Hydrogeology and the Distribution and Origin of Salinity in the Floridan Aquifer System, Southeastern Florida

By Ronald S. Reese

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per day (ft/d)	0.000353	centimeters per second
foot squared per day (ft^2/d)	0.9290	meter squared per day
gallon per minute (gal/min)	0.00006309	cubic meter per second
pound per square inch per foot ($lb/in^2/ft$)	22.6214	kilopascal per meter
gram per cubic centimeter (g/cm^3)	62.43	pound per cubic foot

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

Equations for temperature conversion between degrees Celsius (°C) and degrees Fahrenheit (°F):

°C = 5/9 x (°F – 32)
°F = (9/5 °C) + 32

Abbreviated water-quality units

mg/L = milligrams per liter
µS/cm = microsiemens per centimeter

Acronyms

API	American Petroleum Institute (standard units for natural gamma-ray radioactivity measured in boreholes
FDEP	Florida Department of Environmental Protection
GWSI	Ground-Water Site Inventory System (a U.S. Geological Survey computerized well data storage and retrieval system)
QWDATA	U.S. Geological Survey Water-Quality Data storage and retrieval computer system
RASA	Regional Aquifer System Analysis
USGS	U.S. Geological Survey

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Abstract

The Floridan aquifer system in southeastern Florida consists of the Upper Floridan aquifer, the middle confining unit, and the Lower Floridan aquifer and ranges from Paleocene to Oligocene in age. The top of the rocks of Eocene age in the study area approximates the top of the Upper Floridan aquifer and coincides with an important flow zone.

An upper zone of brackish water and a lower zone of water with a salinity similar to that of seawater are present in the Floridan aquifer system. The brackish-water zone is defined as that in which water has a dissolved-solids concentration of less than 10,000 milligrams per liter (chloride concentration less than about 5,240 milligrams per liter), and water in the saline-water zone has a dissolved solids concentration of about 35,000 milligrams per liter (about 18,900 milligrams per liter chloride concentration). The brackish-water and saline-water zones are separated by a transitional zone, typically 100 feet thick, in which salinity increases abruptly with depth. The base of the brackish-water zone lies within the Upper Floridan aquifer along the coast but extends into the middle confining unit inland. The brackish-water zone is as much as 1,200 feet thick inland, whereas the Upper Floridan aquifer is typically 500 to 600 feet thick. Chloride concentrations range from about 850 to 5,640 milligrams per liter and from about 1,410 to 3,330 milligrams per liter in the upper and lower intervals of the brackish-water zone, respectively.

The base of the brackish-water zone and the top of the saline-water zone were approximately determined mostly through the use of resistivity borehole geophysical logs. Changes in lithology or permeability do not usually control the position of the boundary between the brackish-water and saline-water zones. Calculations of the depth of a brackish-water/saline-water interface using the Ghyben-Herzberg relation show good agreement between calculated and actual positions of the interface, indicating equilibrium between the zones.

Several areas of high salinity (chloride concentrations greater than 3,000 milligrams per liter) are present in the upper interval of the brackish-water zone near the coast, and in one of these areas in northeastern Broward County, salinity decreases with depth from the upper to lower interval. Available data indicate that in areas of high salinities, the Upper Floridan aquifer has relatively high transmissivity. The high salinities could be a result of seawater preferentially encroaching into zones of higher permeability in the Upper Floridan aquifer during Pleistocene high stands of sea level and incomplete flushing of the seawater by the present-day flow system.

INTRODUCTION

The growing population of southeastern Florida (fig. 1) in recent years has local and State officials concerned with finding a supplemental source for public-water supply. The virtually untapped Floridan aquifer system can be used to assist in this need. Three methods regarding its use are currently being explored: (1) blending brackish ground water from the Upper Floridan aquifer with freshwater from the overlying Biscayne aquifer in the surficial aquifer system, (2) temporarily storing excess fresh surface water or Biscayne aquifer water in the Upper Floridan aquifer and withdrawing the water when needed, and (3) treating Upper Floridan aquifer water directly by the reverse osmosis method or other desalination method. In the reverse osmosis method, high pressure is applied to the water being treated, forcing pure water through a

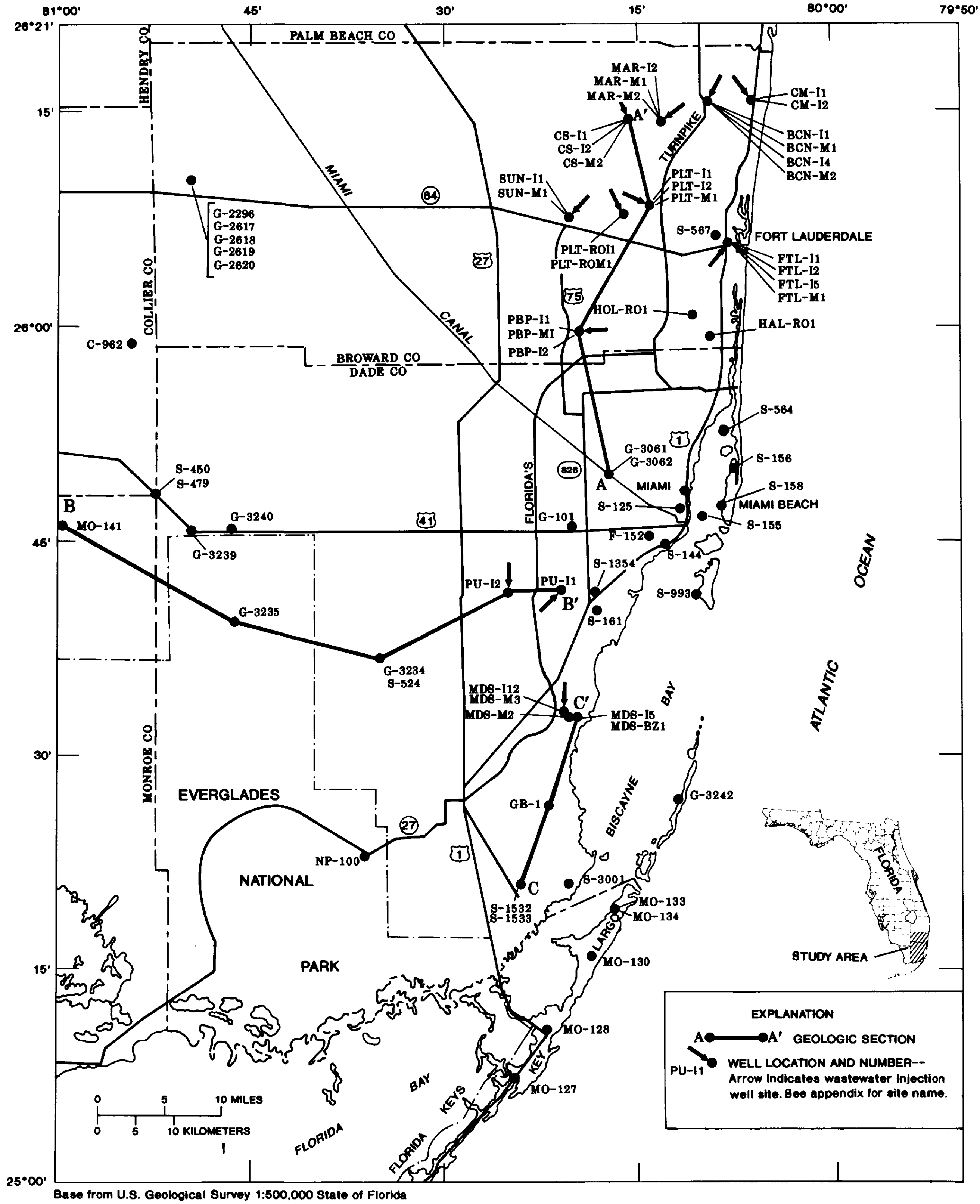


Figure 1. Location of the study area, wells penetrating the Floridan aquifer system used in the study, and geologic section lines.

semipermeable membrane and leaving behind the dissolved salts. Because the salinity of water in the Upper Floridan aquifer is considerably less than that of seawater, the expense of reverse osmosis treatment is also less.

The Miami-Dade Water and Sewer Department plans to construct a new Biscayne aquifer well field (West Well Field) and is considering constructing wells for water-supply augmentation at this site from the Floridan aquifer system using the above methods. Several wells completed in the Floridan aquifer system have been drilled in southeastern Florida in recent years to supply reverse osmosis treatment plants. However, before use of the Floridan aquifer system can be implemented on a large scale in the area, the distribution and controls on the quality of water in the aquifer system need to be characterized and better understood.

To address these information needs, the U.S. Geological Survey (USGS), in cooperation with the Miami-Dade Water and Sewer Department and the South Florida Water Management District, conducted a study from May 1990 to September 1992 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 hydrogeology. The study area includes Dade, Broward, and parts of Monroe and Collier Counties including the upper Florida Keys (fig. 1). Dade and Broward Counties are bounded by the Atlantic Ocean to the east and Monroe and Collier Counties to the west. Land-surface elevation in the study area is generally less than 15 ft and averages 5 to 10 ft.

Water in the Upper Floridan aquifer in southeastern Florida is brackish with chloride and dissolved-solids concentrations generally greater than 1,000 mg/L (Sprinkle, 1989, pls. 6, 8). Salinity in the Upper Floridan aquifer usually increases with depth. 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 to be protected from contamination by injected wastewater through the Underground Injection Control Program of the Safe Drinking Water Act (Fetter, 1988, p. 459). Underground injection control in Florida is regulated by the Florida Department of Environmental Protection (FDEP), formerly known as the Florida Department of Environmental Regulation (1982).

Purpose and Scope

The purposes of this report are to: (1) evaluate the distribution of salinity in the Floridan aquifer system, (2) describe the distribution of salinity in relation to the local hydrogeology, and (3) assess the potential processes that might control or have affected the distribution of salinity. Because most of the water-quality data available in the study area were not comprehensive enough for a complete analysis of water quality in the Floridan aquifer system, the analysis in this report deals only with salinity (principally concentrations of dissolved solids and chloride).

Geologic sections and a map were prepared, showing the altitude of the top of the rocks of Eocene age which approximates the top of the Floridan aquifer system in most of the study area. Borehole geophysical logs were used to correlate geologic units between wells. The hydrogeologic units of the Floridan aquifer system are described, including their thickness, relation to geologic units, and hydraulic properties.

Most of the water-quality data used in this report were not collected as part of this study, and more than half of the 117 analyses used were not collected by the USGS. Most of these non-USGS data were obtained from wastewater injection well systems.

Borehole geophysical logs were used to evaluate formation salinity. The depths of occurrence of threshold salinity values of interest in the Floridan aquifer system were approximately determined using resistivity geophysical logs. 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 chloride concentration and specific conductance using water-quality data from the Floridan aquifer system.

The Floridan aquifer system was divided into three salinity zones. These zones, in order of increasing depths are: the brackish-water zone, the transitional zone, and the saline-water zone. The boundaries between them were determined principally using borehole geophysical logs. Maps were constructed that show the approximate altitudes of the base of the brackish-water zone and the top of the saline-water zone. Using head data from the Upper Floridan aquifer, the altitude of a brackish-water/saline-water interface was calculated in several wells and compared to the altitude of the base of the brackish-water zone determined using geophysical logs.

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, and the distribution of salinity in the upper and lower intervals of this zone were mapped over the study area. This mapping and the map of the altitude of the base of the brackish-water zone were useful in determining processes that could control the thickness and distribution of salinity in the brackish-water zone and in understanding the origin of salinity in the Floridan aquifer system.

Classification and Characterization of Salinity

A classification scheme for water based on dissolved-solids concentrations was primarily used to define salinity in the Floridan aquifer system in southeastern Florida. Brackish water contains dissolved-solids concentrations that range from 1,000 to 10,000 mg/L, slightly saline water contains concentrations from 10,000 to 35,000 mg/L, and saline water contains concentrations from 35,000 to 100,000 mg/L. This scheme is the same as defined by Fetter (1988, p. 368), except that saline water defined by Fetter contains dissolved-solids concentrations that range from 10,000 to 100,000 mg/L and is redefined here. Seawater has dissolved-solids concentrations of about 36,000 mg/L (Nordstrom and others, 1979), which is a common salinity level in the Floridan aquifer system. A well-defined relation between dissolved-solids and chloride concentrations in water produced from the Floridan aquifer system is established in this report, which allows for the interchangeable use of these constituents in characterizing salinity. Chloride concentration is used in mapping the distribution of salinity in this report.

Inventory of Well Data

Data on all the wells used in this report are presented in the appendix and include: local well identifier, site identification number, latitude and longitude, county, ownership, altitude of measuring point, well depth, casing depths and sizes, completed (open) intervals, type of openings, and well-construction date. Wells in the appendix are listed by order of local well identifier; some wells have been plugged and abandoned, and the date of abandonment is given, if known. A completed interval is defined in this report as an interval open to flow in a well regardless of the type of openings in the interval. Completed intervals in a well 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. The location of all wells used in this report are shown in figure 1. Data from most wells that penetrate the Floridan aquifer system in the study area are stored in the USGS Ground-Water Site Inventory (GWSI) computer system.

Many of the wells used in this study were drilled at wastewater injection well system sites. Twelve of these sites are present in the study area, and wells from all of them were used (fig. 1). The injected fluid at all but one of these sites is secondarily treated municipal wastewater. At the site identified by wells PLT-ROI1 and PLT-ROM1 in eastern Broward County, the injectant is reject water produced at a reverse osmosis water-treatment plant. The first part of the well name for wells at these sites is an abbreviation for the name of the wastewater or water-treatment plant at the site, and the names of these plants are given in the appendix. Hereafter, these sites will be referred to using these abbreviations.

Some wells used in the study are located in close proximity to each other. At the wastewater injection system sites, monitoring wells are usually drilled adjacent to an injection well. For example, injection well FTL-I5 and monitoring well FTL-M1 at the FTL site are 90 ft apart. The wastewater injection monitoring wells used in the study are all less than 200 ft from their companion injection well. Data collected from these "twin" wells are considered as data collected from one well in this report, and they are listed sequentially in the appendix.

Extensive data were collected from wastewater injection system wells. Open-hole geophysical logs were run in many of the wells through borehole penetrating sections of the Floridan aquifer system including electrical logs, dual induction-laterlogs, borehole-compensated sonic logs, borehole-compensated neutron-density logs, and natural radioactivity or gamma-ray logs. In some wells, whole diameter cores of selected intervals in the middle confining unit of the Floridan aquifer system were taken and analyzed in a laboratory. Water-quality data collected from these wells (mostly non-USGS data) include samples collected during drilling, samples from open-hole (drill stem) packer tests, and samples from completed intervals. Most monitoring wells have two completed intervals--typically one near the top of the Upper Floridan aquifer and the other in the lower part of the Upper Floridan aquifer or in the middle confining unit of the Floridan aquifer system. Most of the water-quality data used in this study were collected from the wastewater injection system wells.

Data on wells that penetrate the Floridan aquifer system are presented in two USGS publications. Beaven and Meyer (1978) present a record of wells in the Floridan aquifer system in Dade and Monroe Counties. Smith and others (1982) provide data on selected deep wells in southern Florida, including all of the wells penetrating the Floridan aquifer system in the study area. The data in the report by Smith and others (1982) consist of well identification and geographic location, well construction and site use, logs run, and representative water-quality analysis.

Previous Studies

The Regional Aquifer System Analysis (RASA) Program provided background information for this report. The RASA Program began in 1978, following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The final interpretive results of the RASA Program 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 extensively 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 and shows the top of seawater-like salinity in a generalized east-west hydrogeologic section. Miller (1986) 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. Results of the study by Sprinkle (1989, pl. 8) indicated that all of southern Florida is part of an area that has dissolved-solids concentrations greater than 1,000 mg/L from the Upper Floridan aquifer. No further definition of salinity is shown in this area.

Chen (1965) studied the lithology and stratigraphy of Paleocene and Eocene strata in Florida and made paleogeographic interpretations. The Floridan aquifer system in southeastern Florida was mostly deposited during Eocene time (Miller, 1986). Puri and Winston (1974) mapped and described high transmissivity zones in southern Florida. These zones generally occur in Eocene strata and are characterized by cavernous porosity development.

HYDROGEOLOGY OF THE FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system is defined as a vertically continuous sequence of permeable carbonate rocks of Tertiary age that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude greater than that of the rocks bounding the system above and below (Miller, 1986). This section presents a detailed description of the Floridan aquifer system, its component aquifers and confining units, and their relation to stratigraphic units. The hydrogeology of southeastern Florida, as described here, is based largely on data collected from wells that were drilled in Dade, Broward, and parts of Monroe and Collier Counties (fig. 1).

Geologic Framework

The Floridan aquifer system in southeastern Florida includes (from oldest to youngest) the upper part of the Cedar Keys Formation of Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, the Ocala Limestone of late Eocene age, and the Suwannee Limestone of Oligocene age (Miller, 1986). The Hawthorn Formation of Miocene age overlies the Suwannee Limestone and is part of the confining unit that overlies the Floridan aquifer system in the study area.

Preliminary delineation of the geologic units in the study area began with selected wells in which the tops of the units were determined by Miller (1986). These tops were then stratigraphically correlated to other wells in the study area where adequate data were available. Except for one well, the correlations were based on geophysical logs with the natural radioactivity or gamma-ray log being the most useful. The top of the Avon Park Formation in well S-161 was determined using a description of drill-cutting samples. Because few wells were drilled below the base of the Oldsmar Formation, the upper permeable part of the Cedar Keys Formation was not delineated. A total of 43 wells were used in the delineation of geologic units, and these data are given in table 1.

The lithology and thickness of all units in the Floridan aquifer system, except the Ocala Limestone and the Cedar Keys Formation, have been well defined at the MDS site in southeastern Dade County near Biscayne Bay (fig. 1). The geologic units, hydrogeologic units, lithology, and geophysical logs for monitoring well MDS-BZ1 at this site are shown in figure 2. The lithologies found in this well are characteristic of the Floridan aquifer system in the study area.

Lithology and Thickness

The Floridan aquifer system in southeastern Florida is composed predominantly of limestone with dolomitic limestone and dolomite being common in the lower part. A detailed lithologic description of the units in the Floridan aquifer system for all of Florida is presented by Miller (1986). Some important differences in lithology exist between southeastern Florida and the rest of Florida.

The percentage of dolomite in the carbonate rocks of Eocene age in southern Florida was mapped by Puri and Winston (1974, figs. 12-14). The percentage of dolomite in the upper and middle parts of the Eocene is small in the study area, ranging from 0 to 25 percent, and is nonexistent in northern Dade County and most of Broward County. The percentage increases to more than 50 percent to the north and west of the study area.

The lowest unit in the Floridan aquifer system is the upper part of the Cedar Keys Formation, which is about 500-ft thick in the study area (Miller, 1986, pls. 3 and 33). This part of the Cedar Keys Formation is composed of dolomite or dolomitic limestone, and its lower boundary is the top of impermeable, massive anhydrite beds.

The Oldsmar Formation is about 1,000- to 1,200-ft thick in the study area, and its lithology is predominantly micritic limestone. The lower, approximately 300- to 600-ft section of the Oldsmar Formation, locally called the Boulder zone, is predominantly dolomite and contains massively bedded, cavernous or fractured dolomite of high permeability and dense, recrystallized dolomite of low permeability. Zones of similar lithology can also be present in the upper part of the Oldsmar Formation.

The Avon Park Formation is about 1,100- to 1,200-ft thick in the study area and is composed predominantly of micritic or chalky to fine-grained limestone with low permeability. This geologic unit is characterized on gamma-ray logs as having relatively low natural radioactivity, generally less than 20 to 30 American Petroleum Institute (API) standard units. Porosity can be as high as 50 percent at or near the top of the formation and gradually decreases with depth as shown by porosity type well logs which indicate total porosity.

The Ocala Limestone is not present in most of the study area (Miller, 1986, pl. 9). However, this geologic unit is present in northernmost Monroe, northwestern Dade, Collier, and western Broward Counties and reaches a thickness of 150 to 200 ft.

The top of the Suwannee Limestone was difficult to determine on geophysical logs and is not given in table 1; however, this geologic unit ranges from 120- to more than 300-ft thick in the study area. The lower part of the Suwannee Limestone contains beds of marlstone and limestone with as much as 30 percent black phosphate sand (Camp Dresser and McKee, 1987, app. I). Most of the phosphate generally occurs within a 20- to 30-ft thick zone as shown by high natural radioactivity on the gamma-ray log (as high as 150 API units). This zone has been locally called the phosphate rubble zone but is referred to as the phosphatic zone in this report (fig. 3). The top of the phosphatic zone usually coincides with a correlation made in the upper to middle part of the Suwannee Limestone, referred to as the Suwannee Limestone correlation and given in table 1. Some limestone beds in the lower part of the Suwannee Limestone below the phosphatic zone contain quartz sand.

The top of the Suwannee Limestone could be at the base of the phosphatic zone or deeper in the study area. Scott (1988, p. 58) places the base of the

Table 1. Tops of geologic units in selected wells completed in the Floridan aquifer system as determined for this study

[Well locations shown in figure 1; local well identifier used for this report only; *, top not reached by log (depth estimated); **, top determined from sample description; --, top recorded in nearby well; NL, not logged; NP, not present; NR, not reached]

Local well identifier	Altitude measuring point (feet)	Depth to correlation in Suwannee Limestone (feet)	Depth to top of Ocala Limestone (feet)	Depth to top of Avon Park Formation (feet)	Depth to top of Oldsmar Formation (feet)
BCN-I1	14.4	NL	NP	1,034	2,052
BCN-M1	14.4	945	NP	1,030	--
C-962	25.6	870	984	1,150	2,060
CM-I1	19.2	936	NP	1,024	NR
CS-I1	13	1,000	NP	1,082	2,110
CS-I2	13	NL	NP	1,080	2,109
FTL-I5	6.2	NL	NP	992	1,959
FTL-M1	6.1	882	NP	992	--
G-2296	17.4	862	980	1,124	2,100
G-3061	8.7	957	NP	1,038	NR
G-3234	26	NL	NP	1,204	2,195
G-3235	16	950	NP	1,085	2,210
G-3239	24.0	910	980	1,053	2,170
G-3240	19	NL	1,010	1,083	2,160
GB-1	3.1	983	NP	1,130*	NR
HAL-RO1	15	880	NP	972	NR
HOL-RO1	13	910	NP	1,002	NR
MAR-I2	12.6	974	NP	1,054	---
MAR-M1	28	988	NP	1,068	2,120
MDS-BZ1	9.4	922	NP	1,050	2,230
MDS-I12	10	915	NP	1,015	2,180
MO-127	2	1,040	NP	1,240	NR
MO-128	15.2	1,020	NP	1,182	NR
MO-130	16.2	980	NP	1,140	NR
MO-134	4	1,035	NP	1,190*	NR
MO-141	25.4	996	1,112	1,276	NL
NP-100	6.0	1,108	NP	1,243	NR
PBP-I1	10	1,000	NP	1,082	2,100
PLT-I1	9.8	NL	NP	1,076	2,102
PLT-I2	8.4	NL	NP	--	--
PLT-M1	9.3	968	NP	1,074	--
PLT-ROI1	8.5	998	NP	1,098	2,120
PU-I1	8	980	NP	1,071	2,240
PU-I2	10	1,000	NP	1,095	2,292
S-156	5	840	NP	950*	NR
S-161	9.9	NL	NP	1,064**	NL
S-479	18	923	1,010	1,060	NR
S-524	8	1,082	NP	1,190	NR
S-567	11	NL	NP	1,006	NL
S-1533	5.6	1,092	NP	1,295	2,237
S-3001	9.7	982	NP	1,178	NR
SUN-I1	7.5	NL	NP	1,116	2,110
SUN-M1	7.5	1,010	NP	--	NR

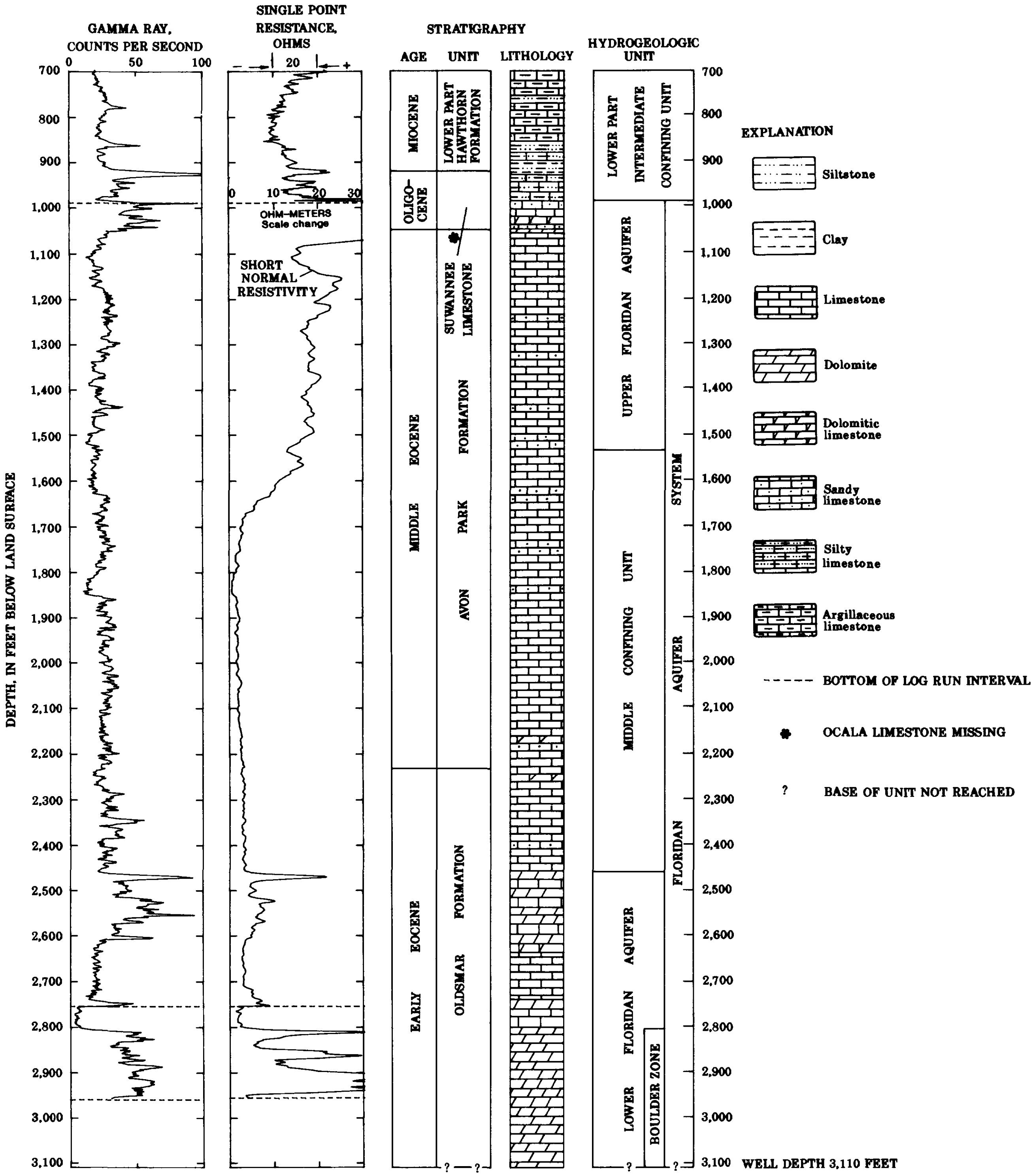


Figure 2. Selected geophysical logs, stratigraphy, and hydrogeologic units for well MDS-BZ1 near Biscayne Bay in southeastern Dade County.

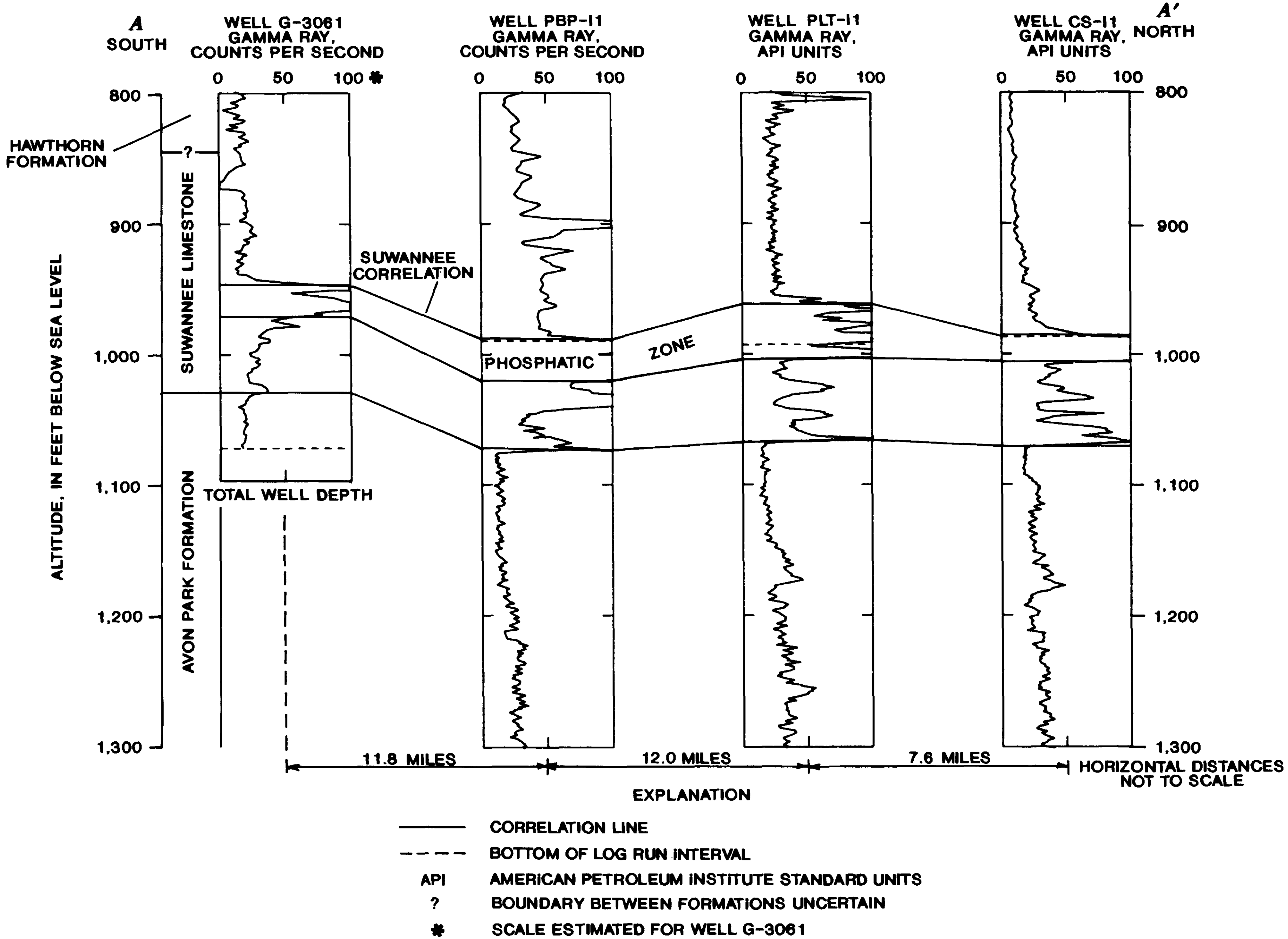


Figure 3. Generalized geologic section A-A′ showing correlations in and at the base of the Suwannee Limestone in northern Dade and southern Broward Counties. Line of section shown in figure 1.

Hawthorn Group of Miocene age in southern Florida at the base of the last occurrence of a sandy, variably phosphatic carbonate. The base of the Hawthorn Group (Scott, 1988, figs. 41 and 42) is at an altitude similar to the top of the rocks of Eocene age, as mapped in this study (shown later). The phosphatic zone is placed in the Suwannee Limestone in this report (fig. 3) based on the position of the top of the Suwannee Limestone as shown by previous investigators in southern Florida (Puri and Winston, 1974; Miller, 1986; and Meyer, 1989). This formation top in these previous studies was determined mostly using characteristic microfossils.

Overall appearance of the lower part of the Suwannee Limestone on a gamma-ray log often gives a characteristic pattern below the Suwannee correlation as shown in figure 3. Beds below the Suwannee correlation seem to be laterally continuous in the study area, at least in a north-south direction (fig. 3). Comparisons between wells indicate that the continuity of beds is greater in the north-south direction than in the east-west direction (fig. 4).

In some cases, resistivity logs were used for correlation, such as for well G-3235 (fig. 4). Correlations for this well are based on comparisons made with resistivity logs run on nearby wells (G-3239 and G-3234) where correlations were established. Well G-3234 is about 600 ft from S-524 in which a gamma-ray log was run (fig. 4). These resistivity logs include a lateral resistivity curve (not shown) which aids in correlation between wells.

According to Miller (1986, pl. 2), regional unconformities in peninsular Florida are present at the top of the rocks of early Eocene age (Oldsmar Formation), rocks of late or middle Eocene age (Ocala Limestone or Avon Formation if no Ocala Limestone is present), and rocks of Oligocene age (Suwannee Limestone). Zones of dissolution occur in association with these unconformities in southern Florida (Meyer, 1989, p. 7). Miller (1986, p. 49) indicates that post-Oligocene erosion was extensive, resulting in the loss of rocks of Oligocene age from much of the RASA study area. In southeastern Florida, it seems that the most significant unconformity in terms of erosion is at the top of the rocks of Eocene age. Correlation work indicates that uppermost Eocene beds present in one well can be absent in a nearby well and that this loss of sediments is accompanied by the thickening of post-Eocene beds above the unconformity in the nearby well (fig. 5). The post-Oligocene unconformity and the post-Eocene unconformity would coincide if, as suggested by Scott (1988), the Suwannee Limestone were absent in southeastern Florida.

Structure

The top of the rocks of Eocene age represents a major unconformity in the study area. Generally, this top which can be readily determined using gamma-ray geophysical logs is closely associated with the top of the Upper Floridan aquifer (described in the next section). The altitude of the top of the rocks of Eocene age is shown in figure 6. This top corresponds with the top of the Ocala Limestone in the westernmost part of the study area and with the top of the Avon Park Formation in the rest of the study area.

The top of the rocks of Eocene age ranged from less than 950 ft below sea level in northeastern Dade County to nearly 1,300 ft below sea level in southern Dade County (fig. 6). Two high areas were mapped, one to the east paralleling the coast and the other trending north-south in westernmost Dade and Broward Counties. A low area was mapped in southernmost Dade County, separating the mainland from Key Largo. Some of the relief on top of this surface might be due to erosion that occurred in association with the unconformity on the top of the rocks of Eocene age.

Hydrogeologic Units

The Floridan aquifer system is divided into three hydrogeologic units: the Upper Floridan aquifer, the middle confining unit, and the Lower Floridan aquifer. In the study area, the Floridan aquifer system ranges in thickness from 2,500 to 3,000 ft, and its top varies in altitude from 900 to more than 1,100 ft below sea level (Miller, 1986, pls. 26 and 27).

Overlying the Upper Floridan aquifer is a confining unit referred to as the intermediate confining unit in this report (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). The surficial aquifer system lies on the intermediate confining unit and extends from land surface to a depth of 160 to 350 ft below land surface in Broward County (Fish, 1988) and from 175 to more than 270 ft below land surface in Dade County (Fish and Stewart, 1991). The Biscayne aquifer is included in the surficial aquifer system.

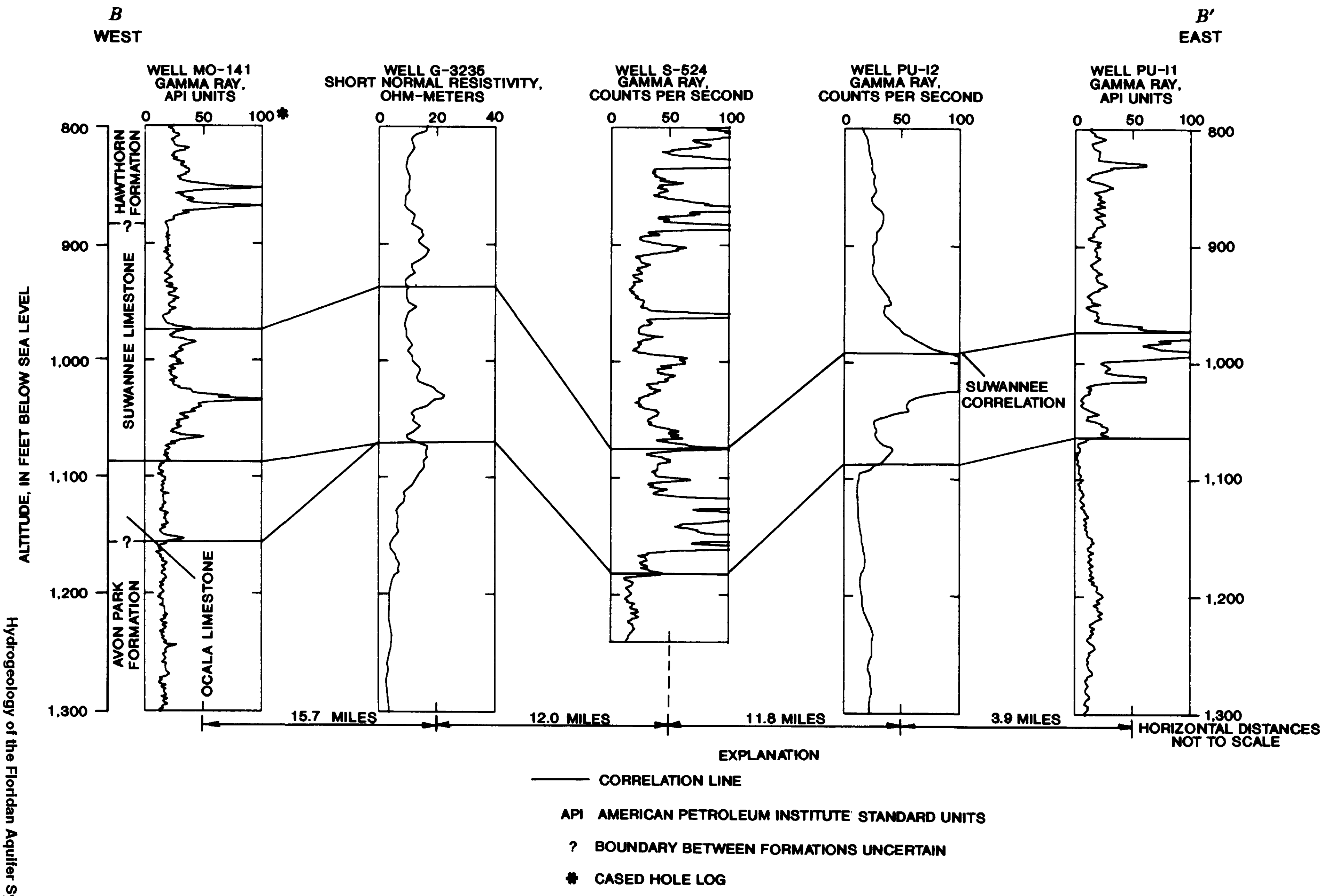


Figure 4. Generalized geologic section B-B′ showing correlations in and at the base of the Suwannee Limestone in eastern Monroe and central Dade Counties. A gamma-ray log was not run on well G-3235 (instead a resistivity log was used). Line of section shown in figure 1.

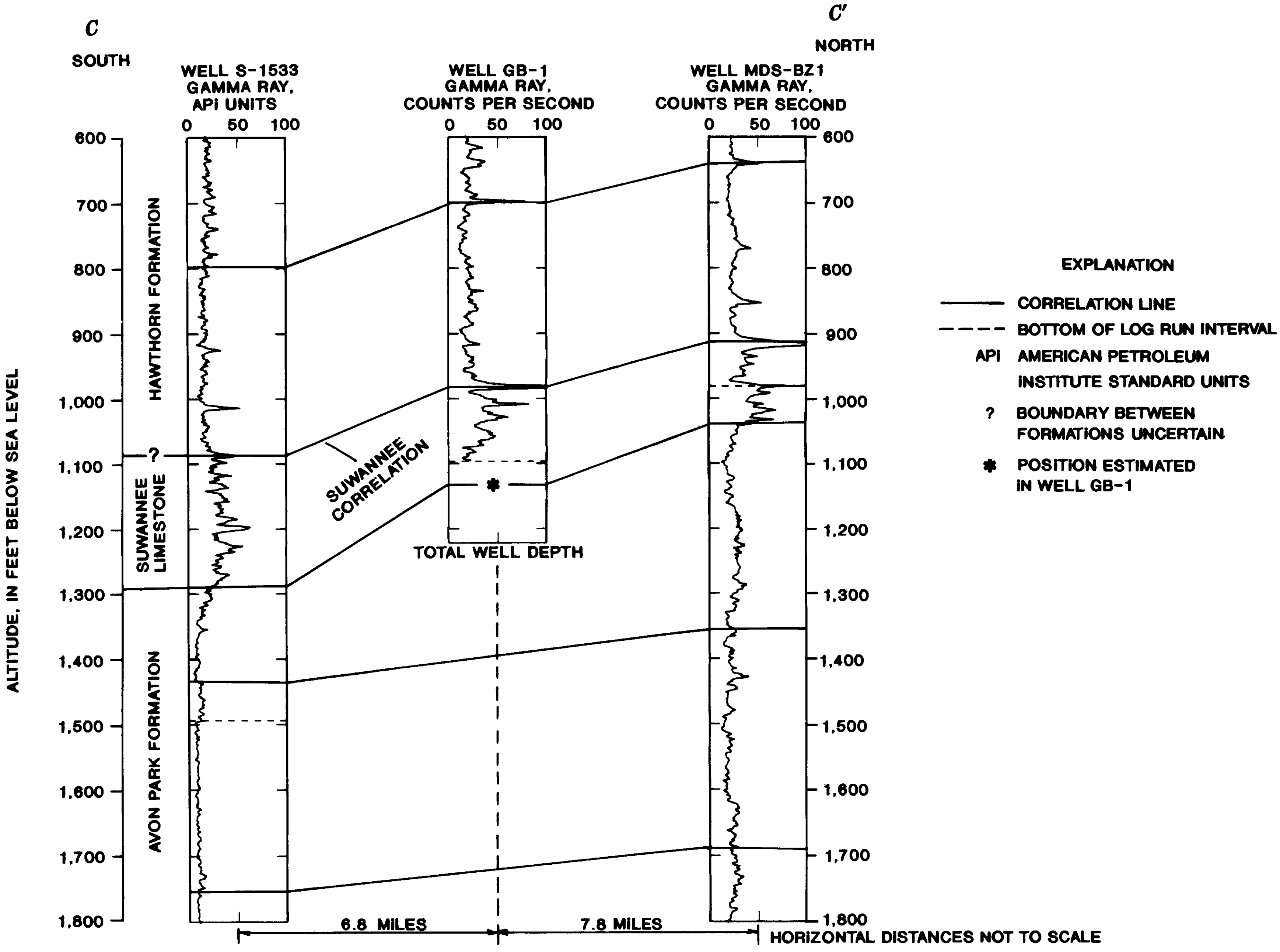


Figure 5. Generalized geologic section C-C′ showing thickening of the Suwannee Limestone in southeastern Dade County. Line of section shown in figure 1.

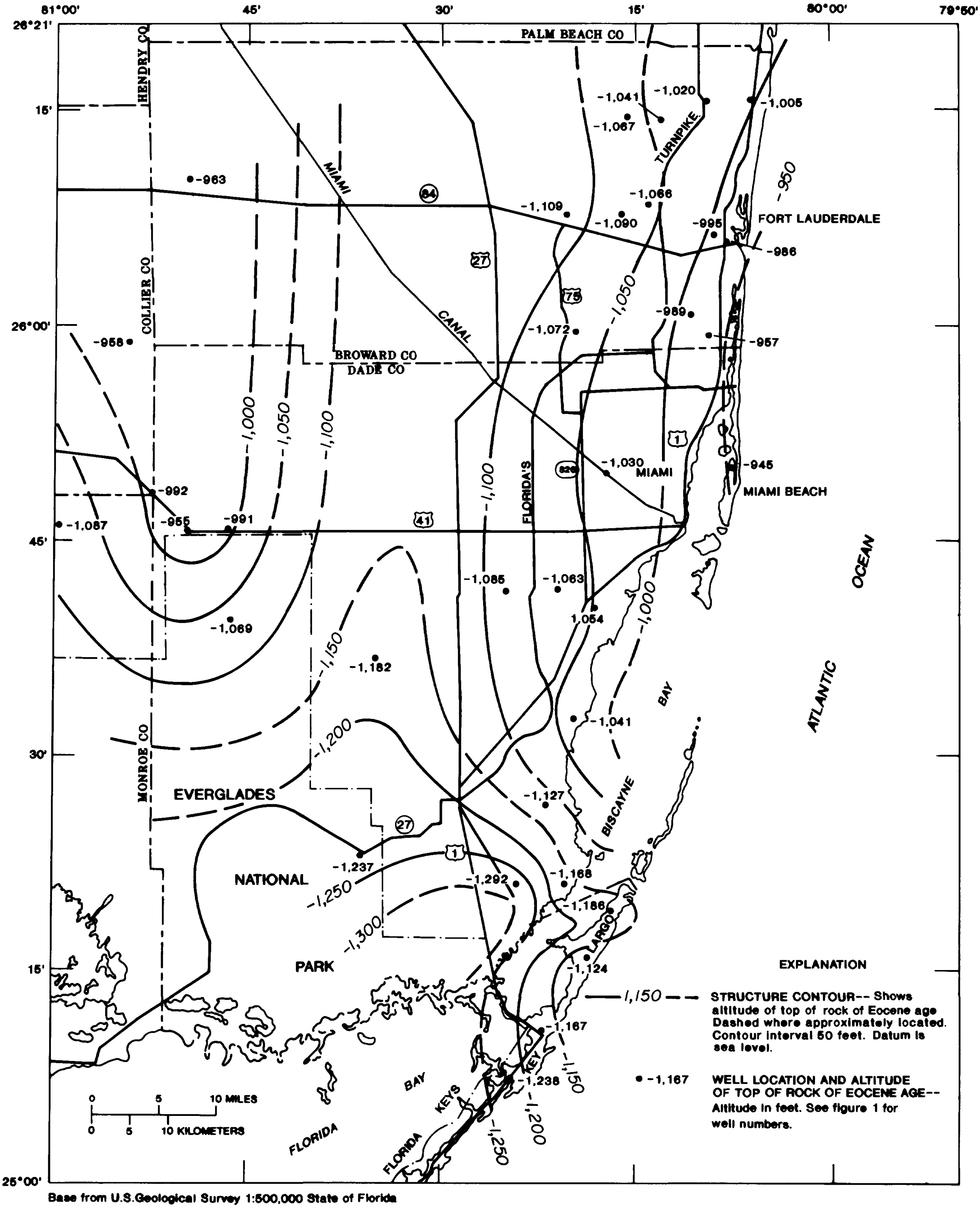


Figure 6. Altitude of the top of the rocks of Eocene age in southeastern Florida.

Intermediate Confining Unit

The intermediate confining unit varies in thickness from about 600 to 1,050 ft. This estimate was derived using the altitude of the top of the rocks of Eocene age (fig. 6) and the base of the surficial aquifer system (Fish, 1988; Fish and Stewart, 1991). The geologic units in the intermediate confining unit generally include the Hawthorn Formation and Suwannee Limestone, but locally the uppermost sediments of the unit can be part of the Miocene-Pliocene Tamiami Formation (Fish and Stewart, 1991).

The lithology of the intermediate confining unit is variable and includes clay, silt, fine sand, siltstone, silty limestone, marlstone, limestone, and phosphatic limestone. A few zones within this sequence can be minor aquifers of local extent, particularly near its base, but generally permeability is relatively low.

Upper Floridan Aquifer

The Upper Floridan aquifer is generally 500 to 600 ft thick in the study area and consists of several thin water-bearing zones of high permeability interlayered with thick zones of low permeability. The most transmissive permeable zone is found at the top of the Upper Floridan aquifer and is associated with the unconformity at the top of the rocks of Eocene age. The Upper Floridan aquifer exists under flowing artesian conditions, so its permeable zones (or flow zones) can be defined in a well by using flowmeter and temperature logs. During flowmeter logging in a well under flowing or pumping conditions, an increase in vertical flow is recorded at the base of a flow zone as the flowmeter tool moves up the borehole, and the increase continues until the top of the zone is reached.

The upper permeable zone of the Upper Floridan aquifer was determined to be 12 ft thick in well G-3061 using flowmeter logging (M.L. Merritt, U.S. Geological Survey, written commun., 1994) as shown in figure 7. The thickness of this zone usually ranges from 10 to 40 ft in the study area but can be much thicker. The zone is at least 163 ft thick in well NP-100 in southernmost Dade County (Meyer, 1971) as determined from lithologic logs and artesian flow measurements during drilling. With casing set at 620 ft, the flow increased from 40 to 1,600 gal/min after drilling through this zone (Meyer, 1971, p. 66).

The upper permeable zone occurs in close association with the top of the rocks of Eocene age, which is considered to approximate the top of the Upper Floridan aquifer in this study; however, the top of the upper permeable zone can extend significantly above this contact. In well HAL-RO1 in southeastern Broward County (fig. 1), the zone extends into the lower 40 ft of the Suwannee Limestone of Oligocene age.

Other lesser flow zones or permeable parts occur deeper in the Upper Floridan aquifer, and the base of the Upper Floridan aquifer is placed at the bottom of the lowest flow zone in the Avon Park Formation. The lithologic and hydraulic properties of most of the rocks in the lower part of the Upper Floridan aquifer are similar to those in the middle confining unit of the Floridan aquifer system. This makes placement of the base of the aquifer difficult and somewhat arbitrary. The base of the aquifer in well MDS-BZ1 is almost 500 ft below the top of the Avon Park Formation (fig. 2). Temperature and flowmeter logs from this well indicate that a water-bearing zone is present between 1,420 and 1,540 ft deep. In well PLT-I2, a straddle packer test of the 40-ft depth interval from 1,569 to 1,609 ft indicates a transmissivity of about 5,000 ft^2/d (Camp Dresser and McKee, Inc., 1991). The top of the rocks of Eocene age in well PLT-I2 is at a depth of about 1,074 ft, giving a thickness of at least 535 ft for the Upper Floridan aquifer.

The transmissivity of the Upper Floridan aquifer in southern Florida is estimated to range from about 10,000 to 60,000 ft^2/d (Bush and Johnston, 1988). However, a single-well aquifer test of the upper completed interval in well MDS-M2 in southeastern Dade County gave a low transmissivity value of 2,700 ft^2/d (Miami-Dade Water and Sewer Department, 1991, p. 56a). The completed interval tested (980-1,020 ft deep) is at the top of the Upper Floridan aquifer but is only 40 ft thick. Transmissivity at the Hialeah site (fig. 1, wells G-3061 and G-3062) was determined by multiwell aquifer testing to be about 10,000 ft^2/d (M.L. Merritt, U.S. Geological Survey, written commun., 1994). At this site, the interval open in the pumped well (G-3061) was 150 ft thick, but only 70 ft of this interval was below the upper flow zone (fig. 7). At the Turkey Point site in southern Dade County (wells S-1532 and S-1533), transmissivity was determined to be about 31,000 ft^2/d (Bush and Johnston, 1988, pl. 2). The interval open in the pumped well (S-1532) was 274 ft thick in this test. Based on drilling characteristics, Puri

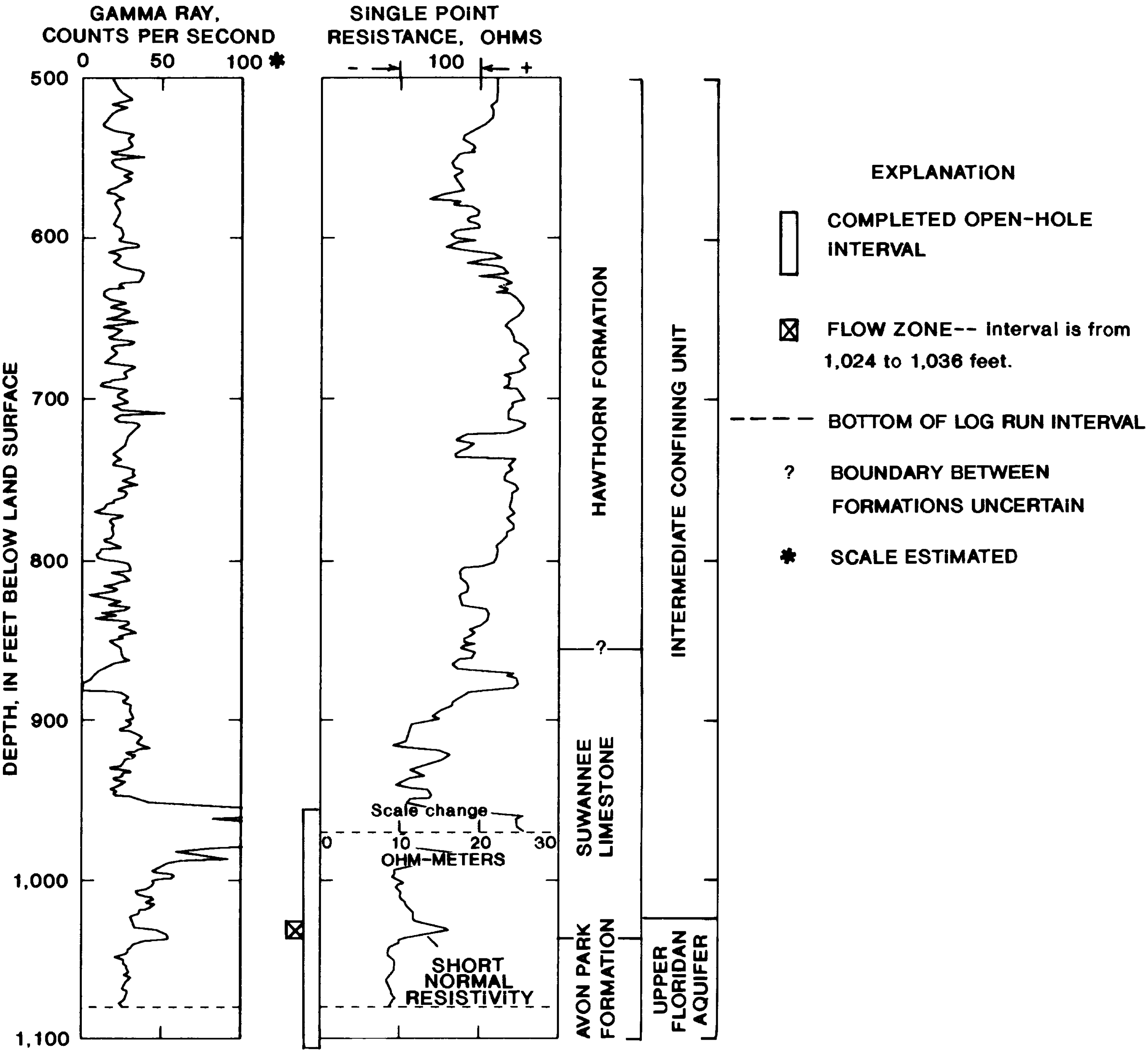


Figure 7. Geophysical logs of well G-3061 showing location of flow zone at the top of the Upper Floridan aquifer and geologic and hydrogeologic units in northeastern Dade County. Flow zone determined from flowmeter log.

and Winston (1974, fig. 35) mapped a belt of high transmissivity in the upper one-third of Eocene rocks that occurs in southern Dade County and northern Key Largo and trends east-northeast. The upper one-third of Eocene rocks, a unit used by Puri and Winston (1974), approximately coincides with the Upper Floridan aquifer.

The above data indicate that the transmissivity of the Upper Floridan aquifer varies widely in the study area, but the intervals tested also vary widely, making comparison between tests difficult. If the thin permeable zone at the top of the aquifer contributes most of the flow in the Upper Floridan aquifer, differences in the thickness of the interval tested might not be that important, provided this zone is included in the interval.

A potentiometric-surface map of the Upper Floridan aquifer, May 1980 (Bush and Johnston, 1988, pl. 5), shows the axis of a potentiometric high, extending from central Florida through the study area and approximately coincident with the axis of the Florida Peninsula. This potentiometric-surface high axis extends from northwestern Broward County to south-central Dade County. East of the axis in the study area, the general direction of ground-water flow is east-southeast or east. Heads range from 60 ft above sea level in northwestern Broward County to less than 40 ft above sea level in northeastern Dade County along the coast and about 40 ft above sea level in Key Largo.

Middle Confining Unit

The middle confining unit of the Floridan aquifer system includes the lower part of the Avon Park Formation and a variable thickness of the underlying Oldsmar Formation. Zones that contain high-permeability dolomite with cavernous porosity are present in the upper or middle part of the Oldsmar Formation in the study area, and the base of the middle confining unit of the Floridan aquifer system is placed at the top of the first such zone. Such a zone is present in well PLT-I1 in eastern Broward County at a depth of 2,145 to 2,224 ft in which the top of the Oldsmar Formation is placed at 2,102 ft. The base of the middle confining unit in well MDS-BZ1 in southeastern Dade County is at a depth of 2,460 ft, which is 230 ft below the top of the Oldsmar Formation (fig. 2).

Many measurements of hydraulic conductivity and transmissivity have been taken in the middle confining unit of the Floridan aquifer system. The hydraulic conductivity of the middle to lower part of this confining unit ranges from 3×10^{-3} to 3 ft/d based on core sample analysis, packer tests, and aquifer tests made at the Miami-Dade South District Wastewater Treatment Plant site (Miami-Dade Water and Sewer Department, 1991). Several of the cores recovered in this part of the unit at the site consist of uncemented micrite or dolosilt with a clay-like texture and could not be tested for permeability because of a very soft consistency. Unconsolidated marine clay generally has a hydraulic conductivity of 3×10^{-4} ft/d or less (Freeze and Cherry, 1979, p. 29). The vertical conductivity measured in eight core samples at a depth of 2,149 to 2,808 ft in well PLT-I1 ranged from about 1.3×10^{-4} to 0.24 ft/d (Camp Dresser and McKee, 1987).

Lower Floridan Aquifer

The Lower Floridan aquifer in southern Florida contains thick confining units above the Boulder zone (Miller, 1986, pl. 17). The lithology of these confining units is similar to the lithology of the middle confining unit of the Floridan aquifer system. The highly transmissive Boulder zone is located in the lower part of the Lower Floridan aquifer (fig. 2), and its thickness is variable. For example, the thickness in well G-3234 in central Dade County was estimated to be 380 ft based on interpretation of an electrical log. At the Fort Lauderdale wastewater treatment plant site in eastern Broward County, its thickness was determined to be about 650 ft (Meyer, 1989, fig. 6). The base of the Lower Floridan aquifer extends 500 to 600 ft below the base of the Boulder zone in southern Florida (Miller, 1986, pl. 17). This lower section consists of permeable dolomite or dolomitic limestone of the Cedar Keys Formation.

The high permeability in the Boulder zone is due to the cavernous porosity and extensive fracturing present. The transmissivity of the Boulder zone is very high, ranging from about 3.2×10^6 ft^2/d (Meyer, 1974) to 24.6×10^6 ft^2/d (Singh and others, 1983).

COLLECTION AND ANALYSIS OF SALINITY DATA

Because of the relative lack of development of the Floridan aquifer system in southeastern Florida, the quality of ground water in the aquifer system is considered to have remained virtually constant during the period 1940-90. Water-quality data used to describe salinity in the Floridan aquifer system in this report were selected from data collected since 1940.

Selected water-quality data collected from known intervals in wells completed in the intermediate confining unit and the Floridan aquifer system are given in tables 2 and 3. In both tables, analyses are listed alphabetically by local well identifier and then in order of increasing depth of the sample interval in a well. If a sample interval included the Upper and Lower Floridan aquifers, these data were not used because of the mixing of waters with large differences in salinity. All of the analyses are of water from either completed intervals or from open-hole intervals sampled by drill-stem packer tools.

Table 2 gives USGS data collected from 36 wells (52 analyses), and table 3 gives non-USGS data collected from 24 wells (65 analyses). Most of the non-USGS data were obtained from the wastewater injection system wells and were collected by engineering consulting firms under contract to municipalities or by County agencies and reported to the FDEP. For two wells (FTL-M1 and MDS-BZ1), USGS and non-USGS data are included. All USGS data are stored in a USGS water-quality data storage and retrieval computer system (QWDATA).

All but four of the USGS analyses in table 2 were made before the beginning of this study. These four analyses are water samples collected from wells G-2296 (for the last sampling date), G-2617, G-2618, and G-2619. Sample collection procedures for USGS-collected data are given by Brown and others (1970).

Water sampling and testing methods for wastewater injection system wells are controlled by FDEP (Florida Department of Environmental Regulation, 1982). According to FDEP rules, the background water quality of the injection zone and monitoring zone(s) shall be established prior to injection. FDEP permits issued to construct and operate injection well systems include specific testing requirements; and for one such requirement, included since about 1988 (possibly earlier), at least three well volumes of fluid should be evacuated from a monitoring system before sampling.

Saltwater slugs used to control artesian pressure during drilling might have invaded the formation in the upper part of the Floridan aquifer system. When a completed interval is contaminated, the initial water samples usually show a change in salinity over time. An attempt was made to select analyses from completed intervals after salinity had stabilized (tables 2 and 3). Most monitoring wells are pumped or allowed to flow only on a periodic basis for sampling purposes, so if the formation were heavily contaminated during drilling, the time required for attaining background water quality could be long. An example of particularly heavy contamination with salty drilling water occurred in the upper monitoring zone (1,193-1,222 ft deep) in well CS-I1 (fig. 1). The chloride concentration of samples from this zone decreased from 9,300 mg/L to a constant value of about 5,600 mg/L, 2 years after the well was completed. For the past several years, barite-weighted bentonite drilling mud has sometimes been used instead of saltwater to control artesian pressure.

Water samples from open-hole packer tests are more often contaminated by drilling fluids than those from completed intervals because the volume of water produced before sampling is relatively small. Water samples from packer tests determined to be contaminated were not used in the study and are not included in tables 2 and 3. This determination was based on comparison with samples from nearby wells at similar depths, samples obtained later from completed intervals, or geophysical log responses.

Wells are commonly drilled in the Floridan aquifer system using 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 and analyzed at regular intervals while drilling.

Because there could be mixing with water moving down from upper zones outside the drill pipe, water samples collected by this method commonly do not accurately represent formation water present at the drill bit. The return flow might or might not be recirculated down the annulus, and if the return flow is recirculated, it could be mixed with storage tank water before being recirculated. Additionally, return flow might become contaminated with sodium chloride, resulting from the placement of a slug of dense saltwater (salt pillow) in the upper annular space to control artesian pressure in the Upper Floridan aquifer during drilling. The reverse-air rotary method is commonly used during drilling in the upper to middle parts of the Floridan aquifer system.

Table 2. Selected U.S. Geological Survey water-quality data collected from known intervals in wells tapping the intermediate confining unit and the Floridan aquifer system

[Well locations shown in figure 1; local well identifier used for this report only; *, packer or straddle packer test]

Local well identifier	Sampling date	Depth to top of sample interval (feet)	Depth to bottom of sample interval (feet)	Chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Specific conductance (microsiemens per centimeter)
C-962	12-13-83	2,228	2,280	17,000	--	40,300
CM-I1	06-02-59	989	1,150	2,360	5,120	7,870
F-152	03-28-40	--	990	1,530	--	--
FTL-I2	04-28-83	2,800	3,525	21,000	37,500	46,400
FTL-M1	10-21-81	1,021	1,072	3,400	6,490	12,100
	10-21-81	2,532	2,705	21,000	37,200	52,000
G-101	11-18-73	798	812	1,400	--	5,760
G-2296	10-19-81	811	816	1,600	3,500	6,200
	03-09-81	895	1,125*	850	2,000	3,330
	03-07-81	1,430	1,620*	1,800	3,640	6,050
	03-03-81	2,450	2,810*	19,500	38,000	50,000
	01-15-92	2,447	2,811	20,000	37,200	50,800
G-2617	01-10-92	1,648	1,728	1,100	2,570	4,220
G-2618	01-14-92	1,104	1,164	620	1,650	2,750
G-2619	01-13-92	895	1,052	1,100	2,590	4,360
G-3061	12-04-74	955	1,105	1,200	2,920	4,750
G-3062	07-24-75	840	844	1,900	--	6,600
G-3242	01-18-78	996	1,002	880	--	3,840
GB-1	12-18-75	1,010	1,225	1,200	2,720	4,630
MDS-BZ1	10-22-81	1,005	1,037	1,400	2,890	5,300
	10-22-81	2,689	2,960	19,000	37,900	52,900
MO-127	07-16-75	696	1,259	2,600	5,470	8,940
	03-21-66	696	1,333	2,450	--	8,100
MO-128	12-11-75	878	1,205	4,500	8,560	13,800
MO-130	12-18-75	1,050	1,379	3,000	5,730	9,600
	12-18-75	1,436	1,714	19,000	34,200	47,900
MO-133	07-22-66	1,050	1,074	2,300	--	8,200
	05-26-77	899	1,135	3,400	--	10,900
NP-100	09-28-64	620	1,125	800	--	2,480
	02-10-67	620	1,333	2,950	--	10,000
PU-I1	03-24-76	545	1,680	2,900	5,880	9,600
	12-17-69	1,810	2,947	19,300	--	50,000
PU-I2	08-08-74	758	1,742	2,600	5,550	8,860
	02-03-72	2,266	3,200	19,600	--	52,000
S-125	12-09-75	730	1,088	1,300	2,290	4,580
S-144	03-28-40	940	1,000	1,480	--	--
S-155	03-30-40	--	1,000	1,460	--	--
	12-05-75	--	1,000	1,400	3,210	5,450
S-156	10-14-40	885	950	2,600	--	8,560
S-158	03-30-40	--	1,066	2,580	4,770	--
S-161	10-14-40	410	1,065	2,040	--	6,920
S-450	06-30-41	1,002	1,046	1,180	--	4,760
	06-30-41	1,200	1,210	1,410	--	5,720
S-524	10-18-73	440	1,248	1,200	--	4,450
S-564	02-01-46	--	955	1,470	--	5,420
S-993	11-25-75	--	957	1,400	3,210	5,400
S-1354	01-21-71	480	1,065	1,300	--	5,300
S-1532	01-18-75	1,126	1,400	3,000	--	10,000
S-1533	12-19-75	1,120	1,330	2,000	4,110	7,000
	12-19-75	1,535	1,920	9,000	16,400	25,000
	05-05-75	2,100	2,304	22,000	40,100	54,000
S-3001	12-19-75	995	2,000	--	--	9,450

Table 3. Selected non-U.S. Geological Survey water-quality data collected from known intervals in wells tapping the intermediate confining unit and the Floridan aquifer system

[Well locations shown in figure 1; local well identifier used for this report only; *, packer or straddle packer test]

Local well identifier	Sampling date	Depth to top of sample interval (feet)	Depth to bottom of sample interval (feet)	Chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Specific conductance (microsiemens per centimeter)
BCN-I1	01-04-90	1,500	1,520*	4,230	5,550	10,100
	01-05-90	1,640	1,660*	6,550	10,800	17,600
	01-03-90	1,690	1,710*	9,650	14,600	29,600
	03-28-90	2,990	3,512	20,700	34,900	3,760
BCN-I4	Unknown	1,603	1,653*	5,000	8,940	27,800
	08-05-90	1,756	1,806*	7,250	12,000	28,900
	08-05-90	1,963	2,013*	18,700	29,800	68,800
	09-26-90	2,511	2,531*	22,500	32,600	67,400
	09-25-90	2,913	2,933*	19,700	36,000	69,500
BCN-M2	11-15-90	1,000	1,130	2,500	5,480	--
	11-15-90	2,000	2,079	18,600	37,500	--
CS-I1	May 1987	1,193	1,222	5,640	--	--
	May 1987	2,153	2,183	15,100	--	--
	01-26-85	2,451	2,498*	15,000	28,300	43,200
	01-26-85	2,874	2,920*	14,800	28,000	42,300
CS-I2	09-07-89	1,090	1,130*	5,400	9,370	15,200
	09-05-89	1,180	1,220*	5,800	10,700	16,800
	10-11-89	2,300	2,340*	17,500	30,000	6,810
	10-12-89	2,450	2,490*	19,800	34,800	7,890
	10-13-89	2,600	2,640*	16,900	39,400	6,930
	11-28-89	2,900	3,510	24,700	35,100	4,110
CS-M2	03-15-90	1,000	1,110	6,550	11,500	--
	03-15-90	1,510	1,650	2,330	4,430	--
FTL-I5	07-20-81	2,820	3,480	20,400	--	--
FTL-M1	07-20-81	1,446	1,562	10,600	24,000	--
HAL-RO1	07-17-89	906	1,040	2,230	--	6,060
HOL-RO1	10-06-89	981	1,320	1,980	--	5,570
	10-06-89	1,250	1,320	1,740	--	5,240
MAR-M2	Jan. 1988	1,029	1,093	3,510	--	10,000
	Jan. 1988	1,600	1,650	3,330	--	9,890
MDS-I5	08-26-77	1,970	2,000*	19,700	36,200	44,500
	08-26-77	2,267	2,397*	19,400	37,000	44,700
	08-27-77	2,567	2,597*	19,200	36,300	44,800
	08-25-77	2,697	2,727*	19,400	36,700	45,300
	10-20-77	2,746	3,193	19,700	39,800	50,500
MDS-BZ1	12-08-80	1,577	1,664	4,200	7,310	11,900
	03-16-81	2,434	2,474	20,100	28,900	45,500
MDS-I12	July 1989	1,110	1,140*	1,080	3,800	--
	July 1989	1,550	1,580*	2,970	11,800	--
	July 1989	1,840	1,870*	17,800	35,600	--
MDS-M3	01-24-91	981	1,050	900	1,840	--
	01-24-91	1,771	1,892	14,800	32,600	--
MDS-M2	Dec. 1984	1,645	1,672	6,550	12,400	16,000
PBP-I1	12-24-86	2,950	3,600	18,800	39,600	57,600
PBP-M1	12-24-86	1,004	1,081	1,550	3,090	4,820
	01-24-89	2,000	2,050	21,000	31,500	44,000
PLT-I1	06-25-87	1,597	1,638	1,760	--	6,000
	06-25-87	2,189	2,239	19,100	--	46,000
	01-08-86	2,330	2,378*	23,500	18,600	45,000
	01-06-86	2,591	2,639*	22,500	35,200	45,000
	01-05-86	2,878	2,926*	21,000	--	36,400
	06-09-86	2,942	3,472	19,700	38,100	60,400
PLT-I2	05-17-90	1,740	1,780*	11,000	13,200	26,600
	05-16-90	2,190	2,230*	12,200	27,600	45,100
	06-19-90	2,500	2,550*	18,700	33,600	75,800
PLT-M1	10-18-90	1,580	1,650	1,750	3,750	6,030
	10-18-90	2,130	2,230	5,110	38,000	14,000
PLT-ROI1	April 1990	1,583	1,653*	2,780	5,490	12,900
	April 1990	1,800	1,870*	9,680	14,300	22,100
	April 1990	1,920	1,990*	15,800	27,500	41,500
	April 1990	2,150	2,300*	11,000	19,900	30,100
	April 1990	2,645	2,655*	--	--	50,000+
SUN-I1	01-09-85	2,700	3,200	19,400	33,200	46,700
SUN-M1	02-21-85	1,015	1,108	2,790	6,210	9,320
	02-19-85	1,600	1,650	1,640	3,740	5,820

Collecting water samples during drilling can show large changes in the salinity of formation water over relatively short-depth intervals. However, even a large increase in the salinity with depth might not be detected if the permeability is so low that little of the return flow is emerging from the formation at or near the drill bit.

EVALUATION OF FORMATION SALINITY USING BOREHOLE GEOPHYSICAL LOGS

Two threshold salinity values of interest in the Floridan aquifer system are 10,000 and 35,000 mg/L of dissolved-solids concentration. As previously defined, 10,000 mg/L of dissolved-solids concentration separates brackish and slightly saline water, and 35,000 mg/L of dissolved-solids concentration separates slightly saline and saline water. The depth to the top of the zones in the Floridan aquifer system that contain water with these dissolved-solids concentrations or greater can be approximately determined using borehole geophysical logs.

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_0 is the water-saturated formation resistivity, a is an empirical constant, $\varnothing$ is total or bulk formation porosity as a fraction, m is the empirical cementation factor, and R_w is the formation water resistivity. The values of R_0 and R_w are at formation temperature.

As previously described, the predominant lithology in the Floridan aquifer system in southeastern Florida is micritic to fine-grained limestone with low permeability. Rock with cavernous or vugular porosity occurs only in a few thin zones in the Floridan aquifer system, except in the Lower Floridan aquifer. 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 using equation 1. The high total porosity in the Floridan aquifer system, particularly in the Avon Park Formation, indicates that: (1) the pore system is dominated by microporosity, which occurs between and within grains (intraparticle porosity) rather than large pores or vugs; and (2) sealing by secondary calcite has not occurred to a great extent.

Porosity was measured from whole diameter cores (4.5 in.) in the middle confining unit of the Floridan aquifer system in well PBP-I1 in Broward County (fig. 1). Six limestone plugs were taken from cores cut between 1,931 and 2,233 ft deep, and the porosity of these plugs determined by Boyle's law (Core Lab, 1974, p. 4-5) ranged from 33.6 to 46.4 percent and averaged 40.2 percent (Post, Buckley, Schuh, and Jernigan, Inc., 1987, table 7-4).

A borehole-compensated neutron-density log used to determine porosity was run on well C-962 in Collier County (fig. 1). The neutron and density devices on this tool produce a signal that responds to porosity changes with depth, and the rock matrix used to compute porosity from both of these signals was limestone. The two porosity curves output from the devices were averaged for well C-962 (fig. 8). The value for porosity output from each device was usually in relatively close agreement (difference of less than 1 or 2 percent porosity), indicating that the rock matrix is limestone, the clay content is low ("clean" formation), and the average porosity is a reasonable estimate of the true total porosity. Descriptions of drill cuttings indicate that the shallowest dolomite present in well C-962 in the Floridan aquifer system is in the Oldsmar Formation at a depth of about 2,270 ft. Log-derived porosity 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. 8). A general tendency for porosity to decrease with depth is indicated.

On the basis of the aforementioned data for wells PBP-I1 and C-962 and other core and log data, porosity in the Upper Floridan aquifer and the middle confining unit of the Floridan aquifer system is generally high (at least 30 percent in the study area). Although sonic logs have been run in many of the wastewater injection system wells in the study area, traveltime (unlike the neutron-density log response), is difficult to calibrate to true total porosity in carbonate rocks. Calculations of R_0 will be made using a range in porosity (30 to 40 percent) because of the lack of usable porosity measurements in most wells in the study area.

The cementation factor, m, was measured using limestone core samples collected from well PBP-I1 at a depth between 1,931 and 2,934 ft. Using equation 1 and assuming a = 1.0, values of m ranged from 1.96 to

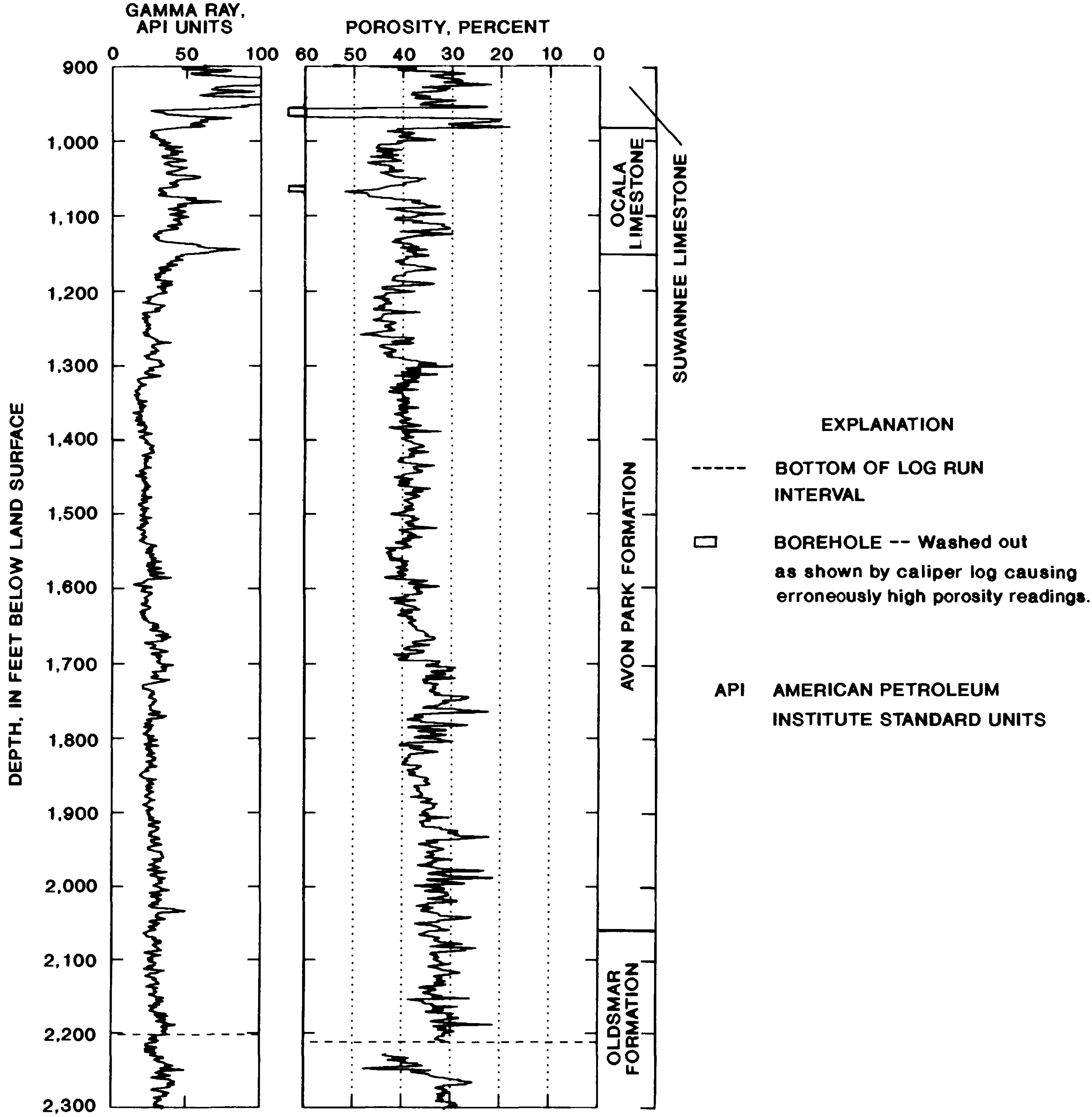


Figure 8. Variations of average porosity with depth derived from a borehole-compensated neutron-density log of well C-962 showing geologic units and a gamma-ray log in eastern Collier County. Porosity is an average of neutron and density responses. Tool was calibrated to a limestone matrix.

2.15 and averaged 2.07 (Post, Buckley, Schuh, and Jernigan, Inc., 1987, table 7-8). The values a = 1.0 and m = 2.0 are recommended for chalky limestone (Schlumberger, 1972a, p. 2). The constant a was assumed to be equal to 1 for most Tertiary carbonates in the Southeastern Coastal Plains of the United States where Kwader (1986) reported the value of m for Tertiary clean "platform type" limestones to range from 1.6 to 1.8. This range for m could be low in comparison to the range expected in southeastern Florida in the Floridan aquifer system because of the possibility of less compaction and cementation in the Coastal Plain area. The depths of the Tertiary section worked within the Coastal Plain area are less than 1,000 ft (Kwader, 1986, fig. 1). Because of the uncertainty in establishing a value for m in the study area and the probability that it does vary given the thick section of interest (Upper Floridan aquifer and middle confining unit of the Floridan aquifer system), calculations of R_o were made using a range of values from 1.8 to 2.1.

The formation water resistivity, R_w, for a given salinity of water in the Floridan aquifer system can be determined from water analysis. From the relation between dissolved-solids and chloride concentrations, chloride concentration can be determined for a given dissolved-solids concentration; then by relating chloride concentration to specific conductance, resistivity can be determined. Finally, resistivity is corrected using formation temperature to give R_w. Chloride concentration was related to specific conductance instead of relating dissolved-solids concentration directly to specific conductance for two reasons. First, many of the analyses of water samples from the Floridan aquifer system (table 2) did not include determination of dissolved-solids concentration, whereas chloride concentration was determined. Second, a better correlation of specific conductance with chloride concentration is expected than with dissolved-solids concentration, as was the case for Floridan aquifer system water in the panhandle area of Florida (Kwader, 1986, fig. 3). Chloride concentration is used later in this report to map the distribution of salinity in the Floridan aquifer system.

Linear regression analysis of dissolved-solids concentration in relation to chloride concentration was made using USGS water-quality data collected from the Floridan aquifer system (fig. 9). Dissolved-solids concentrations from 19 water samples used in this analysis ranged from 2,000 to 40,100 mg/L (table 2). Samples from wells that are not completed in the Floridan aquifer system or for which the depth of the top of the sample interval is unknown were not used. Additionally, samples from wells PU-I1 and PU-I2 were not used because of the large sample interval, and samples from wells G-2617, G-2618, G-2619, and G-2296 (sample on January 15, 1992) were not used because earlier data from well G-2296 (in 1981) at the same location were used. The correlation coefficient for this analysis was good (r = 0.998) as shown in figure 9, and the relation determined was:

$$\text{chloride concentration} = 0.548 \bullet \text{dissolved-solids concentration} - 243 \quad (2)$$

where chloride and dissolved-solids concentrations are in milligrams per liter.

Linear relations were also determined between chloride concentration and specific conductance. Two regression analyses were made using USGS water-quality data collected from the Floridan aquifer system (table 2). In the first analysis, 34 water samples with chloride concentrations ranging from 850 to 22,000 mg/L were used (fig. 10). In the second analysis, the data set used in the first analysis was restricted by selecting only water samples with chloride concentrations less than 5,000 mg/L (fig. 11). This resulted in 24 water samples with chloride concentrations ranging from 850 to 4,500 mg/L.

For the analysis with chloride concentration up to 22,000 mg/L, the relation is:

$$\text{specific conductance} = 2.42 \bullet \text{chloride concentration} + 2{,}142 \quad (3)$$

where specific conductance is in microsiemens per centimeter at 25°C. For the analysis with chloride concentration less than 5,000 mg/L, the relation is:

$$\text{specific conductance} = 2.95 \bullet \text{chloride concentration} + 1{,}085 \quad (4)$$

Each analysis provides a different regression relation, and there is a high degree of linearity with correlation coefficients of greater than 0.99 in both cases. The difference between these relations indicates there is some curvature in the relation between chloride concentration and specific conductance for natural waters (Hem, 1989, fig. 11).

The resistivity of sample water, in ohm-meters, can be calculated from specific conductance, in microsiemens per centimeter at 25°C, by use of the following expression:

$$\text{resistivity} = 10{,}000/\text{specific conductance} \quad (5)$$

The resistivity of Floridan aquifer system formation water for the two threshold salinity values, 10,000 and 35,000 mg/L of dissolved-solids concentration,

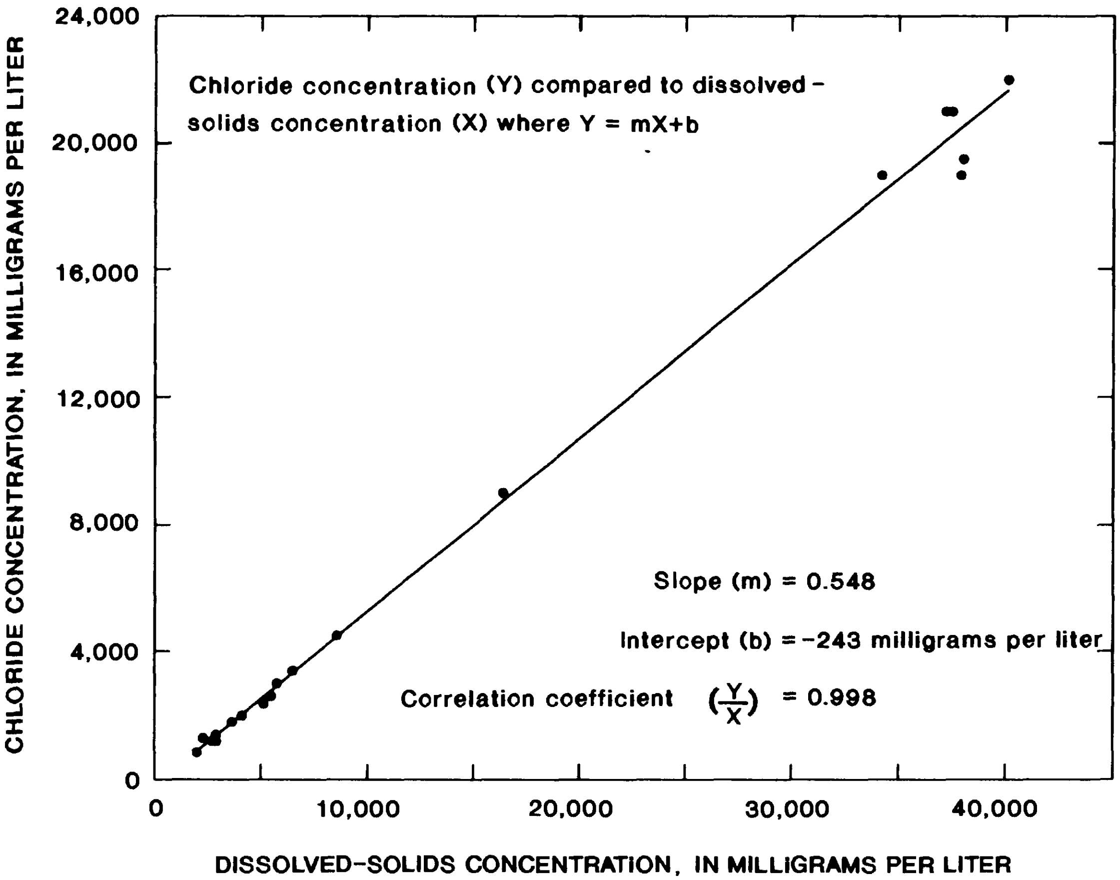


Figure 9. Relation between concentrations of dissolved solids and chloride for 19 water samples from the Floridan aquifer system in southeastern Florida.

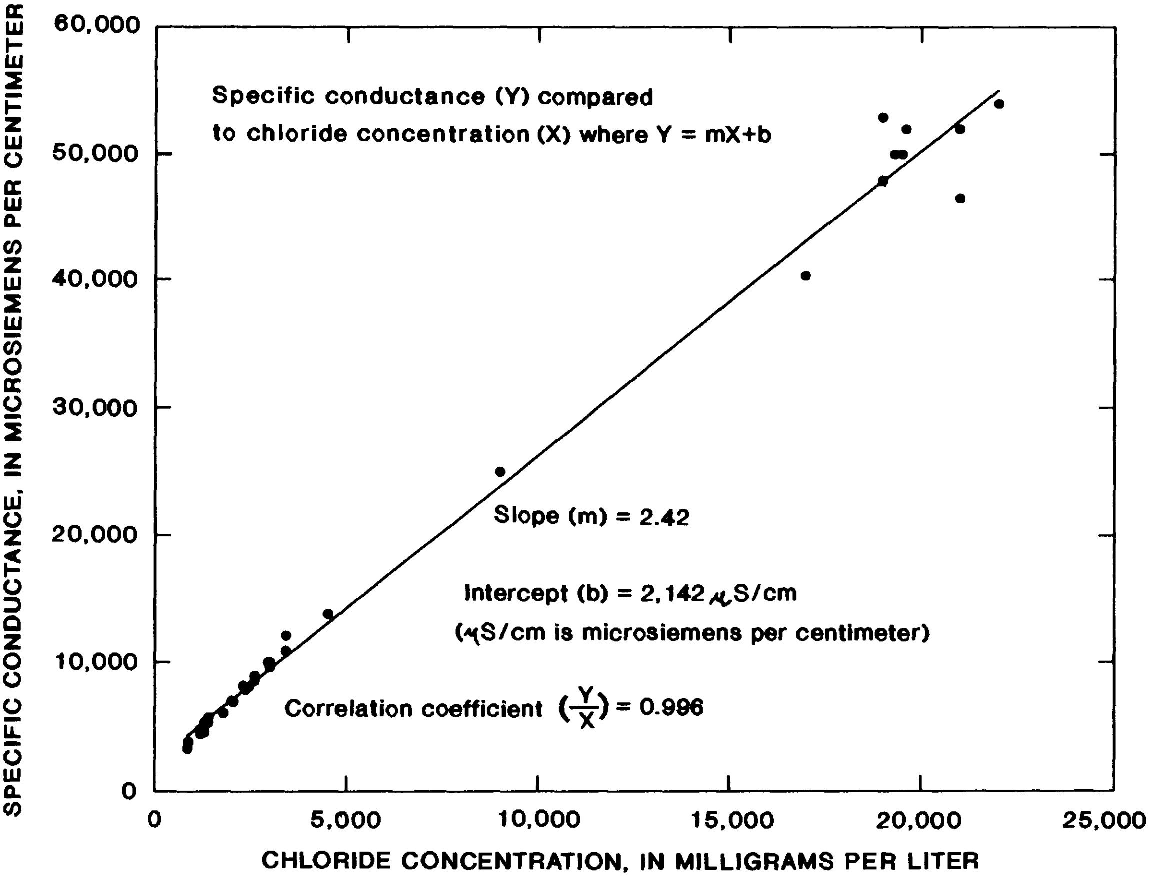


Figure 10. Relation between chloride concentration up to 22,000 milligrams per liter and specific conductance for 34 water samples from the Floridan aquifer system in southeastern Florida.

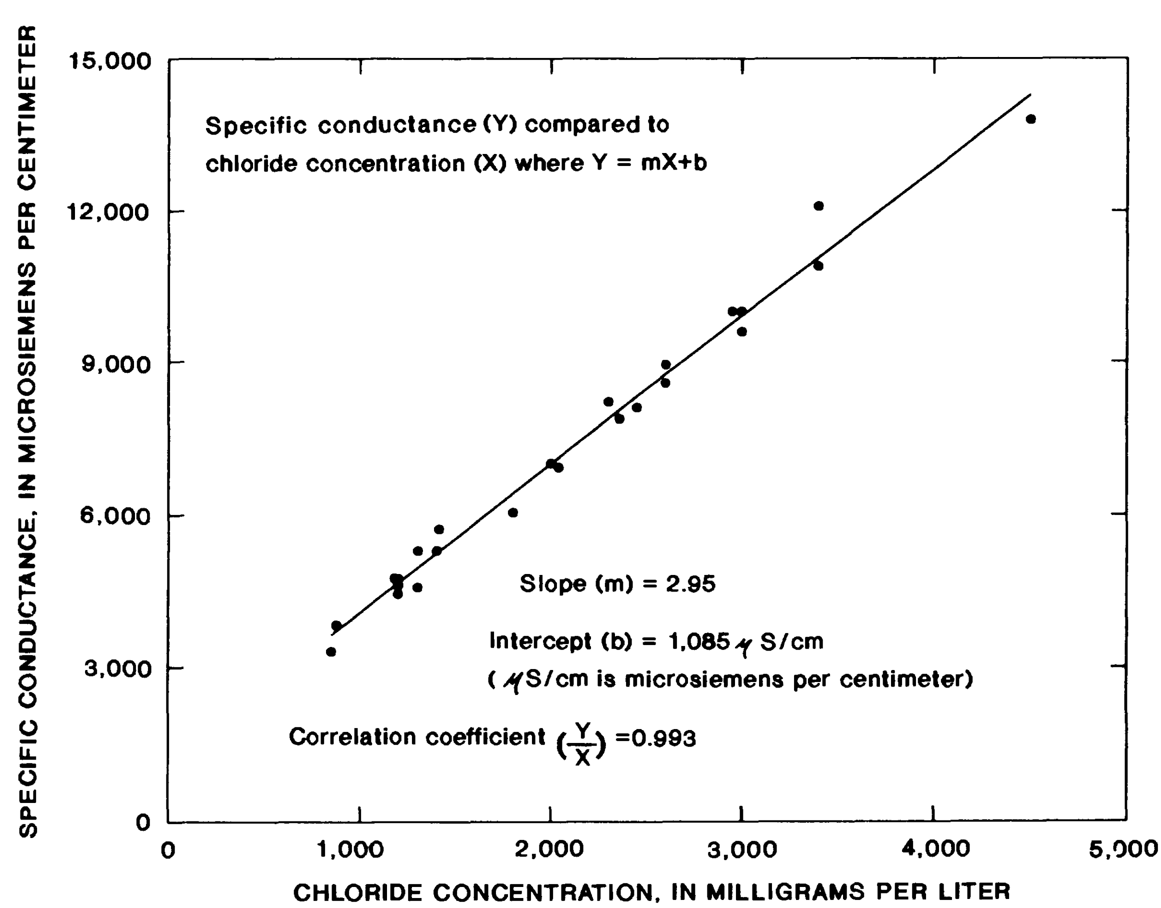


Figure 11. Relation between chloride concentration less than 5,000 milligrams per liter and specific conductance for 24 water samples from the Floridan aquifer system in southeastern Florida.

Table 4. Computations of the resistivity of Floridan aquifer system formation water for two salinities as defined by dissolved-solids concentration

Dissolved-solids concentration (milligrams per liter)	Chloride concentration (milligrams per liter)	Specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Resistivity (ohm-meters at 25 degrees Celsius)
10,000	5,240	16,600	0.604
35,000	18,900	48,000	.208

were calculated and the results are given in table 4. For the 10,000 mg/L dissolved-solids salinity value, the chloride concentration was calculated using the regression equation developed for chloride in relation to dissolved-solids concentration (eq. 2). Specific conductance was then calculated using the regression equation developed for specific conductance in relation to chloride concentration, with chloride concentration less than 5,000 mg/L (eq. 4, second analysis). Equation 4 was used instead of equation 3 because the chloride concentration determined for this salinity (5,240 mg/L) was only slightly higher than 5,000 mg/L. For the 35,000 mg/L dissolved-solids salinity value, after the chloride concentration was determined using equation 2, specific conductance was calculated using the first analysis of specific conductance in relation to chloride concentration (eq. 3).

The resistivity of water that is a sodium chloride type, such as Floridan aquifer system water in southeastern Florida (Sprinkle, 1989, pl. 9), can be adjusted for a change in temperature using a resistivity graph for sodium chloride solutions (Schlumberger, 1972b, chart Gen-9). The calculated resistivity of Floridan aquifer system formation water for the two salinity values of interest can be adjusted from 25°C to the formation temperature to give R_w.

Formation temperature in the Upper Floridan aquifer and the middle confining unit does not vary greatly in the study area. The water temperatures reported for 20 water analyses measured during flow at the wellhead were analyzed. These samples came from 14 wells in the study area with the depth of the intervals sampled, ranging from 900 to 2,475 ft. Temperature ranged from about 20°C to 26°C and averaged 23.8°C. The lack of geothermal temperature increase between that near the ground surface (26°C) and the Floridan aquifer system is because of the cooling effect of cold deep seawater that probably enters the Boulder zone along the southeastern coast in the Straits of Florida (Meyer, 1989, fig. 24).

The formation resistivity (R_o) was computed for the two threshold salinity values using equation 1 for the expected ranges in porosity (Ø), cementation factor (m), and formation temperature (tables 5 and 6). The values for the constant, a, was assumed to be 1.0 (Kwader, 1986, p. 11), and the values used for formation water resistivity at 25°C came from table 4. These computations indicate that the variation in porosity results in the greatest uncertainty in R_o. As salinity increases or decreases with depth in the Floridan aquifer system, a range in depth at which salinity equals 10,000 or 35,000 mg/L of dissolved-solids concentration can be determined using the results given in tables 5 and 6, if variation of true formation resistivity with depth is known and the porosity can be estimated.

Geophysical resistivity devices used in determining the depth of salinity boundaries in this study were the short normal (16 in.), long normal (64 in.), 18-ft 8-in. lateral, spherically focused device, laterlog 8, medium induction, and deep induction. Generally, the devices that have the greatest depth of penetration into the formation were given preference. Conventional electric logging tools usually include short normal (16 in.), long normal (64 in.), and 18-ft 8-in. lateral devices (listed in order of increasing depth of penetration). Although the lateral device from this tool has the greatest depth of penetration, the long normal curve seemed to give a more reasonable response in the Floridan aquifer system in the study area and was usually favored in determining the salinity boundaries.

If the resistivity tool run in a well included a deep induction device and the depth of invasion by drilling fluid was relatively small, salinity boundaries were determined using only the curve from this device

Table 5. 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, cementation factor, and formation temperature

[The formation temperature of 23.8 degrees Celsius is an average value obtained from water samples]

Cementation factor (m)	Formation temperature (degrees Celsius)	Formation resistivity (R_0), in ohm-meters		
		30 percent porosity	35 percent porosity	40 percent porosity
1.8	20.0	5.9	4.5	3.5
	23.8	5.5	4.1	3.3
	26.0	5.2	4.0	3.1
1.9	20.0	6.7	5.0	3.9
	23.8	6.2	4.6	3.6
	26.0	5.9	4.4	3.4
2.0	20.0	7.6	5.6	4.3
	23.8	6.9	5.1	3.9
	26.0	6.7	4.9	3.8
2.1	20.0	8.5	6.2	4.7
	23.8	7.8	5.7	4.3
	26.0	7.5	5.4	4.1

without correction. However, in some cases, deep induction resistivity was corrected for borehole and invasion effects. Experience gained in working with invasion correction charts designed for dual induction logs (Schlumberger Educational Services, 1988, p. 89-91) in the Floridan aquifer system showed that correction for invasion generally was important if the ratio of the medium induction reading to the deep induction reading was greater than about 1.4. This applies only if the borehole fluid is not heavily contaminated with salt (salinity of the borehole fluid less than that of the formation water).

DISTRIBUTION OF SALINITY IN THE FLORIDAN AQUIFER SYSTEM

This section begins with a description of the vertical variations in salinity in the Floridan aquifer system in a well located in southeastern Dade County. The Floridan aquifer system is divided into three salinity zones which, in order of increasing depth, are the brackish-water zone, the transition zone, and the saline-water zone.

The base of the brackish-water zone is determined in all wells with adequate data in the study area. A problem with the determination of this boundary using only water-quality data collected during well drilling by the reverse-air rotary method is described using an example. Slightly saline water can occur above the base of the brackish-water zone in the Floridan aquifer system, and the vertical variations of salinity in the brackish-water zone in one such area are described using a geophysical well log and water-quality data. In this area, the variation is anomalous, with salinity decreasing substantially downward from the Upper Floridan aquifer to the middle confining unit. In some wells, the formation had been invaded with saline drilling fluid during drilling prior to logging, and the difficulties found in using the geophysical logs from these wells to determine salinity boundaries are discussed. In some cases, this invasion was too deep for a resistivity log to be of use. A map showing the altitude of the base of the brackish-water zone in the study area is discussed.

For the purpose of describing salinity variations, the brackish-water zone is divided into upper and lower intervals. A map showing lateral changes in chloride

Table 6. 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, cementation factor, and formation temperature

[The formation temperature of 23.8 degrees Celsius is an average value obtained from water samples]

Cementation factor (m)	Formation temperature (degrees Celsius)	Formation resistivity (R_o), in ohm-meters		
		30 percent porosity	35 percent porosity	40 percent porosity
1.8	20.0	2.1	1.6	1.2
	23.8	1.9	1.4	1.1
	26.0	1.8	1.4	1.1
1.9	20.0	2.3	1.7	1.3
	23.8	2.1	1.6	1.2
	26.0	2.0	1.5	1.2
2.0	20.0	2.6	1.9	1.5
	23.8	2.4	1.8	1.3
	26.0	2.3	1.7	1.3
2.1	20.0	2.9	2.1	1.6
	23.8	2.7	1.9	1.5
	26.0	2.6	1.9	1.4

concentration of water from both the upper and lower intervals in the study area is discussed, and the salinity of the two intervals is contrasted. A map showing chloride concentration of water samples from the lower part of the intermediate confining unit is presented, and these values are compared to those from the upper interval of the brackish-water zone.

Lastly, a map showing the top of the saline-water zone is presented and discussed. Variations of salinity in the saline-water zone are described, and this salinity is compared to that of seawater.

Vertical Variations in Salinity in Southeastern Dade County

The vertical variation in salinity in the upper part of the Floridan aquifer system at the Miami-Dade South District Wastewater-Treatment Plant site in southeastern Dade County is represented by a geophysical log and water-quality data from wells MDS-I12 and MDS-M3 (fig. 12). The three resistivity curves recorded on the geophysical log are from the deep induction, medium induction, and spherically focused devices. The devices have a different depth of investigation away from the borehole and record deep, medium, and shallow measurements of resistivity of the formation, respectively. The resistivity profile below a depth of 1,040 ft, as indicated by these curves in figure 12, shows that the resistivity of the borehole fluid is greater than that of the native formation water, and correspondingly the borehole fluid is fresher than the formation water. Contamination of the formation from salty drilling fluid is not indicated.

Calculation of the true uninvaded formation resistivity in well MDS-I12 shows that the difference between the deep induction resistivity and the true resistivity is minor. At 1,640 ft in well MDS-I12, where the deep induction reading is 5 ohm-meters, correcting for borehole and invasion effects (Schlumberger Educational Services, 1988, p. 83-90) gives a true formation resistivity of 4.73 ohm-meters. These corrections involve using hole size, borehole fluid resistivity, and the shallow, medium, and deep resistivity readings. The difference between 4.73 and 5 ohm-meters is small in comparison to the difference

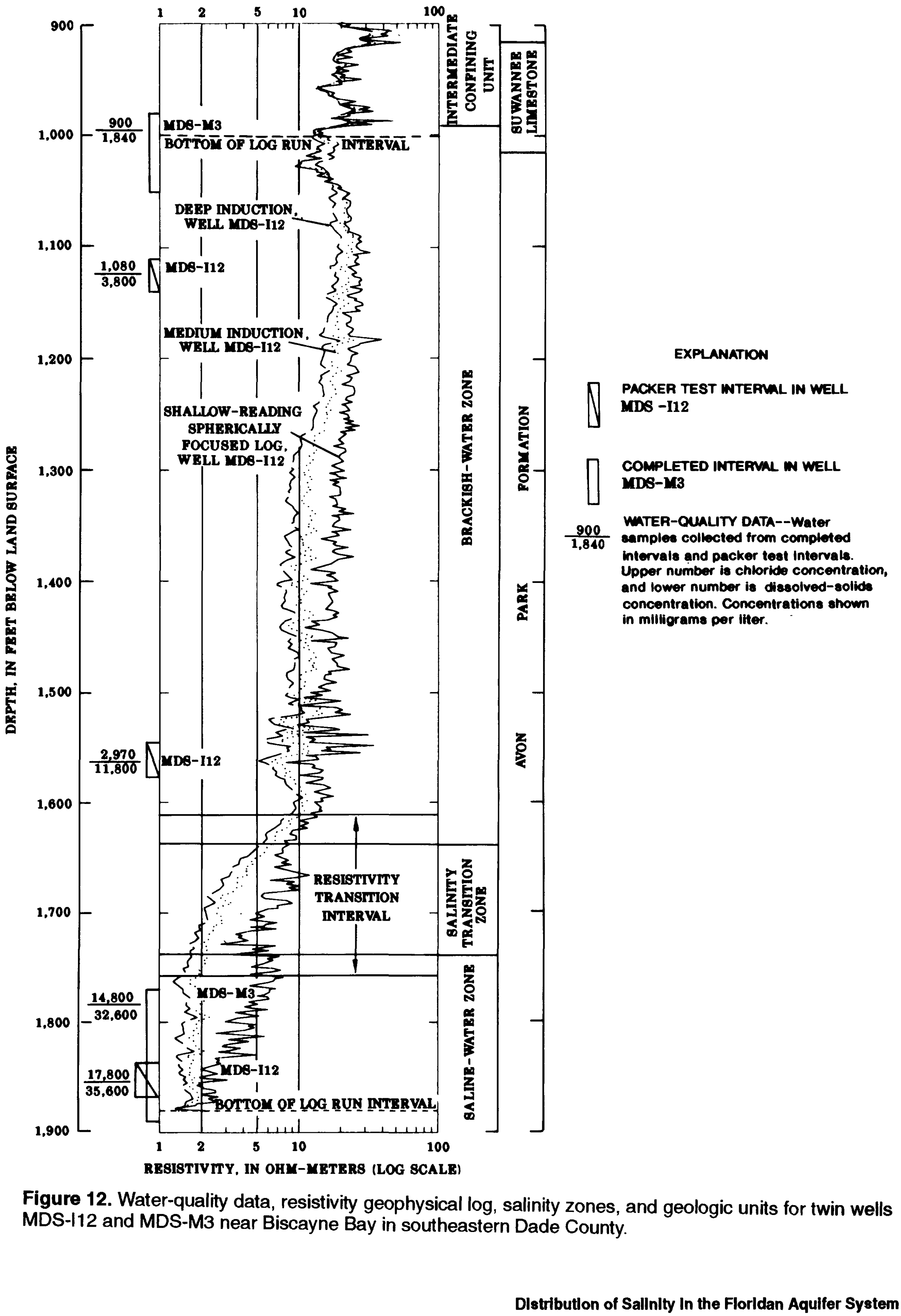


Figure 12. Water-quality data, resistivity geophysical log, salinity zones, and geologic units for twin wells MDS-I12 and MDS-M3 near Biscayne Bay in southeastern Dade County.

between the high and low values computed for R_0 given in table 5. The true resistivity was determined to be about 1.7 ohm-meters at 1,730 ft in well MDS-I12 where the deep induction reading is about 1.8 ohm-meters. In the following analysis, deep induction resistivity is assumed to approximate the true formation resistivity in well MDS-I12.

The variation of deep induction resistivity with depth in well MDS-I12 indicates that resistivity generally ranges from 8 to 20 ohm-meters between the top of the Floridan aquifer system at 985 ft and 1,615 ft (fig. 12). However, between 1,615 and 1,760 ft (referred to herein as the resistivity transition interval), resistivity decreases substantially from about 8 to 1.5 ohm-meters. Below 1,760 ft, resistivity does not decrease further but can increase to as much as 2.0 ohm-meters.

Using the values computed for R_0 in tables 5 and 6, the deep induction resistivity-depth profile in well MDS-I12 indicates that salinity increases with depth from less than 10,000 to about 35,000 mg/L of dissolved-solids concentration in the resistivity transition interval. The latter approximate salinity first occurs near the bottom of the interval and continues at least to 1,880 ft. Based on the two threshold salinity values, the Floridan aquifer system in well MDS-I12 can be divided in order of increasing depth into a brackish-water zone, a salinity transition zone containing slightly saline water, and a saline-water zone (fig. 12). The salinity transition zone is approximated by the resistivity transition interval and ranges in depth from 1,640 to 1,740 ft (fig. 12). The top and bottom of the transition zone were determined using values of R_0 obtained by assuming the average of the values given in tables 5 and 6 for porosity (35 percent), the cementation factor (m = 1.95), and formation temperature (23.8° C). These average R_0 values are 4.9 ohm-meters for a salinity of 10,000 mg/L of dissolved-solids concentration and 1.7 ohm-meters for a salinity of 35,000 mg/L of dissolved-solids concentration.

The expected range in depth for the base of the brackish-water zone and the top of the saline-water zone can be determined in well MDS-I12 using the extreme values computed for R_0, 3.1 to 8.5 ohm-meters in table 5 and 1.1 to 2.9 ohm-meters in table 6. According to the deep induction curve, the base of the brackish-water zone ranges from 1,615 to 1,667 ft deep, and the top of the saline-water zone ranges from 1,675 to at least 1,880 ft deep.

Water-quality data collected from MDS-M2 indicate that the base of the brackish-water zone is 1,645 ft or less at the Miami-Dade South District Wastewater Treatment Plant site. This well produced water with a chloride concentration of 6,550 mg/L and a dissolved-solids concentration of 12,400 mg/L from the lower monitoring interval from 1,645 to 1,672 ft (table 3).

Water-quality data collected from wells in the saline-water zone of the Floridan aquifer system at the MDS injection well site indicate a slight increase in salinity with depth. Dissolved-solids concentrations in wells MDS-I12 and MDS-M3 below 1,771 ft deep and above 1,892 ft deep (fig. 12) were 35,600 and 32,600 mg/L, respectively (table 3). A packer test done in nearby well MDS-I5 at a depth from 1,970 to 2,000 ft produced formation water with a chloride concentration of 19,700 mg/L and a dissolved-solids concentration of 36,200 mg/L (table 3). The salinity of ambient water in the Boulder zone was measured in MDS-I5, the first injection well drilled at the Miami-Dade South District Wastewater Treatment Plant. Analysis of the ambient formation water from the injection zone in this well at a depth from 2,746 to 3,193 ft gave a chloride concentration of 19,700 mg/L and a dissolved-solids concentration of 39,800 mg/L (table 3).

Salinity in the brackish-water zone at the MDS site, as shown by chloride concentrations in water samples (fig. 12), increases by a factor of three from 900 mg/L at the top to nearly 3,000 mg/L near its base. In the transition zone below the brackish-water zone, salinity increases much more rapidly with at least another three-fold increase occurring over an interval of 100 ft.

The average R_0 values of 4.9 (rounded to 5) and 1.7 ohm-meters are used to show the top and base of the salinity transition zone, respectively, in figure 12. These values will be used herein to approximately define the top and base of the salinity transition zone based on geophysical resistivity logs run in other wells in the study area. Justification for use of these average values is as follows:

- The resistivity-depth profile measured in well MDS-I12 (fig. 12) was commonly observed in the Floridan aquifer system in other wells in the study area. The relatively rapid decrease of resistivity with depth in the resistivity transition interval in MDS-I12 also occurs in these other wells. The resistivity logs run on these other wells exhibit a transition interval with a similar range in resistivity values and rate of change of resistivity with depth.

- The error in depth of the top of the salinity transition zone using the average R_0 value of 5 ohm-meters should not be high. As previously discussed, comparison between the depth for boundary in well MDS-I12 determined using the average R_0 and the depths determined using the full range of R_0 values (table 5) produces an error of no more than 25 ft.
- Constant resistivity values for these boundaries should be used throughout the study area because of the general lack of specific data on porosity and the cementation factor. Additionally, the same values for porosity, the cementation factor, and formation temperature should be used for both boundaries because of their vertical proximity.
- Use of the 5 ohm-meter R_0 value for the top of the salinity transition zone places the boundary just below the top of the resistivity transition interval. This helps to avoid placing the boundary at the top of thin low resistivity zones in the lower part of the brackish-water zone, such as in the depth interval between 1,520 and 1,565 ft in well MDS-I12 where deep induction resistivity is as low as 5.2 ohm-meters (fig. 12).

Brackish-Water Zone

The approximate depth to the base of the brackish-water zone was determined in each well in the study area where data were available (table 7). When resistivity geophysical logs were available, the base of the brackish-water zone was determined using the average R_0 value of 5 ohm-meters. The type of resistivity logs and number of wells in the study area used for each type are listed as follows: (1) combination tool with deep and medium induction devices along with a shallow-reading device, such as a spherically focused log (dual induction log)--10 wells; (2) induction-short normal combination tool--4 wells; and (3) conventional electric logs--8 wells (four of these did not include a lateral device).

Water samples collected during well drilling by the reverse-air rotary method were also used to determine the base of the brackish-water zone. The base of the brackish-water zone in well PU-I1 was placed at about 1,750 ft based on where the chloride concentration of drilling fluid samples first began to increase more rapidly with depth (fig. 13). The highest rate of increase in chloride concentration was at about 1,820 ft. The short normal and deep induction resistivity curves read about 2 ohm-meters at 1,830 ft and deeper, indicating a salinity greater than 10,000 mg/L of dissolved-solids concentration. As shown in this example, the base of the brackish-water zone can easily be placed too deep in a well if only drilling fluid sample data are used. Reverse-air rotary water sampling data were solely used to determine the base of the brackish-water zone in wells MAR-I2 and PU-I2 (table 7).

The first occurrence of formation water with 10,000 mg/L of dissolved-solids concentration might not be at the regional base of the brackish-water zone as determined in a well. Examples are presented by data collected from wells CS-I2, CS-M2, MDS-I12, and S-1533. The base of the brackish-water zone in well CS-I2 in northeastern Broward County was determined to be at 2,017 ft using a resistivity geophysical log (fig. 14). Resistivity measurements and water-quality data in wells CS-I2 and CS-M2 indicate an anomalous interval of slightly saline water from the lower part of the Suwannee Limestone to a depth of 1,470 ft. As determined from water samples, salinity is as high as 11,500 mg/L of dissolved-solids concentration (6,550 mg/L of chloride concentration), and deep induction resistivity is as low as 3.1 ohm-meters in the interval. Three beds of varying thickness (5-10 ft) that have anomalous deep induction resistivity readings of only 2 to 4 ohm-meters are present from 1,837 to 1,873 ft. The deep induction resistivity above and below this anomalous interval at 1,837 ft ranges from 8 to 10 ohm-meters, which is normal for the lower part of the brackish-water zone. The depth interval between 1,520 and 1,565 ft in well MDS-I12 has some beds with resistivity as low as 5.2 ohm-meters, and a water sample collected from 1,550 to 1,580 ft has a salinity which borders on the 10,000 mg/L of dissolved-solids concentration (fig. 12). In well S-1533, within the brackish-water zone which extends from 1,295 to 1,530 ft, several 10-ft thick beds having deep induction resistivity as low as 3.7 ohm-meters occur. Some thin beds that apparently contain slightly saline to saline water commonly occur in the lower part of the brackish-water zone.

The low resistivity in the thin beds in the brackish-water zone could also be caused by a change in lithology, such as to limestone with a high clay content or chalk. Calculations for porosity were made in well CS-I2 from 1,860 to 1,873 ft, a zone in which resistivity was as low as 2 ohm-meters (fig. 14). Using a salinity of 5,000 mg/L of dissolved-solids concentration (a salinity not unusual for the brackish-water zone), a cementation factor of 1.8, and a formation temperature

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

[Well locations shown in figure 1; local well identifier used for this report only; method used to determine salinity zone boundaries: 1, short normal (16 inches) and long normal (64 inches) resistivity curves (borehole geophysical log); 2, short normal (16 inches), long normal (64 inches), and long lateral (usually 18 feet 8 inches) resistivity curves; 3, deep induction with short normal resistivity curves; 4, dual induction (medium and deep) and shallow resistivity curves; and 5, water-quality data collected during drilling by reverse-air rotary method; --, top recorded in nearby well; E, estimated; NL, not logged]

Local well identifier	Depth to base of brackish-water zone (feet)	Depth to top of saline-water zone (feet)	Method used to determine salinity zone boundaries	Thickness of salinity transition zone[1] (feet)
BCN-I1	1,623	1,880	4	257
C-962	2,155	2,275	4	120
CS-I1	............CONTAMINATED............			
CS-I2	2,017	2,180	4	163
FTL-I1	1,475	--	4	
FTL-M1	--	1,578	4	103
G-2296	2,170	2,280	1	110
G-3234	1,710	1,875	2	165
G-3235	1,880	1,940	2	60
G-3239	1,960	2,070	2	110
G-3240	2,000	2,120	2	120
MAR-I2	2,100	NL	5	
MAR-M1	............CONTAMINATED............			
MDS-BZ1	1,640	--	1	
MDS-I12	1,640	1,740	4	100
MO-130	1,164	1,370	3	206
PBP-I1	1,784	1,870	1	
PBP-I2	1,762	1,896	4	134
PLT-I1	............CONTAMINATED............			
PLT-I2	1,754	1,966	4	212
PLT-ROI1	1,790	1,990	4	200
PU-I1	1,750	1,830	3,5	80
PU-I2	1,830	NL	5	
S-567	1,514	1,596	4	82
S-1533	1,530	1,760	3	230
S-3001	1,330	1,454	3	124
SUN-I1	1,857E	2,000	1	

[1]Average thickness is 143 feet.

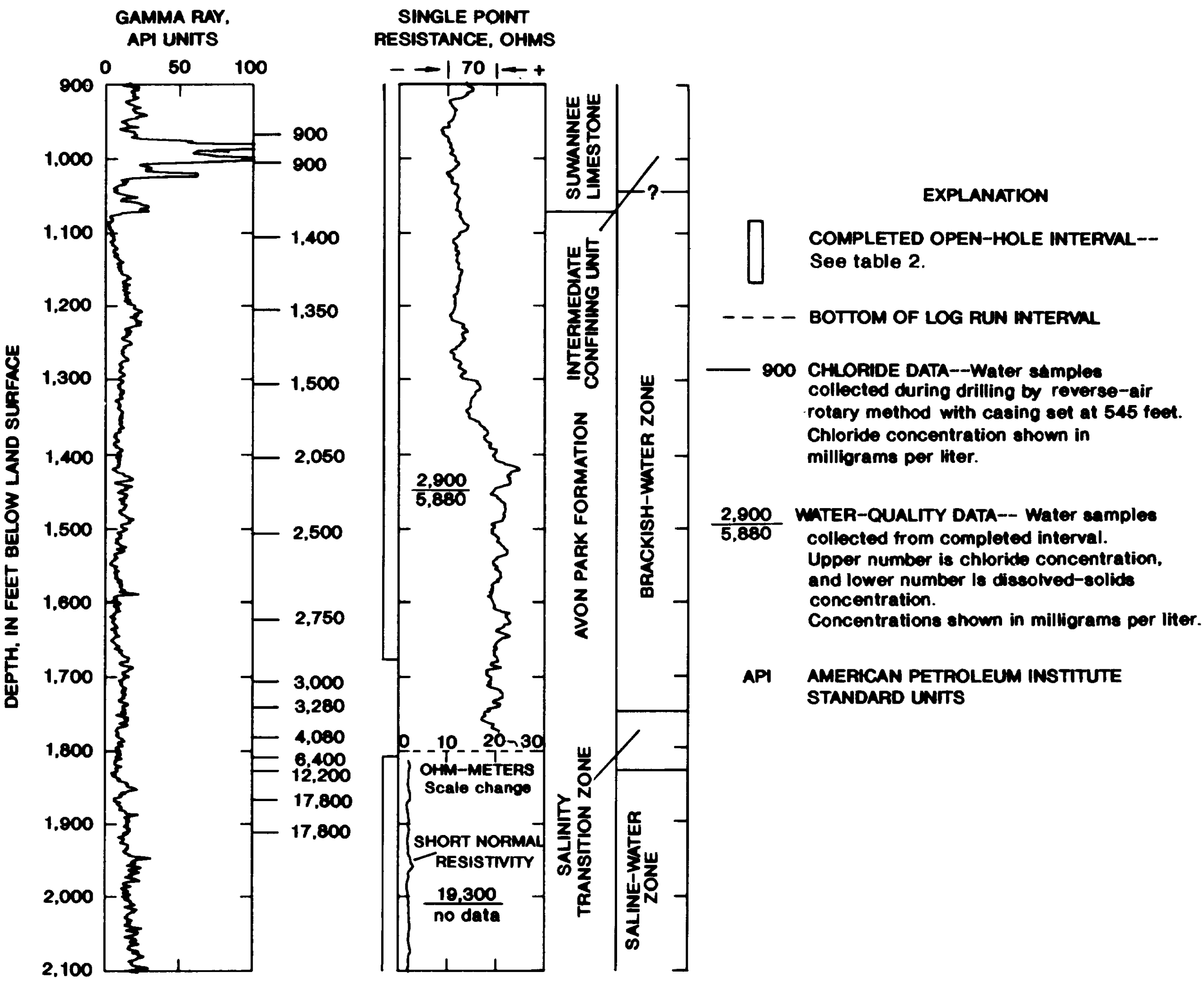


Figure 13. Selected geophysical logs of well PU-I1 showing water-quality data collected during drilling by the reverse air rotary method and from completed intervals, geologic units, and salinity zones in eastern Dade County.

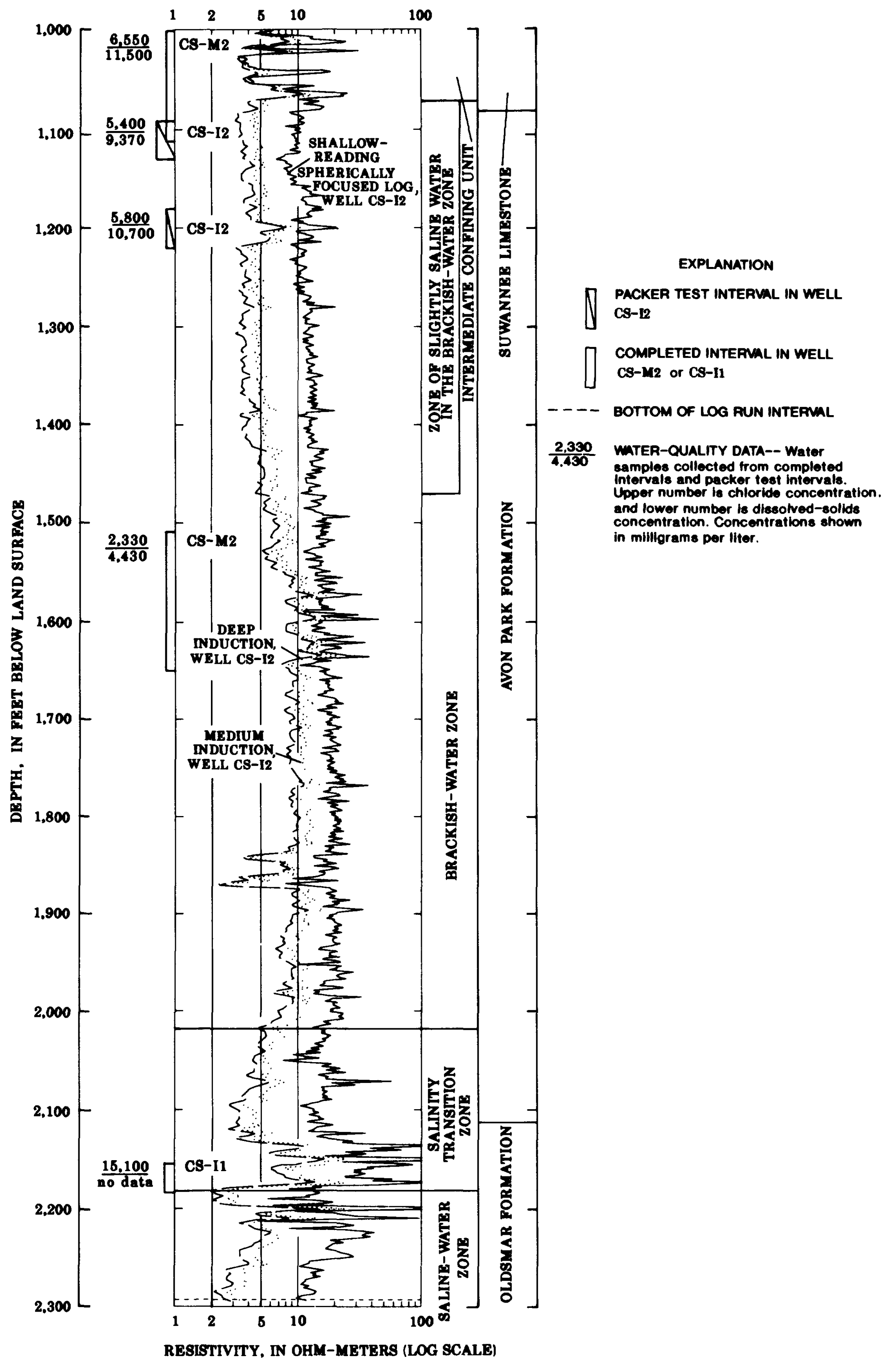


Figure 14. Water-quality data, resistivity geophysical log, salinity zones, and geologic units for twin wells CS-I2 and CS-M2 in northeastern Broward County. One water-quality analysis from well CS-I1, 750 feet south of well CS-I2, is also included in the data.

of 25°C, a very high porosity of 75 percent is required to give an R_0 of 2.0 ohm-meters (eqs. 1, 2, 4, and 5). This required porosity would decrease only to 72 percent if the cementation factor were lowered to 1.6. The lithologic descriptions of drill cuttings in wells CS-I2, CS-M2, MDS-I12, and S-1533 were examined, and there is no evidence that the thin beds with low resistivity in these wells are of a substantially different lithology than is normal for the Avon Park Formation. However, a zone of higher permeability is apparent in well MDS-I12 from 1,500 to 1,550 ft based on geophysical log analysis (Miami-Dade Water and Sewer Department, 1991, p. 67).

In several wells in which resistivity geophysical logs were used to determine the salinity boundaries, the formation was invaded with saline drilling fluid as indicated by the logs. The curve output from the 18-ft 18-in. lateral device in well G-3235 was used to place the base of the brackish-water zone at 1,880 ft deep. However, in many places above this depth, as high as 1,265 ft, the curve decreases below 5 ohm-meters, which could have been caused by invasion of the formation with saline drilling fluid. Well G-3235 was drilled to 3,510 ft with casing at 675 ft before logging, and this could have resulted in upward circulation of saline water from the Boulder zone in the borehole. Additionally, the short normal device indicates invasion with saline drilling fluid because its resistivity response is lower than that from the lateral device. Shallow invasion with saline drilling fluid also occurred in wells G-3234, G-3239, and G-3240, as indicated by comparison of the short normal response with the long normal or lateral response.

The conventional electrical log run in well SUN-I1 to determine salinity boundaries presented some problems. The log run on November 3, 1984, across the interval from 1,790 to 3,207 ft, had resistivity readings that were abnormally low. From the top of the logged interval downward, the short normal and long normal curves decrease to a minimum of 0 to 1 ohm-meter at 2,000 ft and remain in this range for most of the logged interval. This response pattern indicates that the top of the saline-water zone is at about 2,000 ft in the well based on knowledge of other wells in the study area, such as well MDS-I12 (fig. 12). However, resistivity in the saline-water zone should be at least 1 ohm-meter as shown by logs run on other wells in the study area and in table 6.

An earlier conventional electrical log survey run in well SUN-I1 on March 27, 1984, across the interval from 1,014 to 1,822 ft, indicates that the base of the brackish-water zone is at least 1,822 ft deep in this well. The depth of the base of the brackish-water zone was estimated to be at 1,857 ft in well SUN-I1 using the November 3, 1984 log run by assuming an average thickness for the salinity transition zone and subtracting this thickness from the depth of the top of the saline-water zone at 2,000 ft. This average thickness of the salinity transition zone (143 ft) was determined using all of the wells in which the thickness was determined in the study area (table 7).

The altitude of the base of the brackish-water zone in the study area is highest along the coast, particularly at Key Largo, as shown in figure 15. The mapped surface dips inland with contours that parallel the coast. The magnitude of the dip seems to be steepest along the coast. The surface apparently reaches a maximum depth from 2,100 to 2,200 ft below sea level in central to east-central Broward County and northwesternmost Dade County.

The thickness of the brackish-water zone can be approximated using the altitude of the top of Eocene rocks and the base of the brackish-water zone (figs. 6 and 15). This thickness ranges from 1,190 ft in well G-2296 in western Broward County to 24 ft in well MO-130 on Key Largo.

The altitude of the base of freshwater flow in the Floridan aquifer system was mapped by Sprinkle (1989, fig. 23). A chloride concentration in ground water of 10,000 mg/L was used to define the base. The depth of the base was determined using sample data or by calculation using predevelopment freshwater heads. The altitude of the base of freshwater flow determined by Sprinkle (1989, fig. 23) is similar to the altitude of the base of the brackish-water zone shown in figure 15.

For the purpose of describing salinity variations, the brackish-water zone was divided into an upper interval and a lower interval. The break used between the upper and lower intervals is 200 to 300 ft below the top of the rocks of Eocene age. More water-quality data were available for the upper interval of the brackish-water zone than for the lower interval. This reflects the importance of the flow zone at or near the top of the rocks of Eocene age previously described in this report. The upper and lower intervals of the brackish-water zone are described in the subsequent sections of this report.

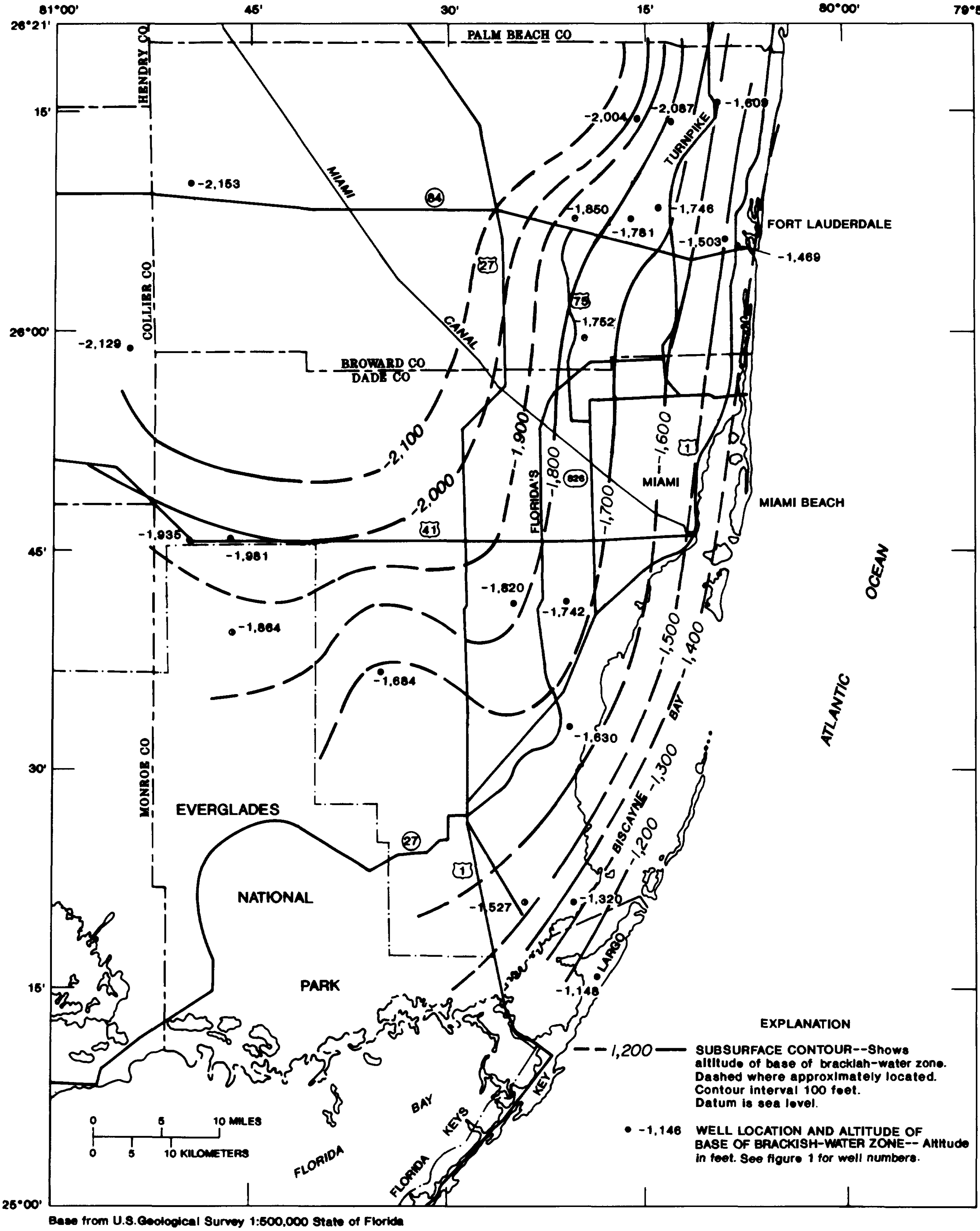


Figure 15. Altitude of the base of the brackish-water zone in southeastern Florida. Method used to determine this altitude in each well is given in table 7.

Upper Interval

Lines of equal chloride concentration in ground water from the upper interval of the brackish-water zone are shown in figure 16, and the sample intervals are given in tables 2 and 3. In some wells, the top of the sample interval is in the Hawthorn Formation, and in five wells (fig. 16) it is unknown because the depth to the bottom of the final casing string was not reported. The depth to the bottom of the sample interval in these five wells is assumed to be the final well depth given in the appendix.

Chloride concentrations range from 1,000 to 1,500 mg/L in much of the study area (fig. 16). However, in some areas, concentrations are higher, ranging from 3,000 to 4,500 mg/L in southern Dade County and Key Largo, 1,500 to 3,400 mg/L along the east coast from about the center of the study northward, and as high as 5,640 mg/L in well CS-I1 in northeastern Broward County. Deep induction resistivity measurements and water-quality data in wells CS-I2 and CS-M2, located at the same wastewater injection well site as well CS-I1, indicate an anomalous interval of slightly saline water from the lower part of the Suwannee Limestone to 1,470 ft deep (fig. 14). The extent of the area around wells CS-I1, CS-I2, and CS-M2 with this relatively high salinity in the upper interval of the brackish-water zone is unknown. However, the pattern of chloride concentration in eastern Broward County suggests that these wells lie in an area of high salinity that trends northeast (fig. 16).

In mapping the variations in chloride concentration in the upper interval of the brackish-water zone, it was assumed that the intermediate confining unit overlying the Floridan aquifer system, if included in the sample interval, did not contribute significantly to the sampled ground water. The measurement of flow in well NP-100 during drilling indicates this to be true (Meyer, 1971). The well was cased at a depth of 620 ft, and a 7 7/8-in. hole was drilled to a depth of 1,333 ft, leaving 350 ft of the Hawthorn Formation open. At a depth of 1,010 ft, the combined flow from three flow zones in this part of the Hawthorn Formation and the upper part of the Suwannee Limestone was only 40 gal/min, as compared to 1,600 gal/min combined flow when the next flow zone, which occurs in association with the top of the rocks of Eocene age, had been penetrated at a depth of 1,170 ft.

Support for placing the flow zone found from 970 to 1,010 ft in well NP-100 in the intermediate confining unit rather than the Upper Floridan aquifer is found in hydraulic head data. The zone at 970 to 1,010 ft had a head of about 11 ft above sea level, whereas the flow zone found at 1,170 ft had a head of about 40 ft above sea level. A potentiometric-surface map of the Upper Floridan aquifer shows the head in all of southern Dade County to be at least 40 ft above sea level (Bush and Johnston, 1988, pl. 5).

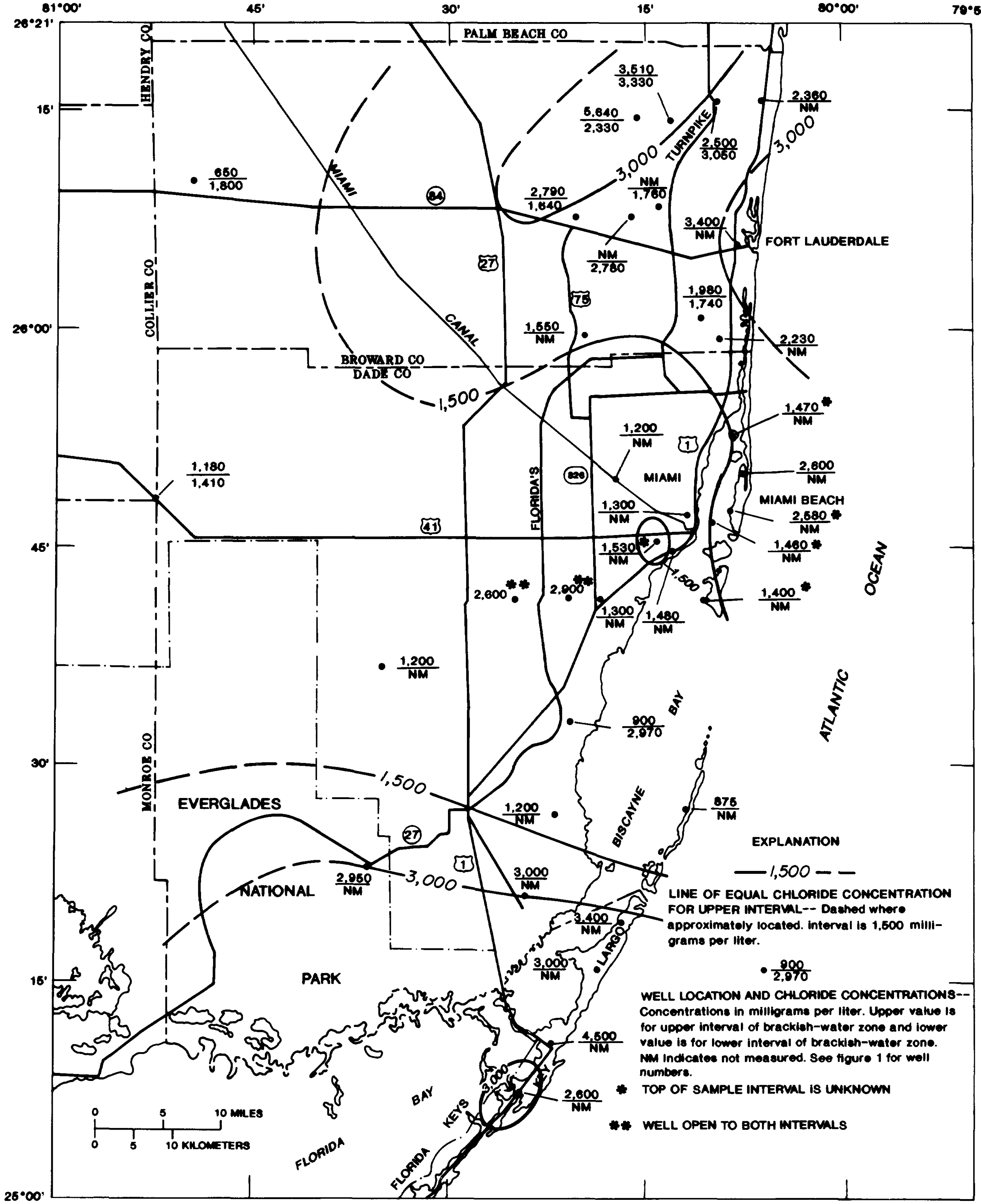
To address the salinity of the lower part of the intermediate confining unit and compare it with that of the upper interval of the brackish-water zone, the chloride concentration of five wells from which samples of this unit were obtained were plotted on a map of the study area (fig. 17). The bottom of the sample interval in these samples is always at least 100 ft above the top of the rocks of Eocene age (tables 2 and 3). For well NP-100 in southern Dade County, the interval open during sampling was 620 to 1,125 ft. Salinity in the lower part of the intermediate confining unit seems to be slightly higher in most of the study area than in the upper interval of the brackish-water zone. Salinity in the lower part of the intermediate confining unit is lower than in the upper interval in wells NP-100 and MO-133 in the southern part of the study area (fig. 17).

Lower Interval

Chloride concentrations were measured in 10 wells in the lower interval of the brackish-water zone (fig. 16). The top of the sample interval in these wells is at least 200 to 300 ft below the top of the rocks of Eocene age. Chloride concentrations in the wells ranged from 1,410 to 3,330 mg/L and averaged 2,280 mg/L.

At the CS injection well site in northeastern Broward County (fig. 1), chloride concentrations were higher in the upper interval of the brackish-water zone (5,640 mg/L) than in the lower interval of the zone (2,330 mg/L) as shown in figure 16. The anomalous decrease of salinity with depth in the brackish-water zone at the CS site also occurs in nearby wells at the MAR and SUN injection well sites, and these three sites together define a northeast-trending area of higher salinity in the upper interval (fig. 16).

The lower interval of the brackish-water zone was sampled in wells MDS-I12 and MDS-BZ1 at the



Base from U.S.Geological Survey 1:500,000 State of Florida

Figure 16. Chloride concentration in ground water from the upper and lower intervals of the brackish-water zone in southeastern Florida. Boundary used between the upper and lower intervals is 200 to 300 feet below the top of the rocks of Eocene age.

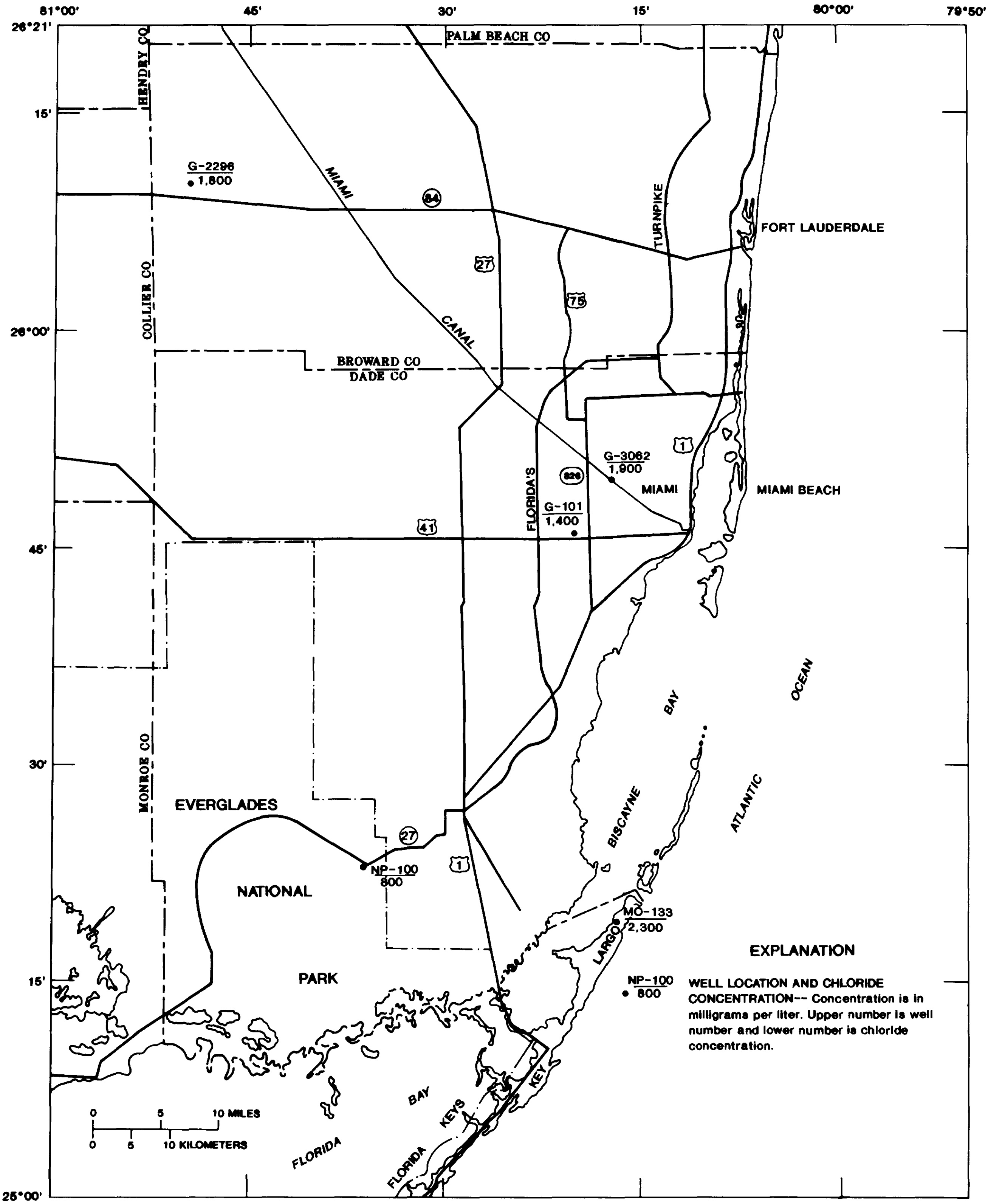


Figure 17. Chloride concentration in ground water from the lower part of the intermediate confining unit in southeastern Florida.

MDS site (table 3). A chloride concentration of 2,970 mg/L was measured in well MDS-I12 at a depth interval of 1,550 to 1,580 ft. In well MDS-BZ1, a chloride concentration of 4,200 mg/L was measured at a depth interval of 1,577 to 1,664 ft. This sample interval extends slightly below the base of the brackish-water zone, which is 1,640 ft deep at the plant site.

The sample intervals for wells PU-I1 and PU-I2 in southeastern Dade County (table 2) include the upper and lower intervals of the brackish-water zone, and water-quality data collected from these two wells are shown in figure 16. Chloride concentrations were 2,900 mg/L at a depth interval of 545 to 1,680 ft in well PU-I1 and 2,600 mg/L at a depth interval of 758 to 1,742 in well PU-I2. These values indicate that the chloride concentrations in the upper interval in these two wells are higher than that indicated by chloride concentration contours in figure 16 (chloride concentration of 1,500 mg/L or less).

Saline-Water Zone

The top of the saline-water zone was determined in wells in which geophysical resistivity logs were run. The depths of this top are given in table 7, and the altitude of the top is mapped in figure 18. A formation resistivity (R_0) of 1.7 ohm-meters was used to determine the depth of the top of the saline-water zone.

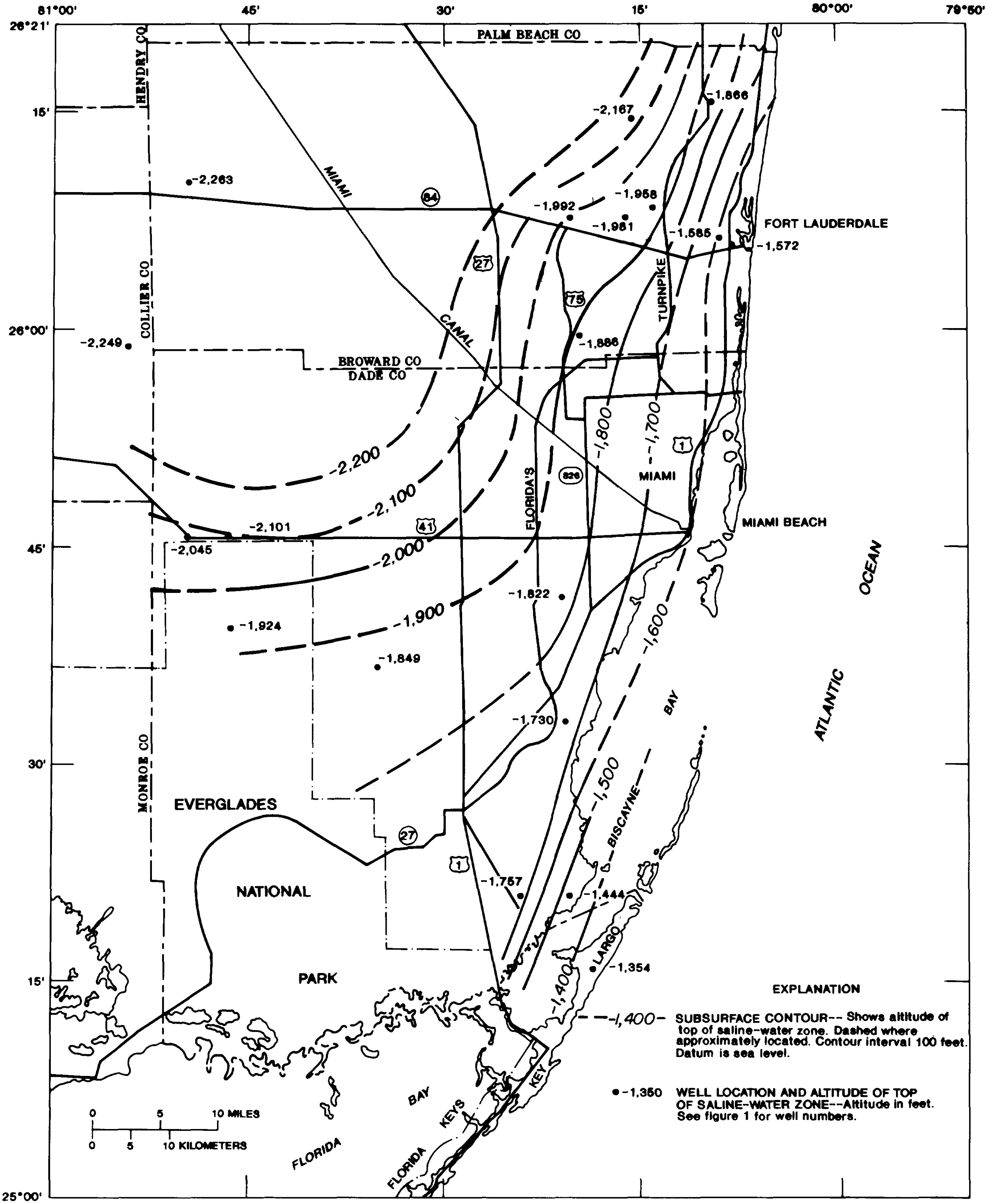
Water-quality data collected from the upper part of the saline-water zone often indicate a salinity that is less than the 35,000 mg/L of dissolved-solids concentration used in resistivity calculations. Dissolved-solids concentrations were 29,800 mg/L in well BCN-I4 from 1,963 to 2,013 ft deep, 30,000 mg/L in well CS-I2 from 2,300 to 2,340 ft deep, 32,600 mg/L in well MDS-M3 from 1,771 to 1,892 ft deep, 31,500 mg/L in well PBP-M1 from 2,000 to 2,050 ft deep, 27,600 mg/L in well PLT-I2 from 2,190 to 2,230 ft deep, and 19,900 mg/L in well PLT-ROI1 from 2,150 to 2,300 ft deep (tables 2 and 3). Additionally, chloride concentration was only 5,110 mg/L in well PLT-M1 from 2,130 to 2,230 ft deep. Although these values were lower than anticipated, except for the values from PLT-ROI1 and PLT-M1 they still indicate a salinity of at least three times higher than that at the top of the transition zone. These lower salinity values in the saline-water zone could have been because of invaded drilling fluid still present in the formation when the water samples were collected. Alternatively, the upper part of the saline-water zone might have once contained water with a salinity much lower than that of seawater, and this water was incompletely flushed when displacement by saline water occurred.

The thickness of the salinity transition zone measured in 18 wells ranged from 60 to 257 ft and averaged 143 ft (table 7). This thickness is 124 ft or less in 10 wells and 200 ft or greater in 5 wells.

Water with salinity similar to or higher than that of seawater is present in the saline-water zone of the Floridan aquifer system. Water samples with a chloride concentration of 22,000 mg/L and a dissolved-solids concentration of 40,100 mg/L were collected from well S-1533 at a depth interval of 2,100 to 2,304 ft (table 2). Water samples from 10 wells completed in the Boulder zone (BCN-I1, FTL-I2, FTL-I5, MDS-I5, MDS-BZ1, PBP-I1, PLT-I1, PU-I1, PU-I2, and SUN-I1) had an average chloride concentration of 19,760 mg/L (tables 2 and 3). The chloride concentration of Boulder zone water from well CS-I2 (24,700 mg/L) was anomalously high and was not included in the average. The average dissolved-solids concentration of Boulder zone water from eight wells was 37,000 mg/L. These averages indicate a salinity similar to seawater if chloride concentration is used for comparison, but slightly more saline than seawater if dissolved-solids concentration is used. This indicates there has been some mineralization of Boulder zone water due to mineral dissolution.

ORIGIN OF SALINITY

The origin of salinity in the brackish-water zone of the Floridan aquifer system in southern Florida, salinity due mostly to the sodium chloride content of the water, has been explained by two contrasting theories. One will be referred to as the convention cell theory and the other as the residual salinity theory. Evidence for and against these theories in southeastern Florida, some of which results from this study, will be discussed in this section. Of special importance to these theories are the processes that could be controlling the depth of the base of the brackish-water zone, and these processes will be examined. In the last part of this section, the residual salinity theory will be used to explain the areas of high salinity found in the Upper Floridan aquifer along the coast.



Base from U.S.Geological Survey 1:500,000 State of Florida

Figure 18. Altitude of the top of the saline-water zone in southeastern Florida. Method used to determine this altitude in each well is given in table 7.

The conventional cell theory, proposed by Kohout (1965), calls for the upward movement of saline water from the Boulder zone through the middle confining unit of the Floridan aquifer system and mixing of this water with seaward-flowing freshwater in the upper part of the aquifer system. The impetus in this theory is geothermal heating under the Florida Plateau. The lower part of the flow cell is the inland movement of seawater into the Boulder zone along the Straits of Florida where the Floridan aquifer system outcrops below sea level at the edge of the plateau. The residual salinity theory explains that the original saline pore water of deposition or later invaded seawater has not been completely flushed out by meteoric water. In southern Florida, salinity in the Upper Floridan aquifer is, at least in part, interpreted to be residual (Sprinkle, 1989, p. 48).

There is evidence presented by Meyer (1989) that supports the convection cell theory, chief among which is the presence of measurable carbon-14 activity (as high as 6.5 percent of modern carbon) in water from the Upper Floridan aquifer in southern Florida (Meyer, 1989, fig. 11). Estimated transit times in the Upper Floridan aquifer from the aquifer's recharge area (Meyer, 1989, table 7) are much longer than the 40,000-year useful range for carbon-14 dating, and therefore the percent of modern carbon should approximate zero in southern Florida. The presence of the measurable carbon-14 in southern Florida suggests another source for the water in the aquifer of an age younger than 40,000 years--probably the upwelling of saline water from the Boulder zone into the Upper Floridan aquifer (Meyer, 1989).

The convection cell theory implies that the saline water in the Boulder zone is heated to a point that its density becomes less than that of water in the Upper Floridan aquifer, causing its upward migration. The maximum temperature of water in the Boulder zone of the Lower Floridan aquifer in southern Florida is 43.4°C (Meyer, 1989, fig. 7) at the northernmost extent of the zone, 70 mi northwest of the study area. (The temperature ranges from 10°C to 24°C in the study area.) Using oceanographic tables that give the density of seawater at various temperatures and salinities, the density of standard seawater at 43.4°C was extrapolated to be 1.017 g/cm^3 (Unesco, 1987). This density is still substantially higher than the density of water in the brackish-water zone at 25°C and with a chloride concentration of 3,000 mg/L (density equals 1.0035 g/cm^3). This density/temperature factor would seem to preclude the upward movement of saline water into the brackish-water zone by thermal convection in the study area and perhaps in most of southern Florida.

If the brackish-water and saline-water zones occur within one hydraulic unit, the thickness of the brackish-water zone might result from a state of density equilibrium that exists between the two zones. Although the permeability of rocks present in the brackish-water zone in the study area is generally low, highly impermeable rock (dense dolomite or clay) is uncommon.

Pressure measured at different depths in a well in the Floridan aquifer system can help determine if vertical hydraulic connectivity exists. A plot of pressure measurements compared to depth was made for well G-2296 (Meyer, 1989, fig. 10). These measurements were made mostly during packer testing or from completed intervals (Meyer, 1989, table 3). A pressure gradient for one measurement made within the brackish-water zone at a depth interval of 1,030 to 1,154 ft was calculated to be 0.4325 lb/in^2/ft on the basis of estimated fluid density and representative depth. A line representing this gradient, drawn on the plot through the measurement, closely coincided with eight other measurements made in the brackish-water zone at depths ranging from 895 to 1,618 ft (Meyer, 1989, fig. 10). This indicates that the interval represented by these measurements is hydraulically connected.

If a state of equilibrium exists between the brackish-water and saline-water zones, an estimate of the depth to the base of the brackish-water zone can be made according to the Ghyben-Herzberg approximation (Bear, 1979, p. 385). Assuming steady-state horizontal flow in the freshwater (brackish) region and no flow in the saltwater region, the altitude below sea level of a sharp freshwater-saltwater interface in a confined aquifer can be calculated according to the following equation (Bear, 1979, p. 385):

$$h_s = [\rho_f / (\rho_s - \rho_f)]\, h_f \qquad (6)$$

where h_s is the depth to the interface below sea level, ρ_f is the density of the freshwater, ρ_s is the density of the seawater, and h_f is the freshwater head.

The depth to a freshwater-saltwater interface in the Floridan aquifer system was calculated using the Ghyben-Herzberg approximation (table 8). The density of water in the brerackish-water zone used in these calculations was estimated using the chloride concentration of Upper Floridan aquifer water produced from a well and a linear relation between chloride concentration and density from freshwater to seawater. The density of seawater used was 1.0268 g/cm^3. This value is the average specific gravity of seawater in the Miami area, referred to distilled water at 25°C/25°C (Parker and others, 1955, p. 573). The Upper Floridan aquifer head data (table 8) were recorded as freshwater heads. They were adjusted using the density of the actual water produced before being used in equation 6. These head data were assumed to not differ greatly from predevelopment heads.

The calculated altitude of a saltwater interface is comparable to that of the base of the brackish-water zone determined in this study. Table 8 indicates that the difference between the altitudes is 56 ft or less in five cases. Some of the difference between the two could be because of the presence of the salinity transition zone rather than a sharp interface. However, as discussed earlier, the thickness of the transition zone is commonly only 80 to 120 ft.

The increase in salinity with depth in the salinity transition zone suggests mixing or diffusion associated with a brackish-water/saline-water interface. The rapid, steady nature of this increase (fig. 12) indicates that diffusion might be a more important process than mechanical mixing or hydrodynamic dispersion in explaining the origin of this zone.

The assumption of horizontal flow above the interface is no longer valid near the coast, and the Ghyben-Herzberg approximation gives a depth that is less than the actual depth to the interface (Bear, 1979, p. 385). The reverse is true for well MO-130 on Key Largo (table 8) with the calculated depth for the interface being much greater than the measured depth. The brackish-water zone is only 24-ft thick in this well and could be underlain by rocks of very low permeability, impeding hydraulic connection between the zone and deeper rocks.

The interface is apparently at or near an equilibrium position in inland areas (table 8, wells G-2296, G-3234, and G-3239). This could be somewhat unexpected in view of the low hydraulic conductivity in the middle confining unit of the Floridan aquifer system (described earlier). The position of this interface should have changed in response to sea-level fluctuations during the Pleistocene. For example, during the last sea-level low stand just before the Holocene transgression, sea level was more than 300 ft below present-day sea level. Reestablishment of equilibrium in the relatively short period of time since these changes indicates that vertical permeability is not too low in at least the upper part of the middle confining unit (probably higher than that of unconsolidated marine clay with a hydraulic conductivity of 3×10^{-4} ft/d).

Table 8. Calculated altitudes of a saltwater interface in southeastern Florida using the Ghyben-Herzberg approximation and comparison with altitudes of the base of the brackish-water zone

[Well locations shown in figure 1; head data from Bush and Johnston (1988), except for well S-1533, which is from Beaven and Meyer (1978); calculated altitude of saltwater interface uses density of Upper Floridan aquifer water produced; altitude of base of brackish-water zone determined in this study]

Well number	Freshwater head, Upper Floridan aquifer (feet)	Calculated altitude of saltwater interface (feet below sea level)	Altitude of base of brackish-water zone (feet below sea level)	Altitude of saltwater interface minus altitude of base of brackish-water zone (feet)
FTL-11	37	1,623	1,469	154
G-2296	57	2,209	2,153	56
G-3234	46	1,804	1,684	120
G-3239	49	1,922	1,935	-13
MDS-I12	41	1,608	1,640	-32
MO-130	40	1,716	1,148	568
PBP-M1	43	1,734	1,752	-18
S-1533	38	1,564	1,527	37

An observation which lends support to the residual salinity theory is that the sediments of the brackish-water zone are generally fine grained, low in permeability, and high in porosity. These characteristics could make complete flushing difficult, even over long periods of time. This theory is also supported by comparing salinity of water from the intermediate confining unit (fig. 17) with that in the upper interval of the brackish-water zone (fig. 16). In two wells (G-2296 and G-3062) in the northern part of the study area, salinity is higher in the intermediate confining unit. Because of the lower permeability of the intermediate confining unit, less complete flushing by freshwater can be expected, resulting in higher salinity.

Areas of higher salinity in the upper interval of the brackish-water zone are present near or along the coast (fig. 16). The higher salinity in these areas is probably also residual, but its occurrence could have resulted from a different process than that for the inland areas. These coastal areas of higher salinity seem to occur where there is higher permeability in the Upper Floridan aquifer, suggesting that inland migration of saline water has occurred somewhat recently in these areas.

The origin of the northeast-trending area of high chloride concentration in northeastern Broward County in the upper interval of the brackish-water zone (fig. 16) might be related to higher than normal permeability in the Upper Floridan aquifer for the study area. This higher permeability could have allowed for the migration of high salinity water laterally from the coast to the northeast. The upper monitoring zone in well CS-I1, open at a depth from 1,193 to 1,222 ft, was heavily contaminated with salty drilling water. This interval is more than 100 ft below the top of the rocks of Eocene age (1,082 ft) and probably below the upper flow zone, which is developed in association with this top. The salinity of samples collected from the interval took 2 years to decrease to a background level, suggesting that there was a large volume of invaded drilling fluid and relatively high permeability in the rocks. Another flow zone could be present in this interval. The base of the zone of slightly saline water in the upper part of the brackish-water zone in well CS-I2 at 1,470 ft (fig. 14) could coincide with a decrease in rock permeability.

It is possible that the zone of slightly saline water in the upper part of the brackish-water zone in well CS-I2 resulted from invasion with salty drilling fluid, migrating from nearby well CS-I1 to CS-I2 drilled 4.5 years after well CS-I1. A dual induction resistivity log run on well CS-I1 indicates deep invasion with a drilling fluid of higher salinity than the formation water. This saline invasion was present from the top of the Floridan aquifer system to a depth of at least 2,050 ft.

Several observations indicate that the zone of anomalous high salinity in the upper part of the brackish-water zone in well CS-I2 is natural in origin. If this thick zone of higher salinity is naturally present, some density equilibration with the saline-water zone would be expected. Thus, the depth to the brackish-water/saline-water interface would probably be greater because of the higher density of water in the brackish-water zone. The base of the brackish-water zone in well CS-I2 is much deeper than expected, given its proximity to the coast (fig. 15).

An analysis of chloride concentrations was made for well CS-I1 in the upper monitoring zone at a depth of 1,193 to 1,222 ft. Chloride concentrations were 9,300 mg/L in May 1985 and decreased to 5,640 mg/L in May 1987. From May 1987 to March 1990, monthly water samples collected from this well indicate no further significant decrease in chloride concentration. This stabilized value (about 5,600 mg/L) is similar to the chloride concentrations from well CS-I2 in the upper part of the brackish-water zone (fig. 14, 5,400-6,550 mg/L). This similarity in salinity would be unlikely if the high salinity of the CS-I2 samples resulted from migration of salty drilling fluid from CS-I1 to CS-I2. A plume of invaded drilling fluid from well CS-I1 would be expected to migrate downgradient (east or east-southeast). However, well CS-I2 is 750 ft to the north of well CS-I1, and this distance could be enough to prevent the plume from having an effect on well CS-I2.

The area of high salinity in the upper interval of the brackish-water zone in southern Dade County and northern Key Largo (fig. 16) correlates with an area of higher permeability in the Upper Floridan aquifer. Data for wells NP-100, S-1532, and S-1533 indicate that the transmissivity of the aquifer in this area is high (31,000 ft^2/d in wells S-1532 and S-1533). Additionally, Puri and Winston (1974, fig. 35) mapped a belt of high transmissivity in the Upper Floridan aquifer in this area based on drilling characteristics.

Transmissivity of the Upper Floridan aquifer is low at the Miami-Dade South District Wastewater Treatment Plant site (2,700 ft^2/d in well MDS-M2). Salinity is also relatively low at this site in the aquifer as shown by a chloride concentration of 900 mg/L in well MDS-M3 (fig. 16, upper interval of the brackish-water zone). Permeability in this area was possibly too low to allow for influx of high salinity water from the east.

High salinity in the Upper Floridan aquifer occurs along the St. Johns River Valley in northeastern Florida (Sprinkle, 1989, fig. 22). This high salinity might have resulted from high sea-level stands during the Pleistocene Epoch, causing the influx of seawater into the aquifer (Stringfield, 1966, p. 172). A high stand of sea level of about 23 ft above present sea level occurred about 140,000 years before present (Cronin, 1983). According to this theory, flushing of this saline water by the present freshwater flow system has been incomplete. The areas of high salinity near or along the coast in this study area might have resulted from a similar process.

The incomplete flushing of the invaded seawater in areas of higher permeability along the coast can be explained by the distribution of permeability in the Floridan aquifer system. Upgradient of these areas, only a few thin permeable zones are present in the Upper Floridan aquifer (the normal distribution of permeability in the study area). Because of this low transmissivity of the aquifer upgradient in the inland areas and the long distance from the recharge area of the aquifer, the rate of freshwater flushing in the invaded areas could be low. Additionally, flushing could have been impeded if the zones of higher permeability in the areas along the coast were not well connected to the thin permeable zones in upgradient areas. If the invasion were relatively recent (such as 140,000 years before present), the time available would not have allowed for complete flushing.

SUMMARY AND CONCLUSIONS

The Floridan aquifer system is considered to be a valuable supplemental source for public-water supply in southeastern Florida in spite of the brackish nature of its contained water in this area. The primary purpose of the study reported here was to describe the distribution of salinity in this thick and complex aquifer system and relate this distribution to the local hydrogeology, thereby allowing for some understanding of processes that control this distribution.

Geophysical logs and lithologic descriptions of wells penetrating the Floridan aquifer system were used to produce a detailed structure map of the top of the rocks of Eocene age. This top at which erosional relief was found to be present in the study area represents an important regional unconformity. The top of the rocks of Eocene age ranged in depth below sea level from 950 ft in northeastern Dade County to at least 1,300 ft in southern Dade County.

The Floridan aquifer system consists of the Upper Floridan aquifer, the middle confining unit, and the Lower Floridan aquifer, and the dominant lithology in the aquifer system is limestone. The unconformity present at the top of the rocks of Eocene age was found to approximate the top of the Upper Floridan aquifer, and the most transmissive zone in this aquifer, normally only 10 to 40 ft thick, occurs in association with this unconformity. Generally, porosity is high and permeability is low in the Upper Floridan aquifer; however, another important permeable zone of lower transmissivity than that of the upper zone occurs at about 500 ft below the upper zone. The Upper Floridan aquifer is generally 500 to 600 ft thick, and its transmissivity has been measured to be as high as 31,000 ft^2/d. Except for the relatively thin permeable zones in the Upper Floridan aquifer, the porosity and permeability in the middle confining unit are not considerably less than in the Upper Floridan aquifer; however, hydraulic conductivity in the middle confining unit can be as low as 10^{-4} ft/d. The top of the Lower Floridan aquifer is usually placed at or near the top of the highest thick dolomite because of the high permeability often present in this rock. This top is variable, ranging from at least 2,140 to 2,460 ft deep. Thick confining units can be present in the Lower Floridan aquifer.

Salinity was defined on the basis of chloride and dissolved-solids concentrations, and the relation between these two values was determined using data from the Floridan aquifer system. Relations were also determined between chloride concentration and specific conductance at low and high salinities. These relations were used to determine formation water resistivity in the Floridan aquifer system at two threshold salinity values, 10,000 and 35,000 mg/L of dissolved-solids concentration. The formation resistivity of the Floridan aquifer system containing water with these two salinity values was then computed.

Vertical variations in salinity in the Floridan aquifer system, defined on the basis of water-quality and geophysical log data, indicate that the Floridan aquifer system can be divided into three salinity zones. These zones, in order of increasing depth, are the brackish-water zone, the transition zone, and the saline-water zone. Salinity increases with depth rapidly in the transition zone. The transition zone was defined using a salinity of 10,000 mg/L of dissolved-solids concentration (about 5,240 mg/L of chloride concentration) at its top and 35,000 mg/L of dissolved-solids concentration (about 18,900 mg/L of chloride concentration) at its base. The concentration used at its base is a salinity value similar to that of seawater.

The base of the brackish-water zone and the top of the saline-water zone were approximately defined using geophysical logs. Using the extreme values computed for formation resistivity, the base of the brackish-water zone in one well ranged from 1,615 to 1,667 ft (a depth interval of only 50 ft). The thickness of the transition zone averaged 143 ft, and ranged from 60 to 124 ft in 10 of the 18 wells in which it was measured. The salinity of water samples obtained from completed intervals near the base of the brackish-water zone supported the position of the base as determined using geophysical logs.

The altitude of the base of the brackish-water zone in the study area ranges from about 1,150 ft below sea level in Key Largo of the Florida Keys to about 2,150 ft below sea level inland. The base of the brackish-water zone lies in the Upper Floridan aquifer along the coast but extends into the middle confining unit of the Floridan aquifer system inland. The brackish-water zone is as much as 1,200 ft thick inland.

Salinity determined by chloride concentration ranged from 850 to 5,640 mg/L in the upper interval of the brackish-water zone. Salinity increases substantially in this interval in some areas along or near the coast, particularly in one area in northeastern Broward County in which salinity becomes slightly saline (dissolved-solids concentration greater than 10,000 mg/L and chloride concentration greater than 5,240 mg/L). In this anomalous area, salinity decreases with depth in the brackish-water zone, whereas salinity typically increases downward in the zone. In the lower interval of the brackish-water zone, chloride concentrations ranged from 1,410 to 3,330 mg/L and averaged 2,280 mg/L. At one location, salinity increased by a factor of three from the top of the brackish-water zone to its lower part.

Salinity from water samples collected in the saline-water zone did not vary greatly. However, salinity in the upper part of the zone can be lower than that of seawater (36,000 mg/L of dissolved-solids concentration) by about 5,000 mg/L of dissolved-solids concentration. Salinity determined by dissolved-solids concentration averaged about 37,000 mg/L in the Boulder zone of the Lower Floridan aquifer, which is slightly higher than that of seawater.

The rapid, steady increase in salinity with depth in the transition zone indicates that the zone is primarily the result of diffusion across a salinity interface. The thickness of the brackish-water zone can be explained by assuming density equilibrium exists between the brackish-water and saline-water zones. Density equilibrium exists far inland where the base of the brackish-water zone extends well down into the lower permeability sediments of the middle confining unit.

Salinity in the brackish-water zone could be residual, being derived from original saline pore water of deposition or later invaded seawater. The fine-grained, low-permeability, but porous nature of the sediments in the brackish-water zone could make complete flushing by meteoric recharge difficult. The presence of the interface would seem to preclude convective upwelling of saline water from the Boulder zone into the Upper Floridan aquifer. Even at the highest temperature expected for Boulder zone water in southern Florida, this water is still more dense than that in the brackish-water zone.

In areas of anomalous higher salinity in the upper part of the brackish-water zone present along or near the coast (chloride concentrations greater than 3,000 mg/L), available data indicate that permeability or transmissivity is also higher in the Upper Floridan aquifer than is typical for the study area. The anomalous salinities in these areas could have resulted from the preferential encroachment of seawater into zones of higher permeability in the Upper Floridan aquifer during Pleistocene high stands of sea level. These anomalies then persisted because of incomplete flushing of this seawater by the present flow system. Flushing by freshwater would be minimized because of the low transmissivity of the aquifer upgradient of the areas and the long distance of transport from the recharge area. This explanation would make salinity much younger in these areas than in the rest of southeastern Florida.

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APPENDIX

Appendix. Inventory of wells used in this report

[Well locations shown in figure 1. Local well identifier used for this report only. Site identification: first six digits are the latitude, next seven digits are the longitude, and last two digits are a sequential number; this number should not be used for the latitude-longitude location of a well (the number is assigned by the U.S. Geological Survey (USGS) for identification purposes in the Ground-Water Site Inventory (GWSI) system. AMP (altitude measuring point): AMP is at land surface for all wells, except C-962, G-3234, G-3235, G-3239, G-3240, MO-141, and S-479; AMP is above land surface for these wells. Type of openings: P, perforations shot through casing and cement (no gravel pack); S, gravel-packed interval (with screen or slotted or perforated liner); and X, open hole. Date at end of construction: P, date of plugging and abandonment; *, second construction date (the abandonment date is not known for some plugged and abandoned wells). WWTP, Wastewater Treatment Plant; WTP, Water Treatment Plant; --, no data]

Local well identifier	Site identification	Latitude	Longitude	County	Well owner or other local name	AMP (feet)	Well depth (feet)	Bottom of casing (feet)	Outside diameter of casing (inches)	Top of open interval (feet)	Bottom of open interval (feet)	Type of openings	Date at end of construction
BCN-I1	261538080092801	261538	0800928	Broward	Broward County North District WWTP injection well #1	14.35	3,512	160 1,000 1,950 2,990	50 42 34 24	2,990	3,512	X	03-28-90
BCN-M1	261538080092701	261538	0800927	Broward	Broward County North District WWTP monitoring well #!1	14.4	2,079	160 1,000 2,000	24 16 6.62	1,000 2,000	1,128 2,079	X X	02-18-90
BCN-I4	261538080091801	261538	0800918	Broward	Broward County North District WWTP injection well #4	14.42	3,500	160 1,000 1,949 2,950	50 42 34 24	2,950	3,500	X	11-25-90
BCN-M2	261538080092001	261538	0800920	Broward	Broward County North District WWTP monitoring well #2	14.75	2,079	160 1,000 2,000	24 16 6.62	1,000 2,000	1,130 2,079	X X	10-31-90
C-962	255846080533001	255845	0805413	Collier	Exxon Raccoon Point Saltwater Disposal System 1, well #1	25.6	3,900	234 2,228 2,499 3,600	13.38 9.63 7 5	3,000 3,600	3,020 3,900	P X	05-05-84
CM-I1	261548080060201	261548	0800602	Broward	Collier Manor WWTP injection well #1, D-365	14.7	1,150	1,004	10	989	1,033	X	05-01-59 05-04-79P
CM-I2	261548080060202	261548	0800602	Broward	Collier Manor WWTP injection well #2, G-2293	14.7	992	976.5	10	--	--	--	1967 05-11-79P
CS-I1	261438080154801	261438	0801548	Broward	Coral Springs WWTP injection well #1	13	3,500	125 995 2,300 3,006	42 34 22 12.75	1,192.2 2,153.4 3,006	1,222 2,183 3,500	S S X	05-29-85
CS-I2	261445080154801	261445	0801548	Broward	Coral Springs WWTP injection well #2	13	3,500	170 1,001 1,800 2,900	54 44 34 24	2,900	3,500	X	11-29-89
CS-M2	261445080154802	261445	0801548	Broward	Coral Springs WWTP monitoring well #2	13	1,650	170 1,000 1,510	24 16 6.63	1,000 1,510	1,110 1,650	X X	11-01-89

Local well identifier	Site identification	Latitude	Longitude	County	Well owner or other local name	AMP (feet)	Well depth (feet)	Bottom of casing (feet)	Outside diameter of casing (inches)	Top of open interval (feet)	Bottom of open interval (feet)	Type of openings	Date at end of construction
F-152	254524080140501	254524	0801405	Dade	City of Miami	10	990	--	6	--	--	--	01-30-29
FTL-I1	260543080074501	260543	0800745	Broward	Ft. Lauderdale WWTP injection well #1, G-2332	6.33	3,520	126 925 1,900 2,800	54 42 34 24	2,800	3,520	X	04-25-83
FTL-I2	260543080074601	260543	0800746	Broward	Ft. Lauderdale WWTP injection well #2, G-2333	7.19	3,525	126 925 1,900 2,800	54 42 34 24	2,800	3,525	X	04-12-83
FTL-I5	260543080075601	260543	0800756	Broward	Ft. Lauderdale WWTP test injection well #5, G-2330A	6.19	3,480	125 950 1,896 2,820	54 42 34 24	2,820	3,480	X	05-27-81
FTL-M1	260543080075602	260543	0800756	Broward	Ft. Lauderdale WWTP monitoring well #1, G-2331	6.1	2,705	125 935 2,568	20 14 3.5	1,021 1,466 2,532	1,072 1,562 2,705	S S S	03-09-81
G-101	254608080200901	254608	0802009	Dade	USGS, Baptist Church	4.9	812	480 798.4	6 4	798	812	X	July 1940
G-2296	261016080492601	261016	0804926	Broward	USGS, Alligator Alley test well monitoring zone 1	15.4	2,811	20 195 834 895 2,447	35 24 2.88 16 2.38	811 895 2,447	816 2,811 2,811	P X X	11-07-80 04-22-87*
G-2617	261016080492602	261016	0804926	Broward	USGS, Alligator Alley test well, monitoring zone 2	15.4	1,728	1,648	1	1,648	1,728	S	04-22-87
G-2618	261016080492603	261016	0804926	Broward	USGS, Alligator Alley test well, monitoring zone 3	15.4	1,164	1,104	1	1,104	1,164	S	04-22-87
G-2619	261016080492604	261016	0804926	Broward	USGS, Alligator Alley test well, monitoring zone 4	15.4	1,052	895	16	895	1,052	X	04-22-87
G-2620	261016080492605	261016	0804926	Broward	USGS, Alligator Alley test well, monitoring zone 5	15.4	816	834	2.88	811	816	P	04-22-87
G-3061	254941080171701	254941	0801717	Dade	USGS, Hialeah aquifer storage and recovery injection well	8.4	1,105	955	14	955	1,105	X	12-09-74
G-3062	254944080171801	254944	0801718	Dade	USGS, Hialeah aquifer storage and recovery monitoring well	5.43	1,064	198 953	14 6	840 953	844 1,060	P X	11-19-74 06-04-80P
G-3234	253648080345801	253648	0803458	Dade	Coastal Petroleum IIF State No. 1 Lease 340A	28	11,519	125 1,051 5,634	20 13.38 9.63	5,634	11,519	X	12-20-49

Local well identifier	Site identification	Latitude	Longitude	County	Well owner or other local name	AMP (feet)	Well depth (feet)	Bottom of casing (feet)	Outside diameter of casing (inches)	Top of open interval (feet)	Bottom of open interval (feet)	Type of openings	Date at end of construction
G-3235	253924080461701	253924	0804617	Dade	Humble 1.1.F, State 1-10	15	11,794	79.6 675 3,797	26 20 13.38	3,809	11,794	X	03-07-65
G-3239	254540080494301	254540	0804945	Dade	Commonwealth Oil No. 1 Wiseheart Street, Board of Education	24.0	11,558	64 89.68 649 3,526 11,557	20 2.88 13.38 9.63 7	11,557	11,558	X	02-01-54
G-3240	254548080463001	254548	0804630	Dade	Gulf Refining State No. 1, Lease 340	18	11,357	154 1,048 5,008 11,340	20 13.38 9.63 7	5,008	11,357	X	04-05-54
G-3242	252704080114801	252704	0801148	Dade	National Park Service, Elliot Key	7.5	1,002	-- 700.75 996.5	14 10 6	996	1,002	X	--
GB-1	252626080222001	252626	0802220	Dade	Florida Power & Light	2.76	1,225	187 1,010	10 6	1,010	1,225	X	03-27-75
HAL-RO1	255918080092201	255918	0800922	Broward	Hallandale reverse osmosis supply well #1	15	1,040	120 340 906	20 12 6	906	1,040	X	06-07-89 1991P
HOL-RO1	260047080104201	260047	0801042	Broward	Hollywood reverse osmosis supply test well #1	13	1,320	120 300 931	24 16 8	931	1,320	X	10-05-89
MAR-I2	261427080130301	261427	0801303	Broward	Margate WWTP injection well #2	12.6	3,204	230 952 1,800 2,552	54 44 34 24	2,552	3,200	X	06-19-84
MAR-M2	261427080130302	261427	0801303	Broward	Margate WWTP monitoring well #2	12.6	1,650	230 1,029 1,600	24 16 6.63	1,029 1,600	1,093 1,650	X	06-19-84
MAR-M1	261256080142301	261424	0801254	Broward	Margate WWTP monitoring well #1 G-2292	12	3,278	312 800 2,030 2,386	20 13.38 3 9.63	1,970	2,300	X	Oct. 1973
MDS-I5	253256080195701	253256	0801957	Dade	Miami-Dade South District WWTP, MDWS-I5	9.4	3,193	134 961 1,794 2,746	48 40 30 20	2,746	3,193	X	10-24-77
MDS-BZ1	263255080195701	253255	0801957	Dade	Miami-Dade So. Dist. WWTP, Boulder Zone monitoring well #1, MDWS-BZ1	9.4	3,110	139 975 2,689 2,689	30 20 6	1,005 1,577 2,434 2,689	1,037 1,664 2,474 2,960	S S S X	02-06-80

Local well identifier	Site identification	Latitude	Longitude	County	Well owner or other local name	AMP (feet)	Well depth (feet)	Bottom of casing (feet)	Outside diameter of casing (inches)	Top of open interval (feet)	Bottom of open interval (feet)	Type of openings	Date at end of construction
MDS-I12	253256080205101	253256	0802051	Dade	Miami-Dade South District WWTP injection well #12	10	3,067	140 980 1,800 2,390	54 44 34 24	2,390	3,067	X	12-28-89
MDS-M3	253256080205102	253256	0802051	Dade	Miami-Dade South District WWTP, monitoring well #3, MDS-FA3	10	1,892	142 981 1,771	20 12.75 6.62	981 1,771	1,050 1,892	X X	10-26-89
MDS-M2	263243080203101	253243	0802031	Dade	Miami-Dade South District WWTP, monitoring well #2, MDWS-FA2	10	1,672	140 980 1,645	20 12 6	980 1,645	1,020 1,672	X X	July 1980
MO-127	250725080243101	250725	0802431	Monroe	USGS, Pennekamp State Park, Key Largo, G-1273	2	1,333	696	6	696	1,259	X	06-24-65
MO-128	251052080220601	251051	0802205	Monroe	Largo Brand Well	11.38	1,205	410 878	12 8.38	878	1,205	X	12-04-74
MO-130	251548080183801	251554	0801835	Monroe	Florida Power & Light well D, Key Largo, S-3002	11.17	1,727	246 760 1,050 1,425	14 8.63 7 5.5	1,050 1,436	1,379 1,714	X X	July 1974
MO-133	251913080165001	251914	0801648	Monroe	Ocean Reef Country Club #1, S-1447	3	1,135	588 899 1,050	6 4 3	1,050	1,135	X	08-27-62 08-15-70P
MO-134	251913080165002	251914	0801648	Monroe	Ocean Reef Country Club #2, S-1447A	3	1,154	60 215 1,049	24 20 12	--	--	--	10-15-71
MO-141	254548080593201	254548	0805932	Monroe	California Time Petroleum, Ivar Axelson	25.4	12,662	--	--	--	--	--	--
NP-100	252255080361101	252255	0803611	Dade	USGS, Everglades National Park	4.5	1,333	620	8	620 --	1,333 --	X --	09-23-64 07-02-65*
PBP-I1	255936080195701	255936	0801957	Broward	Pembroke Pines WWTP injection well #1	10	3,600	120 1,001 2,000 2,950	42 32 26 16	2,950	3,600	X	01-30-87
PBP-M1	255936080195702	255936	0801957	Broward	Pembroke Pines WWTP monitoring well #1	10	2,050	120 1,004 2,000	20 12 6	1,004 2,000	1,081 2,050	X X	12-17-86

Local well identifier	Site identification	Latitude	Longitude	County	Well owner or other local name	AMP (feet)	Well depth (feet)	Bottom of casing (feet)	Outside diameter of casing (inches)	Top of open interval (feet)	Bottom of open interval (feet)	Type of openings	Date at end of construction
PBP-I2	255925080200501	255925	0802005	Broward	Pembroke Pines WWTP injection well #2	10	--	200 1,004 2,281 2,970	52 44 34 24			X	
PLT-I1	260828080141201	260828	0801412	Broward	Plantation North WWTP injection well #1	9.75	3,472	102.5 998 2,297 2,942	54 44 34 24	1,597 2,189 2,942	1,638 2,239 3,472	S S X	06-12-86
PLT-I2	260828080140801	260828	0801408	Broward	Plantation North WWTP injection well #2	8.4	3,502	60 260 1,000 2,300 2,942	64 54 44 34 24	2,942	3,502	X	086-06-90
PLT-M1	260828080140802	260828	0801408	Broward	Plantation North WWTP monitoring well #1	9.25	2,230	260 1,580 2,130	20 12 6	1,580 2,130	1,650 2,230	X X	09-12-90
PLT-ROI1	260739080160801	260739	0801608	Broward	Plantation Central WTP reverse osmosis reject injection well #1	8.52	3,340	--	--	--	--	--	07-27-90
PLT-ROM1	260739080160802	260739	0801608	Broward	Plantation Central WTP reverse osmosis reject monitoring #1	8.5	2,280	--	--	--	--	--	07-31-90
PU-I1	254134080210301	254134	0802103	Dade	Peninsula Utilities Corporation, Sunset Park WWTP injection well #1, I-1	10	2,947	210 545 1,810	26 22 16	545 1,810	1,680 2,950	X X	1969 05-08-90P
PU-I2	254124080245301	254126	0802455	Dade	Peninsula Utilities Corporation, Kendale Lakes WWTP injection well #2, I-2	10	3,200	246 758 2,266	30 24 16	758 2,266	1,742 3,200	X X	1971 06-19-90P
S-125	254717080113001	254717	0801143	Dade	City Ice and Fuel Company	14	1,088	110 730	26 12	730	1,088	X	06-14-25
S-144	254440080125001	254447	0801252	Dade	Deering Estate	14	1,000	1,000	8	925	1,000	X	1916
S-155	254646080094501	254646	0800945	Dade	City of Miami Beach	2.5	1,000	--	8	--	--	--	1919
S-156	254925080073801	254956	0800735	Dade	La Gorce Country Club, Miami Bayshore Company	5	950	885	8	885	950	X	1938
S-158	254731080081701	254731	0800817	Dade	City of Miami Beach	4	1,066	--	8	--	--	--	1916

Local well identifier	Site identification	Latitude	Longitude	County	Well owner or other local name	AMP (feet)	Well depth (feet)	Bottom of casing (feet)	Outside diameter of casing (inches)	Top of open interval (feet)	Bottom of open interval (feet)	Type of openings	Date at end of construction
S-161	254011080180701	254013	0801806	Dade	East Coast Oil Warwick #1	9.91	5,428	410 1,065 3,200 5,400	14 10 8 6	410	1,065	X	1933
S-450	254820080522303	254820	0805223	Dade	Blanchard & Associates, Everglades #2	9	1,280	456 1,280	10 6	1,002 1,200	1,046 1,210	X P	1941
S-479	254820080522301	254820	0805223	Dade	Blanchard & Associates, Everglades #1	17	11,806	137 446 3,237	16 12 8	3,237	10,284	X	06-20-45
S-524	253651080350401	253651	0803504	Dade	Grossman Hammock Well	7.5	1,248	440	12	440	1,248	X	1944 03-07-85P
S-564	255236080081601	255236	0800816	Dade	Indian Creek Country Club	10	955	-- --	8 14	--	--	--	Dec. 1945
S-567	260614080085401	260614	0800854	Broward	Port Everglades oil test well	6	3,010	215 250 2,010	10 12 8	--	--	--	1929 09-25-79P
S-993	254123080103201	254123	0801032	Dade	E.H. Underwood	4	957	--	6	--	--	--	July 1951
S-1354	254140080182001	254130	0801813	Dade	Gay	8.5	1,065	480	6	480	1,065	X	07-09-60 1984P
S-1532	252101080243101	252101	0802431	Dade	Florida Power & Light test well #1, Turkey Point	4.23	1,400	237 872 1,126	36 24 20	1,126	1,400	X	1973
S-1533	252100080242901	252100	0802429	Dade	Florida Power & Light observation well A, Turkey Point	3.13	2,304	239 1,117 1,535 2,100	24 14 8.63 5.5	1,120 1,535 2,100	1,330 1,920 2,304	X X X	1974
S-3001	252058080202501	252058	0802025	Dade	Florida Power & Light research test well	9.7	2,000	156.5 572 995	24 16 9.75	995	2,000	X	Oct. 1972
SUN-I1	260748080201601	260748	0802016	Broward	Sunrise WWTP #3, injection well #1	7.5	3,200	214 1,035 1,790 2,700	54 44 34 24	2,700	3,200	X	01-01-85
SUN-M1	260748080201602	260748	0802016	Broward	Sunrise WWTP #3, monitoring well #1	7.5	1,650	240 1,015 1,600	24 16 6	1,015 1,600	1,108 1,650	X X	11-01-84