dolomitic limestone, dense dolomite, and gypsum
		?		?	
EOCENE	EARLY	OLDSMAR FORMATION		800-1,400	
PALEOCENE		CEDAR KEYS FORMATION		500-700	Dolomite and dolomitic limestone
PALEOCENE		CEDAR KEYS FORMATION		1,200 ?	Massive anhydrite beds

Hydrogeologic unit			Approximate thickness (feet)	
SURFICIAL AQUIFER SYSTEM	WATER-TABLE AQUIFER		20 -100	
SURFICIAL AQUIFER SYSTEM	CONFINING BEDS		0-60	
SURFICIAL AQUIFER SYSTEM	LOWER TAMIAMI AQUIFER		25-160	
INTERMEDIATE AQUIFER SYSTEM	CONFINING UNIT		20-100	
INTERMEDIATE AQUIFER SYSTEM	SANDSTONE AQUIFER		0 -100	
INTERMEDIATE AQUIFER SYSTEM	CONFINING UNIT		10-250	
INTERMEDIATE AQUIFER SYSTEM	MID-HAWTHORN AQUIFER		0-130	
INTERMEDIATE AQUIFER SYSTEM	CONFINING UNIT		100-400	
FLORIDAN AQUIFER SYSTEM	UPPER FLORIDAN AQUIFER	LOWER HAWTHORN PRODUCING ZONE	700-1,200	0-300
FLORIDAN AQUIFER SYSTEM	MIDDLE CONFINING UNIT		500-800	
FLORIDAN AQUIFER SYSTEM	LOWER FLORIDAN AQUIFER	BOULDER ZONE	1,400-1,800	400
	SUB-FLORIDAN CONFINING UNIT		1,200?	

Figure 4. Generalized geology and hydrogeology of southwestern Florida.

Lithologic sample descriptions used in determining the geologic boundaries came from a variety of sources including the Florida Geological Survey, the SFWMD, private consultants, and individuals. Most of the descriptions done by the Florida Geological Survey were obtained from a computer data base known as GeoSys/4G (GeoSys, Inc.), in which lithologic data are coded. Depths to the tops of geologic units, as determined in this study, are given in appendix III.

Avon Park Formation

The deepest unit in the Floridan aquifer system dealt with in this report is the Avon Park Formation of middle Eocene age. Determination of the top of the underlying Oldsmar Formation can be arbitrary and difficult, and thus was not done for this study. According to Winston (1993), the Oldsmar Formation in southern Florida is not identifiable. The lower part of the Avon Park Formation, as discussed and shown in this report, could be placed in the Oldsmar Formation as defined by other investigators, such as Meyer (1989).

The top of the Avon Park Formation is often marked by a zone of thinly bedded, light-brown, finely crystalline to fossiliferous dolomite or dolomitic limestone that is about 50 ft in thickness. The predominant lithology in the Avon Park Formation is fine-grained, micritic to fossiliferous limestone. Dolomitic limestone, dense dolomite, and gypsum can also be present and abundant. Dolomite, dolomitic limestone, and recrystallized limestone become more common in the Avon Park Formation in Lee County and western Collier County, with dolomite often occurring in the lower part of the formation as thick interbeds (30 ft or greater in thickness). Foraminifera characteristic of the Avon Park Formation are *Dictyconus cookei* and *Dictyconus americanus*. The thickness of the Avon Park Formation (rocks of middle Eocene age) ranges from 900 to 1,200 ft in southwestern Florida (Miller, 1986, pl. 7).

The east-west hydrogeologic sections (C′-C″, D-D′, E-E′, and F-F′), which extend to the eastern boundary of the study area (pls. 4-7), show that the Avon Park Formation generally thickens to the east as its top rises in this direction. Correlation between wells based on geophysical logs in this study has shown that this eastward thickening of the Avon Park Formation in the eastern part of the study area is due, at least in part, to a facies change between the formation and the overlying formation. This interpretation is in agreement with Winston (1993; 1995), who found evidence for facies changes and interfingering between the Avon Park Formation, Ocala Limestone, and Suwannee Limestone.

Ocala Limestone

The lithology of the Ocala Limestone varies from micritic or chalky limestone, to a medium-grained calcarenitic limestone, to a coquinoid limestone. The Ocala Limestone is characterized by abundant larger benthic foraminifera, such as *Operculinoides sp.*, *Camerina sp.*, and *Lepidocyclina sp.* (Peacock, 1983). The presence of these foraminifera aids in distinguishing this geologic unit from the overlying Suwannee Limestone and the underlying Avon Park Formation. Gamma-ray log activity is characteristically low, but the upper and lower boundaries of the Ocala Limestone usually are marked by an increase in gamma-ray activity. The thickness of the Ocala Limestone ranges from 0 to more than 400 ft in the study area (fig. 4). It thins toward the east (pls. 4-7) and disappears toward the southeast (pl. 10). The Ocala Limestone is absent southeast of the study area in most of Dade County (Miller, 1986, pl. 9).

Suwannee Limestone

The dominant lithology of the Suwannee Limestone in the study area is pale-orange to tan, fossiliferous, medium-grained calcarenite with minor amounts of quartz sand. Phosphatic mineral grains are rare. Limestone in the lower part of the unit is similar to that in the upper part, but typically contains more fine-grained, phosphatic, clastic material and interbeds of micrite and clay. Because of these interbeds, gamma-ray activity in the Suwannee Limestone often increases downward below the upper part, which has low activity similar to that found in the Ocala Limestone.

The top of the Suwannee Limestone is often well defined on gamma-ray logs because of the much higher levels of natural radioactivity associated with the lower Hawthorn Group as compared to the Suwannee Limestone. However, in some wells this contact appears gradational, with sandy limestone or calcareous sandstone of relatively low gamma-ray response above the contact. The thickness of the Suwannee Limestone ranges from 0 to more than 600 ft (generally becoming thicker from east to west) and is commonly 300 to 400 ft in Lee and western Collier Counties. Thickness can vary rapidly, particularly in

Lee County, because of the relief on top of the Suwannee Limestone. Some of this relief might be erosional in nature. The Suwannee Limestone thins (pls. 7 and 10) and sometimes disappears (pls. 4-6) toward the east. Farther to the east in Dade County, the base of the Hawthorn Group as mapped by Scott (1988, figs. 41 and 42) is at an altitude similar to the top of the rocks of Ecoene age (Reese, 1994, fig. 6), suggesting that the Suwannee Limestone is not present.

Hawthorn Group

The Hawthorn Group is a heterogeneous unit that generally consists of interbedded siliclastics (quartz sand, silts, and clays) and carbonate rocks. The distinguishing characteristics of the Hawthorn Group are its high and variable siliclastic and phosphatic content; its color, which can be green, olive-gray, or light-gray; and its gamma-ray log response. Intervals high in phosphate sand or gravel, typically 30 to 100 ft in thickness, are present in places and have high gamma-ray activity with peaks of 100 to 200 API units (American Petroleum Institute standard units) or more. Phosphate mineral grain content as high as 15 percent is not uncommon.

The Hawthorn Group is subdivided into the Peace River and Arcadia Formations (Scott, 1988). The upper part of the Hawthorn Group, the Peace River Formation, primarily consists of siliclastic material with occasional carbonate and phosphate-rich beds and ranges from 50 to 400 ft in thickness (Scott, 1988, figs. 42 and 43). The lower part of the Hawthorn Group, the Arcadia Formation, predominantly consists of carbonate rocks and ranges from 400 to 550 ft in thickness in the study area (fig. 4). The top of the Arcadia Formation was determined to be 410 ft below sea level in well C-1107 (pl. 5).

The lower part of the Arcadia Formation is referred to as the basal Hawthorn unit in this report, and this unit ranges from about 120 to 460 ft in thickness in the study area. The basal Hawthorn unit is emphasized throughout this report because of its hydrologic significance. The top of the basal Hawthorn unit is defined by a sequence of sediments referred to as the marker unit. The top of the marker unit, also the top of the basal Hawthorn unit, is often marked by two high gamma-ray activity peaks as shown in well C-914 in southwestern Collier County (fig. 5). The top of the marker unit also was determined by examination and comparison of resistivity logs when no gamma-ray logs were run. The thickness of the marker unit generally decreases from about 100 ft in the southeastern part of the study area to about 50 ft in the northwestern part (pls. 9 and 10).

The lithology of the marker unit at the top of the basal Hawthorn unit generally consists of limestone and calcilutite with low phosphorite and quartz sand content. The marker unit corresponds relatively well with unit H-2 defined in the Hawthorn Group in southern Collier County where the benthic foraminifera *Miogypsina sp.* was found (Peacock, 1983, p. 17). The lithology of the marker unit is overlain and underlain by phosphatic dolomite in much of southern Collier County (pls. 6 and 7). To the west along the coast in Collier and Lee Counties, the bounding beds are often dolomitic to calcareous, phosphatic clay. Specifically, this clay is present in wells C-916 (pl. 7), C-1103 (pl. 6), C-1107 (pl. 5), and L-6445 on Sanibel Island (pl. 3).

The upper and lower boundaries of the marker unit at the top of the basal Hawthorn unit are defined by thin beds with high gamma-ray activity, and these beds could be synchronous in their deposition over large areas. The gamma-ray curve of the marker unit and its bounding beds has a characteristic pattern (fig. 5), which remains consistent over large areas as shown by the hydrogeologic sections (pls. 1-10). The thin bounding beds with high gamma-ray activity are high in phosphatic material and are composed of fine-grained sediment. They could have been deposited during high stands of sea level when the Florida platform became flooded, and sedimentation was mostly limited to the settling out of fine material from suspension.

The lithology of the basal Hawthorn unit below the marker unit is variable. The phosphate content ranges from low to high (greater than 5 or 10 percent). In Lee County, the basal Hawthorn unit is thick and consists of white to light-gray, quartz sandy, micritic limestone containing minor amounts of phosphate grains and some beds of abundant fragments of mollusk and gastropods shells and other fossils. These shelly beds can have high moldic porosity. The gamma-ray response of this lithology in Lee County is usually intermediate between that found higher in the Hawthorn Group and that in the upper part of the Suwannee Limestone. Dolomite or dolomitic limestone is commonly present, particularly in the lower part of the basal Hawthorn unit and in southern Collier County. This dolomitic lithology can also contain quartz sand and often is characterized by thin beds

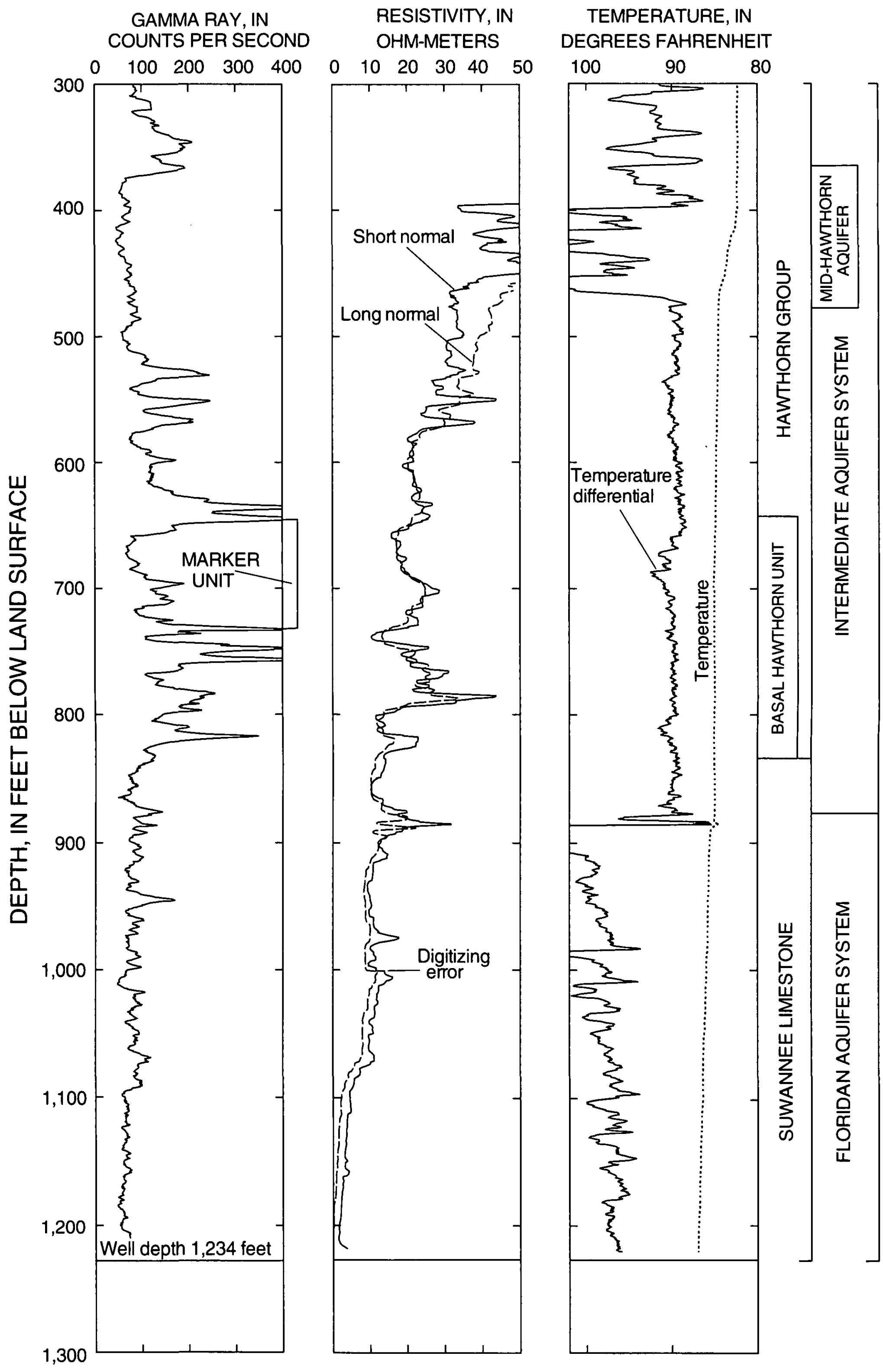


Figure 5. Geophysical logs, geologic units, and hydrogeologic units for well C-914 in southwestern Collier County. Temperature log shows major flow zone at 880 feet, which is below the top of Suwannee Limestone.

with high resistivity (resistivity peaks). Quartz sand-rich limestone and dolomite and thick sand or sandstone beds are present in central Hendry County, where the basal Hawthorn unit is thick (pl. 4, wells HE-1103 and HE-1104).

Unconformity

Regional unconformities in peninsular Florida are present at the top of the rocks of late or middle Ecoene age (Ocala Limestone or Avon Park Formation if no Ocala Limestone is present) and rocks of Oligocene age (Suwannee Limestone) according to Miller (1986, pl. 2). Zones of dissolution occur in association with these unconformities in southern Florida (Meyer, 1989, p. 49). In southeastern Florida, the most important unconformity in terms of erosion and dissolution is at the top of the rocks of Eocene age (Reese, 1994); whereas in southwestern Florida, the most important unconformity is the one at the top of the Suwannee Limestone as found in this study and by Wedderburn and others (1982). The unconformity at the top of the Suwannee Limestone and the post-Ecoene unconformity would coincide in southeastern Florida, if as previously suggested, the Suwannee Limestone is absent in this area.

Additional evidence that the Suwannee Limestone is absent or much thinner in southeastern Florida than in southwestern Florida comes from correlation of gamma-ray logs. A correlation line at the top of a phosphatic zone shown on three geologic sections in southeastern Florida (Reese, 1994, figs. 3-5) correlates with the base of the marker unit at the top of the basal Hawthorn unit in this study. The thickness of the interval between the top of the phosphatic zone and the top of the rocks of Eocene age in southeastern Florida is similar to the thickness of the basal Hawthorn unit below the marker unit in the eastern part of this study area.

Continuous core taken from a well at Long Key in the Florida Keys, about 70 mi south-southeast of the study area, shows that a subaerial erosion surface is present at the contact between the Hawthorn Group and the Suwannee Limestone, and that this contact represents a depositional sequence boundary (Cunningham and Rupert, 1996). The unconformity could have formed during a major low stand in sea level that occurred between the early and late Oligocene (Haq and others, 1988).

Structure

Three maps were constructed that show the altitude of the top of the basal Hawthorn unit, the altitude of the basal contact of the Hawthorn Group, and the thickness of the basal Hawthorn unit in the study area. The base of the Hawthorn Group (base of the basal Hawthorn unit) represents the top of the Suwannee Limestone in most of the study area, but it represents the top of the subjacent Ocala Limestone in some of the eastern part of the study area.

Because of the continuity of the marker unit at the top of the basal Hawthorn unit and the probability that its top surface is isochronous, a map was constructed showing the altitude of the top of the basal Hawthorn unit (fig. 6). Overall, the surface dips from northwest to southeast, ranging from about 400 or 500 ft below sea level in northern Lee County to more than 800 ft below sea level in extreme southeastern Collier County. A major northwest-southeast trending trough or structural sag extends from eastern Lee County into north-central Collier County (fig. 6). This trough has relief of at least 200 ft in eastern Lee County over a distance of only 2 mi (miles), with less pronounced relief in Collier County. An inferred fault has been mapped which parallels this trough and roughly coincides with the high area along its southwest side (Winston, 1996, fig. 19). The trough could be related to this fault. The trace of the fault (fig. 6) is a projection of the "North Port" fault, which was established to the northwest of the study area. In the study area, its presence is indicated by missing Eocene-aged section in one well (C-729) and a thick Eocene-aged section in which the borehole wall collapsed due to fracturing in another well (Winston, 1996, p. 27). The well with wall collapse is an injection well (CH-313) in south-central Charlotte County (fig. 1).

Structure in central to southeastern Lee County is the most complex in the study area (fig. 6). Two closely spaced troughs trending east-northeast are located southeast of the Caloosahatchee River, with pronounced relief of 200 ft or more for both troughs over a distance of 2 or 3 mi. The altitude of the top of the basal Hawthorn unit at the bottom of the two troughs is similar, being about 600 ft below sea level. These troughs could be fault related. The vertical displacement (200 ft) of the basal Hawthorn unit between wells L-6443 and L-5602 (pl. 8) suggests a fault. This fault lies along the northwestern boundary of the northernmost trough, adjacent to and paralleling the Caloosahatchee River. The north block is upthrown. Evidence was found for faults displacing the Hawthorn Group and older sediments in an area southwest of Fort Myers in Lee County along the southeastern bank of the Caloosahatchee River (Sproul and others, 1972, fig. 4). Vertical displacement along these faults is about 50 to 100 ft, and their trend is west-northwest.

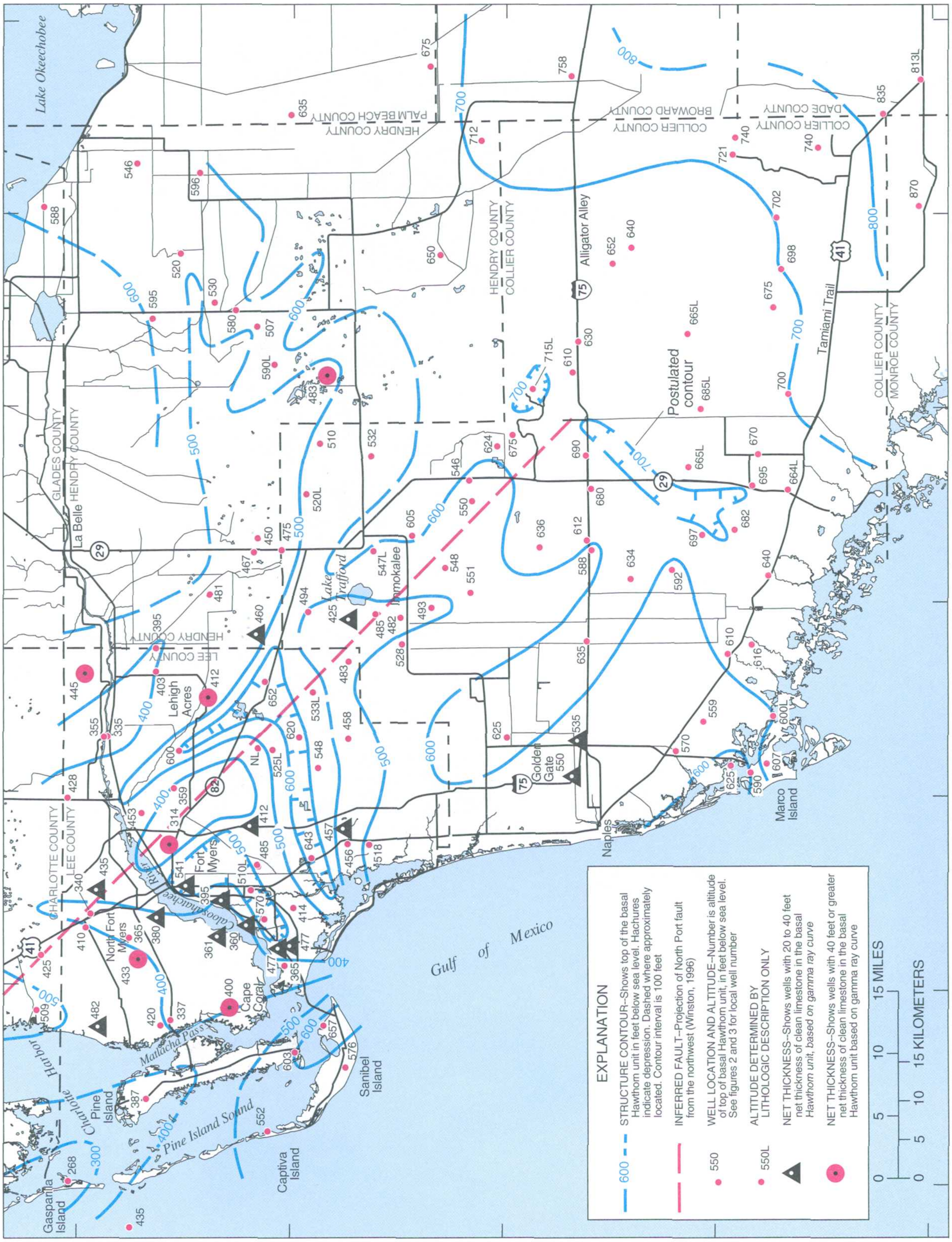


Figure 6. Altitude of the top of the basal Hawthorn unit in the study area.

Indications of faulting exist elsewhere in the study area. In southwestern Collier and central Hendry Counties, contours suggest structural features trending northwest-southeast, parallel to the projection of the North Port fault (fig. 6). Additionally, a narrow low area extends across central Collier County trending northeast-southwest, with the top of the basal Hawthorn unit possibly as low as 700 ft below sea level.

The altitude of the basal contact of the Hawthorn Group ranges from 500 or 600 ft below sea level in northern Lee County to greater than 1,000 ft below sea level in the extreme southeastern part of the study area (fig. 7). A broad, high area as shallow as 600 ft below sea level is present in central and northern Collier County and extends to the northwest through eastern Lee County. Separating this high from another high area in eastern Hendry County is a northwest-southeast trending trough, extending through western Hendry County in which the altitude of the surface is as deep as 1,000 ft below sea level.

Some of the relief shown by the map of basal contact of the Hawthorn Group (fig. 7) probably results from erosion and solution prior to deposition of the Hawthorn Group. To better understand this relief, a map was constructed showing the thickness of the basal Hawthorn unit (fig. 8). Because of the characteristics and continuity of the marker unit at the top of the basal Hawthorn unit, as previously discussed, the thickness of the basal Hawthorn unit could, in part, indicate paleotopography just before or during deposition of this unit. Therefore, areas of the basal Hawthorn unit where the interval is thick would represent paleotopographic lows and areas where the interval is thin would represent paleotopographic highs. A salient feature of this map (fig. 8) is a thin area, which could have been a paleo-ridge, where the interval is 200 ft thick or less extending northwest through central Collier County and eastern Lee County. Areas where the basal Hawthorn unit is thick (300-400 ft or greater), which could have been paleotopographic lows, are located in central and western Hendry County, northeastern Lee County, and the Cape Coral peninsula area of Lee County. The hydrogeologic sections constructed for this study clearly show that a large part of the relief on the basal contact of the Hawthorn Group (fig. 7) is compensated by the thickening and thinning of the basal Hawthorn unit; for example, between wells L-6412 and L-6437 in northwestern Lee County and between wells L-1903 and L-6414 in northeastern Lee County (pl. 1).

The thickening of the basal Hawthorn unit in some areas could be caused by depositional buildup during deposition of the basal Hawthorn unit. One of these features is evident in the Cape Coral peninsula area, centered on well L-6435 (pl. 2), and a thick limestone unit is present from about 500 to 620 ft below sea level in the well. This limestone unit could be related to the buildup if deposition of the limestone unit was biohermal in nature. A similar buildup within the basal Hawthorn unit is evident at wells L-5608 and (pl. 8) and L-1688 (pl. 9).

The net thickness of "clean" (low in clay and phosphate) limestone in the basal Hawthorn unit was determined in wells in which a gamma-ray log was run. This was accomplished by adding all intervals in which the gamma-ray activity was low; that is, at a level similar to the activity in the limestone below the basal contact of the Hawthorn Group. These intervals are present in the middle to upper parts of the basal Hawthorn unit. Wells with 20 to 40 ft and 40 ft or greater net thickness of "clean limestone" are shown in figures 6 and 8. The two wells with the greatest net thickness in the study area are L-6435 (pl. 2) and L-6414 (pl. 1) with 100 and 70 ft of net thickness, respectively.

The depositional buildups previously identified on the hydrogeologic sections at wells L-6435, L-5608, and L-1688 are located where the top of the basal Hawthorn unit is high (fig. 6), where the basal Hawthorn unit is thick (fig. 8), and where there is at least 20 ft of net thickness of "clean" limestone within the basal Hawthorn unit (figs. 6 and 8). Of 21 wells in which there is 20 ft or greater net thickness of "clean" limestone in the basal Hawthorn unit, 20 wells are located where the top of the unit is high relative to surrounding areas, and 18 of these 21 wells are located where the top of the basal Hawthorn unit is 500 ft below sea level or shallower (fig. 6). However, this "clean" limestone unit is not developed in all wells located where the top of the basal Hawthorn unit is high.

Principal Aquifer Systems and Hydrogeologic Units

The Floridan aquifer system is one of three principal aquifer systems in southwestern Florida. The other two are the surficial and intermediate aquifer systems. The major hydrogeologic units that underlie the study area, their stratigraphic equivalents, and approximate thicknesses are shown in figure 4.

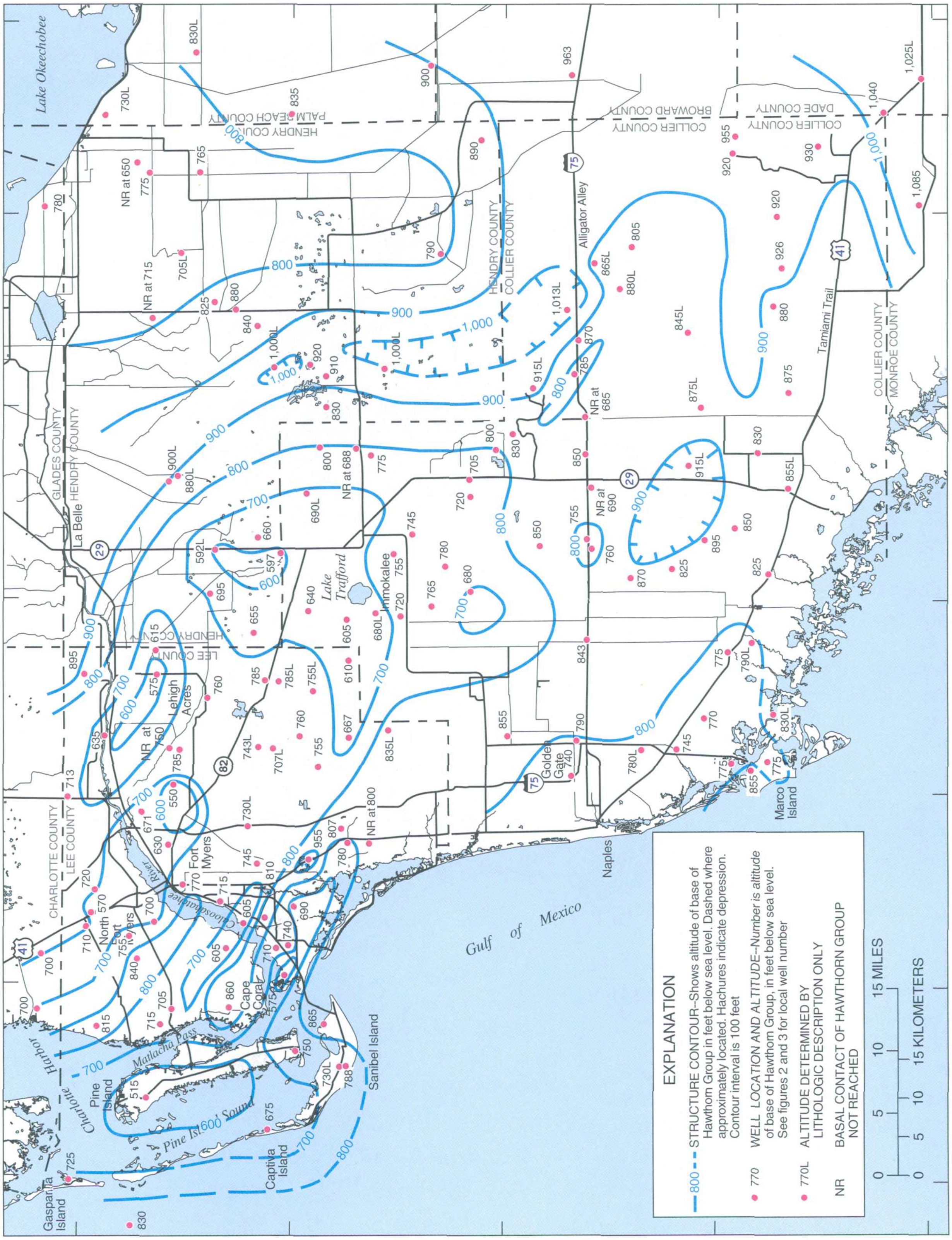


Figure 7. Altitude of the basal contact of the Hawthorn Group in the study area.

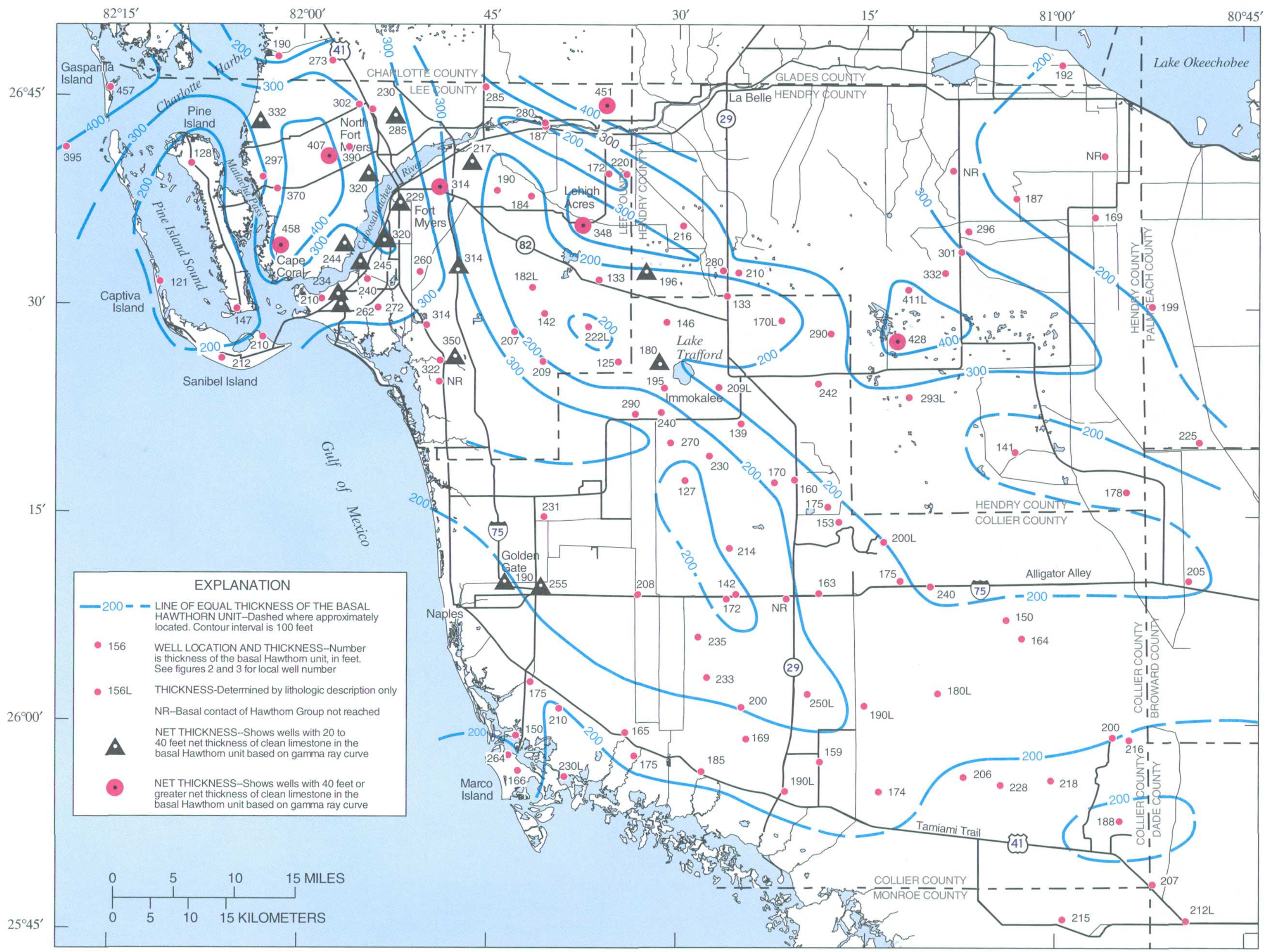


Figure 8. Thickness of the basal Hawthorn unit in the study area.

Although the Floridan aquifer system is the primary focus of this report, the surficial and intermediate aquifer systems are discussed to provide background information on the hydrogeology of southwestern Florida. The nomenclature used in this report for the various water-bearing and confining units of the aquifer systems is compared to that of previous reports in figure 9.

Surficial Aquifer System

The surficial aquifer system consists of the water-table aquifer and hydraulically connected units above the top of the first occurrence of laterally extensive and vertically persistent beds of much lower permeability (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Defini-

Sproul and others (1972) Lee County	Wedderburn and others (1982) Lee County		Boggess and others (1981) Lee, Hendry, and Collier Counties	This report		Series
WATER-TABLE AQUIFER	SURFICIAL AQUIFER	WATER TABLE	SURFICIAL AQUIFER	SURFICIAL AQUIFER SYSTEM	WATER-TABLE AQUIFER	HOLOCENE, PLEISTOCENE, AND PLIOCENE
SHALLOW ARTESIAN AQUIFER		CONFINING BEDS			CONFINING BEDS	
		TAMIAMI PRODUCING ZONE			LOWER TAMIAMI AQUIFER	
	HAWTHORN AQUIFER SYSTEM	UPPER HAWTHORN CONFINING ZONE		INTERMEDIATE AQUIFER SYSTEM	CONFINING UNIT	MIOCENE AND LATE OLIGOCENE
SANDSTONE AQUIFER		SANDSTONE AQUIFER	TAMIAMI AQUIFER		SANDSTONE AQUIFER	
		MID-HAWTHORN CONFINING ZONE			CONFINING UNIT	
UPPER HAWTHORN AQUIFER		MID-HAWTHORN AQUIFER	UPPER HAWTHORN AQUIFER		MID-HAWTHORN AQUIFER	
		LOWER HAWTHORN CONFINING ZONE			CONFINING UNIT	
LOWER HAWTHORN AQUIFER	FLORIDAN AQUIFER SYSTEM	LOWER HAWTHORN/TAMPA PRODUCING ZONE		INTERMEDIATE AQUIFER SYSTEM / UPPER FLORIDAN AQUIFER OF THE FLORIDAN AQUIFER SYSTEM	LOWER HAWTHORN PRODUCING ZONE	
		CONFINING BEDS		UPPER FLORIDAN AQUIFER OF THE FLORIDAN AQUIFER SYSTEM	CONFINING UNIT?	
SUWANNEE AQUIFER		SUWANNEE AQUIFER			PRODUCING ZONES WITHIN THE SUWANNEE LIMESTONE	EARLY OLIGOCENE AND EOCENE
DEEPER AQUIFER		DEEPER AQUIFER			PRODUCING ZONES WITHIN THE OCALA LIMESTONE AND AVON PARK FORMATION	

Figure 9. Aquifer nomenclature for southwestern Florida used in previous studies and in this report.

tion, 1986). In southwestern Florida, the surficial aquifer system includes the water-table aquifer and the lower Tamiami aquifer (fig. 4). Generally, the water-table aquifer occurs in the undifferentiated deposits and the upper part of the Tamiami Formation; however, in some areas no undifferentiated deposits are present, and the water-table aquifer occurs in the Tamiami Formation. The lower Tamiami aquifer mostly consists of sandy, shelly limestone and calcareous sandstone that occurs in the lower part of the Tamiami Formation; commonly, the thickness is less than 60 ft. However, in some areas, the lower Tamiami aquifer extends down into unconsolidated coarse siliciclastics (quartz sand with grain size up to very coarse or granule size) that occur at the top of the Hawthorn Group. The aquifer can be much thicker in these areas (Knapp and others, 1986; Smith and Adams, 1988).

Intermediate Aquifer System

Aquifers that lie beneath the surficial aquifer system and above the Floridan aquifer system in southwestern Florida are grouped within the intermediate aquifer system (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). The intermediate aquifer system does not crop out and contains water under confined conditions (Miller, 1986). The intermediate aquifer system lies within the Hawthorn Group and includes, in descending order, the sandstone aquifer and the mid-Hawthorn aquifer. The two aquifers tend to be thin in comparison to the thickness of confining units above and below (fig. 4).

The sandstone aquifer in Lee County generally is 50 to 100 ft in thickness, with the top of the aquifer ranging from 21 to 167 ft below sea level (Wedderburn and others, 1982). In Hendry County, the sandstone aquifer is divided into clastic and carbonate zones, and mapping of these zones shows that the aquifer does not extend east of the north-south boundary between Collier and Hendry Counties (Smith and Adams, 1988). Mapping of this aquifer in western Collier County shows that at about State Road 84 (Alligator Alley) the top of the aquifer lies at 250 ft below sea level and that south of this road it is absent (Knapp and others, 1986).

The mid-Hawthorn aquifer has been referred to as the upper Hawthorn aquifer by some previous investigators in southwestern Florida (fig. 9). The thickness of the mid-Hawthorn aquifer in Lee County rarely exceeds 80 ft, and the aquifer has low transmissivity. The altitude of the top of the mid-Hawthorn aquifer ranges from 100 to more than 300 ft below sea level, deepening to the east and south (Wedderburn and others, 1982). The aquifer terminates close to the Lee-Hendry County line and is not present in most of Hendry County (Boggess and others, 1981; Smith and Adams, 1988). In western Collier County, the top of the aquifer occurs at 300 to 400 ft below sea level, and the thickness averages 100 ft (Knapp and others, 1986). The geophysical log expression of the mid-Hawthorn aquifer is shown by logs run in well C-914 in southern Collier County (fig. 3 and pl. 7). This aquifer can be traced through much of the study area based on the hydrogeologic sections (pls. 1-10).

Floridan Aquifer System

The Floridan aquifer system is defined as a vertically continuous sequence of permeable carbonate rocks that are hydraulically connected in various degrees, and whose permeability is generally several orders of magnitude greater than that of the rocks bounding the system above and below (Miller, 1986). It is divided into three units; namely, the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer. This section presents a detailed description of these units and their boundaries, thickness, and transmissivity. Also included is a description of some subunits within these three major units (fig. 4).

Upper Floridan Aquifer

The Upper Floridan aquifer includes the lower part of the Hawthorn Group, Suwannee Limestone, Ocala Limestone, and upper part of the Avon Park Formation (fig. 4). Production zones in the lower part of the Hawthorn Group and the upper part of the Avon Park Formation might or might not be present. Production zones in the lower part of the Hawthorn Group, if present, are collectively referred to as the lower Hawthorn producing zone (LHPZ) in this report, and they occur in the basal Hawthorn unit, from the base of the marker unit to the basal contact of the Hawthorn Group. The Upper Floridan aquifer in the study area generally consists of several thin water-bearing zones of high permeability interlayered with thick zones of much lower permeability, which is similar to what is found in southeastern Florida (Reese, 1994). The Suwannee Limestone in parts of Lee County can be an exception to this tendency because of the generally coarser size and good sorting of the carbonate grains contained within the formation.

The top of the Floridan aquifer system, as defined by the Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition (1986), coincides with the top of the vertically persistent permeable carbonate section. According to this definition, the LHPZ can be placed in the Floridan aquifer system in the study area, at least in Lee County; however, important sources of data for determining where the top of the system should be placed are geophysical logs, such as temperature and flowmeter logs, head data, and zones of lost circulation or lost returns.

Water in the Upper Floridan aquifer exists under flowing artesian conditions, so permeable zones (or flow zones) can be defined in a well based on flowmeter and temperature logs. Anomalous changes of temperature with depth (shown by large fluctuations on a temperature differential curve) or a pronounced change in the temperature gradient can help in identifying permeable zones. The vertical distribution of head can help in defining the top of the Floridan aquifer system. Potentiometric-surface maps of the Upper Floridan aquifer show a particular head or range of head values expected for an area. If this level of head has not been reached at a particular depth, the top of the aquifer would then be expected to be deeper; the Upper Floridan aquifer has a higher head than all of the aquifers above. Without detailed data in a well, including flowmeter and temperature logs or the vertical distribution of head, the top of the aquifer could be difficult to determine, particularly if the top is not defined by a lithologic change, such as the one often found at the basal contact of the Hawthorn Group.

In Lee County, the "lower Hawthorn/Tampa producing zone" (fig. 9, a unit equivalent to the LHPZ) is placed in the Floridan aquifer system where it ranges from 80 to 275 ft in thickness (Wedderburn and others, 1982). The major zone of production was found to occur near the top of the LHPZ (Wedderburn and others, 1982, p. 52). Potentiometric-surface maps for this zone (Wedderburn and others, 1982, pls. 27 and 28) show head values that are similar to those expected for the Upper Floridan aquifer in Lee County (Bush and Johnston, 1988, pl. 5). These head values range from 50 ft above sea level in eastern or northeastern Lee County to 20 or 30 ft above sea level along the coast.

Head data indicate some confinement between the LHPZ and the Suwannee Limestone of the Upper Floridan aquifer and good confinement between the mid-Hawthorn aquifer and the Suwannee Limestone. The original head in the Suwannee Limestone was about 5 ft higher than head in the LHPZ in central Lee County as estimated by Sproul and others (1972, p. 10). In the study by Sproul and others (1972), head in the "upper Hawthorn aquifer" (fig. 9, referred to as the mid-Hawthorn aquifer in this report) was estimated to be as much as 20 to 25 ft above sea level before development. Original head in the Suwannee Limestone in the area was estimated to range from 35 to 40 ft above sea level.

The basal contact of the Hawthorn Group (fig. 7) is an unconformity that probably approximates an important hydrogeologic boundary in most of the study area. Even though the top of the Floridan aquifer system is placed higher than this geologic contact, the most permeable flow zone in the Upper Floridan aquifer probably is at or near this contact in most areas. Permeable beds that are developed in the middle to upper part of the basal Hawthorn unit are not laterally continuous and are not present in much of the study area.

The top of the Floridan aquifer system can be placed based on the depth at which zones of lost circulation or lost returns are encountered. Where noted in lithologic descriptions, the tops of these zones are identified on the hydrogeologic sections (pls. 1-10). These zones generally are delimited by intervals of missing sample. The highly permeable or vuggy nature of rock in these zones results in loss of drilling fluid during mud rotary drilling, and the cutting samples that normally are brought up by the mud are lost. The hydrogeologic sections generally show that these zones first occur in the lower part of the basal Hawthorn unit or at the basal contact of the Hawthorn Group, for example, as shown by wells C-1124, C-1125, and C-1126 in Collier County (pl. 10).

In well C-1107 in western Collier County, the top of the Floridan aquifer system can be placed in the upper part of the basal Hawthorn unit (pl. 5). The top of the basal Hawthorn unit in this well is at a depth of 640 ft, and the top of the LHPZ is at 740 ft, which is the top of the first major flow zone, as indicated by the temperature log. The top of the Suwannee Limestone was placed at 870 ft based on gamma-ray log response and lithology. An anomaly on the spontaneous potential curve, recorded on the dual-induction resistivity log, occurs in association with the contact at the top of the Suwannee Limestone. This anomaly consists of a large negative deflection, 40 mV (millivolts), at a depth of between 860 and 895 ft, which could indicate enhanced permeability associated with a flow zone at this contact.

A temperature log run on well C-914 in southwestern Collier County indicated little flow from the basal Hawthorn unit (fig. 5 and pl. 7). Apparently, the LHPZ is not developed in this well. The top of the Floridan aquifer system was placed at the top of the first significant flow zone, 880 ft deep, as indicated by the temperature log. The presence of this major flow zone is confirmed by the lithologic log of well C-914 (Knapp and others, 1986, p. I-54). Lost circulation and large cavities were encountered from 880 to 900 ft with no sample recovery. Based solely on the gamma-ray and resistivity logs, the top of the Floridan aquifer system in this well would have been placed at or just above the top of the Suwannee Limestone, which is at 830 ft. This example illustrates that in wells without additional logs, such as the temperature log, the top of the Floridan aquifer system can be placed at a depth that is too shallow.

In well L-6414 in northeastern Lee County, the basal Hawthorn unit is thick and the LHPZ is well developed (fig. 10 and pl. 1). The first major flow zone occurs at 620 ft, which is almost 300 ft above the top of the Suwannee Limestone. A number of other discrete flow zones occur in this well in the LHPZ and Suwannee Limestone as shown by the temperature differential curve.

The depth to the base of the Upper Floridan aquifer is variable, and the base is difficult to define. Miller (1986) defines the base using a change in vertical hydraulic conductivity of two orders of magnitude. However, the permeability data required to define the base using this definition is rarely present in the study area. Additionally, the nature of the Upper Floridan aquifer can make the use of this definition difficult because much of the aquifer in the study area consists of thick intervals of relatively low permeability. Miller (1986, pl. 29) places the base of the Upper Floridan aquifer at 2,000 to 2,100 ft below sea level in most of the study area; that is, at the top of a confining unit. This confining unit contains gypsiferous dolomite and is located in the Avon Park and Oldsmar Formations. However, the base of the Upper Floridan aquifer has been placed by others (consulting firms) at shallower depths ranging from 1,500 to 1,800 ft below land surface. Using the latter depths for the base, the thickness of the Upper Floridan aquifer ranges from 700 to 1,200 ft (fig. 4).

In western Collier County in well C-1107, ViroGroup, Inc./Missimer Division (1993) placed the base of the Upper Floridan aquifer in the lower part of the Ocala Limestone at a depth of 1,460 ft (pl. 5). Good confinement was shown to be present below a depth of 1,800 ft in well L-5802 (pl. 1) in northern Lee County at the North Fort Myers wastewater injection well site (Post, Buckley, Schuh, and Jernigan, Inc., 1988). In well L-5802, most of the interval from 1,180 to 1,550 ft in the lower Suwannee Limestone, Ocala Limestone, and upper part of the Avon Park Formation is also interpreted to have relatively low permeability (Post, Buckley, Schuh, and Jernigan, Inc., 1988, fig. 2-10). This interpretation is based, in part, on core permeability measurements at depths of 1,341 and 1,443 ft (Post, Buckley, Schuh, and Jernigan, Inc., 1988, table 7-3). The measured specific horizontal permeability to water at these two depths, converted to hydraulic conductivity, was 0.007 and 0.024 ft/d (foot per day), respectively.

Bush and Johnston (1988, pl. 2) mapped the transmissivity of the Upper Floridan aquifer in all of Florida. Transmissivity ranges from more than 100,000 ft^2/d (feet squared per day) in northern Lee and Hendry Counties to less than 50,000 ft^2/d in the southern part of the study area, including most of Collier County. However, the map shows only one aquifer test site within the study area, so most of the interpretation is based on geology and simulation.

Tests to determine the transmissivity of various zones in the Upper Floridan aquifer have recently been conducted in the study area. The transmissivities of several intervals were estimated in well C-1102 (pl. 8) in southwestern Collier County based on step-drawdown data collected from open-hole packer tests (Missimer and Associates, 1991a). The total estimated transmissivity from four intervals with a combined thickness of 471 ft was 33,000 ft^2/d. These intervals were included in an overall interval from 680 to 1,606 ft in depth and are referred to as the lower Hawthorn/upper Suwannee, lower Suwannee, Ocala, and Avon Park aquifers (Missimer and Associates, 1991a). The highest hydraulic conductivity was from the 80-ft thick lower Hawthorn/upper Suwannee aquifer interval; estimated transmissivity for the interval was 15,000 ft^2/d. The four intervals selected probably did not cover all of the permeable parts of the Upper Floridan aquifer at the site.

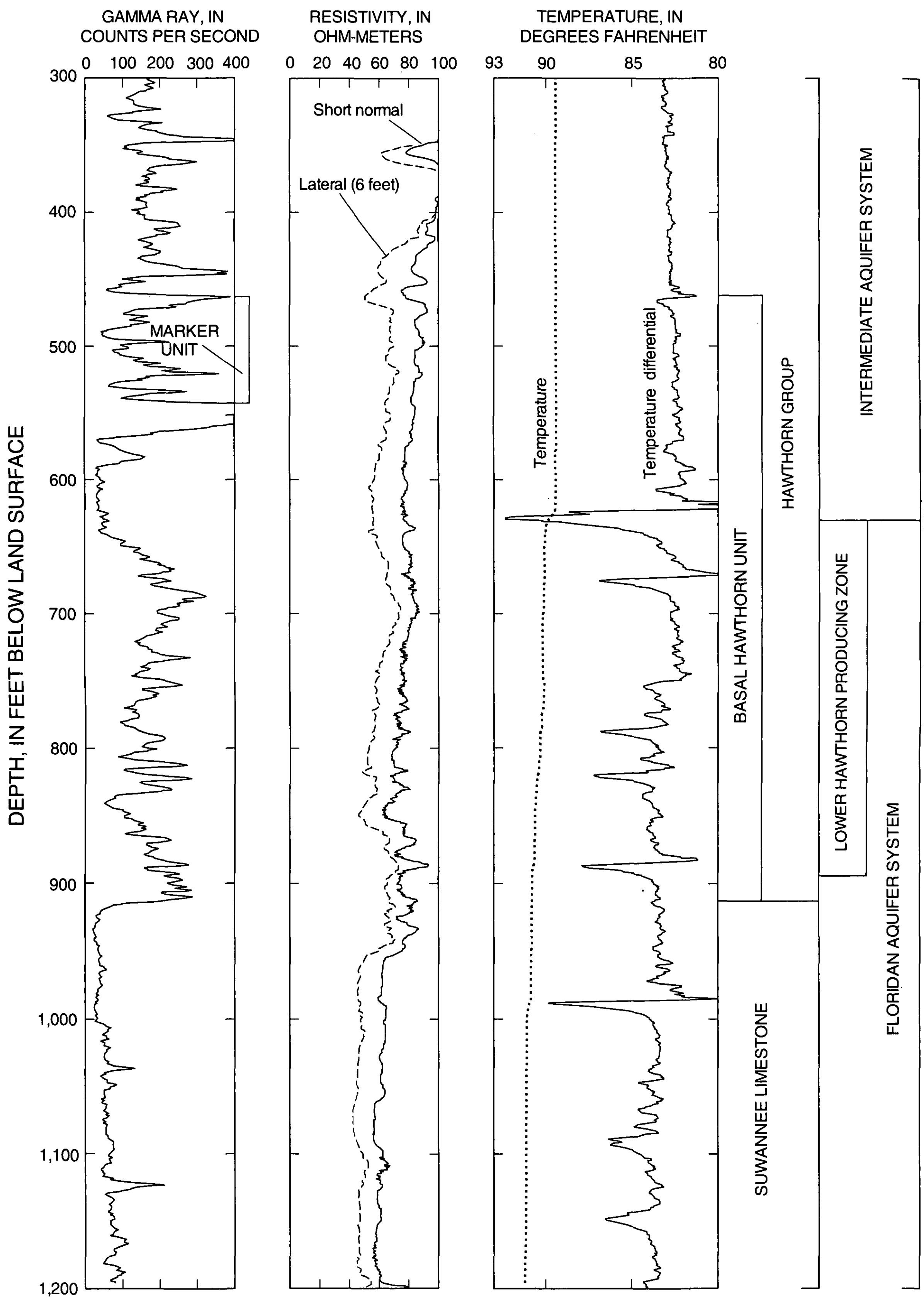


Figure 10. Geophysical logs, geologic units, and hydrogeologic units for well L-6414 in northeastern Lee County.

Three straddle packer tests were conducted in the Ocala Limestone and Avon Park Formation in well L-6471 on Gasparilla Island in northwestern Lee County (pl. 1). The three intervals that were tested (each 51 ft thick) were located in the overall interval of 1,058 to 1,543 ft. Hydraulic conductivity determined from these tests was low, ranging from 0.028 to 0.14 ft/d (Geraghty and Miller, 1986, table 2).

Transmissivity values were determined from aquifer tests in an area extending across western Lee County (Missimer and Associates, 1991b, table 4-1). Tests of the LHPZ at seven sites in the area gave a transmissivity range of between 1,800 and 12,300 ft^2/d, with a corresponding range in hydraulic conductivities of between 12 and 53 ft/d. Tests of the intervals in the Suwannee Limestone or of its upper part at four sites gave a transmissivity range of between 4,400 and 9,100 ft^2/d, and limited packer testing of intervals in the Ocala Limestone within the area indicated a transmissivity range of between 300 and 4,000 ft^2/d (Missimer and Associates, 1991b, p. 87).

The transmissivity of the LHPZ is related to the thickness of the basal Hawthorn unit (fig. 8). When temperature logs were run, the top of the first major flow zone was near the top of the basal Hawthorn unit where the unit is thick, and near the bottom of the unit or in the Suwannee Limestone where the unit is thin (pls. 1-10). In western Lee County, the highest transmissivity of the LHPZ (12,300 ft^2/d) was found in a well (Missimer and Associates, 1991b, fig. 4-12) located about 1 mi east of well L-6435 (pl. 2). The transmissivity of the LHPZ in a well on Sanibel Island near well L-6445 in Lee County (pl. 3) was measured to be only 4,000 ft^2/d. High permeability in at least the upper part of the basal Hawthorn unit of well HE-1104 in central Hendry County is apparent based on lithology, the gamma-ray curve, and the separation between shallow and deep resistivity curves (pl. 4). In comparison to these values or estimates of transmissivity, the thickness of the basal Hawthorn unit in wells L-6435, L-6445, and HE-1104 is 458, 212, and 428 ft, respectively.

Another consideration in defining the transmissivity of the basal Hawthorn unit is the structure on top of this unit (fig. 6). As discussed earlier, there is evidence that some of the high areas on top of the basal Hawthorn unit, particularly those in Lee County, coincide with paleotopographic high areas created by sedimentation. Additionally, the zones of "clean" limestone developed in these paleotopographic high areas in the middle and upper parts of the basal Hawthorn unit (figs. 6 and 8) are indicated by temperature logs to contain important flow zones. Wells with major flow zones, as shown by temperature logs, in these limestone zones are L-5608 (pl. 8), L-1688 (pl. 9), and L-6414 (pl. 1 and fig. 10). All of these wells have at least 20 ft of net thickness of "clean" limestone in the basal Hawthorn unit, and wells L-1688 and L-6414 have at least 40 ft.

Middle Confining Unit

The base of the middle confining unit of the Floridan aquifer system (fig. 4) ranges from 2,300 to 2,500 ft below sea level over most of the study area (Miller, 1986, pl. 31). The lower boundary of the middle confining unit in well C-1107 in western Collier County was placed at a depth of 2,300 ft at the top of a transmissive dolomite. The base of the unit was placed at a depth of at least 2,300 ft in three other wells, including wells C-1104 (Marco Island), L-5802 (North Fort Myers), and CH-313 (Zemel Road Landfill in southern Charlotte County). However, some wells showed evidence of transmissive dolomite or dolomitic limestone zones developed at depths less than 2,300 ft. In well L-6471 on Gasparilla Island in northwestern Lee County (pl. 1), an interval of dolomite with fractures and solution cavities occurs at a depth of 1,742 to 1,845 ft, and this interval was used for injection of wastewater (Geraghty and Miller, 1986, p. 20). Based mostly on drilling characteristics and cores, evidence suggests that zones of high transmissivity exist (Puri and Winston, 1974, fig. 24) at a depth of 2,000 ft or shallower in north-central Collier County (well C-851) and western Hendry County (well HE-343). The approximate thickness of the middle confining unit ranges from about 500 to 800 ft, as determined in this study.

Hydraulic conductivity was estimated for the middle confining unit from packer test and core data from well C-1107 in western Collier County (pl. 5). Hydraulic conductivity values from two packer test depth intervals (1,990-2,022 and 2,050-2,090 ft) ranged from 0.25 to 0.40 ft/d (ViroGroup, Inc./Missimer Division, 1993, table 13). Horizontal permeability to air was measured in six core plugs taken from a depth of between 2,013 and 2,259 ft in well C-1107. The range in values measured in these plugs was 0.01 to 55 millidarcies, which can be converted to an equivalent range in hydraulic conductivity of 3×10^{-5} to 0.15 ft/d. Specific horizontal permeability to water was measured in three core plugs at a depth of between 1,880 and 2,261 ft in well L-5802 (pl. 1) in northern Lee County (Post, Buckley, Schuh, and Jernigan, Inc., 1988, table 7-3). The range in values measured in these plugs was converted to a range in hydraulic conductivity of 1 x 10^{-5} to 0.033 ft/d. By relating sonic log transit time to core permeability measurements in well L-5802, the overall vertical hydraulic conductivity for the middle confining unit was calculated for depth intervals of 1,820 to 2,150 ft and 2,150 to 2,340 ft, giving values of 0.013 and 4 x 10^{-4} ft/d, respectively (Post, Buckley, Schuh, and Jernigan, Inc., 1988, p. 9-7).

Among the most impermeable rock in the middle confining unit is dense, unfractured dolomite. The occurrence of gypsum or anhydrite as bedded deposits or in a disseminated form within the dolomite probably further reduces the overall vertical permeability. Gypsum occurs as interbeds as thick as 40 ft in well C-851 (pl. 5) and nearby oil wells of the Sunniland oil field in north-central Collier County (Puri and Winston, 1974, fig. 18). Based on continuous core, sample description, and geophysical well logs, these gypsum interbeds occur in well C-719 (located 0.3 mi from well C-851) from a depth of about 1,830 ft down to 2,300 ft (pl. 5). An area in western and north-central Collier County contains 50 percent or more anhydrite in the middle one-third portion of the Eocene age section (Puri and Winston, 1974, fig. 13). The thick interval containing dolomite and/or gypsum or anhydrite is referred to as the dolomite-evaporite unit in this report.

The altitude of the top of the dolomite-evaporite unit was mapped in the study area and ranges from 1,530 to 2,540 ft below sea level (fig. 11). The top of the unit was selected at the top of a sequence containing thick beds of dolomite or dolomite and evaporite minerals (gypsum and anhydrite). Beds of dolomite, 30 ft or greater in thickness, often occur in this unit and might be dense and impermeable. However, evaporite, particularly bedded evaporite, probably is not present in appreciable quantities in this unit in much of the study area, such as in eastern Hendry and Collier Counties. The most prominent feature present on the map on top of this unit is a high area trending to the northwest, beginning in central Collier County and extending into north-central Lee County (fig. 11). The top in this area is as much as 400 or 500 ft higher than in adjacent areas in central Collier County, and this high area could coincide with, or be related to, areas of maximum gypsum deposition. Hydrogeologic section D-D′ (pl. 5) extends across the axis of this high area where it is well developed; the top of the dolomite-evaporite unit is at 1,728 ft below sea level in well C-712 and decreases to 2,260 ft below sea level in well HE-282 to the west of the high area. The top of the dolomite-evaporite unit probably represents an important hydrologic boundary when thick beds of dense dolomite or evaporite of low vertical permeability are present. This top could be considered to be the top of the middle confining unit in some of the study area, particularly in areas where the top of the dolomite-evaporite unit is high. However, in eastern Hendry and Collier Counties where the top of the unit is 2,000 ft below sea level or deeper and little if any evaporite is present, dolomite in the unit can be highly permeable and the unit can be included in the Lower Floridan aquifer.

Lower Floridan Aquifer

The altitude of the base of the Lower Floridan aquifer ranges from 3,700 to 4,100 ft below sea level in the study area (Miller, 1986, pl. 33). This aquifer includes the highly transmissive Boulder zone, which contains massively bedded, cavernous, or fractured dolomite of high permeability. The altitude of the top of the Boulder zone ranges from about 2,900 to 3,100 ft below sea level in the study area, and the zone has a thickness of about 400 ft in Collier County (Miller, 1986, figs. 21 and 23). The base of the Lower Floridan aquifer extends below the Boulder zone into permeable carbonates of the upper part of the Cedar Keys Formation, below which are massive, impermeable beds of anhydrite. Previous measurements of transmissivity of the Boulder zone in southern Florida were found to be extremely high, 3.2 x 10^6 ft^2/d (Meyer, 1974) and 24.6 x 10^6 ft^2/d (Singh and others, 1983).

In an east-west cross section of southern Florida extending through Collier County, Meyer (1989, fig. 3) shows that an upper dolostone unit and a middle dolostone unit are present in the Lower Floridan aquifer above the lower dolostone Boulder zone. These overlying dolostone units have transmissivity, which probably is an order of magnitude less than that of the Boulder zone (Meyer, 1989, p. 10).

Evidence obtained from drilling deep wells for injection of wastewater or brine into the Lower Floridan aquifer indicates that zones similar to the Boulder zone are developed higher in the section. A highly permeable "Boulder zone" extends from 2,560 to 3,330 ft below land surface in well C-1107 in

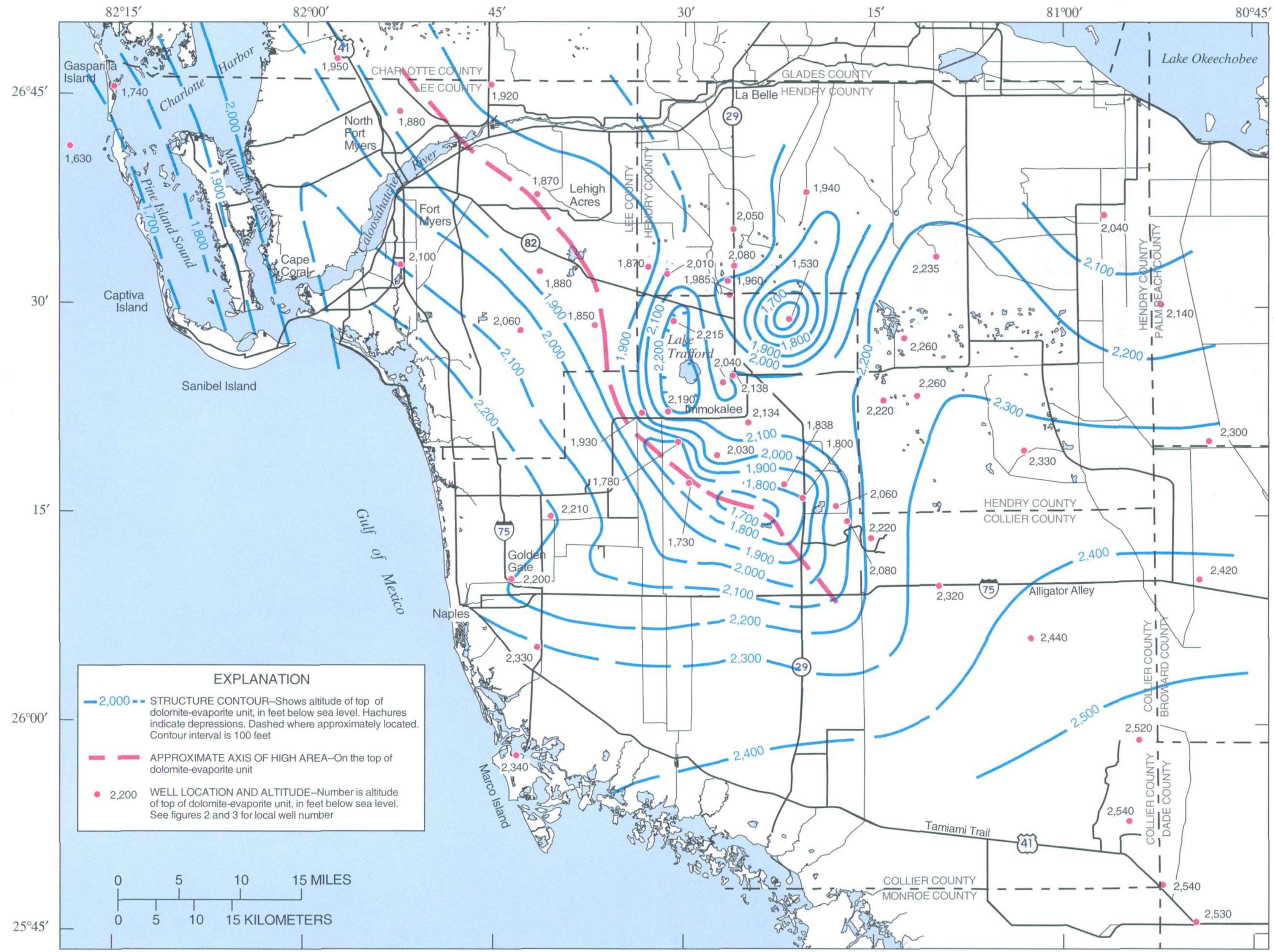


Figure 11. Altitude of the top of the dolomite-evaporite unit in the middle confining unit of the Floridan aquifer system in the study area.

western Collier County as determined by ViroGroup, Inc./Missimer Division (1993, p. 13). This depth interval consists of permeable units alternating with impermeable units, and the thickness of the permeable units ranges from 20 to 130 ft (ViroGroup, Inc./Missimer Division, 1993, p. 14). The depth interval completed for wastewater injection in well C-1107 was 2,497 to 3,390 ft. A depth interval containing cavernous dolomite was found in well L-5802 in northern Lee County, extending from 2,340 to 2,600 ft (Post, Buckley, Schuh, and Jernigan, Inc., 1988, p. 9-1). This same depth interval was completed for wastewater injection in well L-5802, and the transmissivity for the interval was determined to be 67,000 ft^2/d. In well C-820, drilled for the disposal of brine produced in an oil field in north-central Collier County, the depth interval completed for injection was 2,004 to 2,500 ft.

DISTRIBUTION OF SALINITY IN THE FLORIDAN AQUIFER SYSTEM

An investigation of the distribution of salinity in the Floridan aquifer system in southwestern Florida indicated that the system could be divided into the same three salinity zones based on geophysical log responses, as was done in an earlier study in southeastern Florida (Reese, 1994, p. 30). These zones, in order of increasing depth, are a brackish-water zone, a transition zone containing moderately saline water (the salinity transition zone), and a saline-water zone. Salinity increases rapidly with depth in the salinity transition zone. This zone was defined based on a salinity equivalent to a dissolved-solids concentration of 10,000 mg/L (a chloride concentration of about 5,240 mg/L) at its top and 35,000 mg/L (a chloride concentration of about 18,900 mg/L) at its base. The concentration used at its base is a salinity value similar to that of seawater. The boundaries of these three zones were determined in all wells with either geophysical logs or water-quality data or both.

The section includes an evaluation of formation water salinity based on borehole resistivity logs, estimates of porosity, formation temperature, and the empirical cementation factor, *m*. Several types of resistivity tools were used in the study and are described in this report. This section also defines and maps the brackish-water, salinity transition, and saline-water zones; describes the distribution of salinity by salinity zone; and maps the distribution of sulfate. Sulfate can be a significant part of the dissolved solids in ground water from the Floridan aquifer system in southwestern Florida.

Evaluation of Formation Water Salinity Based on Geophysical Logs

Two threshold salinity values of interest in the Floridan aquifer system are dissolved-solids concentrations of 10,000 and 35,000 mg/L. As previously defined, a dissolved-solids concentration of 10,000 mg/L separates brackish and moderately saline water, and a dissolved-solids concentration of 35,000 mg/L separates moderately saline water and saline water. Depths to the tops of zones in the Floridan aquifer system that contain water with these threshold salinity values or greater can be approximated based on borehole geophysical logs (Reese, 1994). Additionally, the salinity of formation water at a particular depth, or an average over a depth interval, can be estimated.

Use of the term "formation" in this report refers to the bulk rock or sediment including the contained water under ambient conditions, and "formation water" is equivalent to the term "ground water." The salinity of formation water is directly proportional to resistivity of the water. If this water resistivity and the formation porosity are known, the resistivity of the formation containing this water can be determined.

Determination of Formation Resistivity

The resistivity of a nonshaley, water-bearing formation is related to the porosity and resistivity of the formation water according to the following equation (Archie, 1942):

$$R_o = a \; \varnothing^{-m} \; R_w \qquad (1)$$

where

R_o is the water-saturated formation resistivity, in ohm-meters,

a is an empirical constant,

$\varnothing$ is total or bulk formation porosity as a fraction,

m is the cementation factor, an empirical number that increases with compaction and cementation, and

R_w is the formation water resistivity, in ohm-meters.

The values of R_o and R_w are at formation temperature.

Equation 1 was applied to the Floridan aquifer system in southeastern Florida by Reese (1994, p. 20) and is used in this study as well. The predominant lithology of the Floridan aquifer system in both areas is similar, with fine-grained to micritic limestone and high intergranular and intraparticle primary porosity. Based on microscopic examination of cuttings, this porosity has not undergone loss to any great extent through sealing by secondary calcite or diagenesis. Oolitic or fragmental limestone that has not been sealed by secondary calcite generally can be analyzed as though it were a clastic rock (MacCary, 1983, p. 335), and clastic rocks are analyzed based on equation 1. Equation 1 was not used for intervals containing dolomite in the Floridan aquifer system because of the difficulty in determining or predicting porosity in dolomite. These dolomite intervals have high potential for the development of extensive secondary porosity (fracture, intercrystalline, and vugular), and this porosity can be highly variable.

A borehole-compensated neutron-density log used to determine porosity was run on well C-962 in eastern Collier County (Reese, 1994, p. 20). Log-derived porosity, an average of the responses from the two devices, ranged from 20 to 45 percent in the upper 1,200 ft of the Floridan aquifer system and from 30 to 40 percent throughout most of this interval (fig. 12). A general tendency for porosity to decrease with increasing depth was observed. Responses from the neutron-density log give a measure of total porosity (eq. 1) rather than effective porosity. Because porosity responses from the density and neutron devices were usually in close agreement and because the neutron device is more affected by borehole conditions (such as hole enlargement), only the density device response from this log and other neutron-density logs run in the study area were used in the determination of porosity in this study.

Determination of porosity from the sonic log was made by calibration of its response to the density porosity response in wells in which both neutron-density and sonic logs were run. For example, both logs were run in well BF-3, which was drilled by the SFWMD in eastern Broward County (outside of the study area). Well BF-3 was drilled into the Floridan aquifer system, reaching the Avon Park Formation at a depth of 1,034 ft. Average responses for the density and sonic logs were determined over 25 zones (each 3 to 10 ft thick), within a depth interval of 1,050 to 2,046 ft. The well was drilled through this interval with a 10.75-in. (inch) diameter bit, and because of this large initial hole size and enlargement of the hole after drilling and before logging, density porosity values were corrected for the hole size as shown by a caliper curve based on a correction chart (Schlumberger Educational Services, 1988, chart Por-15a). An interpreted linear fit was made for data from depths greater than 1,250 ft based on a matrix transit time of 43.5 μs/ft (microseconds per foot) (fig. 13A). This value for matrix transit time is a minimum value for limestone with zero porosity; the range of this parameter is from 43.5 to 47.6 μs/ft (Schlumberger Educational Services, 1988, chart Por-3). The relation for the linear fit (fig. 13A) is:

$$\text{Density porosity} = (\text{sonic transit time} \times 0.60) - 26.0 \quad (2)$$

where density porosity is in percent, and sonic transit time is in microseconds per foot. Data from a depth of less than 1,250 ft do not fall on the trend of deeper data points in figure 13A, probably because the formation is less compacted at shallower depths than implied in equation 2, resulting in a transit time that is longer than that predicted for a given porosity.

Both neutron-density and sonic logs were run in well HE-1104 in central Hendry County, and responses were determined in 10 zones within a depth interval of 964 to 1,240 ft (fig. 13B). The tops of the Suwannee and Ocala Limestones in this well are at depths of 960 and 1,060 ft, respectively. Well HE-1104 was drilled with a large diameter bit of 17.5 in., and density porosity values were corrected for the hole size (Schlumberger Educational Services, 1988, chart Por-15a). An interpreted linear fit was made for the data from wells HE-1104 and BF-3 (at depths of 1,250 ft or less) based on a matrix transit time of 43.5 μs/ft (fig. 13B). The relation for this fit is:

$$\text{Density porosity} = (\text{sonic transit time} \times 0.55) - 23.9 \quad (3)$$

where density porosity is in percent and sonic transit time is in microseconds per foot.

Values of a and m (eq. 1), 1.0 and 2.0, respectively, are recommended for chalky limestone (Schlumberger Educational Services, 1972, p. 2). The constant a also is assumed to be equal to 1 in this study. The value of m ranges from 1.6 to 1.8 for Tertiary clean "platform type" limestones in the Southeastern Coastal Plains of the United States (Kwader, 1986).

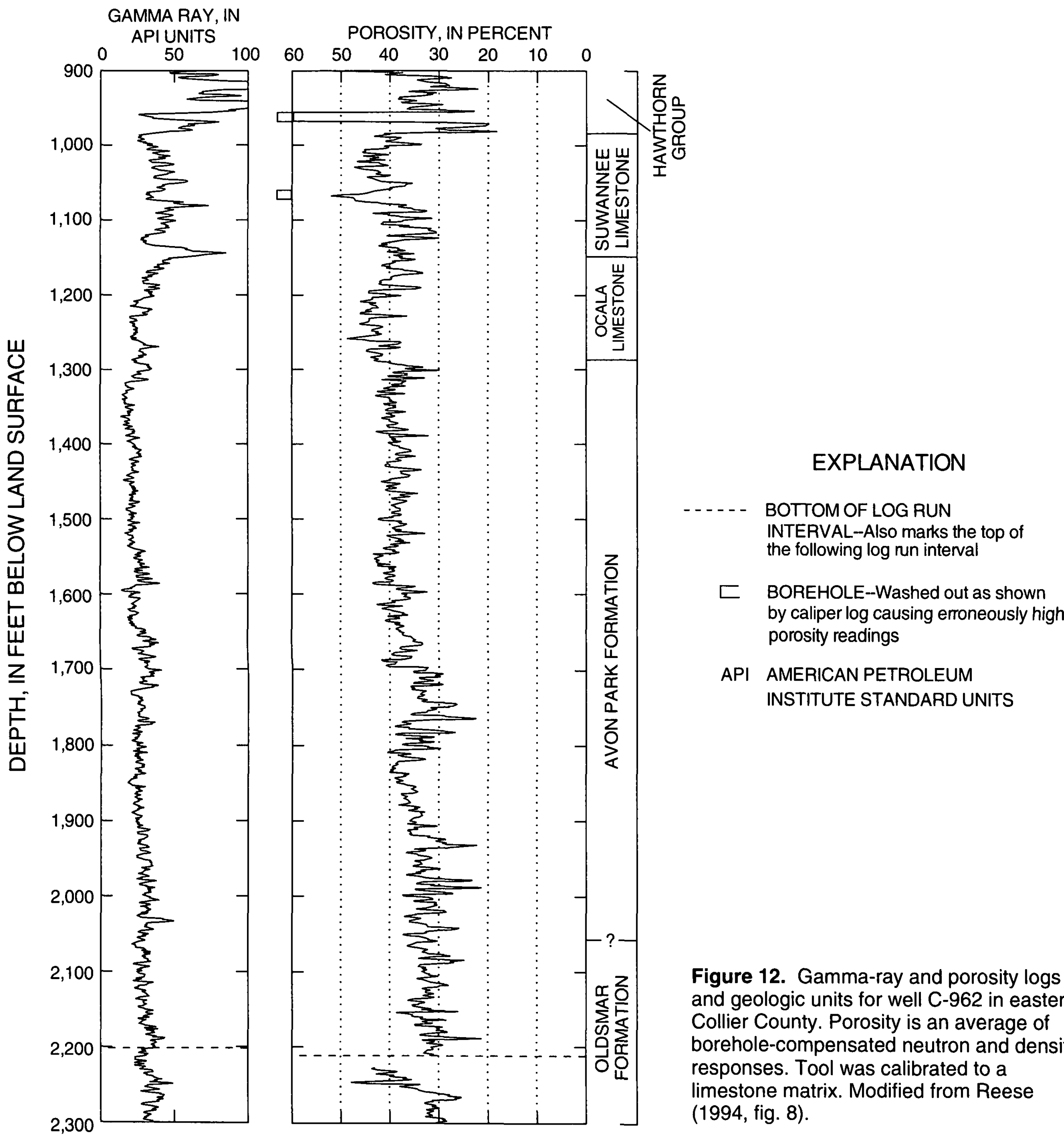
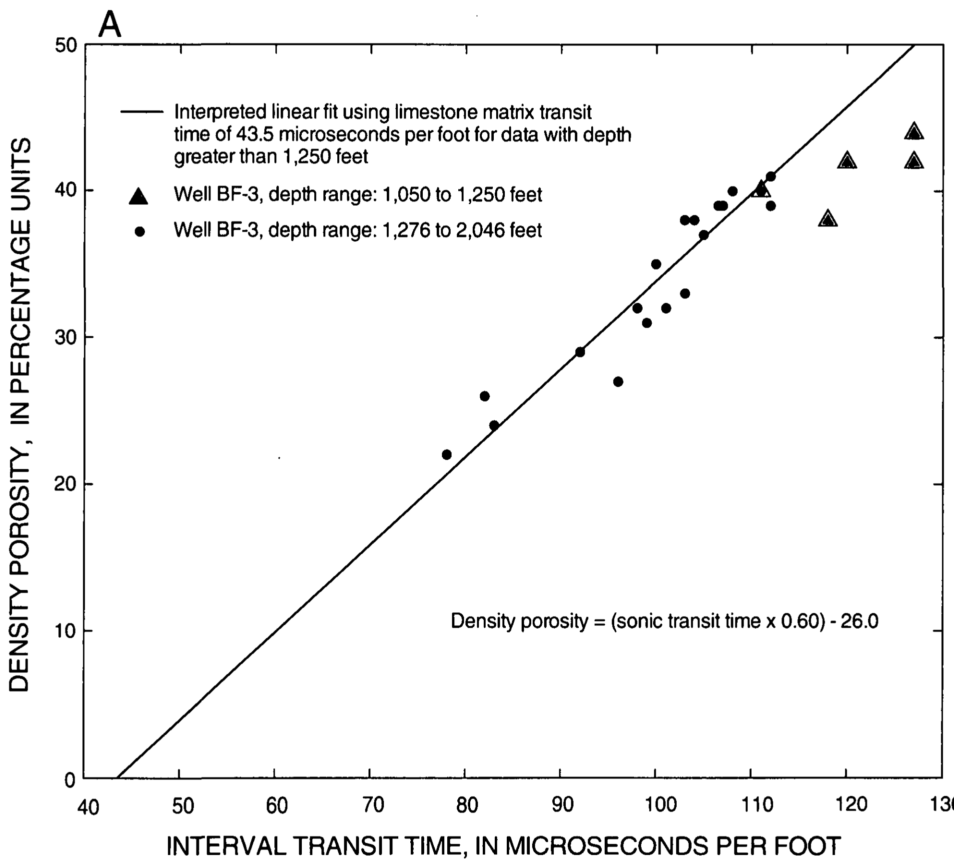


Figure 12. Gamma-ray and porosity logs and geologic units for well C-962 in eastern Collier County. Porosity is an average of borehole-compensated neutron and density responses. Tool was calibrated to a limestone matrix. Modified from Reese (1994, fig. 8).

This range for *m* could be low in comparison to the range expected in southeastern Florida in the Floridan aquifer system because of the likelihood of less compaction and cementation in the area of the Coastal Plains that excludes peninsular Florida. The depths of the Tertiary section worked within the Coastal Plains area are less than 1,000 ft (Kwader, 1986, fig. 1).

Values used for *m* have been determined from analyses of whole diameter core samples in the study area. This parameter ranged from 1.84 to 2.30 and averaged 2.02 based on the analyses of 13 limestone core samples collected from well CH-313 in southern Charlotte County within the depth interval of 1,325 to 2,116 ft (Post, Buckley, Schuh, and Jernigan, Inc., 1992, table 7-4). The value of *m* ranged from 1.53 to 2.13 and averaged 1.92 based on the analyses of six limestone core samples collected from well L-5802 in northern Lee County within the depth interval of 1,341 to 2,261 ft (Post, Buckley, Schuh, and Jernigan, Inc.,



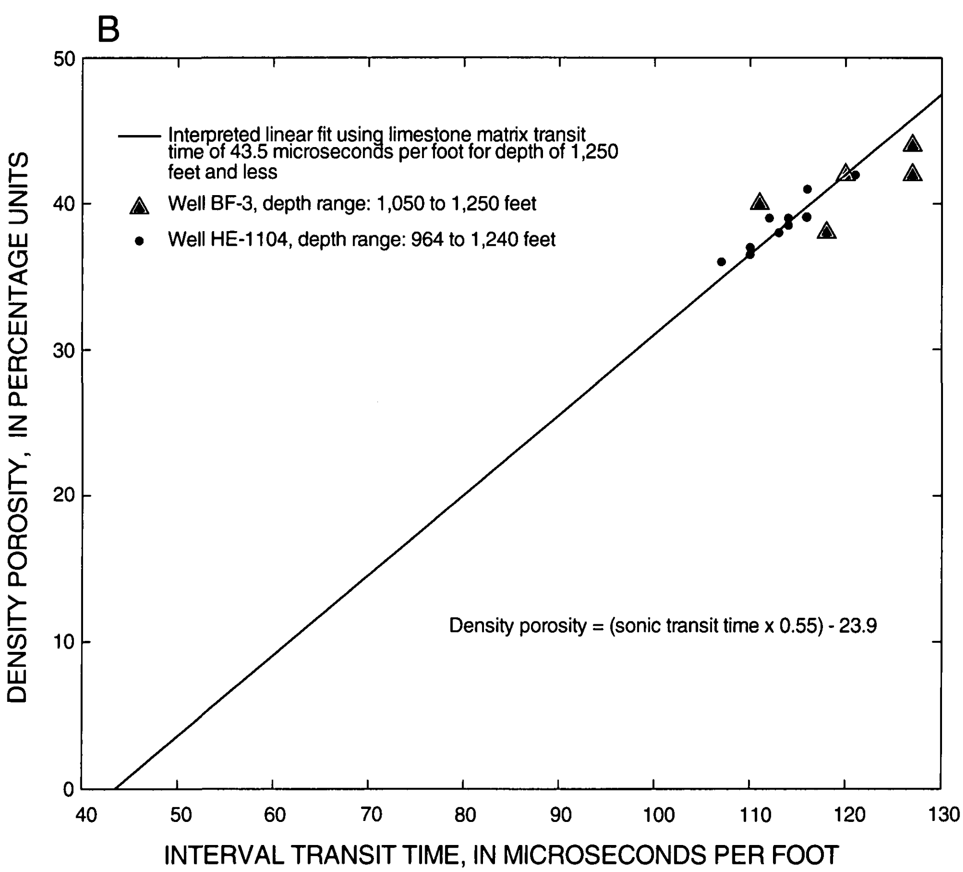


Figure 13. Plots showing relation between sonic log interval transit time and density log porosity for well BF-3 in eastern Broward County and well HE-1104 in central Hendry County. Graph A shows interpreted linear fit for depths greater than 1,250 feet, and graph B shows the fit for depths of 1,250 feet and less.

1988, figs. 7-3 to 7-8). In these analyses, *m* was calculated based on laboratory measured values for porosity, brine-saturated core sample resistivity, and brine resistivity. Formation water was simulated by the brine solutions used in these measurements; the solutions were synthesized based on analyses of formation water samples collected from straddle packer testing of intervals from which the core samples were taken. The value of *a* was constrained to be 1.0 in these calculations. The values used for *m* ranged from 1.8 to 2.1 in the Floridan aquifer system in southeastern Florida, which was based, in part, on core analysis (Reese, 1994, p. 22). Because of increasing compaction and cementation with depth in the Floridan aquifer system, the cementation factor, *m*, generally increases with depth. Average values of *m* used in the present study are 1.8 at depths less than 1,250 ft and 2.0 at depths greater than 1,250 ft. Use of 1,250 ft as a depth for change in the value of *m* is supported by the change at that depth in the relation between sonic and density log responses (figs. 13A and 13B).

Determination of Formation Water Resistivity from Water Analysis

The formation water resistivity, R_w, for a given salinity of water in the Floridan aquifer system, as defined by dissolved-solids concentration, can be determined from water analysis. Chloride concentration can be calculated for a given dissolved-solids concentration, then by relating chloride concentration to specific conductance, water resistivity can be determined. This resistivity is corrected based on formation temperature to give R_w.

Linear regression relations were developed between dissolved-solids and chloride concentrations and between chloride concentration and specific conductance of water samples collected from the Floridan aquifer system in southeastern Florida (Reese, 1994, eqs. 2-4) where water is of a sodium chloride type.

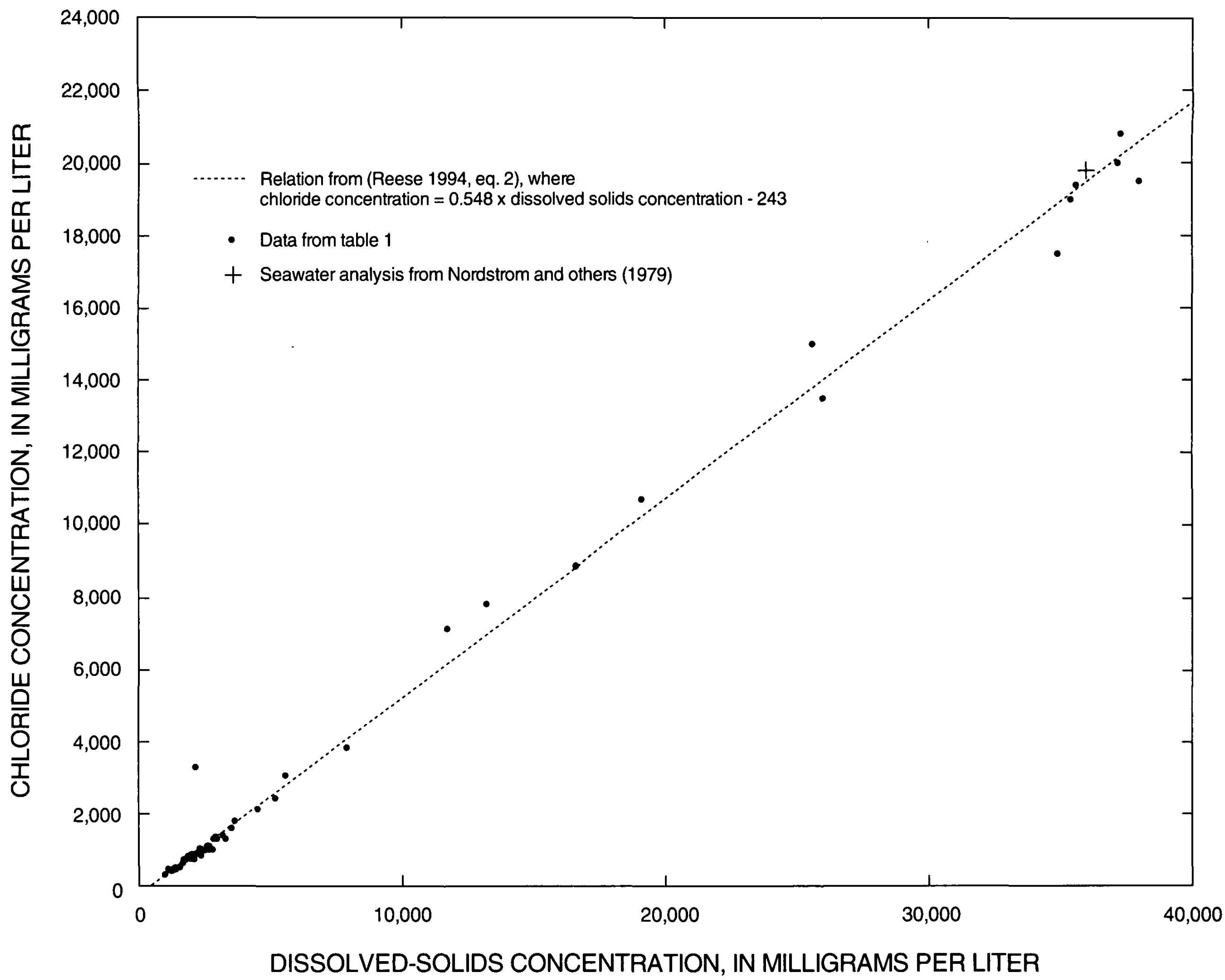


Figure 14. Relation between dissolved-solids and chloride concentrations for 54 water samples from the Floridan aquifer system in the study area.

These relations were applied to the present study of southwestern Florida where water is also a sodium chloride type (Sprinkle, 1989, pl. 9).

A plot of concentrations of dissolved solids and chloride for 54 water samples collected from the Floridan aquifer system is shown in figure 14, and a plot of chloride concentrations and specific conductance for 71 water samples is shown in figure 15. Only selected data from appendix II were used in producing figures 14 and 15 because either a constituent was not determined or the analysis was in error. Comparison of the data from appendix II with plots of lines generated based on equations 2, 3, and 4 from Reese (1994) show that these equations can be used to fit the data in the present study (figs. 14 and 15).

The resistivity of sample water, in ohm-meters, can be calculated from specific conductance, in microsiemens per centimeter at 77 degrees Fahrenheit (25 degrees Celsius), by use of the following expression:

$$\text{Resistivity} = 10,000/\text{specific conductance} \quad (4)$$

The resistivity of Floridan aquifer system formation water for the two threshold salinity values, dissolved-solids concentrations of 10,000 and 35,000 mg/L, was calculated and the results are given in table 2. Chloride concentration was calculated based on equation 2 from Reese (1994) and specific conductance was calculated based on equation 3 from Reese (1994), which is the relation for chloride concentrations up to 22,000 mg/L.

Table 2. Computations of the resistivity of Floridan aquifer system formation water for two salinities as defined by dissolved-solids concentration

[mg/L, milligrams per liter; μS/cm, microsiemens per centimeter at 77 degrees Fahrenheit; ohm-m, ohm-meters at 77 degrees Fahrenheit]

Dissolved-solids concentration (mg/L)	Chloride concentration (mg/L)	Specific conductance (μS/cm)	Resistivity (ohm-m)
10,000	5,240	14,800	0.675
35,000	18,900	48,000	.208

The resistivity of water that is a sodium chloride type can be adjusted for a change in temperature based on a resistivity chart for sodium chloride solutions (Schlumberger Educational Services, 1988, chart Gen-9). The calculated resistivity of Floridan aquifer system formation water for the two salinity values of

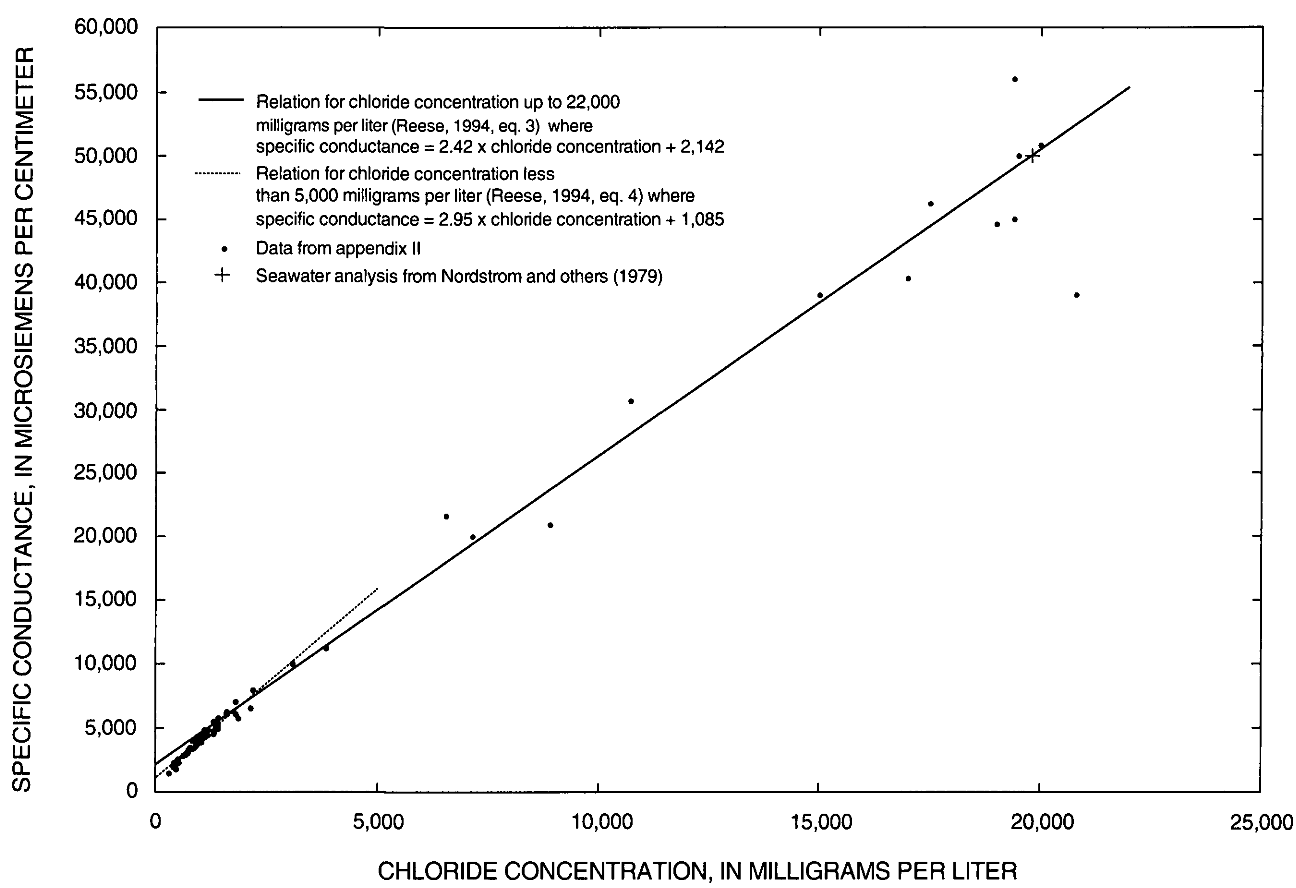


Figure 15. Relation between chloride concentrations and specific conductance for 71 water samples from the Floridan aquifer system in the study area.

interest can be adjusted from 77 degrees Fahrenheit to the formation temperature to give R_w.

Formation temperature in southwestern Florida in the Floridan aquifer system is higher and more variable than in southeastern Florida (Reese, 1994, p. 26). Temperature data from 18 wells were plotted against depth, in feet below land surface, as shown in figure 16. All of these data came from below the basal contact of the Hawthorn Group. Most of the data (17 measurements) came from the maximum temperature recorded during logging by a thermometer placed on a logging tool, and the remaining 7 data points came from 4 wells logged with a temperature log. For the maximum recorded temperature data, the temperature was assumed to have been set at the bottom of the logged open-hole section. A linear regression fit shows that a normal geothermal gradient generally exists in the study area (fig. 16). However, three data points from three wells at a depth greater than 2,000 ft plot well below the linear fit (lower-than-expected temperature for their depth). These three wells are located in southeastern Collier County (wells C-962, C-1126, and C-1127), and these anomalous temperatures could result from the cooling effect of cold deep seawater that probably enters the Boulder zone along the southeastern coast of Florida in the Straits of Florida (Meyer, 1989, fig. 24). Additionally, four data points from four wells (L-6462, C-781, C-820, and HE-1106) within or just outside northern Collier County plot well above the linear fit, and all but one have a temperature of 100 degrees Fahrenheit or higher. This indicates a higher geothermal gradient in northern Collier County than the rest of the study area.

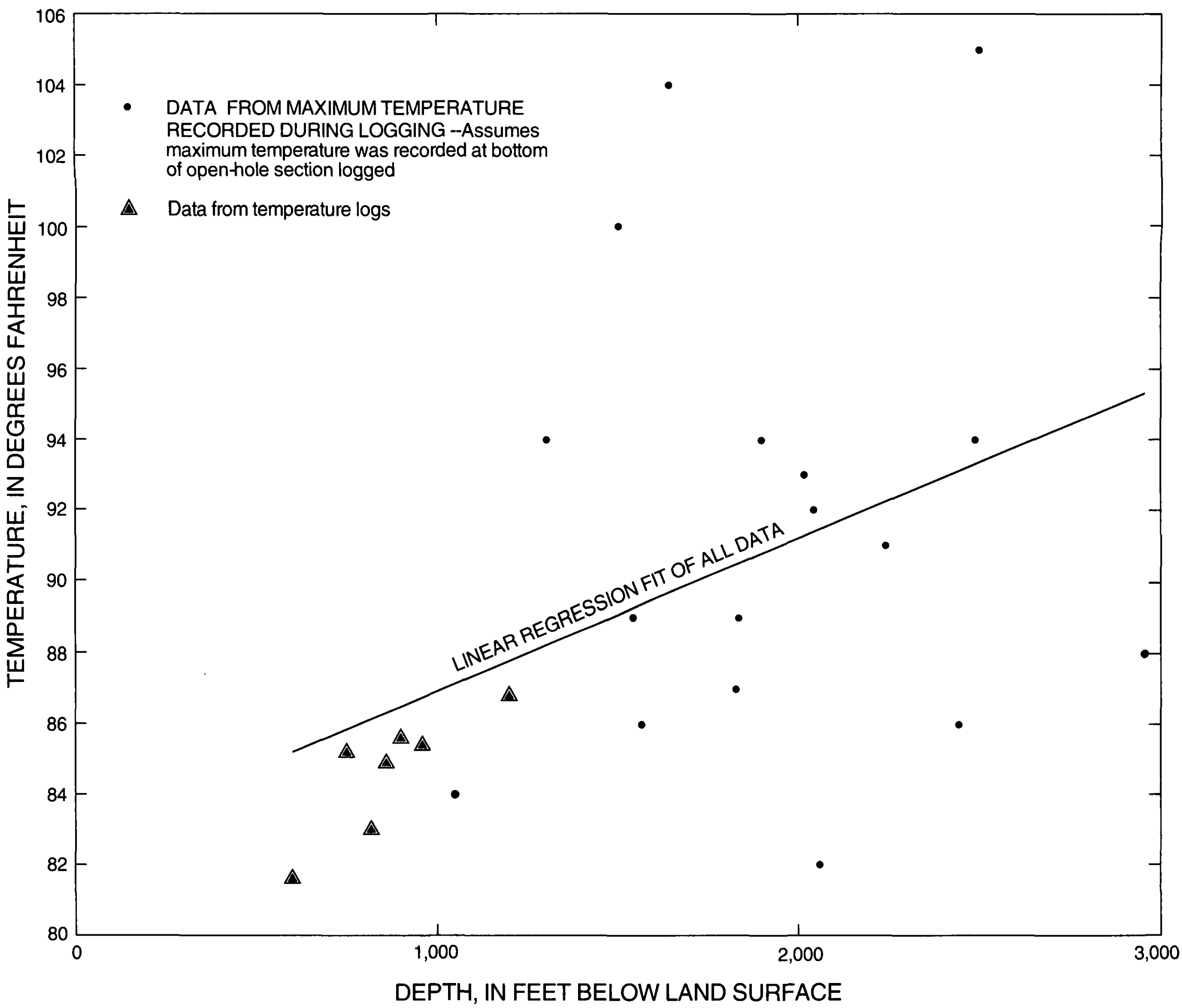


Figure 16. Relation between well depth and formation temperature for 24 water samples from 18 wells in the study area.

Table 3. Computations of formation resistivity for the Floridan aquifer system at a salinity of 10,000 milligrams per liter of dissolved-solids concentration for ranges in porosity and formation temperature

[Values used for the cementation factor, *m*, were 1.8 and 2.0; the value used for the constant, *a*, was 1.0]

Percent porosity	*m* value	Formation resistivity (R_o), in ohm-meters: 80 degrees Fahrenheit	90 degrees Fahrenheit	100 degrees Fahrenheit	110 degrees Fahrenheit
20	1.8	11.8	10.6	9.6	8.8
	2.0	16.3	14.6	13.3	12.1
25	1.8	7.9	7.1	6.4	5.9
	2.0	10.4	9.4	8.5	7.8
30	1.8	5.7	5.1	4.6	4.2
	2.0	7.2	6.5	5.9	5.4
35	1.8	4.3	3.9	3.5	3.2
	2.0	5.3	4.8	4.3	4.0
40	1.8	3.4	3.0	2.8	2.5
	2.0	4.1	3.7	3.3	3.0
45	1.8	2.7	2.5	2.2	2.0
	2.0	3.2	2.9	2.6	2.4

Table 4. Computations of formation resistivity for the Floridan aquifer system at a salinity of 35,000 milligrams per liter of dissolved-solids concentration for ranges in porosity and formation temperature

[Values used for the cementation factor, *m*, were 1.8 and 2.0; the value used for the constant, *a*, was 1.0]

Percent porosity	*m* value	Formation resistivity (R_o), in ohm-meters: 80 degrees Fahrenheit	90 degrees Fahrenheit	100 degrees Fahrenheit	110 degrees Fahrenheit
20	1.8	3.6	3.3	3.0	2.7
	2.0	5.0	4.5	4.1	3.7
25	1.8	2.4	2.2	2.0	1.8
	2.0	3.2	2.9	2.6	2.4
30	1.8	1.8	1.6	1.4	1.3
	2.0	2.2	2.0	1.8	1.7
35	1.8	1.3	1.2	1.1	1.0
	2.0	1.6	1.5	1.3	1.2
40	1.8	1.1	.9	.9	.8
	2.0	1.3	1.1	1.0	.9
45	1.8	.9	.8	.7	.6
	2.0	1.0	.9	.8	.7

Computation of Formation Resistivity for Two Threshold Salinity Values

The formation resistivity (R_o) was computed for the two threshold salinity values based on equation 1 for the expected ranges of values in porosity ($\varnothing$), the cementation factor (*m*), and the formation temperature (tables 3 and 4). The values used for formation water resistivity at 77 degrees Fahrenheit came from table 2. These computations indicate that variation in porosity produces the greatest uncertainty in R_o. As salinity increases or decreases with depth in the Floridan aquifer system, an approximate depth at which salinity equals dissolved-solids concentrations of 10,000 or 35,000 mg/L can be determined based on the results given in tables 3 and 4, if the variation of true formation resistivity with depth is known, and the porosity and formation temperature are also known or can be estimated.

Determination of Formation Resistivity and Salinity Based on Geophysical Logs

Several borehole geophysical resistivity tools were used in this study to determine formation resistivity and salinity. These included conventional tools, such as the 16-in. normal, 64-in. normal, and 18-ft 8-in. lateral (electrical log); tools with focusing electrode devices, such as the spherically focused device, laterologs, and guard or focused log; and tools with induction devices, such as the medium and deep induction. Generally, the induction devices give the best representation of true formation resistivity.

Devices with shallow and deep depths of investigation are run on a single logging tool to estimate the depth of invasion of borehole fluid into the formation. If the depth of invasion of borehole fluid is minimal, the device with the greatest depth of investigation can be used as an approximation of true formation resistivity. If the invasion is moderate, an estimate of the true formation resistivity can be made based on correction charts when a dual induction log (medium and deep induction devices with a shallow penetrating focusing electrode device) is run. For example, with invasion of drilling fluid that contains a salinity lower than that of the formation fluid, an estimate of the true formation resistivity can be made with the dual induction log as long as the diameter of invasion is less than 70 or 80 in. (Schlumberger Educational Services, 1988, p. 90, chart Rint-2b). If the invasion is extensive, which can occur when saltwater slugs are used to control artesian pressure during drilling in the Upper Floridan aquifer, the resistivity log cannot be used. Many of the wells used for geophysical log evaluation in the study area were drilled over the section of interest with a fresh gel mud system. In these wells, invasion was minimal as indicated by the dual induction logs that were run, and the deep induction curve could be used to determine formation resistivity.

Calculation of Salinity Data

Average values of specific conductance and chloride concentration in formation water for depth intervals ranging from 50 to 300 ft in thickness were calculated for wells in which both resistivity and porosity geophysical logs were run. In a depth interval of interest for a given well, 5 to 10 zones, each 3 to 10 ft thick, were selected based on the porosity log curve (10 zones usually were selected for the thicker intervals). These zones were selected so that an average value for density porosity or sonic transit time could be easily determined. Average values of resistivity for the same zones were then determined based on the resistivity log. Based on equations 1, 2, and 3, R_w was calculated for each zone. The value of the cementation factor, *m*, and the relation between sonic and density porosity (eqs. 2 or 3) depended on the depth of the interval as previously discussed. The R_w values for all of the zones in the interval were averaged, and after conversion of the average R_w at formation temperature to an R_w at 77 degrees Fahrenheit, the specific conductance and chloride concentration were calculated based on equation 4 in this report and equation 3 or 4 from Reese (1994). If not measured, formation temperature was calculated based on the relation determined between depth and formation temperature in the study area (fig. 16). If formation temperature for the well was available, but not for the interval of interest, temperature was determined by interpolating between the known temperature in the well and the values shown in figure 16.

Water-quality data calculated from geophysical logs for 21 depth intervals in 17 wells are presented in table 5. Calculated chloride concentration and specific conductance for each depth interval is given. All of these depth intervals, except for four, are in the Suwannee Limestone. The depth interval in well C-962 extends down into the Ocala Limestone, and only the Ocala Limestone is included in the deeper interval calculated in well CH-313. Two other intervals, which are the deeper intervals calculated in wells C-1124 and HE-1105, are in the Avon Park Formation or deeper. For one depth interval, from 810 to 1,033 ft in well C-820, the resistivity values and calculated porosity and chloride concentration values for each of 10 zones were plotted (fig. 17).

Table 5. Water-quality data calculated from geophysical logs

[Abbreviated units: ft, feet; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 77 degrees Fahrenheit; Type of resistivity log used: DIL, deep induction, medium induction, and shallow investigation curves (dual induction); IES, deep induction and short normal curves. Asterisk indicates hole badly washed out which could result in porosity from sonic log being too high and calculated chloride concentration being too low. Depth intervals are from measuring point given in appendix I]

Local well identifier	Depth interval analyzed (ft)	Chloride concentration (mg/L)	Specific conductance (µS/cm)	Type of resistivity and porosity log used
C-820	810-1,033	2,000	7,100	DIL and sonic
C-962	990-1,300	630	2,900	DIL and density
C-1104*	1,046-1,092	13,000	33,000	DIL and sonic
C-1107	896-998	1,900	6,600	DIL and sonic
C-1124	870-1,074	2,600	8,800	DIL and densiy
	1,870-1,913	3,100	10,000	DIL and density
C-1125	854-1,038	610	2,900	DIL and density
C-1126	919-1,038	630	2,900	DIL and density
C-1130	800-1,080	1,000	4,200	DIL and density
HE-949	800-1,008	580	2,800	IES and sonic
HE-1104	964-1,060	680	3,100	DIL and density
HE-1105	750-997	850	3,600	DIL and density
	1,506-1,538	910	3,800	DIL and density
HE-1106	772-1,050	570	2,800	DIL and density
L-6461	828-1,030	450	2,400	DIL and sonic
L-6462	710-1,010	1,200	4,700	DIL and sonic
L-6463	810-1,120	630	2,900	DIL and density
L-6471	730-753	7,600	20,000	DIL and sonic
	890-940	19,000	49,000	DIL and sonic
CH-313	728-1,016	560	2,700	DIL and sonic
	1,350-1,410	840	3,600	DIL and sonic

Comparison of Calculated Values with Water-Quality Data

To help determine the accuracy of the calculated salinity data, a comparison of water-quality data calculated from geophysical logs with water samples collected from the same well (at different but proximal depth intervals) or nearby wells was made, and the results are presented in table 6. The "twin" wells given in table 6 (sequential well identifier) represent an injection (geophysical log analysis) and monitor (water analysis) well, respectively. Wells C-1125 and C-1133, although not twin wells, are located only 2 mi apart. For well L-6471, the comparison was made by assuming, based on the overall level of resistivity in the well below 765 ft, that the depth interval analyzed from 890 to 940 ft was in the saline-water zone. Salinity in the saline-water zone is similar to that of seawater (Reese, 1994), and the threshold resistivity used to define the top of the saline zone is that calculated for formation containing water with a dissolved-solids concentration of 35,000 mg/L (table 4).

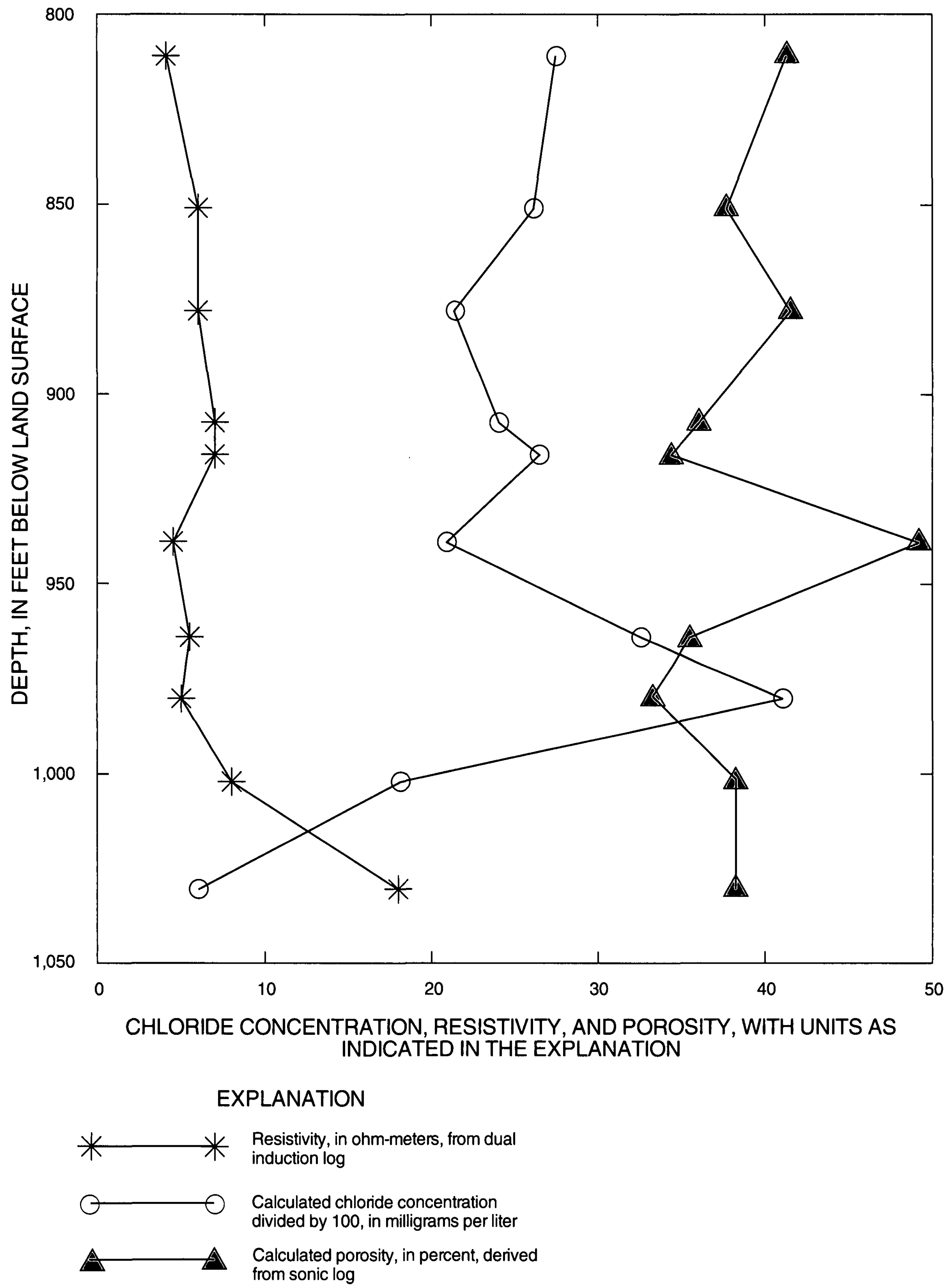


Figure 17. Depth profiles of chloride concentration, resistivity, and porosity for well C-820 in northern Collier County. Each of the 10 data points represents a zone which is 3 to 8 feet thick and is plotted using a midpoint depth for the zone.

Table 6. Comparison of water-quality data calculated from geophysical logs with water samples from same well or nearby well

[Data source: SL, calculated using a sonic log; WA, water analysis; DL, calculated using a density log; SA, seawater analysis from Hem (1985). Abbreviated units or acronyms: ft, feet; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter at 77 degrees Fahrenheit; in., inches; SWZ, saline-water zone below 765 feet. Depth intervals (column 2) are from measuring point given in appendix I]

Local well identifier	Depth interval computed or sampled (ft)	Data source	Chloride concentration (mg/L)	Specific conductance (μS/cm)	Percent error based on chloride concentration	Borehole size from caliper log (in.)
C-1104	1,046-1,092	SL	13,000	33,000	-13	30
C-1105	1,000-1,089	WA	15,000	39,000		
C-1107	896-998	SL	1,900	6,000	-10	18
C-1108	900-995	WA	2,100	7,100		
C-1124	1,870-1,913	DL	3,100	10,000	+26	13-15
	1,840-1,890	WA	2,440	--		
C-1125	854-1,038	DL	610	2,900	-21	18
C-1133	229-1,084	WA	770	--		
HE-1105	1,506-1,538	DL	910	3,800	+25	18
	1,578-1,598	WA	730	--		
L-6471	890-940	SL	19,000	49,000	0	13
	SWZ	SA	19,000	50,000		
CH-313	1,350-1,410	SL	840	3,600	-9	15
CH-314	1,340-1,415	WA	925	4,100		

Average percent error based on chloride concentration = 15

The percent error of calculated chloride concentration values, assuming that the chloride concentration from the water analysis is the true value, is presented in table 6. This error ranges from 0 to 26 percent and averages 15 percent. A likely source for this error is the porosity determination based on sonic logs. If the porosity were too high, the chloride concentration would be too low, which is the case for all of the comparisons involving sonic logs except one. Density porosity was corrected for the hole size in large-diameter boreholes by lowering the porosity (Schlumberger, 1988, chart Por-15a), but no correction chart was available for the sonic log.

Large-diameter boreholes can cause an increase in the transit time measured by sonic logs, which can increase calculated porosity (Schlumberger Educational Services, 1987, p. 34). Logging tools generally are designed for 8- to 10-in. diameter boreholes, but the wells in this analysis tend to have a much larger borehole size. The borehole size was determined for the intervals calculated in table 6 based on caliper logs run at the same time as the porosity logs, with the size ranging from 13 to 30 in. (table 6). These large borehole sizes result not only from the use of large-diameter drilling bits, but also from hole enlargement as the well is drilled deeper before casing is set. The upper part of the Floridan aquifer system is especially prone to hole enlargement because of the soft and friable nature of the limestone. Some of the error associated with sonic log readings in large-diameter boreholes is accounted for in equations 2 and 3 because these relations were determined in wells with large-diameter boreholes in which the density porosity was corrected for hole size.

Another likely source for the error between calculated and measured water-quality data in table 6 is the value used for the cementation factor, *m*. For well C-1124 at a depth of 1,870 to 1,913 ft (table 6), a chloride concentration of 2,600 mg/L is computed if a value for *m* of 1.9 is used instead of 2.0, and the percent error between calculated and measured values decreases from 26 to 8 percent. Although a value of *m* of 2.0 was used for all calculations of depth intervals greater than 1,250 ft in table 5, this value could be as low as 1.8.

Sensitivity of Calculated Salinity for Common Formation Resistivity Values

The sensitivity of a calculated chloride concentration in the Floridan aquifer system to porosity and the cementation factor was determined for two commonly occurring values – 10 and 20 ohm-m (ohm-meters) – of formation resistivity (fig. 18). A formation temperature of 88 degrees Fahrenheit, which is common in the Upper Floridan aquifer and the middle confining unit (fig. 16), and cementation factors of 1.8, 1.9, and 2.0 were used in the calculations from which the curves shown in figure 18 were generated. These curves show that the error in calculating a chloride concentration due to uncertainty in porosity becomes greater as the porosity decreases.

The errors between the calculated and measured water-quality data in table 6 are not large when viewed in the context of the range of variation in salinity commonly found in the Floridan aquifer system in the study area, as will be shown in the next section. The results given in table 5 are considered accurate enough to use in helping to define the distribution of salinity in the Floridan aquifer system.

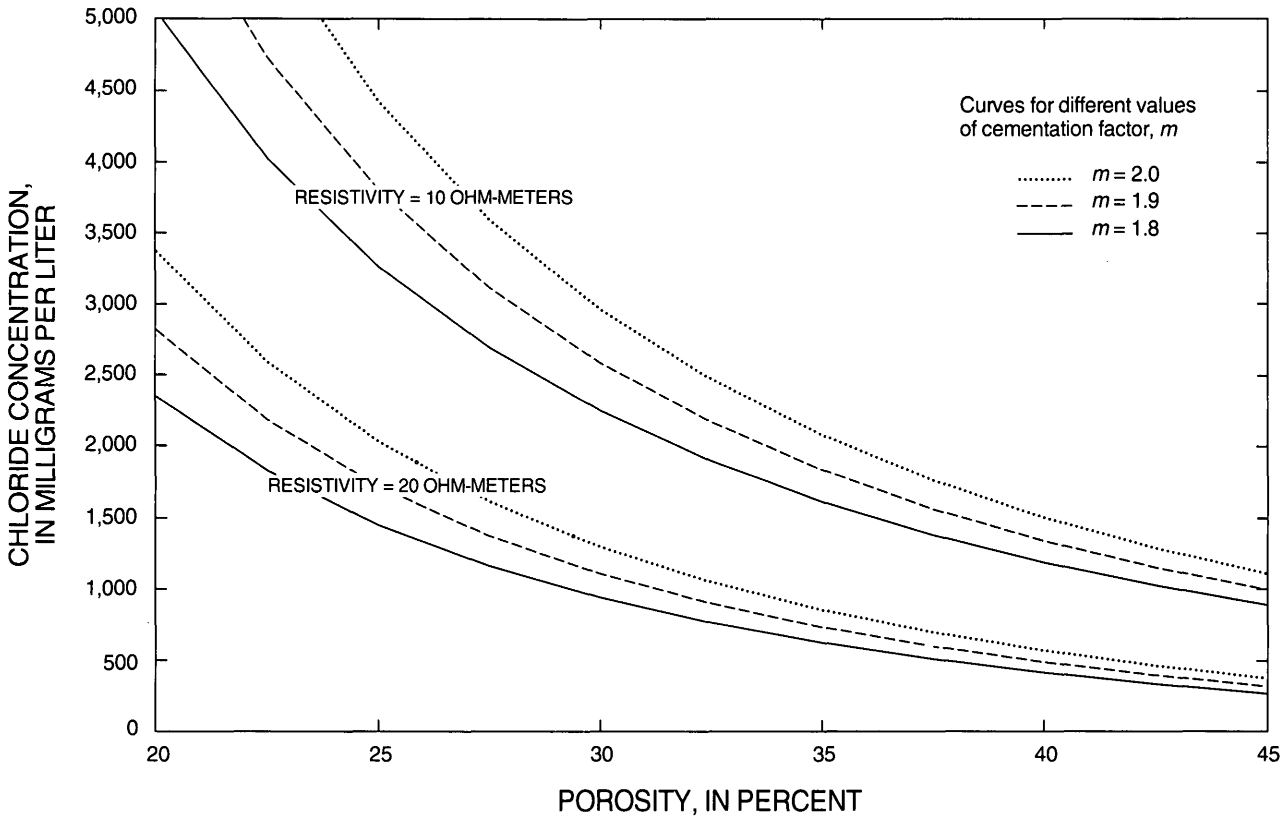


Figure 18. Calculated chloride concentration for formation resistivities of 10 and 20 ohm-meters and a range of porosity and the cementation factor, *m*, in the Floridan aquifer system. A value for formation temperature of 88 degrees Fahrenheit was used.

Determination of the Salinity Zone Boundaries

Geophysical logs, water-quality data collected from known intervals (completed and packer test), and water-quality data collected while drilling were used to determine the boundaries of the salinity zones in the study area. A total of 60 wells are presented in table 7; however, not enough data were available for the exact determination of the depth of one or both zone boundaries for some of the wells. The depths of the salinity zone boundaries in the Floridan aquifer system were mostly determined based on geophysical logs, with an induction resistivity device available for use in 27 wells (table 7). A porosity log (density or sonic) and a resistivity log were used to define the boundaries in 17 wells.

If only a resistivity log was run, an average porosity was used. Determination of the salinity zone boundaries in wells in which both porosity and resistivity logs were run indicated that an average porosity of 30 percent could be used when no porosity log was available. Based on this porosity and assuming a formation temperature of 90 degrees Fahrenheit and a cementation factor, *m*, of 2.0 gives formation resistivity values of 6.5 and 2.0 ohm-m for formation water containing dissolved-solids concentrations of 10,000 mg/L and 35,000 mg/L, respectively (tables 3 and 4). These threshold formation resistivity values were used to determine salinity zone boundaries when no porosity log was run.

Water-quality data were exclusively used for nine wells to determine the boundaries of the salinity zones in the study area (table 7). However, use of water-quality data alone is probably not the most ideal means to accurately determine a salinity zone boundary in a well because of unknown depth intervals, very thick depth intervals, and/or limited number of depth intervals sampled. For water-quality data collected during drilling by the reverse-air rotary method, the depth determined for a boundary should be considered the maximum depth. This is because an increase in salinity of formation water with depth can go undetected if the formation being drilled is of low permeability.

Table 7. Depths to salinity zone boundaries in the Floridan aquifer system as determined in this study

[Methods: E, conventional electrical log (normal and lateral devices); IES, deep induction and short normal devices; DIL, dual-induction log (deep and medium induction and shallow focusing electrode devices); LL, focusing electrode devices, such as laterologs; density, porosity from density device; sonic, porosity from sonic device; QW, water-quality data (samples from known intervals); DQW, water-quality data (samples taken while drilling by reverse-air rotary method). Methods are listed in order of importance in determining boundaries for each well. Other annotations: BBZ, base of brackish-water zone; TSZ, top of saline-water zone; ?, depth of boundary or thickness of zone is uncertain; *, depth of boundary is uncertain because of dolomite interbeds; --, no data; >, greater than the value; <, less than the value. Depths are from measuring point given in appendix I]

Local well identifier	Depth to base of brackish-water zone (feet)	Depth to top of saline-water zone (feet)	Thickness of salinity transition zone (feet)	Method
C-234	Not reached at 1,820	Not found	--	E
C-708	1,510 to 1,960	Not found	--	E
C-710	2,130	Not found	--	E
C-711	1,930	Not found	--	E
C-712	1,660	Not found	--	E
C-719	Not reached at 1,830	Not found	--	E
C-726	1,120?	1,740?	620?	E (top at 1,030)
C-727	Not reached at 2,080	Not found	--	E
C-729	2,050	2,120	70	IES
C-820	2,030	2,365*	335?	DIL-sonic for BBZ; DIL for TSZ
C-823	2,040	2,190	150	DIL-sonic
C-914	1,070	1,110	40	E
C-916	Not reached at 880	Not reached	--	QW
C-962	2,155	2,270	115	DIL-density
C-1102	900?	1,100?	200?	QW and DQW
C-1103	1,200	Not reached at 1,620	>420	QW and DQW
C-1104	760 from well C-1101	910 or shallower	<150	DQW, DIL (top at 910)
C-1106	780 (at top of Suwannee Limestone)	Not reached	--	DQW
C-1107	1,200	1,760	560	DIL-sonic
C-1111	950	1,280	330	DIL and QW
C-1112	1,968	2,030	62	DIL
C-1124	2,010	2,220*	210?	DIL-density
C-1125	2,070	2,220	150	DIL-density
C-1126	1,940	2,070	130	DIL-density
C-1127	Not reached at 2,060 (projected at 2,070 to 2,100)	No log	--	DIL (bottom at 2,061)
C-1130	Not reached at 1,830	No log	--	DIL (bottom at 1,836)
CH-313	1,560	1,730	170	DIL-sonic
G-2296	2,175	2,230	55	E
G-3239	1,960	2,070	110	E
HE-282	2,060	2,260	200	E
HE-343	1,920	2,070	150	IES-sonic

Table 7. Depths to salinity zone boundaries in the Floridan aquifer system as determined in this study--(Continued)

[Methods: E, conventional electrical log (normal and lateral devices); IES, deep induction and short normal devices; DIL, dual-induction log (deep and medium induction and shallow focusing electrode devices); LL, focusing electrode devices, such as laterologs; density, porosity from density device; sonic, porosity from sonic device; QW, water-quality data (samples from known intervals); DQW, water-quality data (samples taken while drilling by reverse-air rotary method). Methods are listed in order of importance in determining boundaries for each well. Other annotations: BBZ, base of brackish-water zone; TSZ, top of saline-water zone; ?, depth of boundary or thickness of zone is uncertain; *, depth of boundary is uncertain because of dolomite interbeds; --, no data; >, greater than the value; <, less than the value. Depths are from measuring point given in appendix I]

Local well identifier	Depth to base of brackish-water zone (feet)	Depth to top of saline-water zone (feet)	Thickness of salinity transition zone (feet)	Method
HE-941	<1,943	2,030	>87	E (top at 1,943)
HE-948	1,860	2,010	150	DIL
HE-949	1,995	2,070	75	IES-sonic
HE-970	2,084	2,214	130	DIL
HE-973	2,000	2,160	160	E
HE-1087	2,070?	No log	--	DIL (bottom at 2,082); QW
HE-1104	2,010	No log	--	DIL-density (bottom at 2,018); QW
HE-1105	1,840	1,900	60	DIL-density
L-2657	Not reached at 916	--	--	E (bottom at 916)
L-4846	1,000?	Not reached	--	E (bottom at 1,010)
L-5000	All saline	--	--	LL
L-5003	1,690	1,790?	100?	E
L-5009	>1,685	Not found	--	LL
L-5013	1,500	1,580	80	E
L-5602	Not reached at 960	--	--	E (bottom at 960)
L-5605	1,640	1,716	76	LL-sonic
L-5802	1,560	1,655	95	E for BBZ; DIL-sonic for TSZ
L-6412	570	592	22	E
L-6423	1,085	1,130	45	E
L-6435	1,060	--	--	DQW
L-6436	900	--	--	DQW
L-6437	1,070	--	--	DQW
L-6445	900	--	--	DQW
L-6461	1,680	1,745	65	DIL-sonic
L-6462	Not reached at 1,300	--	--	DIL (bottom at 1,310)
L-6463	1,530	Not reached at 1,544	--	DIL (bottom at 1,544)
L-6471	<730	765	--	DIL-sonic
PB-1137	2,220	2,540*	320?	E
PB-1138	2,030	2,160	130	DIL-sonic

Geophysical logs of well L-6461 in eastern Lee County provide an ideal example in determining the boundaries of the brackish-water zone, salinity transition zone, and saline-water zone (fig. 19). The threshold formation resistivity values used for defining the salinity boundaries in this well were determined based on porosity as calculated from a sonic log run in the well (eq. 2) and calculated formation resistivity values (tables 3 and 4). For the base of the brackish-water zone, a resistivity value of 6.2 ohm-m was determined with a calculated porosity of about 30 percent and a formation temperature of 95 degrees Fahrenheit. For

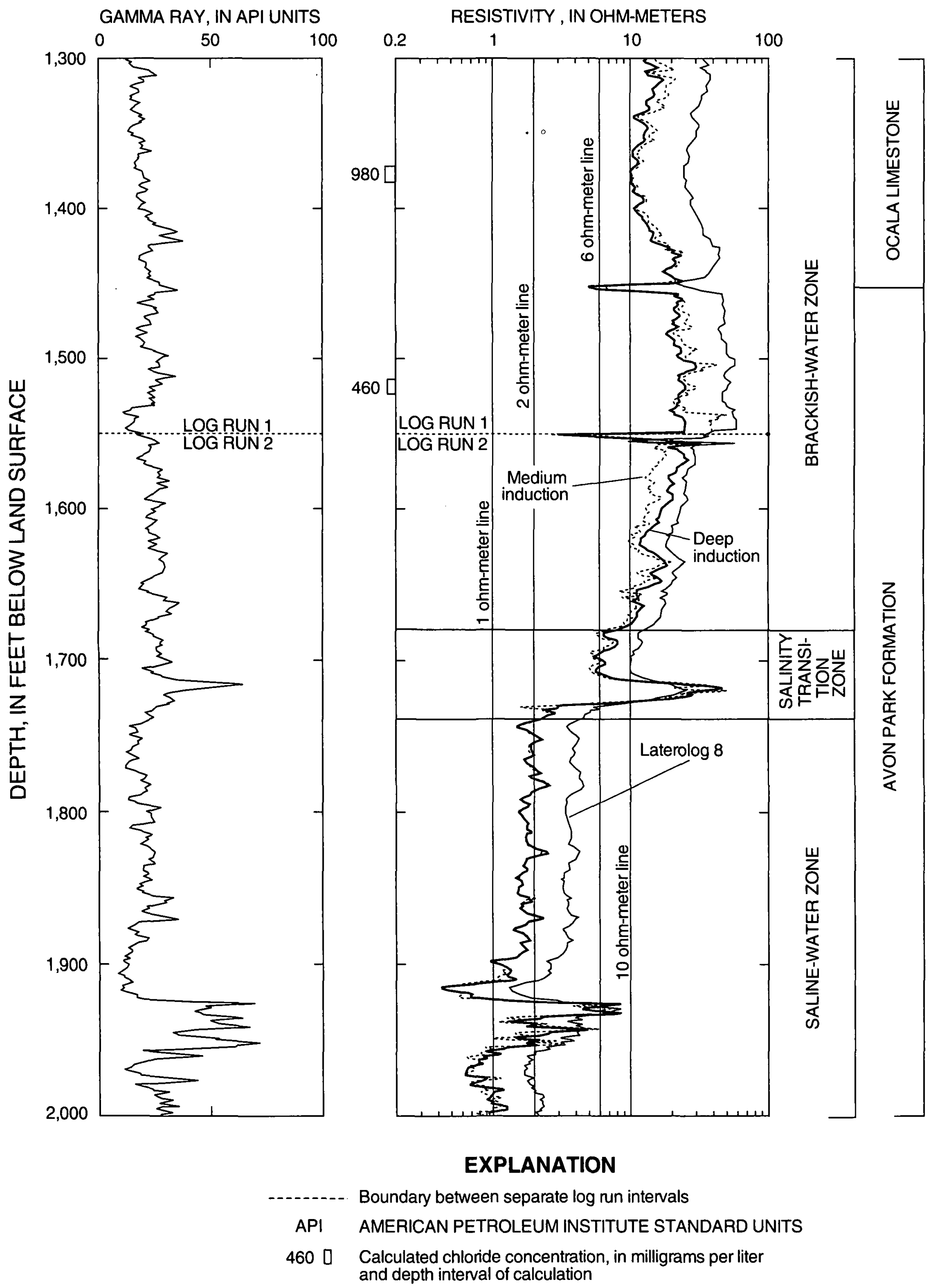


Figure 19. Geophysical logs, calculated chloride concentration, salinity zones, and geologic units for well L-6461 in eastern Lee County in the Floridan aquifer system.

the top of the saline-water zone, a value of 1.7 ohm-m was determined with a calculated porosity of 33 percent and the same temperature.

Chloride concentrations were calculated based on geophysical logs in the brackish-water zone of well L-6461 at three depth intervals, and results indicate that salinity (at least in this well) does not greatly vary in this zone. The chloride concentration was calculated to be 450 mg/L (table 5) in the upper part of the brackish-water zone in the Suwannee Limestone at a depth of 828 to 1,030 ft. The two other depth intervals, 1,376 to 1,385 ft and 1,514 to 1,522 ft, were selected deeper in the brackish-water zone where resistivity was low (10 ohm-m) and high (22.5 ohm-m), respectively, as shown in figure 19. The calculated chloride concentrations were 980 and 460 mg/L, respectively, in these two depth intervals. No water samples were collected from well L-6461.

Salinity boundaries could not be determined in many of the wells in north-central Collier County because the salinity transition zone is either not present, which was the case for well C-727 (pl. 9 and fig. 20), or is poorly developed. Limestone is predomi-

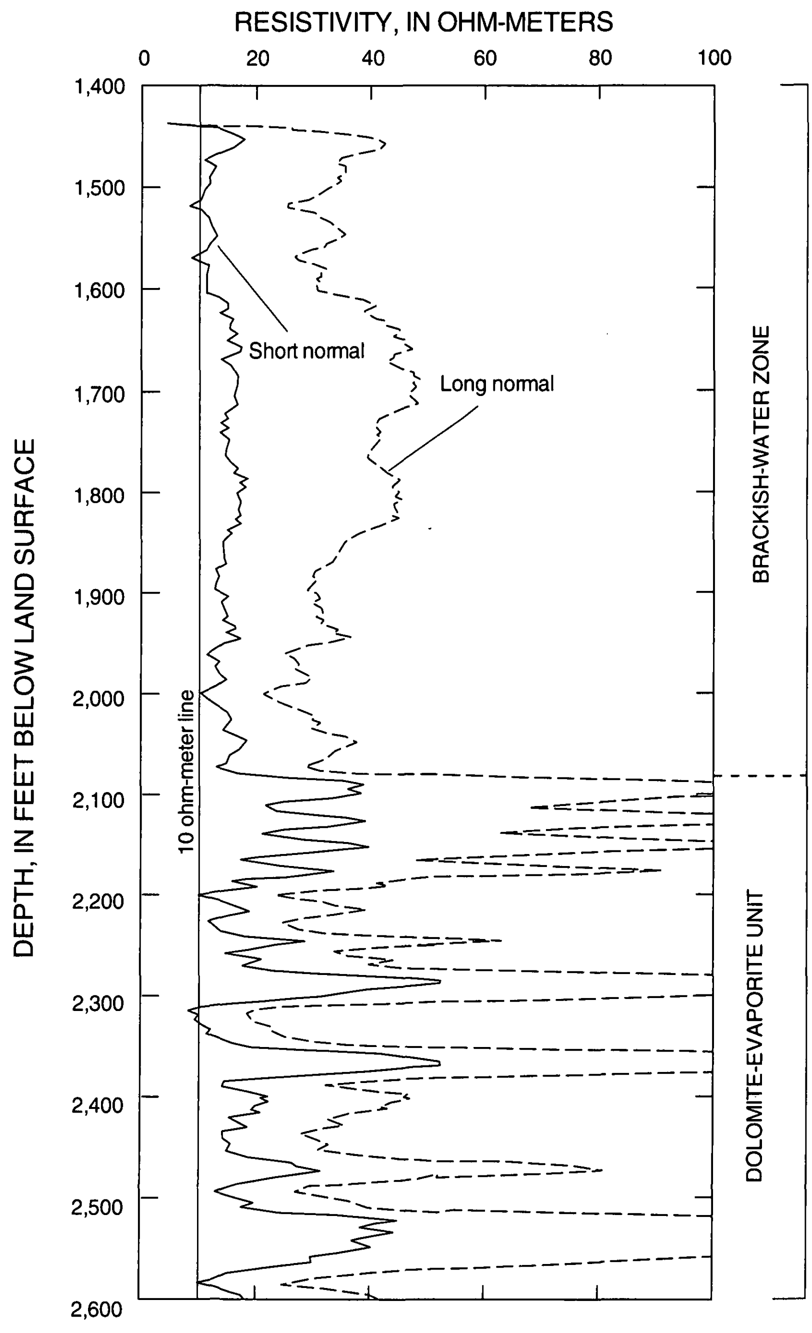


Figure 20. Resistivity geophysical log and salinity zones for well C-727 in northern Collier County. Salinity transition zone is not present.

nant in well C-727 to a depth of 2,080 ft, and thick beds of evaporite occur between 2,080 and 2,190 ft deep. The brackish-water zone extends down to the lithologic contact at 2,080 ft, which is the top of the dolomite-evaporite unit (fig. 11). The very low permeability sediments that are present below this contact probably prevent the development of the salinity transition zone.

The transition zone is not present or is poorly defined in well C-708 in northern Collier County based on a conventional electrical log (fig. 21). The base of the brackish-water zone could be present as high as 1,510 ft based on the increase in resistivity above this depth; however, the resistivity of about 8 ohm-m (medium normal) at this depth is higher than the 6.5 ohm-m value that normally is used to define the base of the brackish-water zone. Additionally, resistivity in the depth interval of 1,510 to 1,960 ft does not sharply decrease, and resistivity recorded by the medium normal device ranges from 6 to 10 ohm-m. The depth of investigation for the three devices on this log increases from the short normal to the medium normal to the long lateral. The resistivity profile with distance away from the borehole shown by the curves recorded from these three devices (fig. 21) indicates invasion by saline borehole fluid. Therefore, true formation resistivity is indicated to be higher than that shown by the medium normal, and could even be higher than that shown by the long lateral curve. The long lateral curve has the greatest depth of investigation in well C-708 and is no lower than 8 ohm-m in the depth interval from 1,510 to 1,960 ft. Thus, the brackish-water zone could extend to 1,960 ft, which is the depth of the top of the dolomite-evaporite unit.

Depth to the Base of the Brackish-Water Zone

The approximate depth to the base of the brackish-water zone was determined for each well in the study area in which adequate data were available (table 7). Difficulties in determining salinity zone boundaries based on geophysical logs and water-quality data were previously described. A map showing the altitude of the base of the brackish-water zone is shown in figure 22. The base of the brackish-water zone ranges from about 565 ft below sea level in northwestern Lee County on Pine Island (well L-6412)

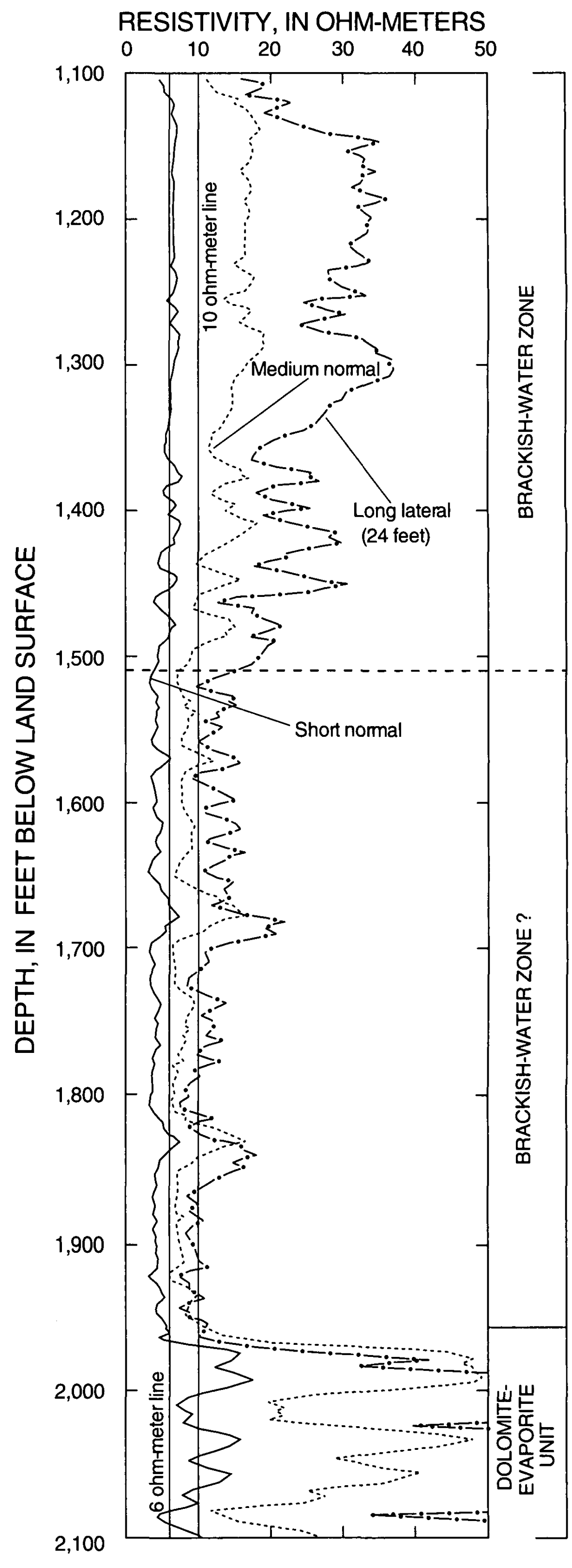


Figure 21. Resistivity geophysical log and salinity zones for well C-708 in northern Collier County. Brackish-water zone extends down to at least 1,510 feet and could extend down to 1,960 feet.

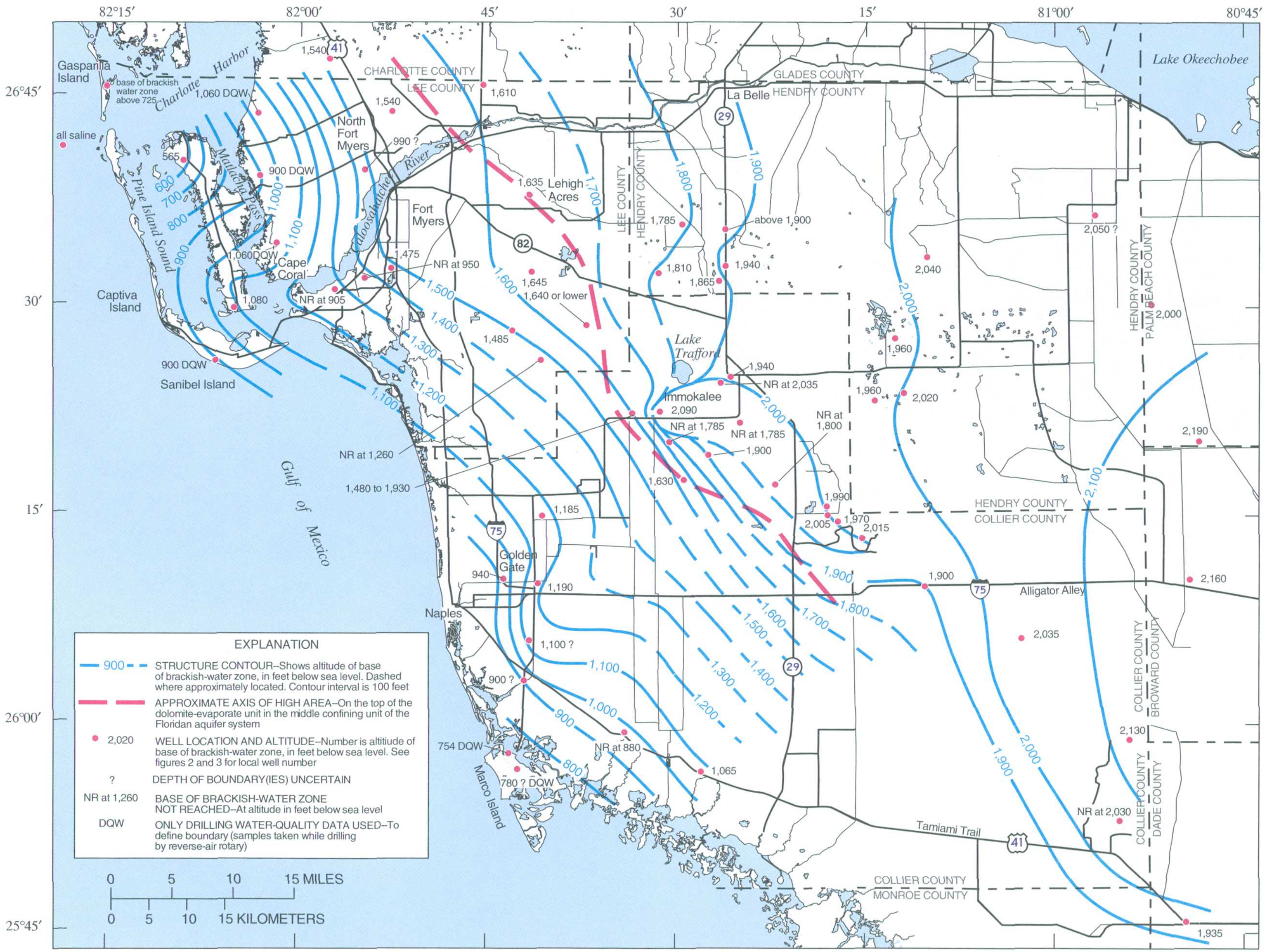


Figure 22. Altitude of the base of the brackish-water zone in the study area.

to about 2,200 ft below sea level in southwestern Palm Beach County (well PB-1137). The mapped surface, in general, rises gently to the west in most of Hendry County and far eastern Collier County and rises more rapidly to the west upon approaching the coast. The direction of the dip is opposite to that of the potentiometric surface of the Upper Floridan aquifer (Bush and Johnston, 1988, pl. 5), supporting the interpretation that the salinity transition zone represents a diffuse salinity interface, the depth of which is controlled by head in the brackish-water zone. This interpretation also is supported by the location of potentiometric-surface contours in Lee County, an area where they are well defined (Bush and Johnston, 1988, pl 5). The dip of the potentiometric surface to the west increases at a position in central Lee County that coincides with where the dip of the base of the brackish-water zone to the east increases (fig. 22).

The base of the brackish-water zone occurs near the basal contact of the Hawthorn Group in several wells within the study area. Because of the lithologic and hydrologic changes that often occur here, determination of the base of the brackish-water zone when it is near or above this contact is uncertain. Marco Island in southwestern Collier County is one area in which the base occurs at or near the top of the Suwannee Limestone. In well C-1104 on Marco Island (pl. 7), the base of the brackish-water zone was located above the basal contact of the Hawthorn Group as shown by water-quality data collected from well C-1101 (app. II), which is collocated with well C-1104 (fig. 3).

A thin zone of brackish or moderately saline water at the top of the Upper Floridan aquifer could extend farther out toward the coast than predicted based on the altitude of the base of the brackish-water zone (fig. 22). In well L-6471 on Gasparilla Island in northwestern Lee County (pl. 1), the top of the saline-water zone is at a depth of 765 ft (table 7) with the top of the Suwannee Limestone present at 730 ft (app. III). The presence of a thin zone of moderately saline water (salinity transition zone) in well L-6471 from 730 to 765 ft, as opposed to saline water, is supported by a chloride concentration of 7,600 mg/L which was calculated based on geophysical logs at a depth interval from 730 to 753 ft (table 5). The presence of this thin salinity transition zone in well L-6471 would not have been expected based on the contours shown in figure 22.

Areas of Anomalous Altitude of the Base of the Brackish-Water Zone

An anomalous low area at the base of the brackish-water zone is present in north-central Collier County (fig. 22). The brackish-water zone in this area extends deeper than expected, by as much as 300 ft. The base is at least as deep as 2,090 ft below sea level (well C-710), and the salinity transition zone is either not present or is poorly defined (figs. 20 and 21, wells C-727 and C-708). Additionally, the base of the brackish-water zone seems to rise very rapidly on the west side of the anomalous area. This is apparent in the area around wells C-711 and C-712, between which the surface rises almost 300 ft in about 3 mi, and between wells C-1107 and C-712 on hydrogeologic section D-D′ (pl. 5), which extend across the anomalous area from west to east.

The origin of this anomalous area is probably related to the permeability of the sediments in the underlying middle confining unit of the Floridan aquifer system. As discussed earlier, gypsum or anhydrite is present in this unit in north-central and western Collier County at a depth as shallow as 1,800 ft, and its presence (together with dense dolomite) could substantially reduce the vertical permeability of the unit. Impermeable beds in the middle confining unit could result in a major hydrologic boundary, preventing the movement of brackish water below the top of the beds. These beds could also prevent the establishment of a normal salinity transition zone above, if this process is dependent on the upward movement of saline water from below, such as from the Boulder zone. Upward movement of saline water from the Boulder zone due to geothermal heating under the Floridan Plateau was proposed by Kohout (1965). Evidence in support of this theory is found by the presence of temperature anomalies in the Upper Floridan aquifer and warm saline-water springs located in western Lee County and north of the study area along the west coast (Meyer 1989, fig. 25).

Comparison of the location of the brackish-water zone anomalous area with the map showing the altitude of the top of the dolomite-evaporite unit (fig. 11) suggests an origin for the anomalous area. The axis of the high area on top of the dolomite-evaporite unit that trends to the northwest, starting in central Collier County, lies adjacent to the anomalous area and parallels its southwestern side (fig. 22). This high area could be acting as an impermeable sill, preventing more dense saline water from moving laterally from the coast to the southwest and beneath the anomalous area, displacing water in the lower part of the brackish-water zone. Additionally, during the rise in sea level since the end of the Pleistocene Epoch, this sill and the dolomite-evaporite unit beneath the anomalous area could have prevented the upward adjustment of the salinity interface in the anomalous area, an adjustment which probably occurred in most other areas.

Another anomalous low area at the base of the brackish-water zone is in western Collier County to the southwest of the area described above (fig. 22). Also in this area, the base of the brackish-water zone is deeper than expected as shown by well C-726 (base at 1,100 ft below sea level), and the salinity transition zone is not well developed as shown by well C-1103, where the thickness of this zone is 420 ft or greater (table 7). Gypsum or anhydrite might also be present in the middle confining unit of the Floridan aquifer system in this area, reducing its permeability and possibly preventing the development of a brackish-water/saline-water interface at equilibrium because of retardation of the upward movement of saline water.

Distribution of Salinity by Zone

Water-quality data used to describe salinity in the Floridan aquifer system in this report were selected from data collected as early as 1941. In most of the study area, conditions are not believed to have changed enough to have significantly affected predevelopment water quality. This is because development of the Floridan aquifer system in southwestern Florida, as in the rest of southern Florida, has been minimal. One exception could be the area along the Caloosahatchee River in Lee County where the potentiometric surface in the LHPZ and Suwannee Limestone portion of the Upper Floridan aquifer declined as much as 8 ft from the 1944-50 to the 1966-73 period (Boggess, 1974, fig. 5). This area extends 4 to 5 mi away from the river on both sides. However, as will be shown based on the data in appendix II, salinity even in this area has not increased relative to surrounding areas. Decline of the estimated predevelopment potentiometric surface of the Upper Floridan aquifer in all of southern Florida was less than 10 ft in May 1980 (Bush and Johnston, 1988, pl. 6).

Many of the wells completed in the Floridan aquifer system in the study area, particularly in Lee County, were short cased, such that either the sandstone aquifer or mid-Hawthorn aquifer of the intermediate aquifer system or both are open for production in addition to the LHPZ of the Upper Floridan aquifer. Samples in appendix II were selected to show water-quality data from the LHPZ or deeper and to avoid wells open in at least the sandstone aquifer. In Lee County an attempt was made to select samples for which the top depth of the interval sampled was at a minimum depth of 300 ft, and the bottom of the sample interval was deeper than about 200 ft above the basal contact of the Hawthorn Group as determined by figure 7. The value of 200 ft is related to the thickness of the LHPZ.

Brackish-Water Zone

Because many wells are open to more than one producing zone, few water-quality data were available to map the distribution of salinity by zone or formation in the upper part of the brackish-water zone; therefore, this was not done for the study. However, if the basal contact of the Hawthorn Group marks a major hydrologic boundary, such as the top of the Floridan aquifer system, a significant change in salinity across the contact could be present. A total of 39 water samples from 38 wells (app. II) were identified where the sampled depth interval did not overlap the basal contact of the Hawthorn Group but was still above the base of the brackish-water zone. The interval was located above the contact for 21 of these samples and was located below the contact for 18 of these samples. A plot of the midpoint depth of the sample interval and chloride concentration for each sample was made with points distinguished by this grouping (fig. 23). This plot shows that salinity does not change substantially between the sampled intervals above and below the basal contact of the Hawthorn Group.

A decrease in salinity with depth can occur across the basal contact of the Hawthorn Group in inland areas. For example, in western Broward County, well G-2296 and monitor tube G-2618 (pl. 6), within the same well, were completed above and below the basal contact of the Hawthorn Group, which is at a depth of 980 ft. Depths of completed intervals sampled were 811 to 816 ft in well G-2296 and 1,104 to 1,164 ft in monitor tube G-2618; chloride concentrations of recovered water samples were 1,600 and 620 mg/L, respectively (app. II).

A map showing the distribution of chloride concentration in the upper part of the brackish-water zone (fig. 24) was constructed based on selected water sample analyses (app. II) and water-quality data calculated from geophysical logs (table 5). The geologic units analyzed include the LHPZ, Suwannee Limestone, Ocala Limestone, and the Avon Park Formation, although only one well has a depth interval in the Avon Park Formation (well HE-1107 from 1,546 to 1,579 ft; app II). Emphasis is on the LHPZ and Suwannee Limestone with all but six of the water analyses from intervals with a bottom depth of about 1,100 ft or less, and all but one log analysis with the depth interval located only in the Suwannee Limestone.

Chloride concentrations in the upper part of the brackish-water zone range from about 400 to 4,000 mg/L (fig. 24). Concentrations are low in three large areas as generally defined by the 400- and 800-mg/L contours shown in figure 24. One of these areas is along the northern side of the Caloosahatchee River in Lee County, extending to the southwest across Pine and Captiva Islands; the second area is in southeastern Lee County, extending southeast into north-central Collier County; and the third area is in eastern Hendry and Collier Counties.

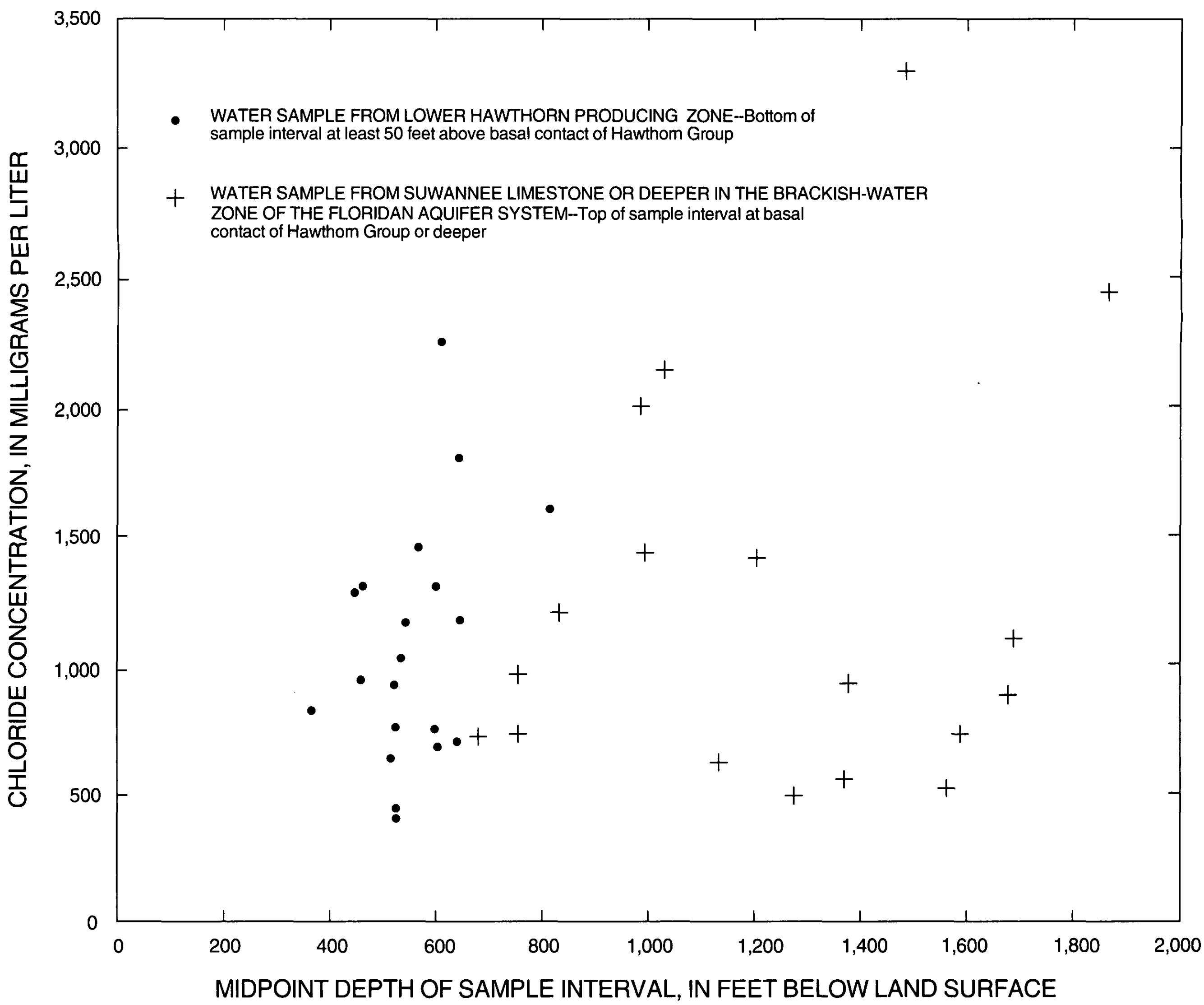


Figure 23. Distribution of chloride concentration in ground water relative to depth above and below the basal contact of the Hawthorn Group.

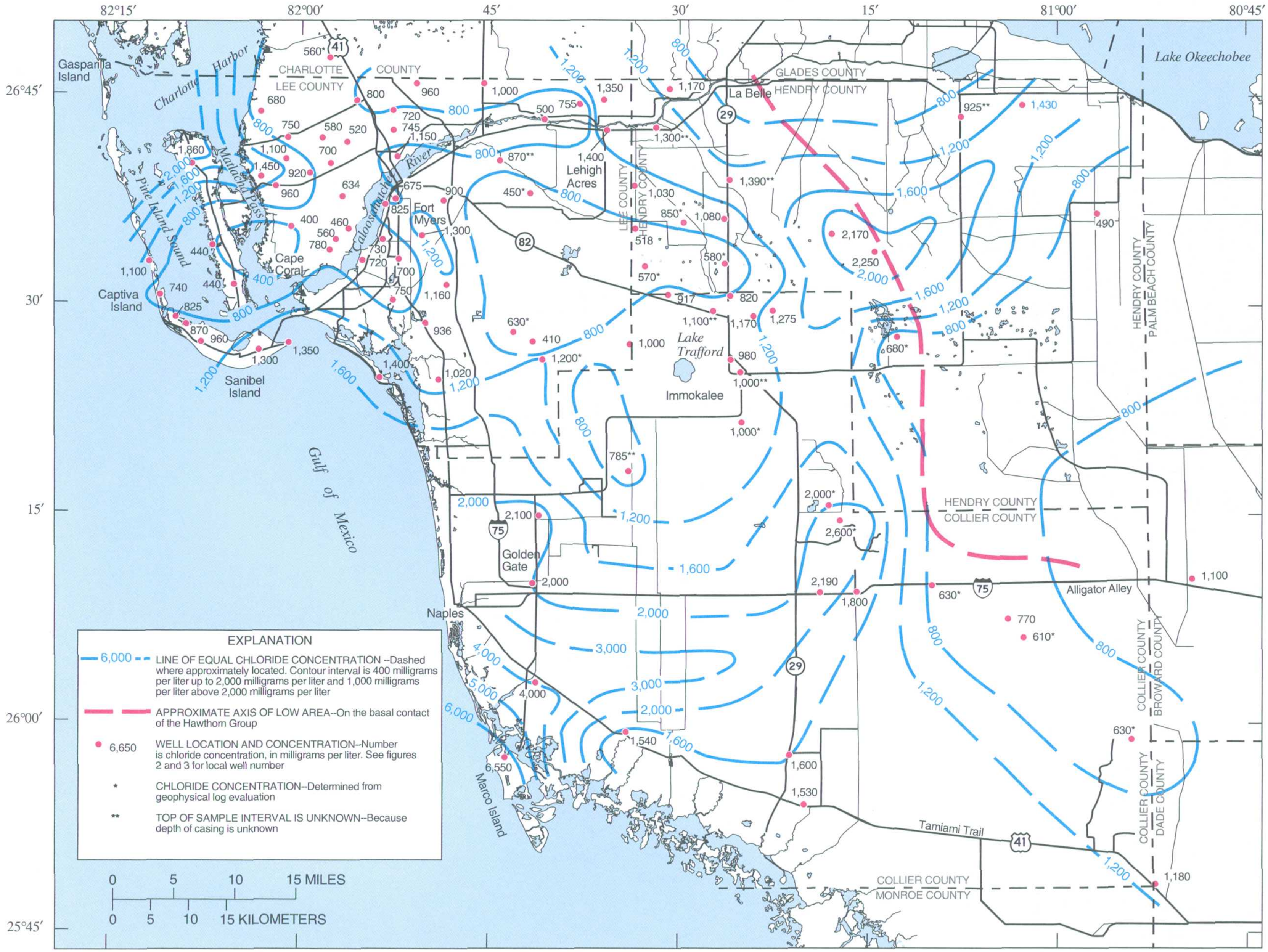


Figure 24. Lines of equal chloride concentration in ground water from the upper part of the brackish-water zone in the Floridan aquifer system in the study area.

A review of the chloride concentrations was made for the area along the Caloosahatchee River in which Boggess (1974, fig. 5) found significant drawdown in the potentiometric surface of the LHPZ and Suwannee Limestone portion of the Upper Floridan aquifer. A matching area of high salinity, which could have resulted from this drawdown due to upward movement of saline water from the saline-water zone, was not found (fig. 24). Well L-5611, located close to the north bank of the river in North Fort Myers, was the only well that had higher-than-expected salinity in this area of drawdown, with a chloride concentration of 1,150 mg/L (app. II). In well L-4846, also located along the northern bank of the river near North Fort Myers, the base of the brackish-water zone occurred at a depth of about 1,000 ft (table 7), which was much shallower than expected based on the altitude of the base of the brackish-water zone in the area (fig. 22).

If the area of low salinity in southeastern Lee County extending into north-central Collier County, as defined by the 800-mg/L line of equal chloride concentration in figure 24, is expanded to include the area defined by the 1,200-mg/L line, this area coincides with an area of high altitude at the basal contact of the Hawthorn Group (fig. 7). The surface mapped at the basal contact of the Hawthorn Group dips away in all directions from this area of relatively low salinity, except to the northwest, and continues to dip down to the east until a low area is reached in western Hendry County, as shown by the axis of low altitude of the basal contact of the Hawthorn Group (fig. 24).

The increase in salinity in central and northwestern Hendry County coincides with the development of a thick basal Hawthorn unit, with higher salinity in this unit than in the underlying formations. Wells HE-296 and HE-297 completed only in the LHPZ are in this area where the unit is thick (fig. 8). The produced water from these wells has a chloride concentration greater than 2,000 mg/L (fig. 24). In well HE-1104 (figs. 1 and 8, pl. 4) also in this area of thick basal Hawthorn unit, salinity in the basal Hawthorn unit is high, as indicated by the low level of resistivity recorded by the deep induction resistivity curve. The resistivity in much of the basal Hawthorn unit in this well is significantly less than 10 ohm-m, whereas in most other areas, resistivity in the unit is higher than 10 ohm-m (pl. 2). The resistivity in the brackish-water zone below the basal Hawthorn unit in well HE-1104 is 20 ohm-m or greater, which indicates relatively low salinity (pl. 4).

The increase in salinity in central Collier County results from a salinity increase in the lower part of the basal Hawthorn unit and the Suwannee Limestone, but not necessarily in deeper units. For example, geophysical log evaluation shows that the calculated chloride concentration in the Suwannee Limestone in well C-820 averages more than 2,000 mg/L over a depth interval of 810 to 1,033 ft (fig. 17); however, the calculated chloride concentration in individual zones within this interval decreases to less than 1,000 mg/L at 1,030 ft, which is toward the base of the Suwannee Limestone (fig. 17). Resistivity in the lower part of the Suwannee Limestone and the upper part of the Ocala Limestone in well C-820 is 10 ohm-m or greater (pl. 5). Additionally, salinity is higher in the Suwannee Limestone than in underlying formations in well C-1124 (near well C-820) as shown by high values on the deep induction resistivity curve (pl. 10).

The areas of higher salinity discussed above in central and northwestern Hendry County and central Collier County have common characteristics and could have a similar origin. In these areas, the higher salinity is within the basal Hawthorn unit or Suwannee Limestone only. Additionally, the basal contact of the Hawthorn Group is relatively deep in these areas. The higher salinity in these areas could have resulted from the influx of seawater into zones of higher permeability in structurally low areas during high sea-level stands of the Pleistocene Epoch. The influx of seawater could have come from the area to the southwest of well C-820 in southwestern Collier County. A similar origin for areas of high salinity in the Upper Floridan aquifer near or along the coast in southeastern Florida was proposed by Reese (1994, p. 45). Flushing of these areas by fresher water after the high stand due to the lowering of sea level and the buildup of head in the Upper Floridan aquifer has not been complete.

The origin of the area of high salinity that extends from southwestern Collier County into central Collier County could also be related to structure and tectonic movements. As previously discussed, a narrow low area trending northeast-southwest at the top of the basal Hawthorn unit is present in this area (fig. 6), and the origin of this low area could be related to possible faults that bound it, particularly along its northwest side. If such faulting does exist, it could have resulted in permeability enhancement in a direction parallel to the faulting due to fracturing and dissolution in the Upper Floridan aquifer, and this enhanced permeability could have allowed the movement of saline water from the southwest.

High salinity occurs in some areas along the coast in the upper part of the brackish-water zone because the base of the brackish-water zone (fig. 22) rises up close to or above the basal contact of the Hawthorn Group (fig. 7). This occurs in the Marco Island area of southwestern Collier County (fig. 24). A water sample collected from well C-1101 had a chloride concentration of 6,550 mg/L at a depth of 800 ft while drilling in the basal Hawthorn unit (app. II). The base of the brackish-water zone extends above the basal contact of the Hawthorn Group in the Marco Island area (pls. 7 and 8, well C-1104). Another area of high salinity along the coast occurs on islands in far northwestern Lee County (fig. 24). The base of the brackish-water zone also rises up to the basal contact of the Hawthorn Group and higher in this area (pl. 1 and fig. 22).

Salinity Transition Zone

The salinity transition zone is an interface that forms because of equilibrium between two water masses of contrasting density. A salinity transition zone with a thickness of 150 ft or less was found in most of the study area (table 7), indicating that a brackish-water/saline-water interface has developed similar to what was found in southeastern Florida (Reese, 1994, p 43). The thickness of the transition zone in southeastern Florida in 10 of the 18 wells in which it was measured was 124 ft or less (Reese, 1994, p. 40). However, the thickness of the transition zone in southwestern Florida can be much greater than 150 ft. In the anomalous area on the surface at the base of the brackish-water zone in western Collier County, the thickness of the salinity transition zone is 560 ft in well C-1107 and possibly as much as 620 ft in well C-726 (table 7).

Saline-Water Zone

Variability in salinity is minor in the saline-water zone as shown, for example, by the low variability in resistivity (at least down to 1,910 ft) in well L-6461 (fig. 19). Depth intervals below 1,910 ft with resistivity less than 1 ohm-m, such as the one from 1,910 to 1,925 ft where resistivity is as low as 0.5 ohm-m, probably are where the borehole is greatly enlarged because of the collapse of fractured dolomite or the presence of cavernous features. Assuming a salinity similar to a dissolved-solids concentration of 35,000 mg/L and a porosity at this depth of not greater than 40 percent, a formation resistivity of at least 1 ohm-m is expected (table 4). The presence of an enlarged borehole in these intervals is confirmed by a caliper curve recorded with the sonic log in well L-6461. If dolomite is present, the resistivity would be expected to be high because of the low porosity characteristic of dolomite; dolomite beds are present from 1,920 to 1,960 ft in well L-6461 as indicated by the high resistivity and gamma-ray spikes (fig. 19).

Although the salinity of water in the saline-water zone is similar to seawater, there is some variability. Based on wells in which the depth to the top of the saline-water zone was determined (table 7), 13 results of analyses in appendix II were found to be from intervals in the saline-water zone. Of these, considering only the analyses from completed intervals, the minimum and maximum values for chloride concentration were 17,500 and 20,800 mg/L, respectively. In comparison, two analyses of seawater give chloride concentrations of 19,000 mg/L (Hem, 1985, table 2) and 19,800 mg/L (Nordstrom and others, 1979). Water samples collected from the Boulder zone of the Lower Floridan aquifer were not used in this report, but the average dissolved-solids concentration of Boulder zone water from eight wells in southeastern Florida was 37,000 mg/L, which is slightly higher than that normally found in seawater (Reese, 1994, p. 40).

Distribution of Sulfate

The influence of gypsum dissolution and mixing with seawater on the concentration of sulfate in water from the Floridan aquifer system can be evaluated by plotting the sulfate-to-chloride equivalent ratio against sulfate concentration (Rightmire and others, 1974). Based on 60 water analyses from appendix II, a plot was constructed showing that sulfate in water from the Floridan aquifer system generally comes from the mixing of dilute ground water with seawater (fig. 25). However, the position of much of the data on the plot indicates that a small portion of the sulfate was derived from gypsum dissolution.

A plot of chloride and sulfate concentrations of the same data used in figure 25 shows that the three salinity zones, as defined in this study, plot in different positions in relation to a pure water-seawater mixing line (fig. 26). The salinity zone from which each water sample came was determined for all of the data points in figure 26 based on determined salinity zone boundaries (table 7). All of the data points with chloride concentrations less than 4,000 mg/L are from water samples collected in the brackish-water zone, and most of these plot above the mixing line. The points that have intermediate chloride concentrations from 7,150 to 17,000 mg/L are from the salinity transition

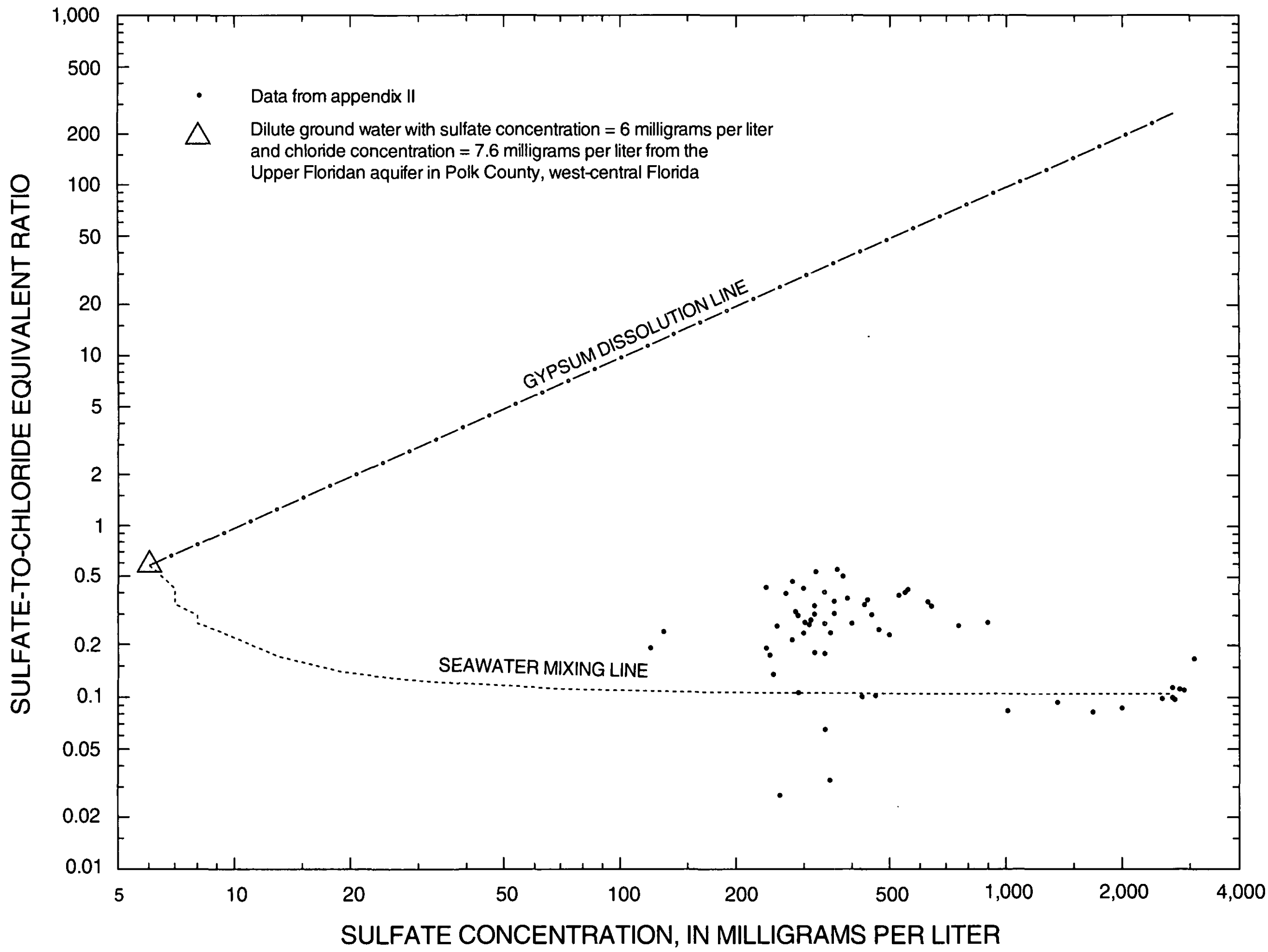


Figure 25. Sulfate concentration and sulfate-to-chloride equivalent ratio for 60 water samples from the Floridan aquifer system with relation to the gypsum dissolution and seawater mixing lines. (Modified from Rightmire and others, 1974.)

zone, and all but one plot below the mixing line. The six points that have chloride concentrations more than 17,000 mg/L plot close to the mixing line, and all of these samples were collected from the saline-water zone. The depletion of sulfate that apparently occurs in the salinity transition zone probably is the result of sulfate reduction. This process commonly occurs in the Upper Floridan aquifer in Florida (Katz, 1992, fig. 22).

The one data point from the salinity transition zone that plots well above the pure water-seawater mixing line in figure 26 has chloride and sulfate concentrations of 13,500 and 3,080 mg/L, respectively. These concentrations were measured in well C-820 in north-central Collier County at a depth interval of 1,998 to 2,500 ft (app. II). Although most of this sampled interval is in the salinity transition zone, the bottom 135 ft could be in the saline-water zone (table 7 and pl. 5). The high sulfate concentration in this water sample can be explained by the occurrence of gypsum or anhydrite at these depths.

Thirty-nine analyses from appendix II were used to map the distribution of sulfate in the brackish-water zone in southwestern Florida (fig. 27). In the interval sampled, five analyses came from the lower part of the brackish-water zone, and the remaining analyses came from the upper part of the brackish-water zone. The area with the highest concentration of sulfate lies in north-central and western Collier County where, for example, 900 mg/L was determined in well C-1124. Another smaller area where the sulfate concentration is relatively high (greater than 300 mg/L) is in north-central Lee County and south-central Charlotte County. The area with the lowest concentration of sulfate (120-300 mg/L) occurs in western Lee County to the west of the Caloosahatchee River.

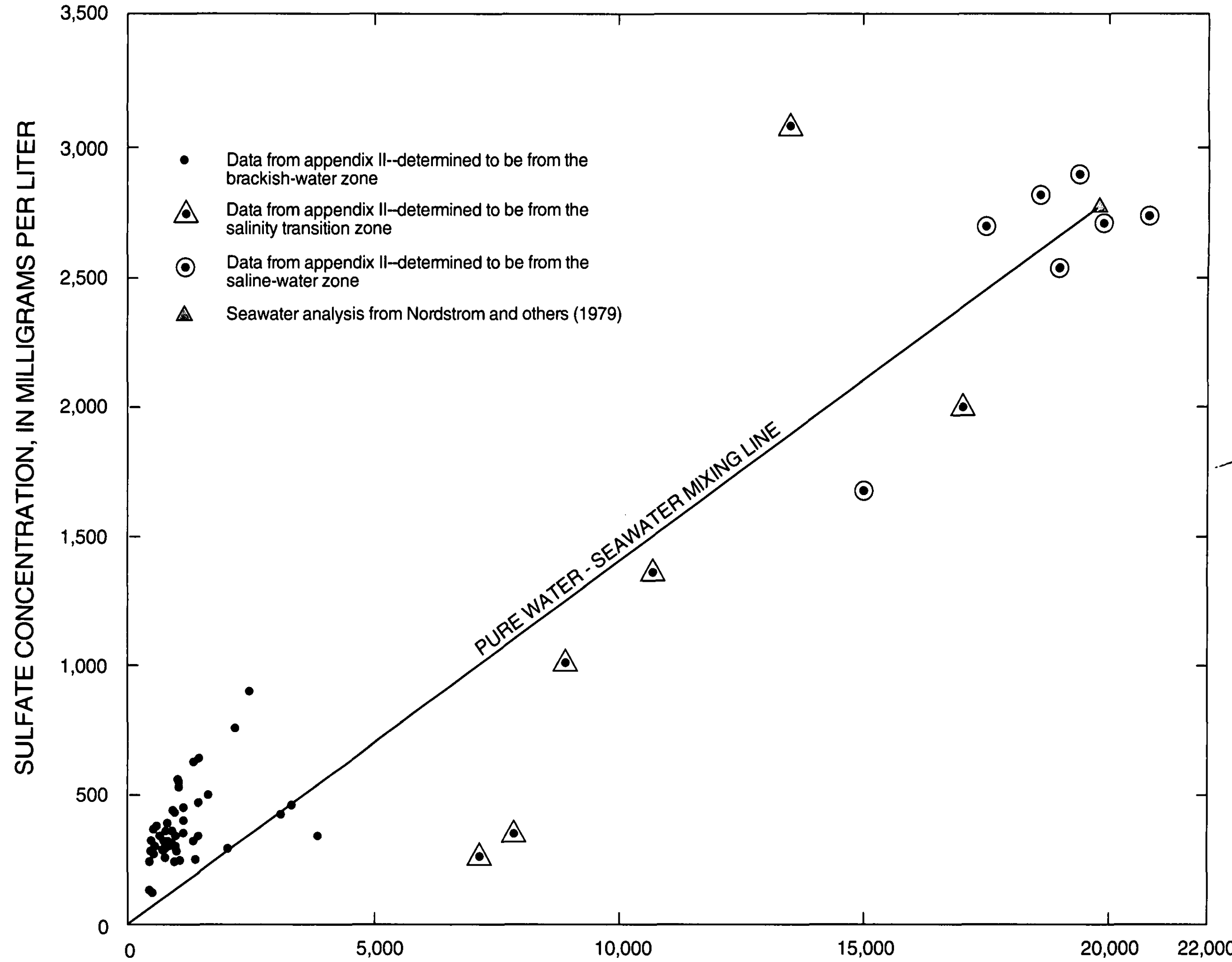


Figure 26. Distribution of chloride and sulfate concentrations in ground water from the Floridan aquifer system relative to a pure water-seawater mixing line. Data showing grouping relative to mixing line by salinity zone.

The area of high sulfate concentration in north-central and western Collier County coincides with the area of gypsum or anhydrite occurrence in the middle confining unit of the Floridan aquifer system, suggesting that the higher sulfate concentration in the brackish-water zone is probably related to this occurrence. Gypsum in the middle confining unit probably also occurs in the other area of higher sulfate concentration in north-central Lee and south-central Charlotte Counties. This is supported by the northwest-trending high area at the top of the dolomite-evaporite unit in the middle confining unit (fig. 11), which probably resulted from gypsum deposition. The axis of this high area passes near or through these two areas of higher sulfate concentration.

High sulfate concentration occurs in the Upper Floridan aquifer in southwestern Florida just to the north of the study area. Geochemical modeling indicates that these elevated sulfate concentrations result from the upwelling of deeply circulating ground water within the freshwater flow system of the Upper Floridan aquifer, with the source of the sulfate being gypsum dissolution in the lower part of the flow system (Sacks and Tihansky, 1996). In all of the area studied in this report, the Upper Floridan aquifer is confined with only the possibility of discharge occurring (Bush and Johnston, 1988). Therefore, some upwelling of deeply circulating ground water could also be occurring in the brackish-water zone in the study area. This upwelling could help to explain the areas of high sulfate concentration (fig. 27) and explain why these higher values are found in the upper part of the brackish-water zone where gypsum is not known to occur.

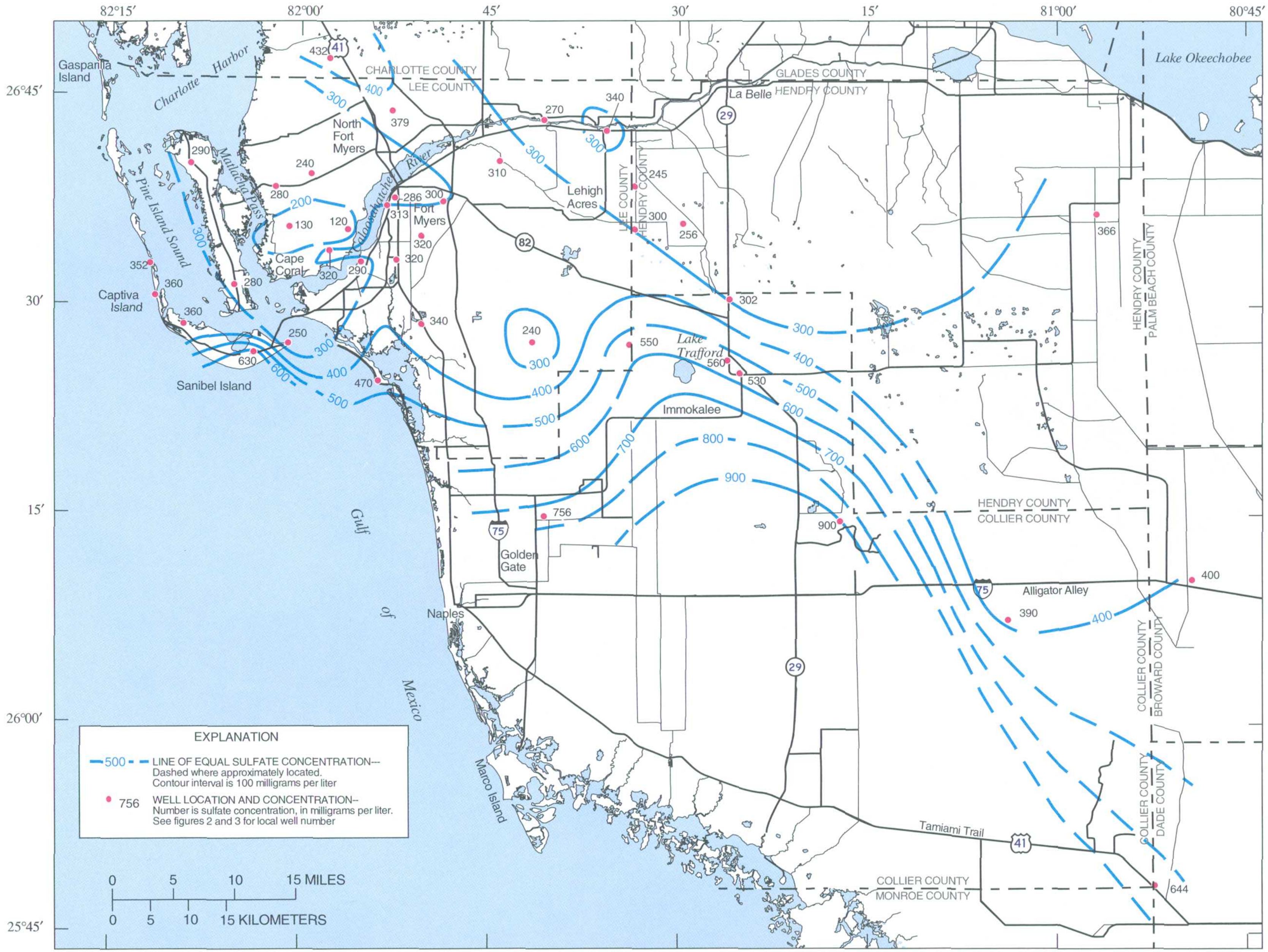


Figure 27. Lines of equal sulfate concentration in ground water from the brackish-water zone of the Floridan aquifer system in the study area.

SUMMARY AND CONCLUSIONS

The Floridan aquifer system is considered to be a valuable supplemental source for public-water supply in southwestern Florida even though it contains only brackish water. Aquifers in shallower aquifer systems in this area are limited by comparison or have been seriously impacted by pumpage or saltwater intrusion. The primary purpose of this study was to establish and describe the hydrogeologic framework, describe and evaluate the distribution of salinity in the aquifer system, and relate the distribution of salinity to the hydrogeologic framework thereby allowing for increased understanding of processes that control this distribution.

The Floridan aquifer system consists primarily of limestone and dolomite of Oligocene and Eocene age. The principal geologic units in the system are the lower part of the Hawthorn Group, Suwannee Limestone, Ocala Limestone, Avon Park Formation, and Oldsmar Formation. A basal portion of the Hawthorn Group, referred to as the basal Hawthorn unit, was defined based on a regionally extensive and correlative marker unit at its top.

The base of the basal Hawthorn unit (basal contact of the Hawthorn Group) usually coincides with the top of the Suwannee Limestone, but also coincides with the top of the Ocala Limestone in the eastern part of the study area; the altitude of this basal surface ranges from about 500 to more than 1,000 ft below sea level. This contact is probably a regionally extensive unconformity that could have formed during a major low stand in sea level occurring at the boundary between early to late Oligocene time. Correlation of this unconformity between southwestern and southeastern Florida in the stratigraphic section indicates that it occurs at the same position as the one mapped on top of rocks of Eocene age in southeastern Florida.

The basal Hawthorn unit ranges from about 120 to 460 ft in thickness in the study area. Its variation in thickness probably relates in most of the study area to the paleotopography prior to its deposition. This paleotopography could have been created by solution and erosion of the underlying limestone. However, in some areas of Lee County where the basal Hawthorn unit is thick, paleotopographic highs formed at the top of the unit due to depositional buildup. A marker bed, which defines the top of the unit, corroborates the depositional origin of these highs. In these high areas, zones of permeable limestone are present in the upper and middle parts of the basal Hawthorn unit and have characteristic gamma-ray log patterns.

The major hydrogeologic units in southwestern Florida are the surficial aquifer, intermediate aquifer system, and Floridan aquifer system. The surficial aquifer generally is unconfined, and its base is defined by the first occurrence of laterally extensive and vertically persistent beds of much lower permeability. These beds are within the intermediate aquifer system. The Floridan aquifer system is confined by beds of low permeability in the intermediate aquifer system. The Floridan aquifer system consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer. This report principally deals with the Upper Floridan aquifer and middle confining unit.

The top of the Upper Floridan aquifer was determined based on head data, zones of lost circulation or returns, and temperature and spontaneous potential logs, which indicate the occurrence of flow zones. Over most of the study area, these data show that the top of the aquifer occurs approximately at the unconformity at the base of the basal Hawthorn unit. However, the lower 10 to 40 ft of the basal Hawthorn unit is often permeable, and if so, is included in the Upper Floridan aquifer. Additionally, where the basal Hawthorn unit is thick, such as in some areas of Lee County, significant flow zones in the Upper Floridan aquifer occur in the middle and upper parts of the unit.

Based on limited measurements of hydraulic conductivity and transmissivity, the base of the Upper Floridan aquifer ranges from about 1,500 to 1,800 ft in depth (giving an approximate range of 700 to 1,200 ft for the thickness of the aquifer). The highest transmissivity value of the Upper Floridan aquifer (33,000 ft^2/d) occurs in southwestern Collier County. The transmissivity of the basal Hawthorn unit is related to the thickness of the unit. For example, in the Cape Coral area in west-central Lee County where the unit is thick, the transmissivity of the unit is the highest measured (12,300 ft^2/d).

The base of the middle confining unit usually extends down to at least 2,300 ft in the study area; its thickness ranges from 500 to 800 ft, and its hydraulic conductivity is as low as 1×10^{-5} ft/d. The top of a sequence in the middle confining unit containing thick beds of dolomite and evaporite minerals, referred to as the dolomite-evaporite unit, was mapped. The altitude of the top of this unit, which ranges from about 1,700 to more than 2,500 ft below sea level, is probably an important hydrologic boundary in much of the study area because of the very low permeability beds in the unit; in areas where the altitude is high, it could mark the base of the Upper Floridan aquifer. Mapping of the top of this unit shows that a prominent feature of higher altitudes is present in central Collier County, which extends to the northwest into north-central Lee County. This feature could have resulted from heavy, localized deposition of gypsum. The top of the unit in this area is as much as 400 to 500 ft higher than in adjacent areas to the east and west in Collier County.

Salinity in the Floridan aquifer system, as defined by chloride and dissolved-solids concentrations, was calculated based on geophysical logs of formation resistivity, porosity, and temperature. Porosity was determined based on sonic and density logs. Relations between sonic log response and density porosity were determined in wells where both logs were run over the same intervals in the Floridan aquifer system below the Hawthorn Group. Calculated values of formation water resistivity were converted to an equivalent chloride concentration based on relations previously derived in southeastern Florida, which are based on analyses of water samples from the Floridan aquifer system. Chloride concentrations were calculated for 21 intervals in 17 wells in which both resistivity and porosity logs were run, and these results were used to help define the distribution of salinity in the Floridan aquifer system. Seven of these intervals had associated water-quality data which could be used for comparisons, and the average difference between the calculated and measured values, expressed as a percent error, was 15 percent. This error is not large in view of the large variation in salinity found in the Floridan aquifer system in the study area.

In much of the study area, the Floridan aquifer system can be divided into three salinity zones. These zones, defined using the threshold salinity values equivalent to dissolved-solids concentrations of 10,000 and 35,000 mg/L are, in order of increasing depth, the brackish-water zone, salinity transition zone, and saline-water zone with the salinity in the saline-water zone similar to that of seawater. These two salinity values equate to chloride concentrations of about 5,240 and 18,900 mg/L, respectively, in the Floridan aquifer system. The base of the brackish-water zone and the top of the saline-water zone were defined in numerous wells in the study area mostly using geophysical logs.

The altitude of the base of the brackish-water zone ranges from 565 ft below sea level along the coast in Lee County to almost 2,200 ft below sea level far inland in Palm Beach County. The direction of dip and shape of this surface reflect the distribution of hydraulic head in the Upper Floridan aquifer, supporting the interpretation that the salinity transition zone represents a salinity interface, the depth of which is controlled by head in the brackish-water zone.

The base of the brackish-water zone is deeper than expected (as much as 300 ft) in north-central Collier County. The base is as deep as 2,090 ft below sea level, and the salinity transition zone is not present or is poorly defined in this area. The origin of this anomalous area is interpreted to be related to the development of the dolomite-evaporite unit in the middle confining unit of the Floridan aquifer system. The top of this impermeable unit occurs at the base of the brackish-water zone in this area, and the axis of a high area at the top of the unit, which trends to the northwest in Collier and Lee Counties, parallels and lies just to the west of the anomalous area. This high area could be acting as an impermeable sill, preventing saline water from moving in laterally from the coast to the southwest and up from the Boulder zone below in the Lower Floridan aquifer. Locating a Floridan aquifer system well field in or near this anomalous area could be optimal. Increases in salinity with time during withdrawal of ground water from the Upper Floridan aquifer could be minimal because of the thickness of the brackish-water zone, lack of a salinity transition zone, and the occurrence of the impermeable beds at depth.

The salinity transition zone is 150 ft or less in thickness in most of the study area. However, in another area where the base of the brackish-water zone is deeper than expected, the zone apparently is very thick (as much as 500 to 600 ft). The underlying saline-water zone extends to the base of the Floridan aquifer system, and variation of salinity within it is small. The chloride concentration of water samples collected from the completed intervals in the saline-water zone ranged from 17,500 to 20,800 mg/L.

In the brackish-water zone, comparison of analyses of water samples collected from depth intervals above the basal contact of the Hawthorn Group with water samples collected from depth intervals located below this contact indicates that chloride concentration generally does not vary across this contact. The distribution of salinity in the upper part of the brackish-water zone, including the basal Hawthorn unit, was mapped. Chloride concentrations range from

400 to 4,000 mg/L, but range from 800 to 2,000 mg/L in most of the study area. Three large areas contain chloride concentrations less than 800 mg/L; two are in Lee County and one is in eastern Collier County and southeastern Hendry County. Increases in chloride concentration generally were not found in a large area of ground-water withdrawal in Lee County over the last 50 years even though there was drawdown of head.

A large area of relatively low salinity, with chloride concentrations ranging from 500 to 1,200 mg/L, in the upper part of the brackish-water zone in southeastern Lee and north-central Collier Counties coincides with an area of high altitude at the basal contact of the Hawthorn Group. As the altitude of this surface decreases away from this area to the northeast, east, southeast, south, and southwest, salinity increases to a chloride concentration of 2,000 mg/L or more. The increase in salinity to the northeast and east coincides with development of the thick basal Hawthorn unit in central Hendry County, with higher salinity in this zone than in the underlying units. To the southeast in central Collier County, the increase occurs only in the basal Hawthorn unit and Suwannee Limestone, but not in deeper formations. These areas of higher salinity could have resulted from the influx of seawater from the southwest into structurally low areas and into units of higher permeability near the top of the Upper Floridan aquifer. This could have occurred during high sea-level stands, with subsequent lower sea levels and incomplete flushing by the modern freshwater flow system.

Comparison of chloride and sulfate concentrations from water samples obtained from the Floridan aquifer system indicates that most of the sulfate is derived from mixing of dilute ground water with seawater; however, a minor portion of the sulfate in water samples from the brackish-water zone comes from gypsum dissolution. Additionally, the concentration of sulfate was compared to that expected for a particular chloride concentration based on a pure water-seawater mixing line, and this showed that sulfate is depleted in water samples obtained from the salinity transition zone.

The concentration of sulfate in the brackish-water zone ranges from 120 to 900 mg/L in the study area. Areas of higher sulfate concentration coincide with the northwest-trending high area at the top of the dolomite-evaporite unit in the middle confining unit and with areas where gypsum is present in the middle confining unit. This indicates that the higher sulfate concentration present in these areas could result from gypsum dissolution occurring near the base of the brackish-water zone. Upwelling of deeply circulating ground water could explain why this higher sulfate concentration is present in the upper part of the brackish-water zone where gypsum is not thought to be present.

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Appendix I
Inventory of Wells Used in this Report

[Well locations are shown in figures 2 and 3. County designations: C, Collier; CH, Charlotte, G, Dade or Broward; GL, Glades; HE, Hendry; L, Lee; MO, Monroe; PB, Palm Beach, and S, Dade. Well and casing depths are from measuring point, which is at land surface or above. Dashes indicate no data]

Local well number	Other well identifier or owner	Site identification number	Latitude (degrees)	Longitude (degrees)	Land-net location	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Diameter of casing (inches)	Date at end of construction
C-21	S-482	263020081260701	263020	0812607	S04 T46S R29E	36	566	-- -- 166	-- -- 4.5	-- -- 1941
C-22	S-483	252557080254601	262557	0812601	S33 T46S R29E	40	845	-- -- 228	-- -- 4.5	-- -- 1941
C-234	W-1885, P-98	262006081304401	262006	0813044	S03 T48S R28E	37	11,900	91 1,007 4,259	20.0 13.4 9.6	-- -- 03-07-49
C-236	617-134-1	261756081340601	261756	0812306	S13 T48S R27E	17	875	--	6.0	--
C-258	625-124-2	262505081245301	262504	0812459	S03 T47S R29E	35	783	--	4.0	--
C-284	629-127-4	262926081272401	262926	0812724	S07 T46S R29E	40	1,119	--	6.0	--
C-308	609-115-1	260919081155901	260919	0811559	S01 T50S R30E	15	700	312 587	4.0 2.5	-- 1959
C-415	P-319	263041081252301	263041	0812523	S04 T46S R29E	38	4,400	89 1,360	20.0 13.4	-- 11-13-64
C-441	Wooten	255403081200901	255403	0812009	S32 T52S R30E	3	915	412	6.0	04-63
C-679	C-2024D, W-14918	260910081252801	260910	0812528	S05 T50S R29E	14	900	264	6.0	--
C-680	C-2022D, W-14601	260908081331701	260908	0813317	S06 T50S R28E	12	1,000	240	6.0	--
C-701	W-820, P-42	261606081202401	261606	0812024	S29 T48S R30E	42	11,626	116 1,644 5,727 11,597	20.0 13.4 9.6 7.0	-- -- -- 09-26-43
C-708	W-2103, P-103	262211081333401	262211	0813334	S19 T47S R28E	31	12,202	96 988 4,244	20.0 13.4 9.6	-- -- 1949
C-710	W-1883, P-86	262217081313001	262217	0813130	S21 T47S R28E	37	12,119	77 1,112 5,011	20.0 13.4 9.6	-- -- 1948
C-711	W-1878, P-92	261910081273801	261910	0812738	S07 T48S R29E	32	11,895	76 1,013 4,268	20.0 13.4 9.6	-- -- 1949

Local well number	Other well identifier or owner	Site identification number	Latitude (degrees)	Longitude (degrees)	Land-net location	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Diameter of casing (inches)	Date at end of con-struction
								48	20.0	--
C-712	W-1820, P-64	261723081293401	261723	0812934	S23 T48S R28E	32	12,206	1,111	13.4	--
								5,111	9.6	1948
								63	20.0	--
C-719	P-38	261704081221801	261704	0812218	S24 T48S R29E	35	11,590	1,013	13.4	--
								5,595	9.6	01-19-47
C-726	W-2420, P-130	260518081414901	260518	0814149	S27 T50S R26E	25	12,516	1,025	13.4	--
								4,492	9.6	08-25-51
C-727	W-3579, P-222	262422081264101	262422	0812641	S08 T47S R29E	45	11,938	1,434	13.4	--
								4,498	9.6	06-08-55
C-729	P-291	261313081152501	261313	0811525	S18 T49S R31E	35	12,961	1,351	13.4	--
								4,302	9.6	01-27-61
C-739	P-345	261724081221101	261724	0812211	S24 T48S R29E	35.6	14,504	3,696	9.6	--
								11,700	7.0	1965
C-742	P-401	262403081311601	262403	0813116	S09 T47S R28E	40	11,987	3,833	9.6	03-18-69
C-753	P-352	263043081261801	263043	0812618	S05 T46S R29E	53.4	11,497	1,140	13.4	--
								3,537	9.6	10-31-65
C-759	P-663	260055081392801	260055	0813928	S24 T51S R26E	20.6	12,701	3,660	9.6	07-28-73
C-764	P-477	262848081310601	262848	0813106	S16 T46S R28E	40	12,049	3,676	9.6	07-24-71
C-781	P-697	262759081180101	262802	0811801	S23 T46S R30E	46.1	13,004	241	20.0	--
								4,213	9.6	01-12-74
C-794	P-778	255731081332901	255731	0813329	S12 T52S R27E	29	18,670	--	--	--
C-802	P-829	255856080553201	255856	0805532	S33 T51S R34E	38	11,658	--	--	--
C-808	P-799	261011081122601	261011	0811226	S34 T49S R31E	39	11,880	--	--	--
C-820	P-856	261531081181201	261531	0811812	S34 T48S R30E	21	2,500	2,004	7.0	01-77
C-823	P-801	261452081181601	261452	0811816	S03 T49S R30E	35	11,608	--	--	--
C-851	W-10252	261716081222701	261716	0812227	S24 T48S R29E	18	2,056	--	--	--
C-876	Alico, Inc.	262930081224001	262930	0812240	S12 T46S R29E	33	593	301	4.0	--
C-913	W-14919	260916081185301	260916	0811853	S12 T46S R29E	15	1,205	--	--	--
C-914	W-14920	255623081280801	255623	0812808	--	--	1,234	--	--	--
C-915	W-14921	255857081425201	255857	0814252	--	--	798	--	--	--
C-916	C-2029D, W-14922	255910081355011	255912	0813413	NW S36 T51S R27E	--	880	360	5.8	--

Local well number	Other well identifier or owner	Site identification number	Latitude (degrees)	Longitude (degrees)	Land-net location	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Diameter of casing (inches)	Date at end of construction
C-917	W-14934	255730081211101	255730	0812111	--	--	785	--	--	--
C-918	W-10180	255708081184501	255708	0811845	--	--	1,282	--	--	--
C-919	W-10183	255530081042501	255530	0810425	--	--	1,151	--	--	--
C-920	W-10184	255555081024501	255604	0810722	--	--	1,171	--	--	--
C-921	W-10187	255550081002501	255550	0810025	--	--	1,140	--	--	--
C-922	W-10188	261300081134501	261300	0811345	--	--	1,112	--	--	--
C-923	W-10190	255500081140501	255500	0811405	--	--	1,302	--	--	--
C-924	W-10201	260112081251001	255845	0812436	--	--	1,373	--	--	--
C-925	W-10202	260102081250001	260102	0812500	--	--	1,380	--	--	--
C-926	W-10223	260605081282701	260605	0812827	--	11	1,359	--	--	--
C-927	W-8899	260200081194501	260200	0811945	--	--	1,032	--	--	--
C-928	W-8951	255500081213001	255500	0812130	--	--	1,247	--	--	--
C-929	W-9413	260110081151501	260110	0811515	--	--	1,491	--	--	--
C-930	W-9905	261035081074001	261035	0810740	--	--	1,265	--	--	--
C-931	W-10014	260205081092501	260205	0810925	--	--	1,198	--	--	--
C-932	LCLC-21-A	255600081390101	255600	0813901	--	10	1,437	--	--	--
C-933	LTC-33-B	260310081274501	260310	0812745	--	8	1,385	--	--	--
C-934	LTC-35	260850081261301	260850	0812613	--	12	1,312	--	--	--
C-935	CC-195	261230081260001	261230	0812600	--	14	1,296	--	--	--
C-938	CC-253	262425081190001	262425	0811900	--	26	1,097	--	--	--
C-962	P-1121	255846080533001	255845	0805413	SW S35 T51S R34E	25.6	3,900	234 2,228 2,499 3,600	13.4 9.6 7.0 5.0	05-05-84 -- -- --
C-1090	W-16434	262528081182801	262528	0811828	NE S03 T47S R30E	25	715	--	--	1989
C-1091	W-16505	260852081212801	260852	0812128	NW S06 T50S R30E	13	702	-- 271	-- --	-- 02-05-90
C-1101	CO-1769	255733081432401	255733	0814324	NE S08 T52S R26E	5	800	390	12.0	01-89
C-1102	CO-2080	260249081414501	260249	0814145	NE S10 T51S R26E	5	1,608	360 650	12.0 4.0	11-01-90 --

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C-1103	CO-2081	260952081410701	260952	0814107	--	10	1,616	315	12.0	01-01-91
								540	4.0	--
C-1104	CO-2271, MARCO-I1	255733081432601	255733	0814326	T52S R26E	6.3	3,354	230	44.0	02-07-92
								400	39.0	--
								910	34.0	--
								2,573	20.0	--
								2,640	24.0	--
C-1105	CO-2272, MARCO-M1	255732081432701	255732	0814327	T52S R26E	6.2	1,600	395	24.0	03-30-92
								1,000	16.0	--
								1,490	6.6	--
C-1106	CO-2305	255625081424201	255625	0814242	T52S R26E	5	810	45	18.0	1992
								405	10.0	--
C-1107	CO-2317, NCRWTP-I1, W-16884	261444081404701	261444	0814047	SE S35 T48S R26E	14	3,380	16	48.0	10-31-92
								425	38.0	--
								1,310	30.0	--
								2,445	16.0	--
								2,497	20.0	--
C-1108	CO-2318, NCRWTP-M1	261444081404601	261444	0814046	SE S35 T48S R26E	14	1,930	420	24.0	10-14-92
								900	16.0	--
								1,815	6.6	--
C-1110	WA-483	262906081241201	262906	0812412	S10 T46S R29E	--	658	304	6.0	--
C-1111	I75-TWB	261012081435101	261012	0814351	SW S29 T49S R26E	10	2,694	490	12.0	12-14-94
								905	12.0	--
C-1112	IWSD-TW	262448081255401	262448	0812554	SW S04 T47S R29E	27	2,354	780	18.0	01-25-96
								1,065	12.8	01-25-96
C-1122	P-1042	261728081205101	261728	0812051	NW S20 T48S R30E	46.6	12,640	1,508	16.0	--
C-1123	P-1057	261858081215701	262858	0812157	SW S18 T46S R30E	49.8	11,561	115	30.0	12-22-81
								220	20.0	--
								1,545	13.4	--
								3,853	9.6	--
C-1124	P-1060	261426081171901	261426	0811719	SE S02 T49S R30E	41.9	11,725	250	20.0	05-22-83
								1,840	13.4	--
								4,000	9.6	--
								11,725	7.0	--

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C-1125	P-1063	260603081024601	260603	0810246	SW S20 T50S R33E	36	11,759	225	20.0	07-01-82
								1,570	13.4	--
								3,813	9.6	--
C-1126	P-1065	260947081100202	260947	0811002	NW S06 T50S R32E	39.8	11,802	250	20.0	02-22-83
								1,565	13.4	--
								3,696	9.6	--
C-1127	P-1086	255255080545901	255255	0805459	NW S10 T53S R34E	32	11,680	222	20	09-04-85
								2,065	13.4	--
								4,062	9.6	--
C-1128	P-1094	260652081060101	260652	0810601	SW S14 T50S R32E	38.2	11,505	248	20.0	10-30-83
								1,997	13.4	--
								3,750	9.6	--
								11,505	7.0	--
C-1129	P-1095	260841081040301	260841	0810403	SW S06 T50S R33E	35.8	11,790	230	20.0	03-06-83
								1,570	13.4	--
								3,945	9.6	--
C-1130	P-1127	262130081250801	262130	0812508	SE S28 T47S R29E	45.5	11,987	246	20.0	02-02-84
								1,842	13.4	--
								3,737	9.6	--
C-1131	P-1134	262249081264001	262249	0812640	NW S20 T47S R29E	46.7	3,934	281	20.0	06-04-84
								1,935	13.4	--
								3,934	9.6	--
C-1132	P-1199	262605081314601	262605	0813146	NW S33 T46S R28E	44.9	11,720	226	20.0	04-29-86
								1,851	13.4	--
								4,060	9.6	--
								11,709	7.0	--
C-1133	P-1216	260723081040001	260723	0810400	NW S18 T50S R33E	37.5	11,755	229	20.0	05-23-88
								3,995	9.6	--
CH-312	LE00017	264745082021201	264745	0820212	T42S R23E	11	1,077	--	--	07-28-82
CH-313	ZRL-I1, W-16889	264729081575301	264729	0815753	SE S25 T42S R23E	26	2,710	73	38.0	06-13-92
								427	30.0	--
								1,566	24.0	--
								2,486	12.0	--

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CH-314	ZRL-M1	264729081575401	264729	0815754	SE S25 T42S R23E	26	1,854	425	22.0	06-24-92
								1,340	16.0	--
								1,795	8.0	--
G-2296	BOF-1	261016080492601	261016	0804926	S03 T50S R35E	17.5	2,811	20	35.0	11-07-80
								195	24.0	04-22-87
								834	2.9	--
								895	16.0	--
								1,104	1.0	--
								1,648	1.0	--
								2,447	2.38	--
G-2617	Monitor tube in G-2296	261016080492602	261016	0804926	--	17.8	1,728	1,648	1.0	03-16-87
G-2618	Same as above	261016080492603	261016	0804926	--	17.8	1,164	1,104	1.0	03-16-87
G-2619	Same as above	261016080492604	261016	0804926	--	17.8	1,052	895	7.9	03-16-87
G-3239	P-167, W-3054	254540080494301	254540	0804945	S16 T54S R35E	24	11,558	64	20.0	--
								90	2.9	02-01-54
								649	13.4	--
								3,526	9.6	--
								11,557	7.0	--
GL-240	W-2912, P-152	264727080593701	264727	0805937	S25 T42S R33E	25	13,408	--	--	--
								3,464	13.4	07-10-53
HE-9	S-522	264415081025401	264415	0810254	S20 T43S R33E	21	1,039	--	--	--
								949	6.0	--
HE-46	Hendry Cattle	264325081074601	264325	0810746	S22 T43S R32E	22	1,465	--	6.0	--
HE-54	HE-538	263852081260701	263852	0812607	S16 T44S R29E	28	1,300	--	6.0	1949
HE-81	Denaud Cemetary	264521081305301	264521	0813053	S10 T43S R28E	13	750	540	6.0	1945
HE-116	Glaser	264235081315901	264235	0813159	S28 T43S R20E	18	700	--	6.0	--
HE-278	FGS-42	263825081334001	263825	0813340	S19 T44S R28E	26	790	--	6.0	07-53
								--	8.0	--
HE-281	W-1995	263359081073901	263359	0810739	S16 T45S R32E	29	1,049	1,049	4.8	08-49
HE-282	W-2631, P-133	262328081114701	262328	0811147	S14 T47S R31E	39.6	11,796	110	20.0	--
								1,409	13.4	--
								4,328	9.6	02-03-52
HE-293	FGS-35	263604081263401	263604	0812634	S05 T45S T29E	31	792	--	--	--
								277	6.0	03-57

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HE-296	FGS-31	263345081143601	263345	0811436	S17 T45S R31E	31	872	-- 346	-- 6.0	-- --
HE-297	FGS-30	263501081180101	263501	0811801	S11 T45S T30E	30	782	-- 319	-- 6.0	-- --
HE-343	P-323	263142081265001	263142	0812650	S32 T45S R29E	36	3,200	1,368	13.4	01-65
HE-941	W-3441, P-207	263525081262101	263525	0812621	S05 T45S R29E	47.9	4,121	1,943	13.4	11-08-54
HE-948	P-442	263212081313801	263212	0813138	S28 T45S R28E	48.5	11,586	9,000	7.0	11-15-70
HE-949	P-342	263246081281501	263247	0812619	SE S20 T455 R29E	53	11,492	2,928 11,492	9.6 5.5	-- 09-06-65
HE-953	P-346	263224081252401	263224	0812524	S28 T45S R29E	45	11,469	1,099 3,500	13.4 9.6	-- 10-27-65
HE-970	P-768	263328081101801	263328	0811018	S19 T45S R32E	45.1	15,998	1,494 4,201	13.4 9.6	-- 05-26-75
HE-973	P-171	262308081142701	262308	0811427	S17 T47S R31E	40	8,494	1,415 4,354	13.4 9.6	-- 11-11-53
HE-976	W-10747, P-418	261932081032001	261932	0810320	S08 T48S R33E	38.5	12,490	-- 3,995	-- 9.6	-- 05-03-70
HE-981	CC-197	262736081151401	262736	0811514	--	32	1,322	--	--	--
HE-982	CC-178	262845081115601	262845	0811156	--	30	1,086	--	--	--
HE-983	ALICO-18	263227081085601	263227	0810856	--	31	987	--	--	--
HE-984	ALICO-16	263528081070401	263528	0810704	--	29	955	--	--	--
HE-986	MILLS-1	263751081031401	263751	0810314	--	23	872	--	--	--
HE-987	U.S.SUGAR-2	264003080565901	264003	0805659	--	15	916	--	--	--
HE-1084	W-16387	264055080561301	264055	0805613	NE S09 T44S R34E	14	662	-- 300	-- --	-- 01-07-89
HE-1085	W-16329	263950081081801	263950	0810818	NW S16 T44S R32E	25	740	--	--	04-24-89
HE-1086	HY-123	263840081204501	263840	0812045	NW S20 T44S R30E	27	1,000	--	--	1984
HE-1087	L2-TW, T-17093	263630080565801	263630	0805658	NW S04 T45S R34E	15	2,235	120 742 1,400	18.0 12.0 4.0	01-28-94 -- --
HE-1088	WA-510	263036081305901	263036	0813059	S04 T46S R28E	--	738	220	6.0	--
HE-1101	P-903	261638080542801	261638	0805428	SW S26 T48S R34E	30.4	11,633	3,817	9.6	12-13-77

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HE-1102	P-1048	263802081203701	263802	0812037	SE S20 T44S R30E	49	12,224	245 1,550 3,777	20.0 13.4 9.6	11-28-81 -- --
HE-1103	P-1050	263114081115201	263114	0811152	SE S35 T45S R31E	49	12,312	203 1,555 3,882	20.0 13.4 9.6	09-16-81 -- --
HE-1104	P-1085	262737081124901	262737	0811249	NE S27 T46S R31E	49	11,672	245 2,186 4,005	20.0 13.4 9.6	05-01-83 -- --
HE-1105	P-1089	263546081294701	263546	0812947	NW S02 T45S R28E	53.2	11,452	242 1,575 3,802	20.0 13.4 9.6	01-07-83 -- --
HE-1106	P-1147	263239081325001	263239	0813250	SE S20 T45S R28E	54.9	11,545	220 1,724 3,609	20.0 13.4 9.6	10-03-84 -- --
HE-1107	P-1058	263520081333801	263520	0813338	SW S06 T45S R28E	51.6	11,570	251 1,547 3,603	20.0 13.4 9.6	07-11-82 -- --
L-448	Shanklin	263659081531701	263659	0815317	S26 T44S R24E	8	847	390	5.0	03-46
L-468	O'Brian	263028082111801	263028	0821118	S03 T46S R21E	5	689	438	4.5	02-46
L-470	Gresham	263729081523101	263729	0815231	S26 T44S R24E	16	843	427	6.0	--
L-550	WA-133	262945081540701	262945	0815407	S03 T46S R23E	4	900	--	6.0	1950
L-562	WA-464	263009081524901	263009	0815249	S04 T46S R24E	--	863	698	4.0	--
L-591	--	262822082091201	262822	0820912	--	--	654	--	--	--
L-592	632211114	263247082115201	263247	0821152	S22 T45S R21E	3	724	-- 367	-- 4.0	-- --
L-755	Betts	263301081475401	263301	0814754	S22 T45S R25E	21	748	--	--	--
L-907	WA-125	265534081360501	264434	0813605	S10 T43S R27E	18	894	337	6.0	1964
L-912	Simms Groves	265223081355301	264223	0813553	S26 T43S R27E	10	836	650	6.0	--
L-964	Sunset Towers	263344081575201	263344	0815752	S13 T45S R23E	4	808	-- 362	24.0 8.0	09-69 --
L-1018	Gulf-America	264044081581601	264044	0815816	S01 T44S R23E	13	1,001	--	--	--
L-1044	WA-64	264401081544001	264401	0815440	S16 T43S R24E	20	1,000	--	--	--

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L-1094	WA-931	262831081501401	262831	0815014	S17 T46S R25E	5	1,015	170	8.0	--
L-1157	Seven Lakes Sub	263306081522301	263306	0815223	S23 T45S R24E	12	740	589	4.0	12-20-70
L-1186	Stokes	262633082032701	262633	0820327	S24 T46S R22E	5	700	500	6.0	--
L-1242	WA-690	264432081374801	264432	0813748	S09 T43S T27E	20	1,100	--	--	--
L-1318	WA-129	264029081464801	264029	0814648	SE S02 T44S R25E	--	814	80	5.0	--
L-1396	WA-70	263836081492101	263836	0814921	SW S16 T44S R25E	19	857	126	6.0	--
L-1569	WA-143	262427081491101	262427	0814911	S03 T47S T25E	12	809	-- 294	-- 4.0	-- 05-72
L-1595	WA-423	263735081522701	263735	0815227	S23 T44S R24E	15	928	-- 322	5.0 4.0	-- --
L-1634	Beach Golf Course	262435081535101	262435	0815351	S03 T47S R24E	4	950	740	6.0	09-72
L-1646	--	262853082100201	262853	0821002	NW S12 T46S R21E	5	673	382	4.0	1972
L-1687	Searboard Railroad	264323082153401	264323	0821534	S26 T43S R20E	4	900	141	6.0	1965
L-1688	WA-25	263554081375401	263554	0813754	NE S05 T45S R27E	26	966	126	5.0	--
L-1817	452325BN	263006081570901	263006	0815709	S36 T45S R23E	5	744	--	--	--
L-1903	WA-77	264253081405201	264253	0814052	NE S26 T43S R26E	15	670	190	4.0	1964
L-1962	WA-526	264220081525101	264220	0815251	S26 T43S R24E	--	788	315	5.0	--
L-1967	LM-1267	262734082031501	262734	0820315	S18 T46S R23E	3	896	700	6.0	1974
L-2003	Tweed	263448081503401	263448	0815034	S07 T45S R25E	6	685	240	6.0	--
L-2061	Baum	263151081363201	263151	0813632	SE S28 T45S R27E	30	899	325	6.0	03-13-75
L-2063	W-LE001	263053081363701	263053	0813637	S33 T45S R27E	31	1,450	--	8.0	02-13-75
L-2115	The Landings	263259081551601	263259	0815516	S20 T45S R24E	8	750	610	8.0	1975
L-2201	Pine Island	263818082020902	263818	0820209	S17 T44S R23E	7	850	125 625	18.0 12.0	-- 04-73
L-2292	--	263718081485003	263718	0814850	--	--	616	--	--	--
L-2313	--	262703081340203	262703	0813402	--	--	670	--	--	--
L-2319	Lee County	262713081414402	262713	0814144	S22 T46S R26E	20	750	--	4.0	08-76
L-2401	Light House	262704082010501	262704	0820105	S21 T46S R23E	5	855	470	6.0	12-76
L-2426	Brown	263515081562301	263515	0815623	S05 T45S R24E	6	665	385	4.0	01-25-77
L-2433	Franklin	264011081442301	264011	0814423	S08 T44S R26E	10	700	--	4.0	1915
L-2434	Cape Coral	263526082010201	263526	0820102	S04 T45S R23E	7	700	353	4.0	03-77

Local well number	Other well identifier or owner	Site identification number	Latitude (degrees)	Longitude (degrees)	Land-net location	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Diameter of casing (inches)	Date at end of construction
L-2458	WA-27	263931081335801	263931	0813358	S12 T44S R27E	18	1,300	-- 120	-- 6.0	-- --
L-2460	WA-12	263931081354701	263931	0813547	S11 T44S R27E	21	760	115	6.0	--
L-2525	Lee County	263117082051001	263117	0820510	S26 T45S R22E	6	645	405	4.0	10-77
L-2527	--	263955082083101	263955	0820831	--	--	605	--	--	--
L-2528	Lee County	263907081592701	263907	0815927	S11 T44S R23E	11.4	625	420	4.0	1977
L-2530	Lee County	265308081405402	264308	0814054	S23 T43S R26E	5	620	340	4.0	1977
L-2657	WA-85	263057081572202	263057	0815722	S36 T45S R23E	6	916	162	6.0	--
L-2901	Lee County Water Plant	26530908145101	264309	0814051	SE S23 T43S R26E	8	705	64	--	12-05-78
L-4817	WA-21	263818081433501	263815	0814440	NW S21 T44S R26E	--	780	195	6.0	--
L-4846	WA-68	263935081550101	263935	0815501	NW S09 T44S R24E	--	1,012	144	8.0	--
L-5000	P-289	264107082190301	264107	0821903	S09 T44S R24E	39	13,970	107 220 1,470 4,410	24.0 20.0 13.4 9.6	-- -- -- 10-11-60
L-5001	P-919	262858081411801	262924	0814051	S11 T46S R25E	53	11,893	3,866	9.6	1977
L-5003	W-2979, P-160	263219081414401	263219	0814144	S27 T45S R26E	43	12,858	1,086 5,011	13.4 9.6	-- 09-23-53
L-5009	W-4839, P-271	262828081372101	262828	0813721	S16 T46S R27E	46.6	11,910	1,206 4,312	13.4 9.6	-- 11-28-58
L-5010	P-408	262557081345701	262557	0813457	S35 T46S R27E	41.9	11,955	3,741	9.6	09-01-69
L-5013	W-3073, P-161	263245081524701	263245	0815247	S23 T45S R24E	24	12,877	1,018 4,282	13.4 9.6	-- 08-06-53
L-5601	WA-98	263456081534501	263456	0815345	NE S10 T45S R24E	9	920	114	5.5	--
L-5602	WA-99	263148081550001	263148	0815500	SW S28 T45S R24E	5	966	--	--	--
L-5605	W-LE007, U.S. Gypsum	264541081453901	264541	0814539	SW S06 T43S R26E	27	2,150	542 1,865	12.0 --	12-05-80 --
L-5608	WA-105	262625081480201	262625	0814802	SW S27 T46S R25E	16	828	198	4.0	--
L-5609	WA-193	263022081583701	263022	0815837	NW S02 T45S R23E	5	824	164	5.0	--
L-5611	WA-439	264027081523101	264027	0815231	S35 T43S R24E	--	870	302	4.0	--
L-5612	WA-512	263736081564401	263736	0815644	S19 T44S R24E	--	669	360	6.0	--
L-5613	WA-642	263430081534001	263430	0815340	S10 T45S R24E	--	760	750	6.0	--

Local well number	Other well identifier or owner	Site identification number	Latitude (degrees)	Longitude (degrees)	Land-net location	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Diameter of casing (inches)	Date at end of con-struction
L-5614	WA-702	263410082065001	263410	0820650	S09 T45S R22E	--	861	350	4.0	--
L-5615	WA-761	263221081504801	263221	0815048	SW S19 T45S R25E	5	860	148	6.0	--
L-5616	WA-841	264540081510001	264540	0815100	S06 T43S R25E	--	787	300	4.0	--
L-5641	LM-1841	263115081483501	263115	0814835	--	--	1,230	--	--	--
L-5735	LM-2464S	262706082080201	262706	0820802	NW S20 T46S R22E	--	770	750	1.3	08-01-85
L-5801	LM-1842	263115081483502	263115	0814835	NE S33 T45S R25E	19	635	450	11.0	05-12-92
L-5802	NFM-I1	264345081525301	264345	0815253	SE S14 T43S R24E	20	2,603	1,096 1,582 2,340	24.0 20.0 --	10-01-87 -- --
L-5803	NFM-M1	264345081525301	264345	0815253	SE S14 T43S R24E	20	2,526	8 200 1,318 1,950	26.0 16.0 10.0 4.0	08-01-86 -- -- --
L-6400	W-16242	263129082112901	263129	0821129	SW S26 T45S R21E	2	760	--	--	12-88
L-6401	W-16523	262558081490801	262558	0814908	NW S33 T46S R25E	11	822	--	--	04-15-90
L-6403	W-15286C	263834081415001	263834	0814150	SE S15 T44S R26E	20	770	--	--	04-06-82
L-6411	W-LE004	262628082063301	262628	0820633	NE S28 T46S R22E	4	774	660	--	02-05-81
L-6412	W-LE014, LM-1622, W-14790	264002082090301	264002	0820903	SW S06 T44S R22E	3	963	360	9.8	05-22-81
L-6413	W-LE017	262309081402301	262309	0814023	NW S13 T47S R26E	5	1,460	--	--	01-26-81
L-6414	W-LEO22D	264433081360602	264433	0813606	SE S10 T43S R27E	19	1,200	340	7.8	11-17-81
L-6415	W-LE023, P-979	263117081415001	263117	0814150	NE S34 T45S R26E	43	1,350	--	--	09-14-79
L-6417	L-3004D	263820082022701	263820	0820227	SW S17 T44S R23E	3.2	778	450	9.8	--
L-6421	LE00005	263318081552701	263318	0815527	--	5	1,200	--	--	07-17-80
L-6423	W-LE035, W-15916	262935082052101	262935	0820521	SW S02 T46S R22E	5	1,420	--	--	10-11-85
L-6431	LM-3247, Site P	264147082011301	264147	0820113	S00 T43S R23E	8	740	455	5	12-90
L-6432	LM-3273, Site V	264128081563101	264128	0815631	S00 T43S R24E	15	800	560	12.0	12-90
L-6433	LM-3353, Site M	263858082032001	263858	0820320	S00 T44S R23E	3	645	488	5.0	12-90
L-6434	LM-3366, site N	264316082033301	264316	0820333	S00 T43S R22E	4	720	485	5.0	12-90
L-6435	LM-3367, site O	263416082020101	263416	0820201	S00 T45S R23E	2	1,402	58 980	14.0 8.0	12-01-90 --
L-6436	LM-3479, site M	263906082032101	263906	0820321	S00 T44S R23E	3	1,080	898	5.0	12-90

Local well number	Other well identifier or owner	Site identification number	Latitude (degrees)	Longitude (degrees)	Land-net location	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Diameter of casing (inches)	Date at end of construction
L-6437	LM-3480, site N	264334082033201	264334	0820332	S00 T43S R22E	6	1,205	800	5.0	12-90
L-6438	LM-3482, site Q	264145081582901	264146	0815829	S00 T43S R23E	16	780	494	5.0	12-90
L-6439	LM-3483, site R	264421081554501	264421	0815545	S00 T43S R24E	18	760	505	5.0	12-90
L-6440	LM-3484, site S	263956081574801	263956	0815748	S00 T44S R23E	13	760	520	5.0	12-90
L-6441	LM-3485, site T	264001082002601	264001	0820026	S00 T44S R23E	11	750	395	5.0	12-90
L-6442	LM-3486, site U	263429081572401	263429	0815724	S00 T45S R23E	5	740	430	5.0	12-90
L-6443	LM-3487, site U	263430081572301	263430	0815723	S00 T45S R24E	5	930	700	5.0	12-90
L-6444	LM-3509, site V	264118081563001	264118	0815630	S00 T43S R24E	15	1,585	785	6.0	10-01-90
L-6445	LM-1916	262600082063001	262600	0820630	NE S28 T46S R22E	4	588	502	10.0	09-15-82
L-6461	P-850	263751081415701	263751	0814157	S22 T44S R26E	46.1	3,600	228 1,550	20.0 13.4	10-29-76 --
L-6462	P-851	262556081405701	262556	0814057	NE S35 T46S R26E	37.7	1,310	150	30.0	11-11-7
L-6463	P-1068	262804081431401	262804	0814314	SE S17 T46S R26E	44.7	11,915	97 520 1,548 3,840	30.0 20.0 13.4 9.6	01-01-83 -- -- --
L-6471	GIWA-I1, W-15749	264524082153601	264524	0821536	S04 T43S R20E	5	1,928	121	16.0	12-84
MO-141	P-564	254548080593201	254548	0805932	S11 T54S R33E	25	12,662	--	--	--
PB-1137	W-4661, P-265	262039080484201	262013	0804841	S02 T48S R35E	31	12,810	276 1,988 4,602	20.0 13.4 9.6	-- -- 02-02-57
PB-1138	P-740	263039080515101	263003	0805227	S07 T46S R35E	31.1	16,848	302 1,672 4,198	26.0 20.0 9.6	-- -- 02-06-75
PB-1163	W-10080	263657080473701	263647	0804737	--	12	1,120	--	--	---
PB-1164	W-10213	264310080523001	264310	0805230	--	12	840	--	--	--
S-450	W-466	254820080522303	254820	0805223	S31 T53S R35E	9	1,280	456 1,280	10.0 6.0	1941 --
S-479	W-935, P-129	254820080522301	254820	0805223	S31 T43S R35E	17	11,806	137 446 3,237	16.0 12.0 8.0	-- -- 06-20-45

Appendix II
Selected Water-Quality Data Collected from Known Intervals in Wells from the Intermediate and Floridan Aquifer Systems

[Well locations are shown in figures 2 and 3. Source of water sample: completed, data from completed interval; DQW, data collected while drilling by the reverse-air rotary method; packer, data from open-hole interval by packer test; WAQW, data collected during SFWMD well abandonment program; USGS, U.S. Geological Survey; SFWMD, South Florida Water Management District; unless denoted as USGS, SFWMD, or WAQW, the samples were collected by private consultants. Other annotations: ft, feet; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter; --, no data or unknown; ?, depth to top of sample interval is unknown; *, USGS data not in QWDATA data base; **, chloride concentration calculated from specific conductance in wells C-914 and C-916; sample interval depths are from the measuring point given in appendix I]

Local well identifier	Sampling date	Depth of sample interval (ft)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	Specific conductance (μS/cm)	Source of water sample
C-21	12-15-41	166-566	820	302	1,850	3,310	Completed-USGS
C-22	12-15-41	228-845	980	560	2,500	4,200	Completed-USGS
C-236	03-16-59	?-875	785	--	2,070	--	Completed-USGS*
C-258	10-07-81	?-783	1,000	530	2,660	--	Completed-USGS
C-284	10-08-59	?-1,119	1,100	--	2,660	--	Completed-USGS*
C-308	11-21-75	587-700	1,800	--	--	7,000	Completed-USGS
C-415	12-23-64	752-912	1,200	--	--	--	Completed-USGS*
C-441	03-14-66	412-915	1,530	--	--	--	Completed-USGS*
C-820	02-08-77	1,998-2,500	13,500	3,080	26,000	--	Completed
C-876	11-13-75	301-593	1,280	--	--	--	Completed-USGS*
C-913	01-11-83	300-1,220	2,190	--	--	7,910	Completed-SFWMD
C-914**	12-19-80	390-1220	2,900	--	--	9,570	Completed-SFWMD
C-916**	07-22-81	360-880	1,540	--	--	5,630	Completed-SFWMD
C-917	01-11-83	430-880	1,600	--	--	6,030	Completed-SFWMD
C-962	12-13-83	2,228-2,280	17,000	2,000	--	40,300	Completed-USGS
C-1101	1990	390-800	6,550	--	--	21,600	DQW
C-1102	11-90	650-770	4,000	--	--	--	Completed
	11-90	970-1,010	10,000	--	--	--	Packer
	11-90	1,220-1,270	17,000	--	--	--	Packer
	11-90	1,330-1,610	18,000	--	--	--	Packer
C-1103	01-91	940-1,030	2,000	--	--	--	Packer
	01-91	1,290-1,620	13,300	--	--	--	Packer
C-1105	09-93	1,000-1,089	15,000	1,680	25,600	39,000	Completed
	09-93	1,490-1,600	19,000	2,540	35,400	44,600	Completed
C-1108	10-20-92	900-995	435	725	5,330	7,000	Completed
	01-10-94	900-995	2,100	660	4,900	7,100	Completed
	07-19-92	1,010-1,050	2,140	756	4,500	6,490	Packer
	07-22-92	1,300-1,331	8,900	1,010	16,600	20,900	Packer
	10-20-92	1,815-1,930	20,800	2,740	37,300	39,000	Completed
C-1110	02-14-85	304-658	1,170	--	--	2,620	Completed-WAQW
C-1111	--	1,158-1,185	10,200	1,340	17,600	25,400	Packer-SFWMD
	--	1,287-1,318	14,300	1,750	27,300	35,700	Packer-SFWMD
	--	1,469-1,524	17,000	2,260	35,100	45,000	Packer-SFWMD
	--	1,851-1,901	16,300	2,140	34,900	45,100	Packer-SFWMD
	--	2,195-2,251	19,300	2,510	34,600	46,600	Packer-SFWMD
C-1124	12-10-82	1,840-1,890	2,440	900	5,170	--	Completed

Local well identifier	Sampling date	Depth of sample interval (ft)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	Specific conductance (μS/cm)	Source of water sample
C-1133	04-23-88	229-1,084	770	390	1,870	--	Completed
CH-313	02-06-92	427-992	301	--	959	1,400	DQW
	03-03-92	1,536-1,568	3,840	340	7,880	11,200	Packer
CH-314	03-02-92	1,566-1,601	89	290	15,400	22,300	Packer
	06-24-92	1,340-1,415	925	432	--	4,100	Completed
	06-23-92	1,795-1,830	17,500	2,700	34,900	46,200	Completed
G-2296	10-19-81	811-816	1,600	500	3,500	6,200	Completed-USGS
	03-09-81	895-1,125	850	--	2,000	3,330	Packer-USGS
	03-07-81	1,430-1,620	1,800	--	3,640	6,050	Packer-USGS
	03-03-81	2,450-2,810	19,500	---	38,000	50,000	Packer-USGS
	01-15-92	2,447-2,811	20,000	2,700	37,200	50,800	Completed-USGS
G-2617	01-10-92	1,648-1,728	1,100	450	2,570	4,220	Completed-USGS
G-2618	01-14-92	1,104-1,164	620	340	1,650	2,750	Completed-USGS
G-2619	01-13-92	895-1,052	1,100	400	2,590	4,360	Completed-USGS
HE-9	01-05-43	949-1,039	1,430	--	--	--	Completed-USGS
HE-46	05-07-53	?-1,110	925	--	--	3,840	Completed-USGS
HE-54	05-01-53	?-1,300	1,390	--	--	4,880	Completed-USGS
HE-81	12-02-75	540-750	1,170	--	--	4,400	Completed-USGS*
HE-116	03-07-75	?-700	1,300	--	2,950	4,460	Completed-USGS
HE-278	12-10-53	520-790	1,030	245	2,300	3,820	Completed-USGS
HE-293	12-04-75	277-792	1,080	---	--	--	Completed-USGS*
HE-296	05-14-58	346-872	2,250	--	--	--	Completed
HE-297	05-14-58	319-782	2,170	--	--	--	Completed
HE-1087	01-94	1,266-1,284	490	366	1,370	2,240	Packer-SFWMD
	01-94	1,442-1,494	445	322	1,370	2,230	Packer-SFWMD
	01-94	1,652-1,704	882	440	2,160	--	Packer-SFWMD
	01-94	1,890-1,908	3,080	424	5,550	9,990	Packer-SFWMD
	01-94	2,072-2,124	10,700	1,360	19,100	30,800	Packer-SFWMD
HE-1088	04-23-85	220-738	917	--	--	2,640	Completed-WAQW
HE-1104	04-04-83	2,020-2,070	7,850	350	13,200	--	Completed
HE-1105	10-20-82	1,578-1,598	730	256	2,090	--	Completed
HE-1107	06-12-82	1,546-1,579	518	300	--	--	Completed
L-448	04-08-46	390-847	825	313	--	3,330	Completed-USGS
L-468	06-15-77	438-689	740	360	1,970	3,250	Completed-USGS
L-470	04-11-46	427-843	675	286	--	2,840	Completed-USGS
L-562	01-14-85	698-863	750	--	--	2,180	Completed-WAQW
L-591	03-29-75	405-654	870	360	2,090	4,020	Completed-USGS

Local well identifier	Sampling date	Depth of sample interval (ft)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	Specific conductance (μS/cm)	Source of water sample
L-592	01-09-73	367-724	1,100	352	--	4800	Completed-USGS
L-907	04-22-81	340-997	1,350	--	--	4,850	Completed-WAQW
L-912	03-07-73	650-836	1,400	340	--	5,000	Completed-USGS
L-964	12-13-72	362-808	780	320	--	3,380	Completed-USGS
L-1094	02-07-73	508-1,009	940	340	--	3,810	Completed-USGS
	01-21-88	508-1,009	936	--	--	4,280	Completed-WAQW
L-1157	02-21-73	589-740	700	320	--	2,980	Completed-USGS
L-1186	03-29-75	500-700	1,300	630	3,280	5,440	Completed-USGS
L-1242	10-22-86	318-730	755	--	--	1,880	Completed-WAQW
L-1569	09-23-81	296-772	1,020	--	--	4,000	Completed-WAQW
L-1634	08-28-80	740-950	1,400	470	3,160	5,310	Completed-USGS
L-1646	01-07-77	382-673	825	--	2,350	3,910	Completed-USGS*
L-1687	03-65	755(?)-760	17,600	--	--	--	Packer
L-1903	06-24-80	190-669	413	--	4,930	2,060	Completed-WAQW
L-1962	05-22-85	315-788	745	--	--	2,300	Completed-WAQW
L-1967	07-11-84	700-881	2,700	--	--	8,050	Completed-WAQW
L-2003	12-24-74	240-685	1,300	320	2,820	4,650	Completed-USGS
L-2061	02-06-75	325-899	1,150	--	--	--	Completed-USGS*
L-2115	06-30-75	610-750	720	290	1,690	2,970	Completed-USGS
L-2201	08-20-80	625-850	960	280	2,390	3,730	Completed-USGS
L-2292	06-07-78	302-616	940	300	2,320	3,690	Completed-USGS
	10-05-82	302-616	900	--	--	3,500	Completed-USGS
L-2313	06-07-78	400-670	1,000	550	2,790	4,400	Completed-USGS
L-2319	06-08-78	492-750	410	240	1,250	2,210	Completed-USGS
L-2401	11-10-77	470-855	1,350	250	2,900	5,000	Completed-USGS
L-2426	01-26-77	385-665	460	120	1,090	1,730	Completed-USGS
L-2433	02-10-77	?-700	870	310	1,980	3,400	Completed-USGS
L-2434	06-16-78	353-700	400	130	1,200	1,900	Completed-USGS
L-2525	11-30-77	405-645	440	280	1,230	2,000	Completed-USGS
L-2527	12-19-77	360-605	2,000	290	3,660	6,000	Completed-USGS
	10-05-82	360-605	1,860	--	--	5,700	Completed-USGS
L-2528	06-09-78	420-625	920	240	2,220	3,650	Completed-USGS
L-2530	09-25-79	340-620	500	270	1,520	2,500	Completed-USGS
L-5605	11-18-80	542-945	1,000	--	--	4,000	DQW
	12-19-80	1,865-1,985	19,400	2,900	--	45,000	DQW-USGS
L-5611	09-14-84	302-870	1,150	--	--	3,490	Completed-WAQW
L-5612	04-24-85	360-670	634	--	--	1,480	Completed-WAQW

Local well identifier	Sampling date	Depth of sample interval (ft)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	Specific conductance (μS/cm)	Source of water sample
L-5613	06-16-86	750-760	730	--	--	2,180	Completed-WAQW
L-5614	11-25-86	350-861	440	--	--	1,930	Completed-WAQW
L-5616	07-09-87	300-787	960	--	--	3,500	Completed-WAQW
L-5641	04-82	305-1,100	1,000	--	--	--	DQW
L-5735	10-27-87	740-770	960	--	--	3,830	Completed-USGS
L-5801	04-22-92	450-635	1,160	--	--	4,380	Completed-USGS
L-5802	06-07-87	1,479-1,489	3,300	460	2,140	3,700	Packer
L-5802	06-05-87	1,559-1,569	7,150	260	11,700	20,000	Packer
L-5803	10-23-87	1,318-1,422	720	--	1,770	3,000	Completed
L-5803	12-12-90	1,318-1,422	555	379	1,580	2,600	Completed
L-5803	10-30-87	1,930-2,004	19,400	--	35,600	56,000	Completed
L-5803	12-12-90	1,930-2,004	18,600	2,820	35,200	49,900	Completed
L-6412	--	360-590	6,000	--	--	--	DQW
L-6431	05-90	455-740	750	--	--	--	Completed
L-6432	07-90	560-800	520	--	--	2,210	Completed
L-6433	07-90	488-645	1,450	--	--	--	Completed
L-6434	07-90	485-720	680	--	--	--	Completed
L-6435	--	980-1,060	5,450	--	--	10,100	DQW
L-6436	--	900-940	13,100	--	--	--	DQW
L-6437	--	800-1,070	5,200	--	--	17,000	DQW
L-6438	05-90	494-780	580	--	--	--	Completed
L-6439	05-90	505-760	800	--	--	--	Completed
L-6440	07-90	520-760	700	--	--	--	Completed
L-6441	07-90	395-750	1,100	--	--	--	Completed
L-6442	07-90	430-740	560	--	--	--	Completed
S-450	06-30-41	1,002-1,046	1,180	--	--	4,760	Completed-USGS
S-450	06-30-41	1,200-1,210	1,410	644	--	5,720	Completed-USGS

Appendix III

Tops of Geologic Units in Selected Wells as Determined for this Study

[Well locations are shown in figures 2 and 3. Asterisk indicates top determined using lithologic description only. Dashes indicate well not deep enough or inadequate data available to determine top. Tops for Ocala Limestone and Avon Park Formation not determined for all wells in this appendix. Depths are from measuring point, which is at land surface or above]

Local well identifier	Altitude measuring point (feet)	Depth to top of basal Hawthorn unit (feet)	Depth to basal contact of Hawthorn Group (feet)	Depth to top of Ocala Limestone (feet)	Depth to top of Avon Park Formation (feet)	Depth to top of dolomite-evaporite unit (feet)
C-234	37	530	800	1,000	1,280	1,820
C-679	14	626	768	--	--	--
C-680	12	647	855	--	--	--
C-701	34	--	860*	970	1,230	1,835
C-708	32	560	850	--	--	1,960
C-710	38	520	760	910	1,330	2,230
C-711	32	580	810	1,000	1,540	2,070
C-712	32	583	710	1,010	1,264	1,760
C-719	35	--	--	1,020	1,398	1,873
C-726	25	--	805*	1,270	1,625	2,350
C-727	45	592*	801*	--	1,365	2,080
C-729	35	--	--	--	--	2,250
C-739	36	586	756	--	--	--
C-742	40	525	720*	1,060	1,382	--
C-753	42	517	650	1,055	1,394	2,027
C-759	21	580	790	1,110	--	--
C-764	40	534	680	1,090	1,360	2,255
C-781	46	556	846	1,134	1,441	--
C-794	29	645	820	1,020	--	--
C-802	39	760	960	1,150	1,300	--
C-808	40	650	825	1,200	--	--
C-820	41	665	840	1,080	1,395	2,100
C-851	18	--	--	968	1,381	--
C-913	5	695	858	--	--	--
C-914	6	646	880	--	--	--
C-915	5	630	780	--	--	--
C-916	5	615	780	--	--	--
C-917	6	701	--	--	--	--
C-918	8	678	837	1,227	--	--
C-919	9	707	935	1,081	--	--
C-920	9	684	890	1,140	--	--
C-921	10	712	930	1,088	--	--
C-922	5	720*	920*	1,070	--	--
C-923	8	708	882	1,272	--	--

Local well identifier	Altitude measuring point (feet)	Depth to top of basal Hawthorn unit (feet)	Depth to basal contact of Hawthorn Group (feet)	Depth to top of Ocala Limestone (feet)	Depth to top of Avon Park Formation (feet)	Depth to top of dolomite-evaporite unit (feet)
C-924	7	689	858	1,267	--	--
C-925	8	705	905	1,330	--	--
C-926	11	645	880	1,350	--	--
C-927	5	670*	920*	--	--	--
C-928	6	670*	860*	--	--	--
C-929	5	690*	880*	1,270	--	--
C-930	15	--	1,028*	1,240	--	--
C-931	5	670*	850*	1,170	--	--
C-932	10	610*	840*	1,225	--	--
C-933	8	600	833	1,320	--	--
C-934	12	600	852	1,260	--	--
C-935	14	650	864	1,240	--	--
C-938	26	558	800	1,055	--	--
C-962	26	766	982	1,150	1,290	2,550
C-1091	13	693	Not reached at 702	--	--	--
C-1102	5	575	750	1,100	1,350	--
C-1103	10	545	800	1,300	--	--
C-1104	6	596	860	1,300	1,500	2,350
C-1106	5	612	778	--	--	--
C-1107	14	639	870	1,270	1,540	2,220
C-1111	10	560	750	1,240	1,485	2,210
C-1112	27	--	--	--	1,460	2,165
C-1122	24	570	730	970	--	--
C-1123	50	570*	740*	1,010	1,337	1,580
C-1124	42	717	870	1,130	1,420	2,120
C-1125	36	676	840	1,080	1,240	2,480
C-1126	40	670	910	1,130	1,328	2,360
C-1127	32	772	960	1,140	1,270	2,570
C-1128	38	--	920*	1,200	1,450	--
C-1129	36	--	900*	1,130	--	--
C-1130	56	651	790	1,120	1,403	2,180
C-1131	47	--	800*	1,100	--	--
C-1132	45	470	650	1,020	--	--
C-1133	38	690	840	--	--	--

Local well identifier	Altitude measuring point (feet)	Depth to top of basal Hawthorn unit (feet)	Depth to basal contact of Hawthorn Group (feet)	Depth to top of Ocala Limestone (feet)	Depth to top of Avon Park Formation (feet)	Depth to top of dolomite-evaporite unit (feet)
CH-312	11	520	710	--	--	--
CH-313	22	447	720	1,250	1,580	1,970
G-2296	17	775	980	980	1,128	2,440
G-3239	25	838*	1,050*	Not present	1,155	2,550
GL-240	25	613	805	850	--	--
HE-281	29	609	910	980	--	--
HE-282	40	747*	1,040*	1,160	1,390	2,300
HE-343	54	--	--	--	--	2,010
HE-941	48	--	640*	1,010	1,400	2,100
HE-948	49	--	--	--	1,409	2,060
HE-949	53	520	800	1,050	--	2,130
HE-953	40	490	700	960	1,327	--
HE-970	45	--	--	--	--	2,280
HE-973	40	--	--	--	--	2,260
HE-976	39	689	830	1,151	1,426	2,370
HE-981	32	--	862	950	--	--
HE-982	30	--	950	--	--	--
HE-983	31	538	870	935	--	--
HE-984	29	559	855	905	--	--
HE-986	23	543	730*	835	--	--
HE-987	15	--	790	860	--	--
HE-1084	14	560	Not reached at 622	--	--	--
HE-1085	25	620	Not reached at 740	--	--	--
HE-1086	27	--	930*	--	--	--
HE-1087	15	611	780	780	1,010	2,060
HE-1101	30	742	920	1,165	1,430	--
HE-1102	49	--	930*	--	--	1,990
HE-1103	49	639*	1,050*	1,050	--	Not reached at 2,180
HE-1104	49	532	960	1,060	1,290	2,310
HE-1105	53	534	750	1,030	1,330	--
HE-1106	54	514	710	1,054	1,380	1,920
L-550	4	418	690	--	--	--
L-755	22	434	748	--	--	--

Local well identifier	Altitude measuring point (feet)	Depth to top of basal Hawthorn unit (feet)	Depth to basal contact of Hawthorn Group (feet)	Depth to top of Ocala Limestone (feet)	Depth to top of Avon Park Formation (feet)	Depth to top of dolomite-evaporite unit (feet)
L-1018	13	446	853	--	--	--
L-1044	20	360	590	--	--	--
L-1094	5	648	962	--	--	--
L-1318	15	468	685	--	--	--
L-1396	20	334	648	--	--	--
L-1569	12	530	Not reached at 809	--	--	--
L-1595	15	556	785	--	--	--
L-1688	30	442	790	--	--	--
L-1817	5	482	744	--	--	--
L-1903	15	350	537	--	--	--
L-1967	3	660	870	--	--	--
L-2061	30	682	815	--	--	--
L-2063	31	--	815*	1,300	--	--
L-2458	25	420	640	--	--	--
L-2460	5	408	580	--	--	--
L-2657	9	486	720	--	--	--
L-2901	5	360	640	--	--	--
L-4817	21	380	570	--	--	--
L-4846	10	390	710	--	--	--
L-5000	40	475	870	--	--	1,670
L-5001	53	673	815	1,175	1,380	--
L-5003	43	--	786*	1,190	1,450	1,920
L-5009	47	537*	802*	1,120	1,450	1,900
L-5010	42	525	650	--	--	--
L-5013	24	534*	--	1,206	1,420	2,120
L-5601	5	400	720	--	--	--
L-5602	10	580	820	--	--	--
L-5605	27	455	740	1,200	1,500	1,950
L-5608	16	473	823	--	--	--
L-5609	5	370	580	--	--	--
L-5615	5	490	750	--	--	--
L-5802	20	455	740	1,210	1,520	1,900
L-6400	2	554	675	--	--	--
L-6401	11	467	789	--	--	--

Local well identifier	Altitude measuring point (feet)	Depth to top of basal Hawthorn unit (feet)	Depth to basal contact of Hawthorn Group (feet)	Depth to top of Ocala Limestone (feet)	Depth to top of Avon Park Formation (feet)	Depth to top of dolomite-evaporite unit (feet)
L-6411	4	--	732*	--	--	--
L-6412	3	390	518	--	--	--
L-6413	5	--	840*	--	--	--
L-6414	19	464	915	--	--	--
L-6415	43	568*	750*	1,113	--	--
L-6417	3	340	710	--	--	--
L-6421	5	365	610	--	--	--
L-6423	5	608	755	1,225	--	--
L-6435	2	402	860	1,220	--	--
L-6436	3	423	720	1,050	--	--
L-6437	6	488	820	1,120	--	--
L-6439	18	428	730	--	--	--
L-6443	5	366	610	--	--	--
L-6444	15	380	770	1,170	1,570	--
L-6445	4	580	792	1,144	1,479	--
L-6461	46	646	830	1,170	1,460	1,920
L-6462	38	496	705	1,085	--	--
L-6463	45	593	800	1,205	1,470	2,104
L-6471	5	273	730	1,050	1,360	1,740
MO-141	25	895	1,110	1,270	1,390	--
PB-1137	32	707	932	932	1,112	2,330
PB-1138	31	666	865	956	1,098	2,170
PB-1163	12	--	--	840	1,020	--
PB-1164	18	--	750*	800	--	--
S-479	18	853	1,060	1,115	1,150	2,560

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