Hydrogeology, Ground-Water Movement, and Subsurface Storage in the Floridan Aquifer System in Southern Florida

By FREDERICK W. MEYER

REGIONAL AQUIFER-SYSTEM ANALYSIS—FLORIDAN AQUIFER SYSTEM

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

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

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

Dallas L. Peck
Director

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units, rather than the inch-pound terms used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per foot (ft/ft)	0.3048	meter per meter (m/m)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
mile (mi)	1.609	kilometer (km)
mile per foot (mi/ft)	5.279	kilometer per meter (km/m)
gallon (gal)	3.785	liter (L)
	0.003785	cubic meter (m^3)
gallon per minute (gal/min)	0.00006309	cubic meter per second (m^3/s)
million gallons (Mgal)	3,785	cubic meter (m^3)
billion gallons per year (Ggal/yr)	3,785,000	cubic meter per year (m^3/yr)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
pound per square inch per foot [(lb/in^2)/ft]	22.6214	kilopascal per meter (kPa/m)

A barrel (bbl) contains 42.0 U.S. gallons (gal).
Tritium concentrations in picocuries per liter (pCi/L) can be converted to tritium units (TU) as follows (based on half life of 12.43 years):

$$TU = pCi/L \times 0.313$$

Temperature in degrees Fahrenheit (°F) and temperature in degrees Celsius (°C) are as follows:

$$°F = 1.8 \times °C + 32$$
$$°C = 5/9 \times (°F - 32)$$

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

REGIONAL AQUIFER-SYSTEM ANALYSIS—FLORIDAN AQUIFER SYSTEM

HYDROGEOLOGY, GROUND-WATER MOVEMENT, AND SUBSURFACE STORAGE IN THE FLORIDAN AQUIFER SYSTEM IN SOUTHERN FLORIDA

By FREDERICK W. MEYER

ABSTRACT

The Floridan aquifer system of southern Florida is composed chiefly of carbonate rocks that range in age from early Miocene to Paleocene. The top of the aquifer system in southern Florida generally is at depths ranging from 500 to 1,000 feet, and the average thickness is about 3,000 feet. It is divided into three general hydrogeologic units: (1) the Upper Floridan aquifer, (2) the middle confining unit, and (3) the Lower Floridan aquifer. The Upper Floridan aquifer contains brackish ground water, and the Lower Floridan aquifer contains salty ground water that compares chemically to modern seawater. Zones of high permeability are present in the Upper and Lower Floridan aquifers. A thick, cavernous dolostone in the Lower Floridan aquifer, called the Boulder Zone, is one of the most permeable carbonate units in the world (transmissivity of about 2.5×10^7 feet squared per day). Ground-water movement in the Upper Floridan aquifer is generally southward from the area of highest head in central Florida, eastward to the Straits of Florida, and westward to the Gulf of Mexico.

Distributions of natural isotopes of carbon and uranium generally confirm hydraulic gradients in the Lower Floridan aquifer. Ground-water movement in the Lower Floridan aquifer is inland from the Straits of Florida. The concentration gradients of the carbon and uranium isotopes indicate that the source of cold saltwater in the Lower Floridan aquifer is seawater that has entered through the karst features on the submarine Miami Terrace near Fort Lauderdale. The relative ages of the saltwater suggest that the rate of inland movement is related in part to rising sea level during the Holocene transgression. Isotope, temperature, and salinity anomalies in waters from the Upper Floridan aquifer of southern Florida suggest upwelling of saltwater from the Lower Floridan aquifer. The results of the study support the hypothesis of circulating relatively modern seawater and cast doubt on the theory that the saltwater in the Floridan aquifer system probably is connate or unflushed seawater from high stands of sea level.

The principal use of the Floridan aquifer system in southern Florida is for subsurface storage of liquid waste. The Boulder Zone of the Lower Floridan aquifer is extensively used as a receptacle for injected treated municipal wastewater, oil field brine, and, to a lesser extent, industrial wastewater. Pilot studies indicate a potential for cyclic storage of freshwater in the Upper Floridan aquifer in southern Florida.

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INTRODUCTION

In October 1978, the U.S. Geological Survey began a 4-year (yr) study of the Floridan aquifer system (formerly called the Tertiary limestone aquifer) of the Southeastern United States, as part of a national ground-water resources investigative program called Regional Aquifer-System Analysis (RASA). The objectives of the Florida RASA project were to describe the hydrogeology, geochemistry, and flow of ground water in the aquifer system (Johnston, 1978). Variations in water quality, hydraulic head, and water temperature within the carbonate rocks that make up the Floridan aquifer system in southern Florida suggest that the flow system is complex. Movement of fresh and brackish ground water through the upper part of the Floridan aquifer system has been documented chiefly on the basis of measured head and hydraulic gradients. Movement of saltwater in the lower part, however, has been the subject of speculation because definitive head data are lacking.

Kohout (1965) and Kohout and others (1977) hypothesized inland flow of seawater through the lower part of the Floridan aquifer system on the basis of a temperature anomaly (reversed geothermal gradient) in several deep wells in southern Florida. The driving force, Kohout concluded, was geothermal heat which produced a convection flow cell wherein cold seawater was heated as it flowed inland through the lower part, called the Boulder Zone, then moved upward through vertical

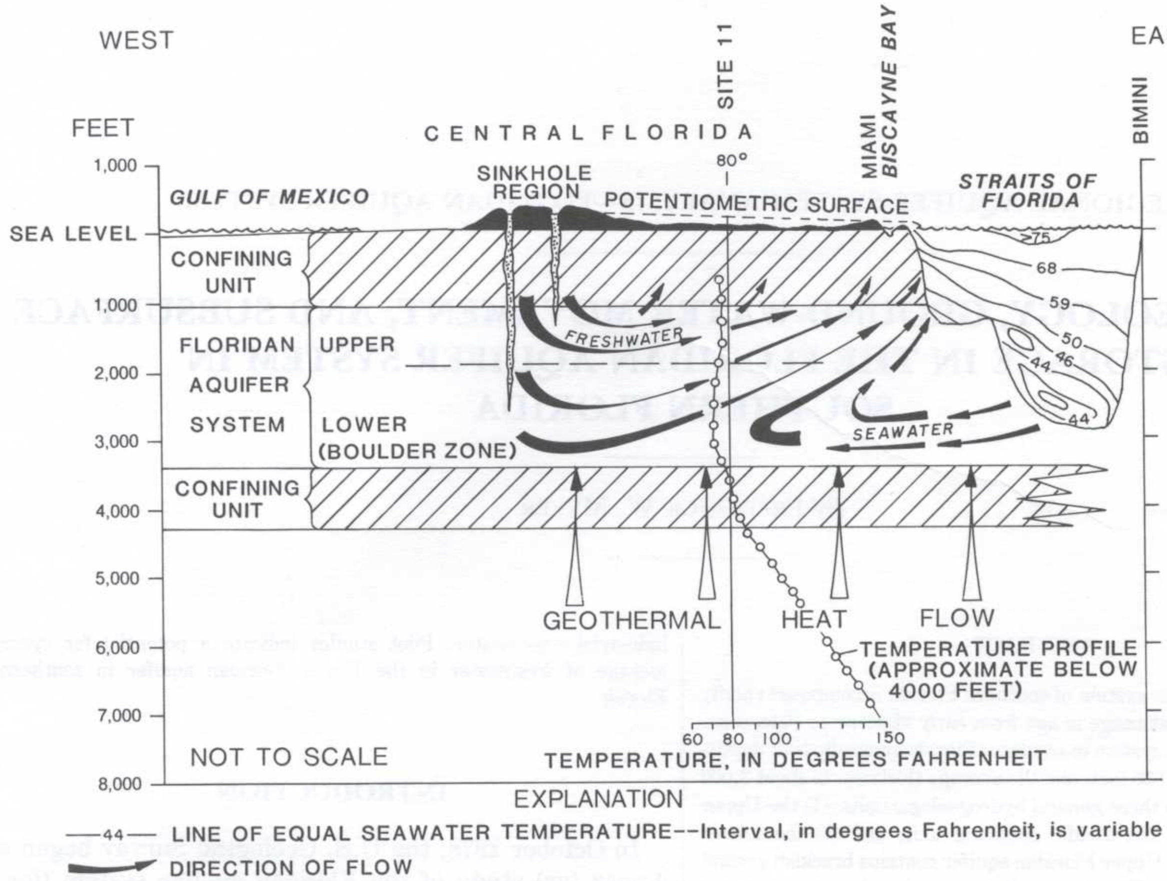

FIGURE 1.—Idealized hydrogeologic cross section through peninsular Florida showing concept of cyclic flow of seawater induced by geothermal heating (proposed by Kohout, 1965). (Location of site 11 shown in fig. 2.)

paths (such as ancient sinkholes) in the overlying confining units and mixed with the seaward-flowing freshwater in the upper part (fig. 1). Opposing views were expressed by Vernon (1970), who suggested that the temperature anomaly was due only to heat conduction, and Sproul (1977), who concluded that existing data were insufficient to support either hypothesis.

A major part of the RASA investigation in southern Florida involved drilling a test well, G–2296, also referred to as the Alligator Alley test well (fig. 2, site 10). About 44 miles (mi) west of Fort Lauderdale, the well was drilled to a depth of 2,811 feet (ft) during 1980–81 to obtain hydrogeologic and hydrochemical data, including selected isotopic analyses, within the Floridan aquifer system. Data from the Alligator Alley test well indicated that carbon-14 might be useful in determining the direction and rate of ground-water movement in the lower saltwater part of the aquifer system—information that would be useful in assessing the long-term effects of deep-well injection. Earlier studies by Osmond and others (1968) suggested that uranium isotopes also could be used to assess ground-water movement. Supplementary data were obtained from deep wells that were drilled by local utilities at Fort Lauderdale, Miami, and Stuart for injection of treated wastewater into the Boulder Zone—a cavernous, highly transmissive dolostone that underlies southeastern Florida at a depth of about 3,000 ft.

Injection of liquid wastes into the saline water of the Boulder Zone as a pollution-control measure was started in 1943 with the injection of brine at an oil field a few miles west of Naples. Subsequently, the practice expanded rapidly, and numerous high-capacity, municipally operated, wastewater injection wells are now in use along the southeastern coast of Florida (Vernon, 1970; Vecchioli and others, 1979; Meyer, 1984). Determination of the direction of ground-water movement in the lower part of the Floridan aquifer system was, therefore, a very necessary and important part of the RASA project in southern Florida.

This report is one of nine chapters in U.S. Geological Survey Professional Paper 1403 that describe various aspects of the geology, hydrology, and geochemistry of the Floridan aquifer system. Those chapters most related to this report (chapter G) include the summary

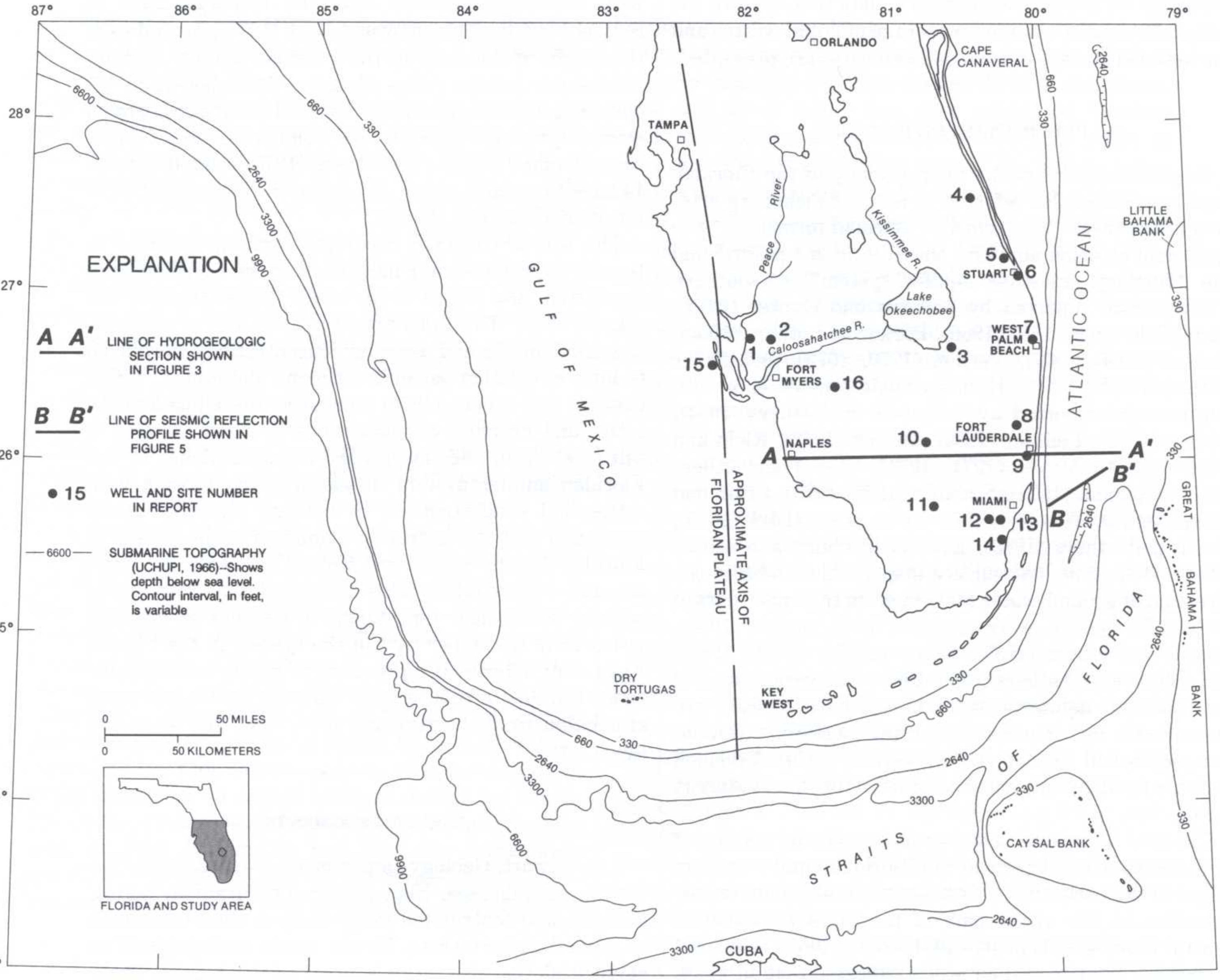

FIGURE 2.—Selected wells, hydrogeologic sections, and submarine topography, south Floridan Plateau.

(chapter A) by Johnston and Bush (1988) and chapters on the hydrogeologic framework (chapter B) by Miller (1986), regional ground-water hydraulics (chapter C) by Bush and Johnston (in press), and ground-water geochemistry (chapter I) by Sprinkle (in press).

PURPOSE AND SCOPE

The purpose of this report is to describe the hydrogeology and, most importantly, the flow in the Floridan aquifer system of southern Florida. To accomplish this, geologic, isotopic, and hydraulic data that would indicate or suggest the rate and direction of the ground-water movement were collected during 1980–83 by the U.S. Geological Survey and others. Included are data on hydraulic head, water temperature, dissolved solids (salinity), and selected isotopes. The natural isotopes used for the study are chiefly carbon-13, carbon-14, uranium-234, and uranium-238. Data were primarily collected from 14 widely distributed deep wells in southern Florida, of which the Alligator Alley test well (fig. 2, site 10) was the most important. Temperature data are presented for 16 wells, isotopic data for 8 wells, and hydraulic data for 2 wells. Also included are selected uranium isotope analyses from 46 wells and 10 springs in central and southern Florida that were compiled from existing reports and files. The ground water in the lower part of the Floridan aquifer system in southern Florida is too saline for most uses; therefore, data that concern the use of the aquifer system for storage of liquid wastes and for seasonal storage of surplus freshwater are presented.

PREVIOUS INVESTIGATIONS

Regional aspects of the hydrogeology of the Floridan aquifer system (also referred to as the "Vicksburg artesian limestones," the "principal artesian formation," the "principal artesian aquifer," the "Floridan aquifer," and the "Tertiary limestone aquifer system") in southern Florida were reported by Sellards and Gunter (1913), Stringfield (1936, 1953, 1966), Parker and others (1955), Kohout (1965, 1967), Vernon (1970, 1973), and Miller (1982a, 1982b, 1986). Hydrogeologic studies of a local nature were reported by Schroeder and others (1954), Bishop (1956), Lichtler (1960), McCoy (1962), Klein and others (1964), Meyer (1971, 1974), Sproul and others (1972), Boggess (1974), Sutcliffe (1975, 1979), Crain and others (1975), Wilson (1977), Reece and others (1980), Smith and others (1982), and Wedderburn and others (1982). Potentiometric surface maps, which indicate the direction of ground-water movement in the upper part of the aquifer system, were compiled by Stringfield (1936), Parker and others (1955), Healy (1975a, 1975b, 1982), and Johnston and others (1980, 1981). The various uses of the Floridan aquifer system in southern Florida are presented by Garcia-Bengochea (1970), Garcia-Bengochea and Vernon (1970), Vernon (1970), Vecchioli and others (1979), Merritt and others (1983), and Merritt (1985).

The use of natural isotopes as tracers in studies of ground-water movement in the Floridan aquifer system began in the early 1960's with estimates of ground-water velocities in the upper part of the aquifer system in central Florida by Hanshaw and others (1965), who used carbon-14. Results of their study indicated that although absolute ages of the ground-water samples may be unreliable, the relative ages of the samples are reasonably reliable for estimating rates and direction of ground-water movement. In a later study of the same area, Plummer (1977) examined transient changes in water chemistry in relation to the earlier carbon-14 ages, and new ages (slightly younger) were assigned to the Hanshaw samples on the basis of mass-transfer reaction coefficients.

Pearson and Bodden (1975, p. 143) reported the first results of carbon-14 analyses of ground water from the Floridan aquifer system in southeastern Florida. The samples were obtained from the upper and middle parts of the aquifer system, and the uncorrected activities of 5.6 and 4.3 percent of modern carbon (PMC) were anomalous compared with Hanshaw's results in central Florida (that is, the samples seemed to become younger with increasing distance from the recharge areas in central Florida). Hanshaw and Back (1971), in studies of the origin of dolomite in the Floridan aquifer system, used stable isotope ratios of carbon-13/carbon-12 ($\delta^{13}C$) and oxygen-18/oxygen-16 ($\delta^{18}O$) to distinguish between marine (primary) dolomite and nonmarine (stoichiometric) dolomite. Tamers and others (1975) related carbon-14 ages to ground-water movement in the surficial aquifer of southeastern Florida.

The use of naturally occurring uranium isotopes as tracers of ground-water movement in the Floridan aquifer system also began in the early 1960's (Osmond and others, 1968). The alpha-activity ratio (AR) of uranium-234/uranium-238 and uranium concentrations were used to infer circulation patterns (Osmond and others, 1968). Cowart and others (1978) compared the alpha-activity ratios and uranium concentrations in three samples of saltwater from the lower part (Boulder Zone) of the Floridan aquifer system in southeastern Florida with ratios and concentrations in modern seawater. They concluded that the saltwater originated in the Straits of Florida, thereby supporting Kohout's hypothesis. Cowart and others (1978) also concluded that low alpha-activity ratios (less than unity) in samples of brackish water from the upper part of the system in the Florida Keys may indicate the presence of highly transmissive zones containing relic waters that are residual of rapid circulation from the recharge area when sea level was much lower.

ACKNOWLEDGMENTS

J.B. Cowart, Geology Department, Florida State University, Tallahassee, Fla., provided all uranium isotope analyses and contributed many ideas on their usefulness as ground-water tracers. He also wrote some pages of an early draft that was a predecessor to this report. Those pages are included in this report in the section on isotopes. The author also thanks the following people, who provided technical assistance and data for the study: J.I. Garcia-Bengochea, C.R. Sproul, and J.D. Lehnen, CH_2M Hill, Inc., Gainesville, Fla.; R.J. Kerrn, Alsay-Pippin Corporation, Lake Worth, Fla.; V.P. Amy and J.A. Wheatley, Geraghty and Miller, Inc., West Palm Beach, Fla.; P.E. Robbinson and P.A. Davis, Hazen and Sawyer, Inc., Hollywood, Fla.; J.R. Peralta, General Development Utilities, Inc., Miami, Fla.; W.R. Mehner, City of Fort Lauderdale, Fla.; Garrett Sloan, Miami-Dade Water and Sewer Authority, Miami, Fla.; E.E. Mitchel, City of Stuart, Fla.; T.M. Missimer, Missimer and Associates, Cape Coral, Fla.; E.L. Fennell and R.T. Mooney, Exxon Company, New Orleans, La.; C.W. Hendry, C.H. Toodle, and E.C. Lane, Florida Bureau of Geology, Tallahassee, Fla.; N. Van Devender and R.L.

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B.H. Lidz, U.S. Geological Survey, Fisher Island Station, Miami Beach, Fla., identified planktonic foraminifers in selected samples of drill cuttings. Conrad Newman, University of North Carolina, Chapel Hill, N.C., provided data on Pleistocene and Holocene sea-level fluctuations. Peter Popenoe, R.P. Freeman-Lynde, and M.M. Ball of the U.S. Geological Survey, Woods Hole Oceanographic Institution, Woods Hole, Mass., provided seismic reflection profiles for the western Straits of Florida. Albert Yang, U.S. Geological Survey, Denver, Colo., and H.G. Ostlund, Director, Tritium Laboratory, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Coral Gables, Fla., supervised the radiocarbon analyses and provided much useful discussion on carbon isotopes during the study. The carbon-14 analyses of water samples from the deep wells at Fort Lauderdale and Port St. Lucie were contributed by the city of Fort Lauderdale and General Development Utilities, Inc., Miami, Fla., respectively.

HYDROGEOLOGY OF SOUTHERN FLORIDA

Southern Florida is underlain by rocks of Cenozoic age to a depth of about 5,000 ft. These rocks are principally carbonates (limestone and dolostone), with minor amounts of evaporites (gypsum and anhydrite) in the lower part and clastics (sand and clay) in the upper part. The movement of ground water from inland areas to the ocean and vice versa occurs principally through the carbonate rocks.

FLORIDAN AQUIFER SYSTEM

Evaporite deposits in the Cedar Keys Formation of Paleocene age probably constitute the lower confining unit, or base of the active flow system (fig. 3). Overlying the evaporites, in ascending order, are limestone and dolostones of the Cedar Keys, Oldsmar, and Avon Park Formations and the Ocala and Suwannee Limestones that make up the Floridan aquifer system, part of which was once called the Floridan aquifer (Parker and others, 1955) and all of which was once called the Tertiary limestone aquifer system (Johnston and others, 1980). In southwest Florida, the lower part of the Tampa Limestone is also included in the Floridan aquifer system.

The Floridan aquifer system is defined in chapter B of this Professional Paper (Miller, 1986) 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 that bound the system above and below. In Florida, the Floridan aquifer system includes rocks ranging from Paleocene to early Miocene age, and locally in southeast Georgia, it includes rocks of Late Cretaceous age. Chapter B presents a detailed geologic description of the Floridan aquifer system, its component aquifers and confining units, and their relation to stratigraphic units. Previous definitions of the term "Floridan" and superseded terms are also discussed in chapter B (Miller, 1986).

Overlying the Floridan are alternating beds of sand, clay, marl, and limestone in the Tampa Limestone and Hawthorn Formation (both of Miocene age) that contain intermediate artesian aquifers and make up the upper confining unit for the Floridan aquifer system. In southeastern Florida, clay in the Tamiami Formation of Pliocene age is included in the upper confining unit. Overlying these deposits are limestones and sands of the Tamiami Formation and of undifferentiated Pleistocene deposits that make up the surficial aquifer and contain unconfined ground water.

Ground water in the Floridan aquifer system in southern Florida is generally too saline for most uses. The Lower Floridan aquifer contains ground water that is similar in composition to seawater and is chiefly used as a receptacle for injected liquid wastes; the Upper Floridan aquifer contains brackish water and is chiefly used as a source of limited industrial amd agricultural supply and for feedwater to desalting plants. Pilot studies indicate that the upper part of the Floridan aquifer system in southern Florida can be used for seasonal storage of surplus freshwater (Merritt and others, 1983). Limestone aquifers in Miocene deposits, as parts of the upper confining unit, are important local sources of ground water for supply in parts of southwestern Florida. However, the surficial aquifer generally is the major source of potable water in southern Florida. In southeastern Florida, the surficial aquifer is called the Biscayne aquifer (Parker and others, 1955; Schroeder and others, 1958), and in southwestern Florida, it is called the "shallow aquifer" (McCoy, 1962). The hydrogeology of southern

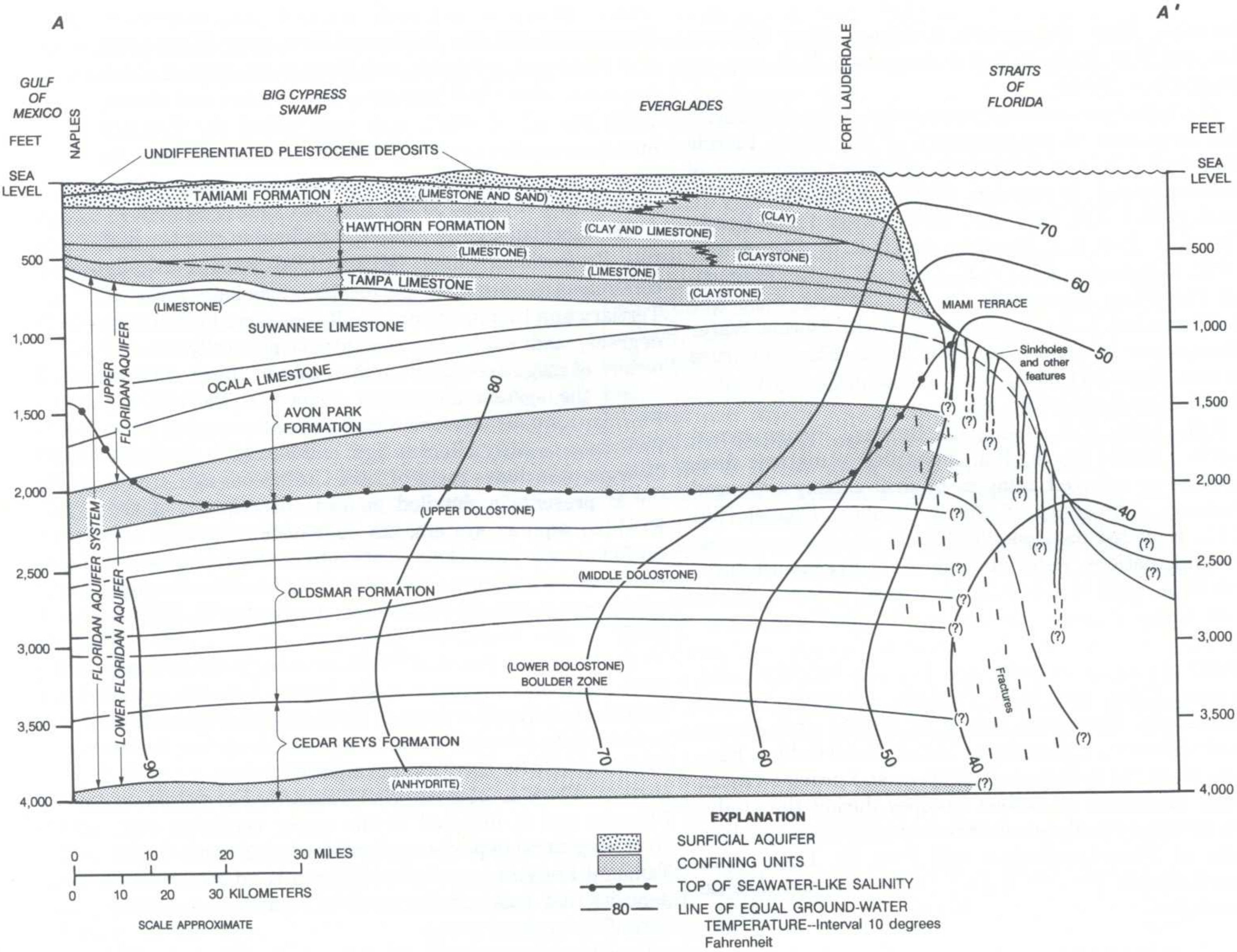

FIGURE 3.—Generalized hydrogeologic section *A-A'* through southern Florida showing isotherms and top of saltwater in the Floridan aquifer system. (Line of section shown in fig. 2.)

Florida, as described here, is based largely on data collected from an exploratory test well (Alligator Alley test well; fig. 2, site 10) that was drilled near the center of the Everglades and from test wells that were drilled in Collier County by the South Florida Water Management District.

In southeastern Florida, the Floridan aquifer system includes (from shallowest to deepest) all or part of the Suwannee Limestone of Oligocene age, the Ocala Limestone of late Eocene age, the Avon Park Formation of middle Eocene age, the Oldsmar Formation of early Eocene age, and the upper part of the Cedar Keys Formation of Paleocene age (fig. 3). In southwestern Florida, it locally includes the lower part of the Tampa Limestone of early Miocene age.

Some investigators place the top of the Floridan aquifer system in the lower part of the Hawthorn Formation of middle Miocene age wherever it contains permeable limestone hydraulically connected to deeper layers (Parker and others, 1955; Stringfield, 1966). Using regional criteria based largely on lithologic changes in the rocks, Miller (1986) placed the top of the Floridan aquifer system at or near the top of the Suwannee Limestone in southwestern Florida and at or near the base of the Suwannee Limestone in southeastern Florida. The top of the Floridan aquifer system, as used in this report, ranges from about 500 to 1,000 ft in depth. The base of the Floridan aquifer system (the lowest confining unit) generally coincides with the top of evaporite beds in the Cedar Keys Formation (Miller, 1986), and it ranges from about 3,500 to 4,100 ft in depth.

The rocks that make up the Floridan aquifer system vary greatly in permeability so that the system resembles a "layer cake" composed of many alternating zones of low and high permeability. Crossflow (vertical flow) between permeable zones probably occurs through sinkholes and fractures. However, the amount of crossflow is probably small compared with the amount of horizontal flow. The zones of highest permeability generally are at or near unconformities and are generally parallel to bedding planes.

The temperature of ground water in the Floridan aquifer system in areas near the southeastern coast generally decreases with increasing depth; however, anomalies frequently occur, probably owing to local upwelling through fractures and sinkholes (a phenomenon that is discussed later in the report). Ground-water temperatures are generally coolest along the southeast coast, where the temperature of seawater in the adjacent Straits of Florida is the lowest. Ground-water salinity is generally highest in coastal parts of southern Florida and in the lower part of the aquifer system owing to inland circulation of seawater.

In southern Florida, the Floridan aquifer system can generally be divided—largely on the basis of the geology, hydrochemistry, and hydraulics interpreted from data obtained at the Alligator Alley test well (fig. 2, site 10)—into three hydrogeologic units, as follows:

1. The Upper Floridan aquifer, which contains brackish ground water. The specific conductance of the ground water ranges from about 2,500 to 25,000 microsiemens per centimeter (μS/cm) at 78 °F (25 °C) and averages about 5,000 μS/cm.
2. The middle confining unit, which contains salty ground water. The specific conductance of the ground water ranges from about 35,000 to 37,000 μS/cm and averages about 36,000 μS/cm.
3. The Lower Floridan aquifer, which contains ground water that is similar in composition to seawater. The specific conductance of the ground water ranges from about 43,000 to 50,000 μS/cm and averages 49,000 μS/cm.

UPPER FLORIDAN AQUIFER

The Upper Floridan aquifer in southern Florida chiefly consists of permeable zones in the Tampa, Suwannee, and Ocala Limestones and in the upper part of the Avon Park Formation. On the basis of aquifer tests and a regional flow model, the transmissivity is estimated to range from 10,000 to 60,000 feet squared per day (ft^2/d) (Bush and Johnston, in press). The contained ground water is brackish. The salinity of the ground water generally increases with increasing depth and with distance downgradient and southward from central Florida. Ground-water temperatures also generally increase downgradient and southward from the recharge area in central Florida. However, temperatures along the southeastern coast are lowest (about 70.0 °F) owing to heat transfer to the Atlantic Ocean (Straits of Florida) (Sproul, 1977, p. 75) and (or) to heat transfer to cooler saltwater in the Lower Floridan aquifer (Kohout, 1965). Temperature and salinity anomalies that are related to upwelling ground water from the Lower Floridan aquifer are discussed later in this report.

Water movement is chiefly lateral through highly permeable zones of dissolution at or near the top of each formation. Ground-water movement in May 1980 was generally southward from the area of highest head near Polk City in central Florida to the Gulf of Mexico and to the Atlantic Ocean (fig. 4). The area of highest freshwater head is herein referred to as the "Polk City high." Prior to development (late 1800's or early 1900's), the head in south Florida probably was 5 to 10 ft higher than at present. As water use increased and wells were drilled in the area north of Lake Okeechobee, water levels were lowered and a saddle formed in the potentiometric surface, as shown by the close spacing of the 40- to 70-ft contours toward the center of the peninsula. Hydraulic gradients in southern Florida were reduced, resulting in a decrease of natural discharge by submarine springs along the southeastern coast and the movement of seawater inland to a new position of equilibrium.

The concave shape of the contours on the 1980 potentiometric surface map along the southeastern coast indicates convergence of flow toward the submerged karst on the Miami Terrace between Fort Lauderdale and Miami. Ground-water discharge in this area is also suggested by computer flow modeling as described by Bush and Johnston (in press). The rugged topography of the submarine terrace was formed by the collapse of solution features (sinkholes) in the underlying limestone. A seismic reflection profile (fig. 5) across the Miami Terrace shows the pinnacles and troughs associated with the submerged karst and the northward-prograding sediments of Miocene through Pleistocene age unconformably overlying the Suwannee Limestone. Currents and perhaps upwelling freshwater from submarine springs are probably responsible for the lack of sediment on the terrace and terrace slope. Malloy and Hurley (1970) reported that rock samples from dredge hauls on the Miami Terrace by the University of Miami's Institute of Marine Science (now the Rosenstiel School of Marine and Atmospheric Sciences) indicated that the ocean floor is

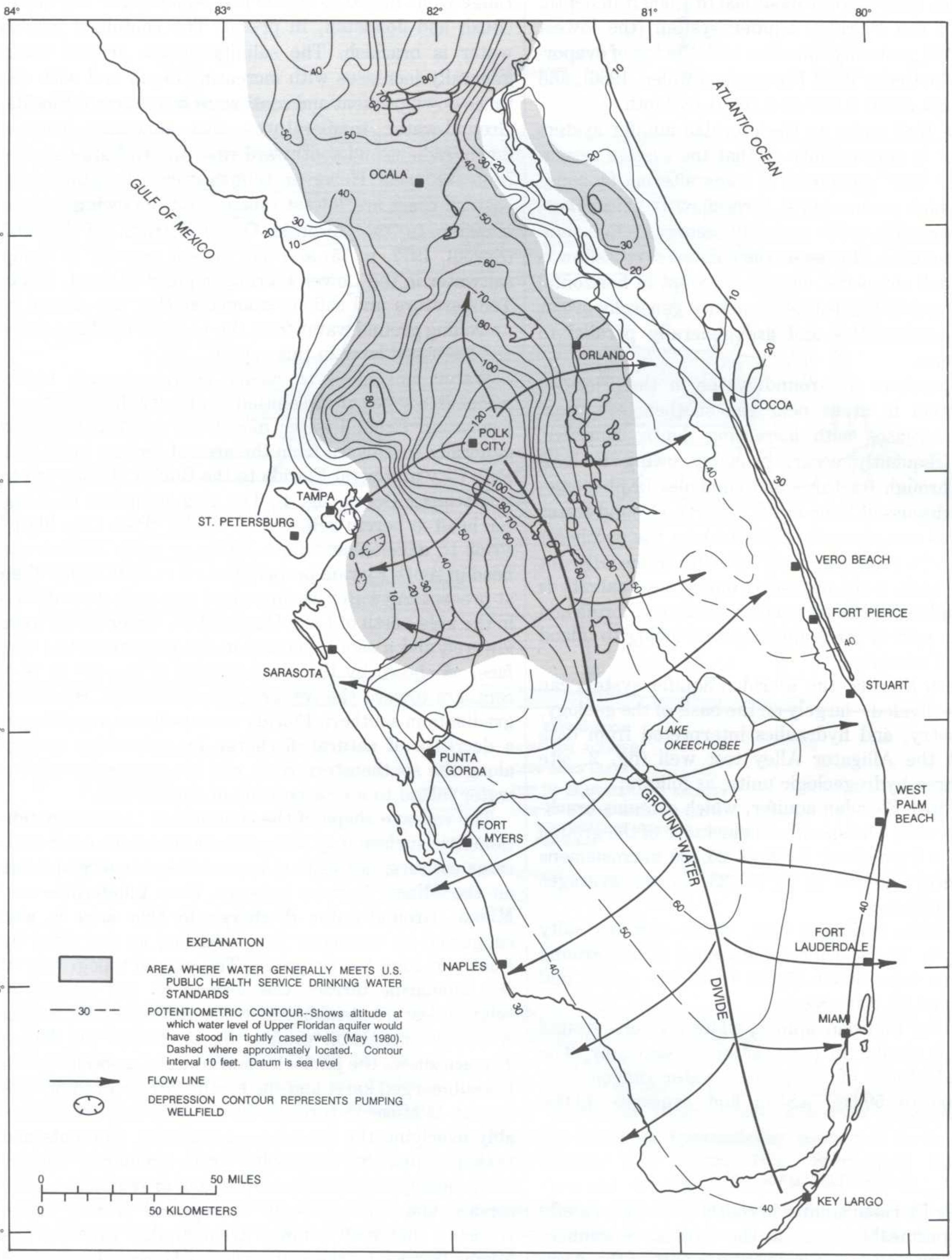

FIGURE 4.—Potentiometric surface of peninsular Florida in May 1980 and the area of potable ground water, Upper Floridan aquifer (revised from Johnston and others, 1981, and Healy, 1982).

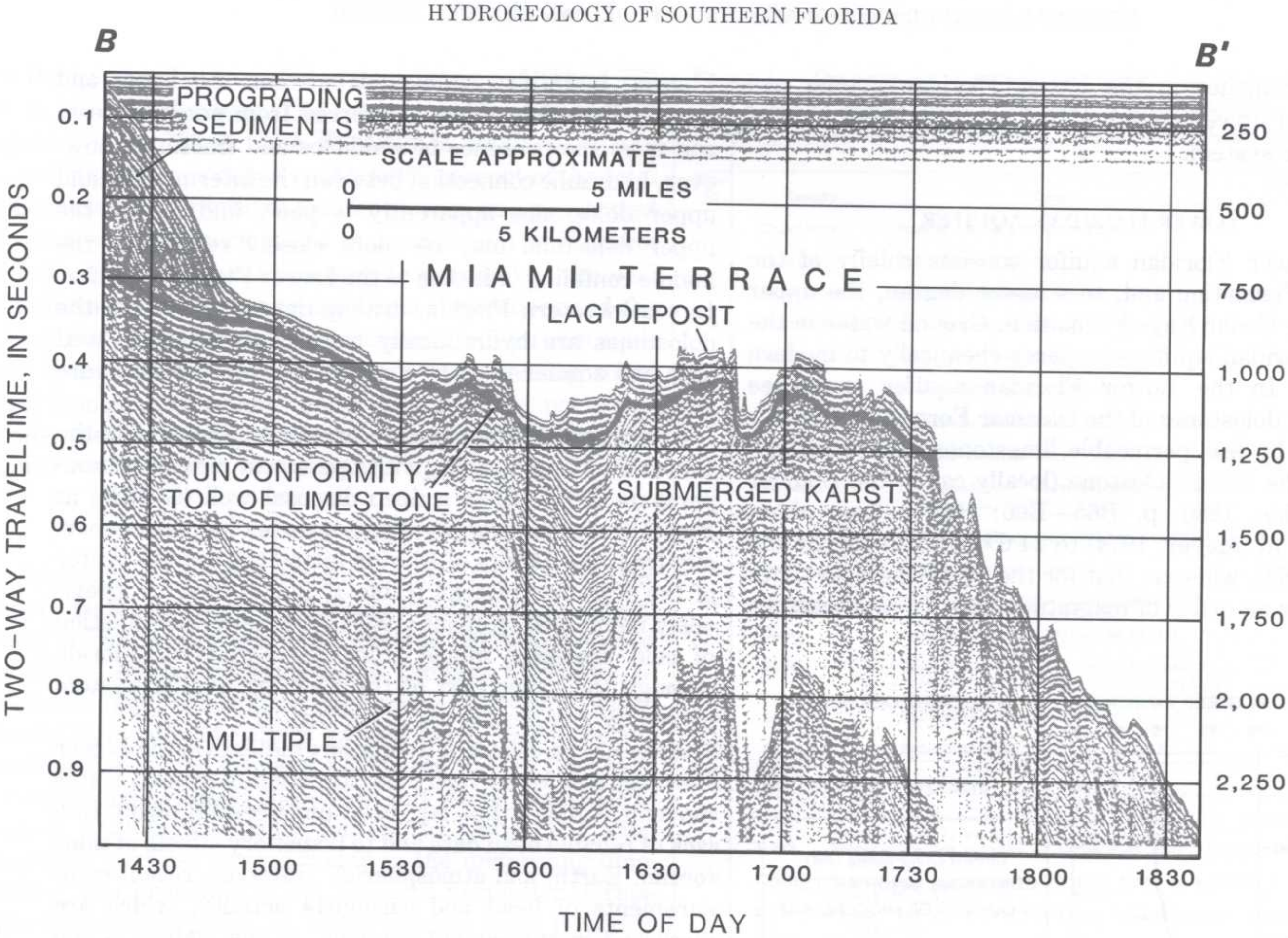

FIGURE 5.—Seismic reflection profile *B-B'* in the western Straits of Florida showing submarine karst on the Miami Terrace. (Line of section shown in fig. 2.)

composed of fossiliferous phosphatic limestone that contains numerous foraminifers, chiefly *Miogypsina* sp., *Globigerina* sp., miliolids, and rotalids. Rock samples from equivalent depths in artesian wells at Miami and Fort Lauderdale contain the same fossil assemblages and are identified as the Suwannee Limestone of Oligocene age.

Sinkholes on the Miami Terrace are both filled and unfilled. Those that are unfilled probably are active submarine springs. The large filled sinkhole in the center of the seismic profile (fig. 5) is about 2 mi wide and may be related to the collapse in the highly cavernous dolostone (the Boulder Zone) in the lower part of the Oldsmar Formation. The Boulder Zone is discussed by Miller (1986, p. B65–B66). Sinkholes generally are present throughout Florida and are prominent in central Florida as chains of sinkhole lakes. The sinkholes are chiefly in Tertiary limestones along joints or fractures that trend generally northwestward to southeastward (and to a lesser extent southwestward to northeastward). Sinkholes in southern Florida are virtually obscured because they are filled by deposits that are Miocene or younger in age. Their presence, however, is often indicated by drilling and by local salinity or temperature anomalies.

MIDDLE CONFINING UNIT

The middle confining unit of the Floridan aquifer system consists chiefly of the lower part of the Avon Park Formation but locally includes the upper part of the Oldsmar Formation. The unit has relatively low permeability, and it generally separates the Upper Floridan aquifer, containing brackish ground water, from the Lower Floridan aquifer, containing ground water that compares closely to seawater. Hydraulic connection between the upper and lower aquifer is inferred from sinkholes and fractures that transect the middle confining unit. Ground-water movement in southern Florida is estimated to be chiefly upward from the Lower Floridan aquifer through the middle confining unit, then horizontally toward the ocean through the Upper Floridan aquifer. Salinity varies greatly at the top of the middle confining unit as the upward-moving saltwater is blended with the seaward-flowing freshwater in the Upper Floridan aquifer. As previously stated, temperature and salinity anomalies in the Upper Floridan aquifer are evidence of upwelling saltwater from the lower part of the aquifer system.

LOWER FLORIDAN AQUIFER

The Lower Floridan aquifer consists chiefly of the Oldsmar Formation and, to a lesser degree, the upper part of the Cedar Keys Formation. Ground water in the Lower Floridan aquifer compares chemically to modern seawater. In the Lower Floridan aquifer are three permeable dolostones of the Oldsmar Formation that are separated by less permeable limestones. The transmissivity of the lower dolostone (locally called the Boulder Zone; Miller, 1986, p. B65—B66) ranges from about 3.2×10^6 ft^2/d (Meyer, 1974) to 24.6×10^6 ft^2/d (Singh and others, 1983), whereas that for the overlying dolostones is probably an order of magnitude less. In southeastern Florida, hydraulic connection between the lower and intermediate dolostones is inferred from pumping tests and from the presence of sinkholes and fractures; however, hydraulic connection between the intermediate and upper dolostones apparently is poor, and locally the upper dolostone may be more closely related to the middle confining unit than to the Lower Floridan aquifer. In southwestern Florida, drilling data suggest that the dolostones are hydraulically connected, although head data and aquifer tests to confirm this interpretation are lacking.

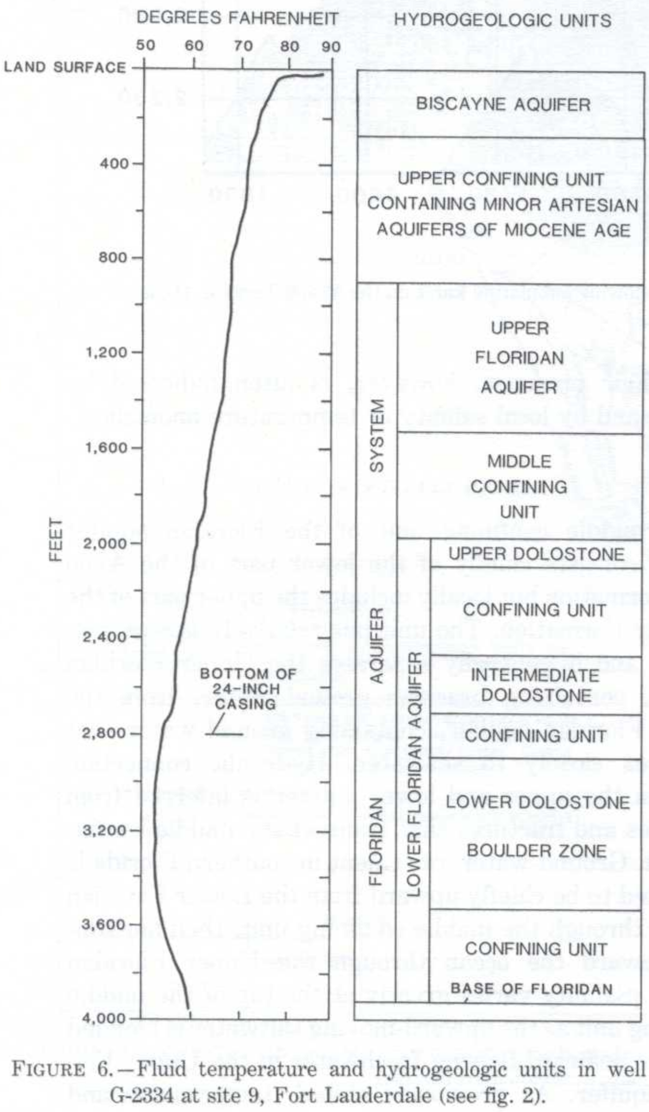

FIGURE 6.—Fluid temperature and hydrogeologic units in well G-2334 at site 9, Fort Lauderdale (see fig. 2).

A pronounced temperature anomaly is present in the Lower Floridan aquifer, with the lowest measured temperature (50.5 °F) in a deep disposal well (G–2334) at Fort Lauderdale (fig. 6). Temperatures increase generally from the Straits of Florida inland toward the center of the Floridan Plateau (table 1, fig. 7), and, as previously mentioned, Kohout (1965) hypothesized circulation of cold seawater inland from the Straits of Florida through the lower part of the Floridan aquifer system driven by geothermal heat flow (fig. 1).

Attempts to calculate hydraulic gradients in the Lower Floridan aquifer to verify the direction of ground-water movement have, thus far, been unsuccessful owing to a lack of reliable head data and to transitory effects of tides (ocean, Earth, and atmospheric). However, recent measurements of head and carbon-14 activity, which are discussed in subsequent sections, in the waters of the Boulder Zone at site 9 (fig. 2) in well G–2334 and at site 10 (fig. 2) in well G–2296 substantiate the Kohout hypothesis.

HYDROGEOLOGY AT THE ALLIGATOR ALLEY TEST WELL SITE

A 2,811-ft-deep test well (Well G–2296) was drilled in 1980 during this RASA study in the Everglades of southern Florida along Alligator Alley (Interstate 75) at a point between Naples and Fort Lauderdale (fig. 2, site 10). A steel casing 16-inches (in) in diameter was installed with cement grout from land surface to a depth of 895 ft, below which a nominal 8-in-diameter hole was drilled to a depth of 2,811 ft (fig. 8). A 2-in-diameter steel monitor tube with perforations from 811 to 816 ft was grouted with cement in the outer annulus. Hydraulic packers were used to isolate selected zones in the well to collect samples of ground water and measure water levels.

The well penetrated the surficial and intermediate aquifer systems and extended into the Floridan aquifer system (fig. 9). The surficial aquifer system is about 180 ft thick and is composed chiefly of sandy limestone of the Tamiami Formation of Pliocene age. Three artesian limestone aquifers and related confining beds are present in the intermediate aquifer system between 180 and 770 ft in Miocene deposits. The top of the Floridan aquifer system is at 770 ft. The Floridan is confined by the overlying Miocene deposits. About 67 percent of the total thickness of the Floridan aquifer system was penetrated by the well. The formations that make up the Floridan aquifer system (from shallowest to deepest) at the well site include the Suwannee and Ocala Limestones and the Avon Park and Oldsmar Formations. The Floridan aquifer system is composed of several water-bearing zones and associated confining units. The well did not penetrate the Cedar Keys Formation, which contains the lower confining unit of the aquifer system.

SURFICIAL AQUIFER SYSTEM

The surficial aquifer system is about 180 ft thick; the upper 60 ft is composed of unconsolidated shelly, quartz sand of Pleistocene age, and the lower 120 ft is composed of sandy, shelly limestone of the Tamiami Formation of Pliocene age. Phosphate containing uranium, which emits high rates of natural gamma rays, marks the top and bottom of the Tamiami Formation (fig. 8). The sand is chiefly fine grained and yields only small quantities of water with high organic content to wells. The sand partially confines ground water in the underlying limestone. The limestone in the Tamiami Formation is relatively permeable (fig. 9, water-bearing zone 1) and is capable of yielding large quantities of potable freshwater. In 1982, a sample of ground water from a zone between 50 and 150 ft in depth in a shallow test well (G–2329) near the Alligator Alley test well had a chloride concentration of 120 milligrams per liter (mg/L) and a specific conductance of about 1,000 μS/cm (J.E. Fish, U.S. Geological Survey, oral commun., 1983).

INTERMEDIATE AQUIFER SYSTEM

The intermediate aquifer system is about 590 ft thick and is composed of three confined limestones (fig. 9, water-bearing zones 1 through 3) of Miocene age. Water-bearing zone 1, the upper intermediate aquifer, ranges in depth from about 220 to 360 ft and is composed of thinly bedded, gray, shelly limestone and interbedded sand and clay in the upper part of the Hawthorn Formation of middle Miocene age. The hydraulic and water-quality characteristics were not determined from the test well, but the rock type suggests that small quantities of brackish water (less than 1,000 gallons per minute; gal/min) can be obtained by wells that tap the entire thickness. Water-quality data are not locally available, but potable water is known to be present in equivalent rocks in parts of Charlotte and Lee Counties on the Gulf Coast, west of Lake Okeechobee. Zone 1 is confined above by a thick and extensive bed of silty, green clay of late Miocene age and below by a thick and extensive bed of green, micaceous clay of middle Miocene age.

TABLE 1.—*Temperatures of salty ground water in selected wells that tap the Boulder Zone of the Lower Floridan aquifer*

[WWTP, wastewater-treatment plant. Site locations shown in fig. 2]

Site No.	County	Owner	Temperature °F
1	Charlotte	Humble-Lowndes-Treadwell No. 1	96.0
2	Charlotte	Gulf-Stevens No. 1	100.0
3	Palm Beach	Quaker Oats injection well 4	79.3
4	Indian River	Hercules injection well 1	89.6
5	St. Lucie	South Port WWTP injection well 1	72.1
6	Martin	Stuart WWTP injection well 1	70.6
7	Palm Beach	West Palm Beach WWTP injection well 2	60.8
8	Broward	Margate monitor well	59.0
9	Broward	Fort Lauderdale Port Everglades WWTP injection well 1.	50.5
10	Broward	Alligator Alley test well	76.1
11	Dade	Gulf-State Lease 340 No. 1	74.0
12	Dade	Kendale Lakes WWTP injection well 1	61.3
13	Dade	Sunset Park WWTP injection well 1	60.5
14	Dade	Miami-Dade Water and Sewer Authority South District WWTP injection well 1.	60.6
15	Lee	California-Coastal 224B-1	108.8
16	Collier	Sun-Collier No. 1	97.0

Site No.	Depth (feet)	Remarks
1	1,641	Slightly above Boulder Zone. Local well CH-57. Kohout and others (1977, p. 21).
2	3,245	Temperature log appears to be on cool side. Kohout and others (1977, p. 18).
3	2,794	Temperature log shows 79.3°F from 2,794 to 3,208 feet. Local well PB-1142.
4	2,735	Packer test 2,735 to 3,015 feet. Pumped sample. Source, CH_2M Hill, Inc.
5	3,180	Temperature log shows 72.0°F from 3,180 to 3,424 feet. Source, CH_2M Hill, Inc. Local well STL-254.
6	3,290	Temperature log shows coolest from 3,140 to 3,290 feet. Source, CH_2M Hill, Inc. Local well M-1034.
7	3,250	Pumped sample. Open hole 3,025 to 3,680 feet. Local well G-2292.
8	3,070	Pumped sample. Open hole 2,457 to 3,301 feet. Local well G-2292.
9	2,920	Temperature log. Cold seawater 2,920 to 3,430 feet. Local well G-2332. Source, Geraghty and Miller, Inc.
10	2,811	Temperature log. Bottom of hole at 2,811 feet. Local well G-2296.
11	3,100	Temperature log. Kohout and others (1977, p. 20). Local well G-3236.
12	3,000	Temperature log. Source, Florida Bureau of Geology. Zone 3,000 to 3,160 feet. Local well I-2.
13	2,944	Temperature log. Source, Florida Bureau of Geology. Local well I-1.
14	2,975	Temperature log. Source, CH_2M Hill, Inc. Zone 2,975 to 3,130 feet. Local well MDSWI-1.
15	2,800	Temperature log. Kohout and others (1977, p. 20).
16	3,000	Temperature log. Kohout and others (1977, p. 20). Local well G-415.

Water-bearing zone 2 ranges in depth from about 460 to 530 ft at the test well site and is composed chiefly of sandy, shelly limestone in the lower part of the Hawthorn Formation of middle Miocene age. The hydraulic and water-quality characteristics of zone 2 were not determined from the test well, but the rock type is comparable to an aquifer in north-central Collier County (McCoy, 1962, p. 18) that in 1959 produced artesian water having a chloride concentration of 985 mg/L and a

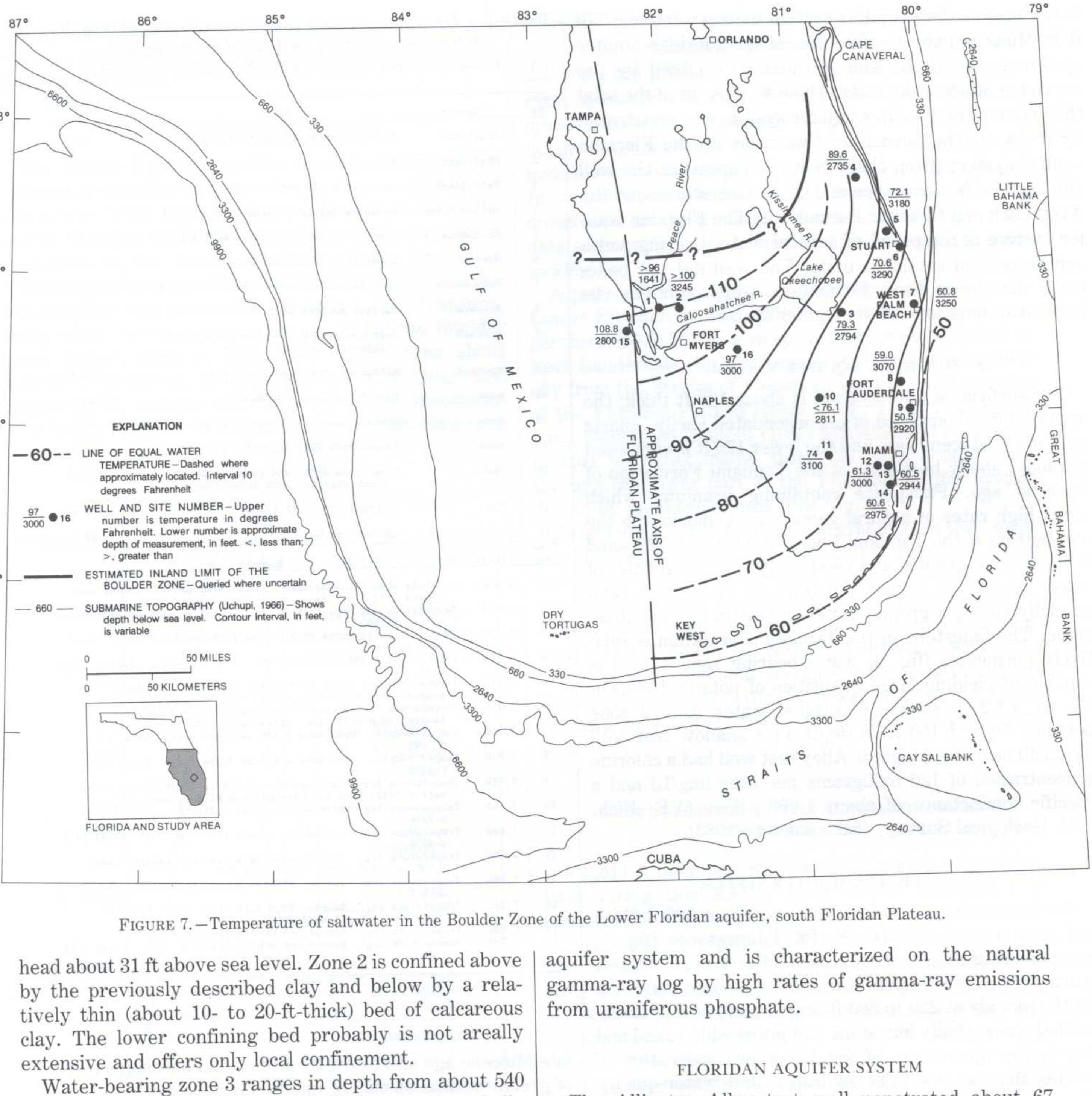

FIGURE 7.—Temperature of saltwater in the Boulder Zone of the Lower Floridan aquifer, south Floridan Plateau.

head about 31 ft above sea level. Zone 2 is confined above by the previously described clay and below by a relatively thin (about 10- to 20-ft-thick) bed of calcareous clay. The lower confining bed probably is not areally extensive and offers only local confinement.

Water-bearing zone 3 ranges in depth from about 540 to 600 ft and is composed of slightly sandy, shelly limestone of the Tampa Limestone of early Miocene age. The hydraulic and water-quality characteristics of zone 3 were not determined from the test well, but the rock type suggests that they are similar to those of the overlying aquifer (zone 2). Zone 3 is confined above by a thin, calcareous clay at the base of zone 2 and below by calcareous clay of early Miocene age. The lower bed of clay is the principal confining unit above the Floridan aquifer system and is characterized on the natural gamma-ray log by high rates of gamma-ray emissions from uraniferous phosphate.

FLORIDAN AQUIFER SYSTEM

The Alligator Alley test well penetrated about 67 percent of the estimated thickness of the Floridan aquifer system in southern Florida. The top of the Floridan aquifer system in this test well is considered to coincide with the top of the Suwannee Limestone of Oligocene age at 770 ft (fig. 9), on the basis of hydraulic head and water chemistry data. Miller (1986), in describing the regional hydrogeologic framework of the Floridan, placed the top of the Floridan at about 950 ft at this test well on the

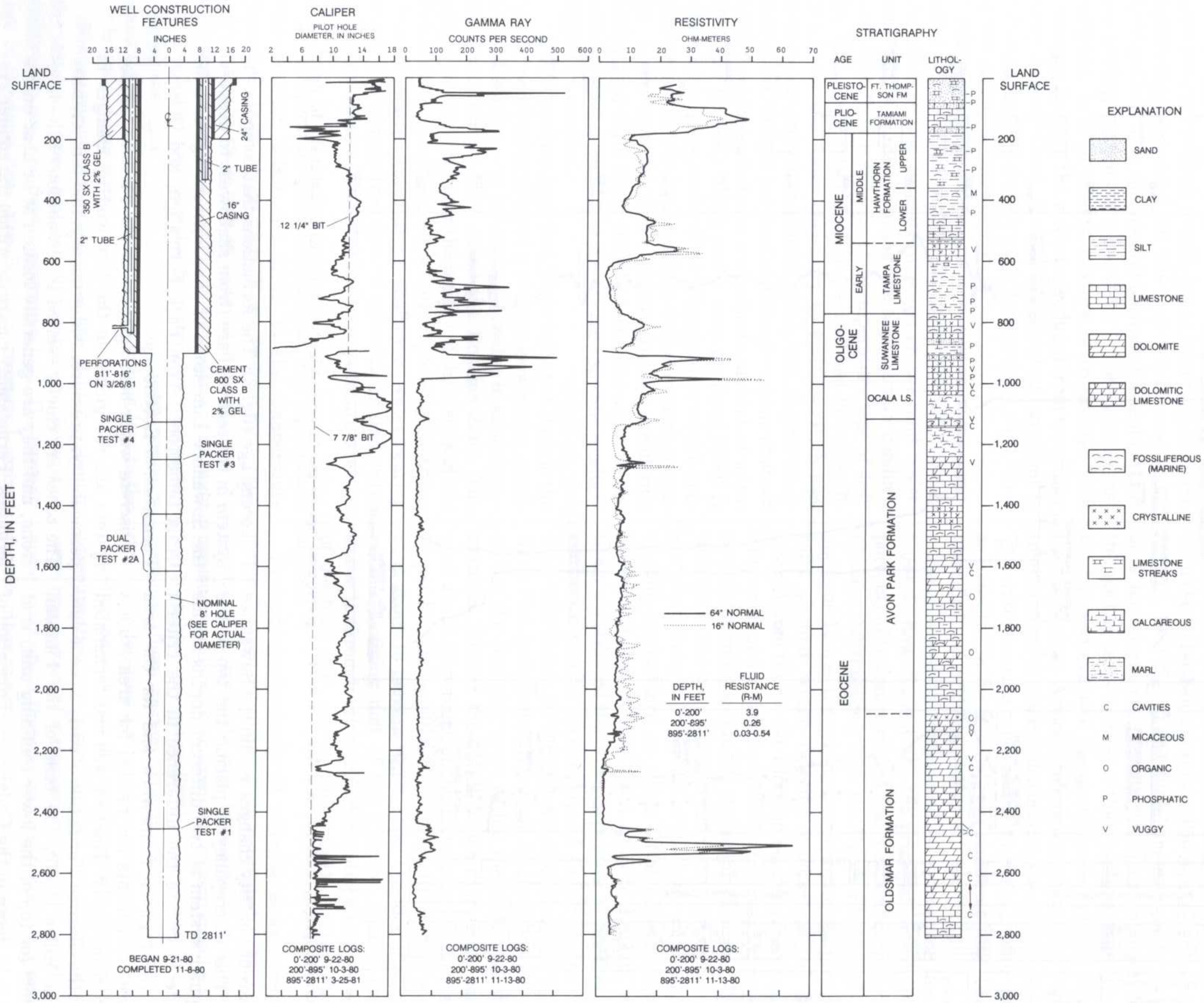

FIGURE 8.—Construction features, selected geophysical logs, and stratigraphy for the Alligator Alley test well (well G-2296 at site 10, fig. 2).

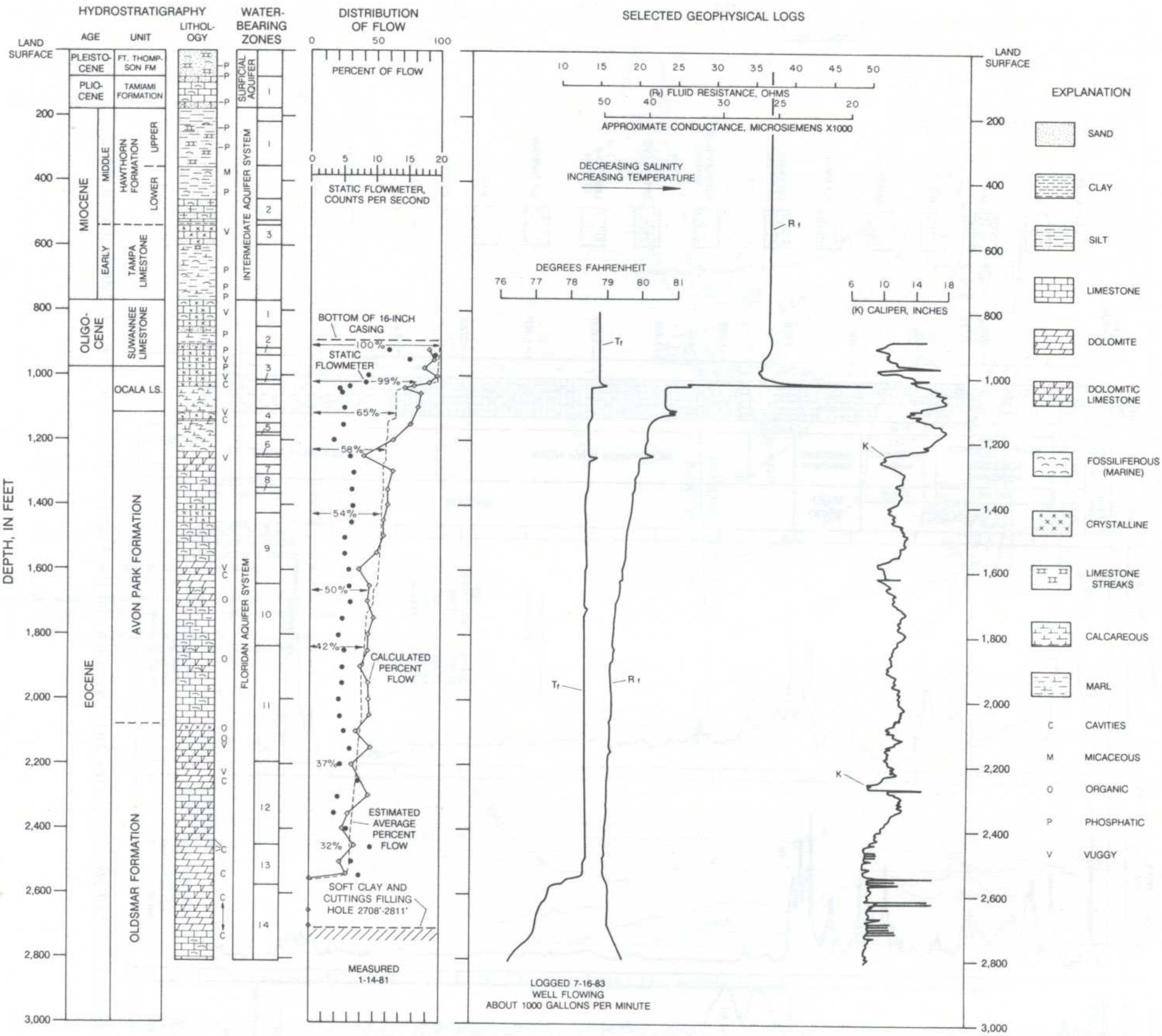

FIGURE 9.—Hydrostratigraphy, distribution of flow, and selected geophysical logs for the Alligator Alley test well (well G-2296 at site 10, fig. 2).

basis of apparent porosity changes within the Suwannee Limestone. This discrepancy of placing the top of the Floridan aquifer system at two different depths at this test well site is due to the difference in the criteria defined for the regional framework and for the area studies; more refinements are needed for area studies than for a regional study. The test well was terminated at 2,811 ft in the Oldsmar Formation of early Eocene age. According to Miller (1986), the base of the Floridan aquifer system (or top of the lower confining unit) is at about 3,800 ft in depth in the Cedar Keys Formation of Paleocene age (fig. 3). The formations that compose the system in the test well are (from shallowest to deepest) the Suwannee Limestone of late Oligocene age and the Ocala Limestone, Avon Park Formation, and Oldsmar Formation of Eocene age.

Discrete water-bearing zones in the Floridan aquifer system are recognized in the test well by changes in permeability, pressure, water quality, and temperature. The zones are chiefly related to dissolution of the limestone, and they are generally located at or near unconformities. Permeability contrasts within the aquifer system suggest that locally, and perhaps regionally, some of the major water-bearing zones act as distinct aquifers (fig. 9, zones 3 and 13).

Although the 16-in casing penetrated most of the Suwannee Limestone, a 2-in monitor tube with perforations from 811 to 816 ft provided data from the part of the aquifer that was cased off. The test well flows at about 1,000 gal/min from the interval between 895 and 2,811 ft and produces a blend of saline water (25,500 μS/cm) that compares to a 50-percent mixture of freshwater with seawater. Most of the water is produced from two major water-bearing zones. A reverse geothermal gradient is indicated, and the coolest water temperature (76.1 °F) is at the bottom of the well (fig. 9).

Fluid resistance and temperature logs show the cumulative effects of inflow from the water-bearing zones in the borehole (fig. 9). Superimposed on the fluid resistance logs is a scale showing the approximate conductance. The fluid resistance and temperature logs of July 16, 1983, were obtained after the well had flowed sufficiently for the water chemistry to stabilize. Both logs indicate several water-bearing zones, but, as previously mentioned, two are the most significant—a zone at about 1,030 ft which contributes a significant amount of warm (79.2 °F) brackish water and a zone at about 2,560 ft which contributes cooler (77.1 °F) saltwater whose specific conductance is comparable to that of modern seawater. According to the fluid resistance log, the cumulative conductance of all water-bearing zones was about 26,000 μS/cm, which is similar to the average specific conductance of 14 samples.

All temperature logs that were collected during the drilling and testing showed a reverse geothermal gradient that is related to the cooler saltwater in an underlying water-bearing zone called the Boulder Zone. The coldest temperature is at the bottom of the well, and the flow becomes progressively warmer uphole by contributions of warm water from shallower water-bearing zones. The cumulative effect of inflowing ground water uphole produces a blend that has a temperature of about 78.8 °F.

The temperature and fluid resistance logs (fig. 9) show that between 2,560 and 2,811 ft the temperature decreased from about 78.3 °F to 76.7 °F and that, concomitantly, there was an increase in resistivity. The temperature decrease is probably related to a very slight upward flow of cool saltwater from the lowermost water-bearing zone (the Boulder Zone) that probably occurs at about 2,900 ft (Meyer, 1974, 1984) or to heat loss to the cooler underlying zone.

Water-bearing zones of the Floridan aquifer system in the test well were identified primarily from flowmeter, fluid resistance, and fluid temperature logs. The percentage of the total flow (the discharge measured at land surface) was calculated at about 50-ft intervals from point velocities on the flowmeter log and from the hole diameter as derived from the caliper log. The flowmeter-caliper calculations were supplemented by calculations based on the contributions (blending) of inflowing water from the water-bearing zones. The fluid resistance log of July 16, 1983 (fig. 9) and miscellaneous specific conductance measurements of water samples obtained during the packer tests and by a thief sampler were used to identify and evaluate the quantity and quality of water from each zone. Acoustic televiewer photos and borehole television surveys were also used to identify the sources. The water-bearing zones in the Floridan aquifer system as indicated in the borehole are numerous, but 14 were identified and evaluated (table 2).

Zones 3 and 13 contributed 66 percent of the total borehole flow. Zone 3 was the principal contributor (34 percent) of brackish ground water (specific conductance of about 3,300 μS/cm) from the Upper Floridan aquifer, and zone 13 was the principal contributor (32 percent) of salty ground water (specific conductance of 50,000 μS/cm) from the Lower Floridan aquifer. The remaining 34 percent of the total flow was contributed by many less permeable zones within the remaining 12 zones. Zones 2 through 9, the interval from 920 to 1,645 ft, collectively contributed about 50 percent of the flow, with composite specific conductance at about 5,000 μS/cm. Zones 10 through 14, the interval from 1,645 to 2,811 ft, collectively contributed the other 50 percent of the flow, with composite specific conductance of 45,500 μS/cm. Zones that contributed little or no water to the well (that is, those that contributed 1 percent or less) probably constitute the confining units within the individual aquifer systems. Zones 1 through 9, which collectively contributed about 50 percent of the flow, are identified as the Upper Floridan aquifer. Zones 10 and 11, which contributed about 13 percent of the flow, are identified as the middle confining unit of the Floridan aquifer system. Zones 12 through 14, which contributed about 37 percent of the total flow, are identified as the Lower Floridan aquifer.

Pressure gradients for 11 water-level measurements (table 3) were calculated from estimated densities and depths. Measurements that have similar densities and pressure gradients (for example, measurements 4, 6, 8, and 10, table 3) are generally representative of a common pressure (flow) system, and measurements that have dissimilar densities and pressure gradients (for example, measurements 3 and 10) are generally from different pressure (flow) systems. The fact that static conditions were reached only for measurements 3, 10, and 11 raises some doubt about the calculations of total static pressure for the other measurements.

TABLE 2.—*Estimated distribution of flow and fluid conductance for the Floridan aquifer system at the Alligator Alley test well*

[Conductance in µS/cm (microsiemens per centimeter). Well located at site 10, fig. 2]

Zone	Depth (feet)	Percent of flow	Cumulative percent of flow[1]	Estimated average conductance	Estimated conductance load (percent of flow times µS/cm)	Remarks
			Upper Floridan aquifer			
1	770-840	0		6,200	0	Zone cased off. Sampled from perforated monitor tube at 811 to 816 feet.
2	920-940	1	100	4,600	46	Minor inflow from numerous cavities.
3	1,020-1,034	34	99	3,300	1,122	Major inflow from large cavities at 1,025 and 1,032 feet.
4	1,110-1,154	6	65	3,300	198	Major inflow from large cavities at 1,114, 1,120, 1,125, 1,127, and 1,132 feet.
5	1,180-1,192	1	59	2,500	25	Minor inflow from small cavities.
6	1,248-1,256	2	58	2,500	50	Minor inflow from small cavities at 1,248 and 1,256 feet.
7	1,280-1,310	1	56	3,300	33	Minor inflow from small cavities at 1,284, 1,286, 1,288, 1,304, and 1,308 feet.
8	1,350-1,370	1	55	3,300	33	Minor inflow from small cavities at 1,356, 1,360, 1,365, and 1,367 feet.
9	1,430-1,645	4	54	25,000	1,000	Major inflow from cavities at 1,642 feet; minor inflow from small cavities at 1,430, 1,468, 1,476, 1,506, 1,570, 1,578, 1,592, 1,600, 1,606, 1,610, and 1,625 feet.
			Middle confining unit of the Floridan aquifer system			
10	1,645-1,840	8	50	35,000	2,800	Major inflow from cavities at 1,715 feet; minor inflow from cavities at 1,678, 1,690, 1,739, 1,754, 1,764, 1,793, and 1,809 feet.
11	1,840-2,200	5	42	36,900	1,845	Major inflow from cavities at 1,896, 2,070, and 2,172 feet; minor inflow from cavities at 1,856, 1,874, 1,960, 2,028, and 2,126 feet.
			Lower Floridan aquifer			
12	2,200-2,457	5	37	42,600	2,130	Major inflow from cavities at 2,250 feet; minor inflow from cavities at 2,228, 2,258, 2,308, and 2,340 feet.
13	2,457-2,580	32	32	50,000	16,000	Major inflow from cavities at 2,490 to 2,491, 2,544 to 2,546, 2,550 to 2,552, and 2,560 to 2,562 feet.
14	2,580-2,811	<1		50,000		Very minor inflow from cavities at 2,616, 2,635, 2,653, 2,672, 2,703, and 2,715 feet.
Total					25,282	

[1]In reverse order with depth.

TABLE 3.—*Measurements of head and pressure in the Floridan aquifer system at the Alligator Alley test well*

[Pressure gradient in pounds per square inch per foot; pressure at depth in pounds per square inch. Well located at site 10, fig. 2]

Measurement No.	Measured head (feet above sea level)	Depth (feet)[1]	Estimated pressure gradient[2]	Estimated representative depth[3] (feet below sea level)	Estimated pressure at depth
1	>52.0	895-934	0.43284	879.6	403.23
2	>51.1	895-2,457	.43518	879.6	405.02
3	7.0	2,463-2,811	.44426	2,447.6	1,090.48
4	>51.5	895-1,428	.43253	879.6	402.73
5	>50.5	1,433-1,618	.43323	1,417.6	636.02
6	>56.6	895-1,249	.43253	879.6	404.93
7	>52.4	1,254-2,811	.43435	1,238.6	560.75
8	>57.7	895-1,124	.43253	879.6	405.41
9	>54.1	1,129-2,811	.43388	1,113.6	506.64
10	58.8	1,030-1,154	.43253	1,014.6	464.28
11	55.7	811-816	.43314	795.6	368.73

[1]Datum is land surface, which is 15.4 feet above sea level.

[2]Estimated pressure gradient is on the basis of estimated fluid density and representative depth.

[3]Estimated representative depth is top of measured depth minus 15.4 feet.

For comparison, the pressure versus depth data for each measurement is shown in figure 10, a pressure-depth diagram. The plotted data suggest two distinct relations, as indicated by lines of brackish water gradient (G_{BW}), represented by water at the depth of measurement 10, and saltwater-like gradient (G_{SW}), represented by water at the depth of measurement 3. The lines through the points represent the respective pressure gradients for each measurement. The points for measurements 1, 2, 4 through 9, and 11 in the upper (brackish) part of the Floridan aquifer system (water-bearing zones 1 through 9) generally fall near or on the line (G_{BW}) represented by water at the depth of measurement 10, thereby suggesting that they are part of the same flow system (although minor variations in respective pressures and pressure gradients suggest the presence of local confining units). Pressures at selected depths within the body of brackish ground water in the upper part of the aquifer system may be approximated by the following equation:

$$P = G_{BW}(D+43.4) \quad (1)$$

where

P = pressure, in pounds per square inch;

G_{BW} = pressure gradient of brackish water (0.43253 pound per square inch (lb/in^2) per foot of depth), represented by the water at depth of measurement 10 (1,030 to 1,154 ft at the Alligator Alley test well site);

D = depth below land surface, in feet; and

43.4 = head above land surface of the water at depth of measurement 10 (58.8 ft−15.4 ft=43.4 ft).

Measurement 3, which represents the deeper seawater-like zones below a depth of 2,463 ft, plots slightly above the downward extension of the line (G_{BW}) that represents the pressure-depth relation for the upper part of the system. Pressures in the deep, saltwater part of the Floridan aquifer system may be approximated by the following equation:

$$P=G_{SW}(D-8.4) \quad (2)$$

where

G_{SW} = pressure gradient of saltwater (0.44426 lb/in^2 per foot of depth);

8.4 = head below land surface of the water at depth of measurement 3 (15.4 ft−7 ft=8.4 ft); and

D = depth below land surface, in feet.

The upward extension of the line G_{SW}, representing the pressure-head relation for the saltwater part, intersects that for the brackish water part at 1,918.5 ft, the point of equal pressure. Two interpretations of the data are possible: (1) the saltwater and brackish water systems are unrelated and function independently because of intervening confining units; and (2) the two systems are interconnected and related by buoyancy, and the point of intersection (1,918.5 ft) is the approximate brackish water-saltwater contact, or interface.

The conductance or resistance of water that entered the borehole from all water-bearing zones (fig. 9, table 2) while the well was flowing suggests that the base of the brackish water part of the system is in zone 9, which ranges in depth from 1,430 to 1,645 ft, and that the top of the saltwater part is in zone 12, which ranges in depth from 2,200 to 2,457 ft. Between the upper brackish water zones and the lower saltwater zones are zones 10 and 11, which contain mixtures of both—much the same as the zone of diffusion in unconfined coastal aquifers such as the Biscayne aquifer (Cooper and others, 1964, fig. 8).

According to the fluid resistance log of July 16, 1983, while the well was flowing (fig. 9) there was no obvious indication that the saltwater-brackish water contact occurred at 1,918.5 ft, as projected by buoyancy relations in figure 10. The fluid resistance logs of November 13, 1980, and April 13, 1981 (not shown), obtained while the well was shut-in (not flowing), suggest that the pressure in the upper brackish water part is sufficient to displace the saltwater in the borehole to a depth of about 2,250 ft. The maximum head for the upper zone was 43.4 ft above land surface, or 58.8 ft above sea level, on April 21, 1981, when the average density of the 2,250-ft fluid column was estimated to be 1.002 grams per milliliter (g/mL) at ambient temperature. Theoretically, given sufficient time, brackish water from the high-pressure upper zone would have completely displaced the saltwater to about 2,250 ft with a water column of density 0.998 g/mL. The brackish water head required for the displacement would, however, be about 9.2 ft higher than the maximum measured on April 21, 1981. Therefore, the static head in the upper part of the Floridan aquifer system could be as high as 68 ft above sea level. The discrepancy between the heads (measured and displacement) could be caused by intraborehole flow (from high-pressure zones to low-pressure zones) during shut-in.

The static head for zone 1 (table 3, measurement 11) was 55.7 ft above sea level at the ambient density on April 24, 1981. Comparisons show that the head in zone 1 (measurement 11) was about 3.1 ft lower than that in zone 3 (measurement 10) at ambient density. At the same density, the difference in head would only be 2.1 ft. The slight differences in head and in density suggest that confining beds separate these zones (at least locally) or that the differences are due to significant permeability contrasts, which suggests that ground water moves faster and more freely through zone 3. The widespread occurrence of fractures and sinkholes in the limestones that make up the Floridan aquifer system rules out the possibility that water-bearing zones within the aquifer system are isolated from each other.

Comparison of the highest measured head (table 3, 58.8 ft above sea level) in the well with the 1974 potentiometric surface map by Healy (1975b) indicates that the head extrapolated from the map was about 9 ft lower than the measured head at the Alligator Alley test well. Potentiometric surface maps by Johnston and others (1980, 1981) were recently modified on the basis of the head measured at the Alligator Alley test well. As more detailed information on the vertical distribution of head in the Floridan aquifer system is obtained from other test wells in southern Florida, the mapped configuration of the potentiometric surface can be expected to change, particularly in the area between the Alligator Alley test well and the potentiometric surface high in central Florida.

Flowmeter, fluid resistance, and fluid temperature logs indicated that zone 13 contributed a significant amount of saltwater to the well during natural flow. Prior to the packer tests it was assumed that the static head of saltwater in zone 13 was above land surface in order to account for the saltwater flow. That assumption proved to be incorrect. The pressure-depth diagram (fig. 10) suggests that at 1,030 ft the static pressure for the saltwater column (extension of line G_{SW}) is lower than the static pressure in zone 3. The pressure at 1,030 ft in terms of the saltwater gradient (G_{SW}) would be 453.86 lb/in^2, and that for the brackish water gradient (G_{BW}) would be 464.28 lb/in^2. The fluid pressure in zone 3, therefore, would be 10.42 lb/in^2 greater than the fluid pressure at 1,030 ft in the static column of saltwater above zone 13. The difference in static pressure is equivalent to about 23.5 ft of saltwater head or about 24.1 ft of brackish water head. Because the borehole provides physical connection between the upper and lower zones, the fluid pressure in zone 3 is sufficiently

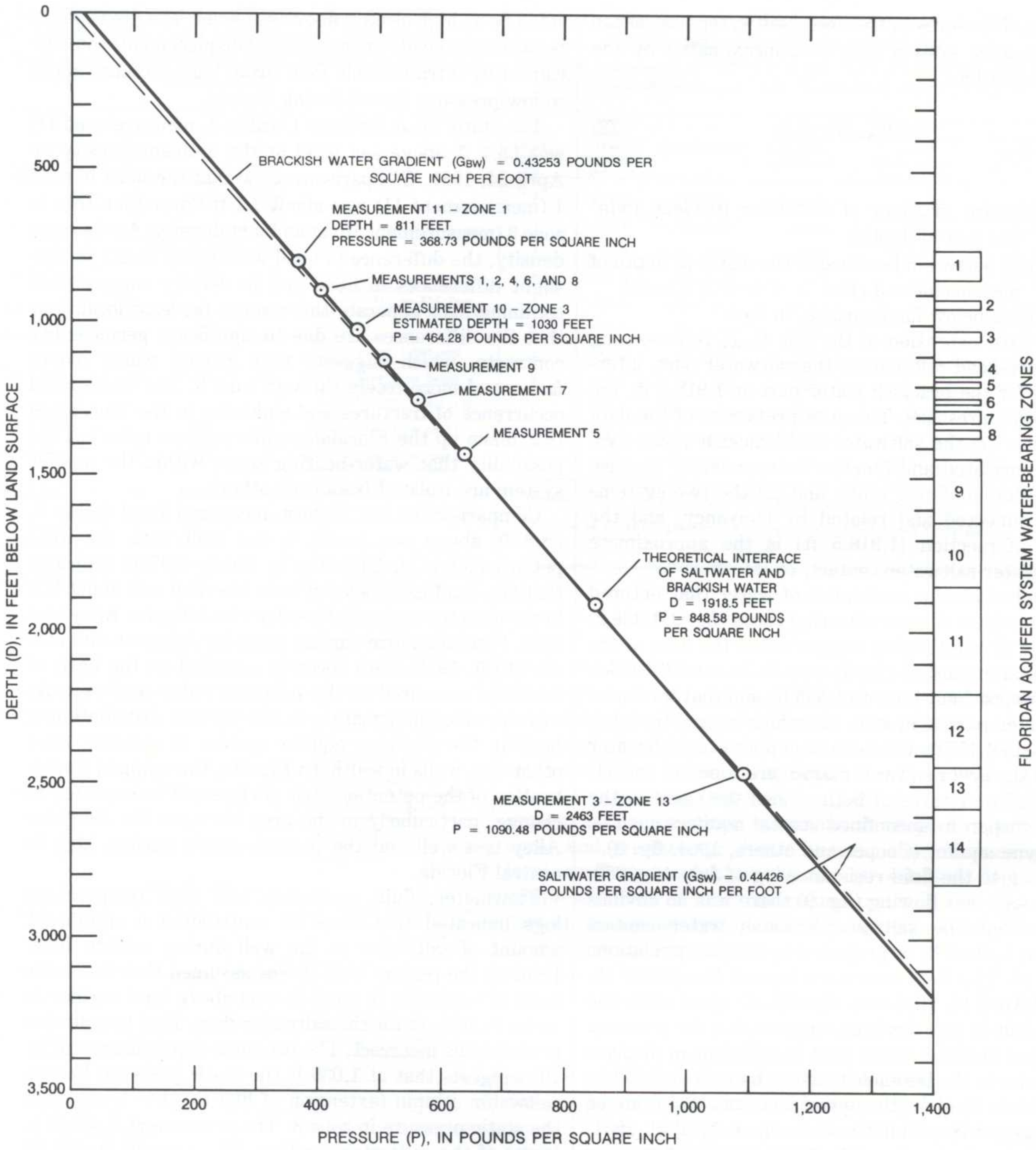

FIGURE 10.—Pressure-depth relation for water-level measurements in the Floridan aquifer system at the Alligator Alley test well (well G-2296 at site 10, fig. 2).

greater to displace the saltwater column below the point of intersection (about 1,030 ft).

If the brackish water head is reduced by 24.2 ft or more (a reduction that would occur when the well is permitted to flow naturally), the pressure of the brackish water column at the intersection (1,030 ft) is exceeded by that of the saltwater column, and saltwater will move up the borehole from zone 13 to displace and mix with brackish water from zone 3. The inflowing brackish water from zone 3 effectively dilutes and entrains the saltwater in the upper part of the saltwater column and transports the saltwater to the surface as a blend that is equivalent to a 50-percent concentration of saltwater. This phenomenon is, in some respects, comparable to the operation of an airlift pump, and its effects have led to misinterpretation of static head distribution in flowing wells.

GROUND-WATER MOVEMENT IN THE FLORIDAN AQUIFER SYSTEM IN SOUTHERN FLORIDA

GROUND-WATER MOVEMENT BASED ON NATURAL ISOTOPES AS TRACERS

Naturally occurring isotopes of carbon and uranium in samples of ground water from the Floridan aquifer system at nine sites in southeastern Florida were compared with those in modern seawater (table 4) to assess their potential as tracers of ground-water movement. Carbon isotopes were determined in 20 samples and uranium isotopes in 9 samples. Included are data on chloride and dissolved solids concentrations, which also were compared with concentrations in present-day seawater. Tritium was determined in selected samples to evaluate possible contamination of the sample by modern water. Oxygen isotopes were determined in 12 samples to assess their usefulness as climate indicators.

CARBON ISOTOPES

The radiocarbon dating technique has been an important and accepted research tool in archeology and geology since its inception in 1946 by Libby (1955). However, its use in hydrogeology has been dubious because of the uncertainties in comparing the carbon-14 in dissolved carbon species in ground water with respect to that in the water when it was last in contact with the atmospheric reservoir of carbon-14. An understanding of the involved chemical processes and the reservoir through which the ground water moves is essential to the interpretations and corrections that would apply to the measured carbon-14 in the sample.

Carbon-14 measurements by the U.S. Geological Survey were by liquid scintillation counting of benzene which was synthesized from the carbonate in a 30-gallon (gal) sample of ground water (Pearson and Bodden, 1975; Thatcher and others, 1977); however, measurements by the Tritium Laboratory, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, were by gas proportional counting of carbon dioxide from a 55-gal water sample (Stuiver and Ostlund, 1980). By convention, the measurements were compared with standard National Bureau of Standards oxalic acid to determine

TABLE 4.—*Summary of isotope analyses of selected water samples from the Floridan aquifer system, southeastern Florida, 1971–83*

[Site locations shown in fig. 2. Dashes indicate no data]

County: B, Broward; D, Dade; M, Martin; PB, Palm Beach; STL, St. Lucie. ^{3}H tritium: Values in picocuries per liter.

$\delta^{13}C$: $^{13}C/^{12}C$ stable isotope ratio of sample with respect to that of the standard (Pee Dee Belemnita).

R: Relative activity of sample with respect to standard × 100.

$d^{14}C$: Millesimal difference with respect to standard.

$D^{14}C$: Millesimal difference normalized for isotopic fractionation.

PMC: Percent of modern carbon (normalized).

Apparent age: Years before present (1950), in Libby years.

AR: $^{234}U/^{238}U$ alpha-activity ratio.

$\delta^{18}O$: $^{18}O/^{16}O$ stable isotope ratio of sample with respect to that of standard mean ocean water.

Laboratory: GS, U.S. Geological Survey; UM, University of Miami; FS, Florida State University Geology Department.

Site No.	County	Local well No.	Depth (feet)	Date of sample	in milligrams per liter: Chloride	in milligrams per liter: Dissolved solids	^{3}H tritium	$\delta^{13}C$ (per mil)	R (percent)
3	PB	PB-1141	2,914-3,163	6/29/76	19,000	36,100	--	--	--
5	STL	STL-255	898-1,268	2/4/83	1,700	3,240	--	-3.3	<0.19
			1,610-1,663	2/23/83	530	1,280	--	+4.3	<.04
		STL-254	2,715-3,418	11/2/82	20,000	35,300	--	-1.3	19.7
6	M	M-1034	1,990-2,980	6/6/74	20,000	36,500	--	--	--
7	PB	PB-965	3,025-3,680	5/30/77	21,000	37,400	--	--	--
8	B	G-2292	2,046-3,278	3/29/74	20,000	35,900	--	--	--
9	B	G-2331	2,532-2,705	10/21/81	21,000	37,200	0	-4.2	[1]<.72
			1,008-1,072	10/21/81	3,400	6,490	--	-2.4	3.1
			2,532-2,705	12/16/82	20,000	37,500	--	-1.7	[1]1.17
		G-2333	2,800-3,525	4/28/83	21,000	37,500	--	-2.4	65.9
10	B	G-2296	895-934	10/18/80	1,200	2,670	--	--	[1]17.5
			2,463-2,811	3/3/81	19,500	38,800	0	-3.8	[1]30.3
			1,433-1,618	3/7/81	1,800	3,640	0	-1.6	4.7
			895-1,249	3/8/81	760	1,930	3	-2.6	5.8
			895-1,124	3/9/81	850	2,000	0	-2.4	4.7
			[2]895-2,811	10/19/81	1,100	2,400	--	-1.2	11.9
			811-816	10/19/81	1,600	3,500	--	-1.8	7.3
			2,500-2,811	10/19/81	22,700	36,700	0	-3.7	[1]7.6
			2,520-2,811	7/7/83	19,000	37,800	--	-2.1	38.9
12	D	I-2	1,280-1,300	7/7/71	1,960	--	--	--	5.6
			1,902-1,922	7/9/71	4,740	--	--	--	4.3
14	D	MDWSI-5	2,746-3,200	12/19/79	19,400	38,300	--	--	--
		MDWSBZ-1	1,005-1,037	10/22/81	1,400	2,890	--	-3.9	6.8
			2,689-2,960	10/22/81	19,000	37,900	0	-5.3	41.2
Gulfstream seawater[3]					19,300	35,800	12	+0.5e	

Site No.	Local well No.	$d^{14}C$ (per mil)	$D^{14}C$ (per mil)	PMC (percent)	Apparent age	AR	U (uranium) (micrograms per liter)	$\delta^{18}O$ (per mil)	Laboratory
3	PB-1141	--	--	--	--	1.24	2.0	--	FS
5	STL-255	-998.1	-998.2	<0.18	>49,900	--	--	--	UM
		-999.6	-999.6	<.04	>55,000	--	--	--	UM
	STL-254	-803	-812.3	18.8	13,400	1.26	7.97	--	UM,FS
6	M-1034	--	--	--	--	1.50	.45	--	FS
7	PB-965	--	--	--	--	1.21	1.42	--	FS
8	G-2292	--	--	--	--	1.15	3.42	--	FS
9	G-2331	-992.8	-993.1	<.69	40,000	--	--	+0.2	GS
		-969	-970.4	3.0	28,200	--	--	-1.7	GS
		-998.3	-998.8	1.12	36,100	2.08	.244	--	UM,FS
	G-2333	-341	-370.8	62.9	3,700	1.14	3.04	--	UM,FS
10	G-2296	-825	-833e	[1]16.7e	14,400	--	--	-2.2	GS
		-697	-709.8	29	9,900	--	--	-.3	GS
		-953	-955.2	4.5	24,900	--	--	-2.3	GS
		-942	-944.6	5.5	23,300	--	--	-2.6	GS
		-953	-955.1	4.5	24,900	--	--	-2.6	GS
		-881	-886.7	11.3	17,500	--	--	-2.2	GS
		-927	-930.4	7.1	21,200	--	--	-1.8	GS
		-924	-927.2	<7.3	>21,000	--	--	-.2	GS
		-611	-628.8	37.1	8,000	1.20	2.44	--	UM,FS
12	I-2	-944	-946.6e	5.4	23,400	--	--	--	GS
		-957	-959e	4.1e	25,700	--	--	--	GS
14	MDWSI-5	--	--	--	--	1.22	2.50	--	FS
	MDWSBZ-1	-932	-934.9	6.5	22,000	--	--	-2.3	GS
		-588	-604.2	39.6	7,400	--	--	+1.2	GS
Gulfstream seawater[3]			-60e	94e	500	1.14	3.30	+0.8e	

[1]Probably contaminated.
[2]Probably represents zone 895 to 1,160 feet.
[3]Estimated from Stuiver and Ostlund, 1980.
e = estimated.

the relative activity (R) for age-dating. The carbon-13/carbon-12 stable isotope ratio ($\delta^{13}C$) was determined by mass spectrometry. Also by convention, the measured relative carbon-14 activity (R) was normalized to a $\delta^{13}C$ value of −25 ‰ (per mil), the value for wood with respect to the standard Pee Dee Belemnita (PDB), to compensate for isotopic fractionation. The generally accepted equation for isotopic fractionation normalization is

$$D^{14}C = d^{14}C - 2\,(\delta^{13}C + 25)\left[1 + \frac{d^{14}C}{1{,}000}\right] \quad (3)$$

where the normalized activity, $D^{14}C$, equals the determined activity, $d^{14}C$, corrected for isotopic fractionation, assuming that a carbon-13/carbon-12 change from the accepted value for wood ($\delta^{13}C$=25 ‰ with respect to PDB) induces a change in the carbon-14/carbon-12 ratio of the sample. A 10 ‰ change in $\delta^{13}C$ value, therefore, results in a 20 ‰ change in the carbon-14 millesimal difference ($d^{14}C$).

The percent of modern carbon (PMC), corrected for isotopic fractionation normalization or the percentile difference, was calculated using the following equation:

$$PMC = 100 + \frac{D^{14}C}{10} \pm s\,\frac{D^{14}C}{10} \quad (4)$$

where s $D^{14}C/10$ is the standard error. The age of the sample is expressed as apparent age owing to the uncertainty about past production of carbon-14 and the origin of the carbon in the water. The apparent age is based on the Libby half-life of 5,568 yr and was calculated using the following equation:

$$\text{Apparent age (before 1950)} = -8033 \ln (PMC \times 10^{-2}) \quad (5)$$

The measured relative carbon-14 activities, R (that is, uncorrected for isotopic fractionation normalization), ranged from about 0.04 to 65.9 percent, and the normalized activities, PMC, ranged from about 0.04 to 62.9 percent. The experimental error for the analyses by the U.S. Geological Survey ranged from 0.2 to 1.5 percent, and that for the Tritium Laboratory, University of Miami, ranged from 0.1 to 0.3 percent. The corrections for isotopic fractionation normalization had relatively insignificant effects on the activities of the samples. No corrections for dilution or chemical reaction during transit were applied; therefore, the activities do not represent absolute age. Ages calculated according to equation 5 are maximum estimates. Corrections for reactions led to younger age estimates. However, insufficient data are available to correct PMC for reaction effects. Generally, the samples of brackish ground water from the Upper Floridan aquifer had lowest carbon-14 activities.

Upper Floridan Aquifer

The PMC (carbon-14 activity corrected for isotopic fractionation normalization) of samples of brackish ground water from the Upper Floridan aquifer at sites 5, 9, 10, 12, and 14 (table 4) ranged from about 0.04 (a value that is near the limit of the dating technique) to 16.7 percent. The stable isotope ratios ($\delta^{13}C$) ranged from +4.3 to −3.9 ‰ (table 4).

Variations in the PMC with depth are indicated. At site 10, location of the Alligator Alley test well, the PMC of samples between 895 and 1,618 ft ranged from 4.5 to 16.7 percent and the carbon-13 stable isotope ratios ($\delta^{13}C$) ranged from −1.6 to −2.6 ‰. The well was cased to a depth of 895 ft (225 ft below the estimated top of the Floridan aquifer system), and the open borehole was drilled to a depth of 2,811 ft into the limestone and dolostone of the Lower Floridan aquifer. Samples from various depths in the open hole were obtained chiefly with packers. A monitor tube 2 inches in diameter with perforations from 811 to 816 ft provided samples of ground water from near the top of the Upper Floridan aquifer. The chief water-bearing zone in the Upper Floridan aquifer at the well site is at about 1,030 ft, at the unconformable contact of the Ocala Limestone with the overlying Suwannee Limestone. Samples of ground water, presumably from the Suwannee-Ocala contact in the Upper Floridan aquifer, generally had higher carbon-14 activities (except the seawater-like samples from the Lower Floridan aquifer), thereby suggesting that they are relatively younger in age.

At site 5 (well STL–255), the PMC for samples of brackish ground water from depths of about 898 to 1,663 ft in the Upper Floridan aquifer were virtually zero (0.18 and 0.04 percent), and the respective carbon-13 stable isotope ratios were −3.3 and 4.3 ‰. The deeper sample (1,610 to 1,663 ft), which had a chloride concentration of only 530 mg/L, contained an unusually high concentration of carbon-13. The high carbon-13 concentration in the deeper sample may indicate dissolution of dolomite (Hanshaw and Back, 1971, p. 147) and, therefore, greater dilution of carbon-14. The carbon-14 activity of the deeper sample would, therefore, be lower chiefly because of the dilution. The presence of brackish ground water at that depth is further evidence of the variability of water chemistry in the aquifer system.

The distribution of carbon-14 and carbon-13 in the brackish ground water of the Upper Floridan aquifer is apparently very complex and probably is more affected by dissolution-precipitation reactions than is the distribution in the Lower Floridan aquifer (saltwater). The distribution of carbon-14 activity (corrected for isotopic fractionation) and carbon-13 stable isotope ratios ($\delta^{13}C$) in the upper part (from about 900 to 1,200 ft deep) in southern Florida is shown in figure 11; also shown is the

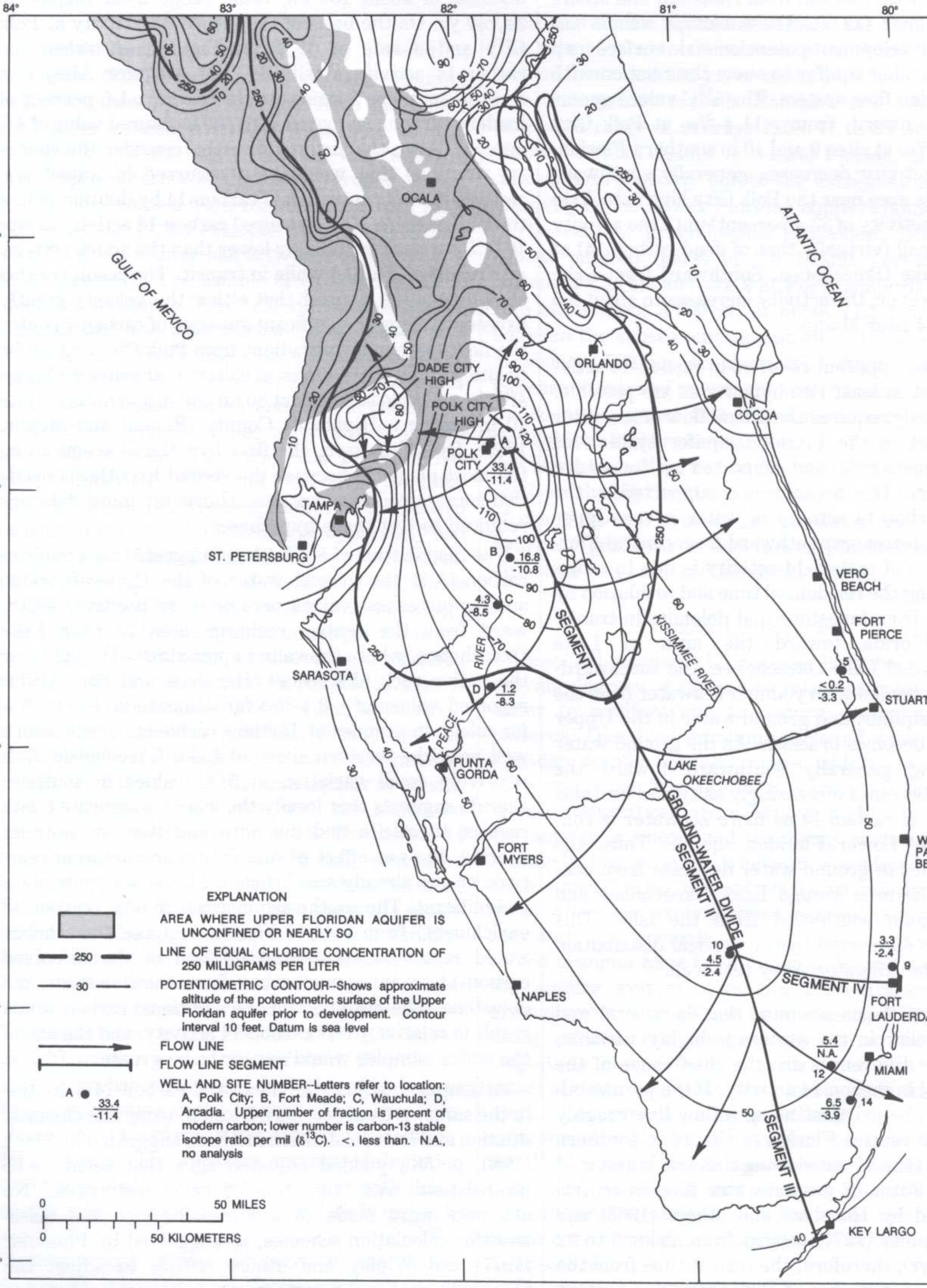

FIGURE 11.—Carbon-14 activities and carbon-13 stable isotope ratios in samples of ground water from the Upper Floridan aquifer, peninsular Florida.

distribution in central Florida, from Hanshaw and others (1965) and Plummer (1977). These isotope values are plotted on a predevelopment potentiometric surface map of the Upper Floridan aquifer to show the relation with the Upper Floridan flow system. The $\delta^{13}C$ values generally increase southward, from −11.4 ‰ at Polk City (site A) to −2.4 ‰ at sites 9 and 10 in southern Florida. The carbon-14 activity decreases generally southward from the recharge area near the Polk City high (site A) in central Florida (activity of 33.4 percent) until the activity becomes very small (virtually that of dead carbon-14) at site 5 east of Lake Okeechobee. Southward from Lake Okeechobee, however, the activity increases to about 6.5 percent at site 14 near Miami.

The cause of the apparent reversal in carbon-14 activity is unclear, but at least two hypotheses are possible. The first hypothesis requires the inland flow of seawater in the lower part of the Floridan aquifer system, as proposed by Kohout (1965) and supported by the isotope data in this report. This hypothesis is supported by the evidence that carbon-14 activity in water in the Upper Floridan aquifer decreases southward from central Florida. The reduction of carbon-14 activity is due to radioactive decay during the residential time and to dilution by inorganic carbon from limestone and dolomite in transit from central Florida toward the area of Lake Okeechobee. Beyond Lake Okeechobee, the southward-flowing water is blended with younger seawater from the Lower Floridan aquifer, and ground water in the Upper Floridan aquifer becomes brackish. As the ground water continues flowing generally southward toward the coastal areas, it becomes increasingly salty and contains greater amounts of carbon-14 as more seawater is contributed from the Lower Floridan aquifer. Thus, the carbon-14 activities in ground water decrease from central Florida to the area around Lake Okeechobee and then increase again southward from the lake. This hypothesis also is supported by the vertical distribution of carbon-14 in the Alligator Alley test well.

The second hypothesis assumes that horizontal and vertical permeability in the system is highly variable, and that velocity differences are the chief cause of the apparent reversal in carbon-14 activity. If the permeability is assumed to be greatest along a flow line roughly from Polk City in central Florida to site 14 in southern Florida, then the time of travel along that line is assumed to be the least. Rates of ground-water flow in central Florida estimated by Hanshaw and others (1965) and modified by Plummer (1977) ranged from about 6 to 32 feet per year (ft/yr); therefore, the transit time from the central Florida recharge area at Polk City (33.4 percent of modern carbon) to the Alligator Alley test well (site 10) in southern Florida (4.5 percent of modern carbon), a distance of about 150 mi, could range from 132,000 to 24,750 yr. On the basis of the measured activity at Polk City and a rate of 32 ft/yr (the highest rate), the carbon-14 activity at site 10 (the Alligator Alley test well) in southern Florida would be about 1.5 percent of modern carbon, compared with the measured value of 4.5 percent. Also, the analysis does not consider the chemical reactions that would have occurred in transit and reduced the concentration of carbon-14 by dilution to less than 1.5 percent. The measured carbon-14 activity at site 10 (4.5 percent) is probably lower than the actual activity as a result of dilution while in transit. The results of this sample analysis suggest that either the velocity greatly exceeds 32 ft/yr or significant amounts of carbon-14 enter the flow system downgradient from Polk City and closer to site 10. Possible sources of closer freshwater recharge are the sinkhole lakes about 80 mi north-northwest of site 10 in southern Highlands County (Kohout and Meyer, 1959). By comparison, the first hypothesis seems to be the most plausible because the second hypothesis needs two constrained assumptions. However, more data are required to test these hypotheses.

The distribution of $\delta^{13}C$ values suggests that dissolved carbon-13 in the ground water of the Upper Floridan aquifer increases (values become more positive) southward from the central recharge area to near Lake Okeechobee, where the values approximate the value for the native rock (dolostone). Hanshaw and Back (1971) reported values of −3.1 ‰ for dolomite and −0.4 ‰ for calcite in samples of Tertiary carbonate rocks from a well near the western shore of Lake Okeechobee. The relatively small variation in $\delta^{13}C$ values in southern Florida suggests that locally the water is saturated with respect to calcite and dolomite and that in southern Florida, the net effect of dissolution-precipitation reactions on the already small carbon-14 activity probably is insignificant. The southward increase in $\delta^{13}C$ (carbon-13 enrichment) from central Florida to Lake Okeechobee would result in substantial dilution of the dissolved carbon-14 by inorganic carbon from the limestone and dolostone. The net effect of the additional carbon would result in relatively less carbon-14 activity, and the age of the water samples would appear to be greater.

Attempts to adjust the measured carbon-14 activities in the samples from southern Florida, using the chemical dilution and isotopic dilution methods suggested by Mook (1980, p. 58), yielded adjusted ages that seem to be inconsistent with the time-of-travel estimates. No attempts were made to use mass-balance and mass-transfer calculation schemes, as suggested by Plummer (1977) and Wigley and others (1978), to adjust the measured carbon-14 activity or $\delta^{13}C$ values because existing data are insufficient to accurately describe the hydrochemistry of the flow system.

Lower Floridan Aquifer

The carbon-14 activities, presented by percent of modern carbon (PMC), of samples of salty (salinity comparable to seawater) ground water from the Lower Floridan aquifer ranged from less than 0.69 to 62.9 percent (table 4). Of the eight samples, only four are considered representative of the native ground water. Apparently, four samples were contaminated with salty drilling fluid. At site 10, for example, three samples from the Lower Floridan aquifer had activities of about 29.0, 7.3, and 37.1 percent. The sample of October 19, 1981, which had an unusually high chloride concentration (22,700 mg/L) and the least carbon-14, probably contained residual, artificially produced, salty drilling fluid. The artificial drilling fluid was chiefly artesian water from the Upper Floridan aquifer and sodium chloride.

Likewise, three samples collected at site 9 yielded activities of about 0.69, 1.12, and 62.9 percent. The samples of October 21, 1981, and December 16, 1982, which had low carbon-14 activities, were from an isolated zone in a deep monitor well (G–2331) that apparently had not been completely flushed of artificially produced drilling fluid. However, the sample of April 28, 1983, which had the highest carbon-14 activity, was pumped at a high rate (10,000 gal/min) from a nearby municipal wastewater disposal well (G–2333) and is, therefore, considered representative of the native fluid (a conclusion that is supported by the concentrations of uranium isotopes).

The normalized carbon-14 activities (PMC) and the carbon-13/carbon-12 stable isotope ratios ($\delta^{13}C$) for salty ground water from the Lower Floridan aquifer at sites 5, 9, 10, and 14 (table 4) are shown with the estimated values for modern seawater in figure 12. The carbon-14 activity in the salty ground water generally decreased radially inland from site 9 at Fort Lauderdale, whereas the stable isotope ratio ($\delta^{13}C$) decreased generally southward from site 5. The apparent ages of the four samples are shown in figure 13 with the differences in age relative to that at site 9 (Fort Lauderdale). Because the deep ground-water flow system is virtually closed to atmospheric carbon, except in the Straits of Florida where exchange with modern seawater is inferred, the relative age difference probably indicates depletion of carbon-14 primarily by radioactive decay (aging) rather than dilution of the carbon-14 content in the water by dissolution-exchange processes. The apparent southward depletion of carbon-13 is probably related to reactions with dolostone, but the relative effect on the activities is insignificant.

The apparent age of the saltwater in the Lower Floridan aquifer increases radially inland from site 9, suggesting that seawater enters the aquifer chiefly through submerged karst in the Straits of Florida, east of Fort Lauderdale, and then travels inland through highly permeable dolostones (chiefly the Boulder Zone). The rate of movement between sites 9 and 10 is about 44.5 mi in about 4,300 yr, or about 54.6 ft/yr, an average rate that greatly exceeds Hanshaw and others' (1965) estimated range in average rates (7 to 39 ft/yr) for the Upper Floridan aquifer in central Florida. Most of this difference is probably due to the extremely high transmissivity of the Lower Floridan aquifer (Boulder Zone).

The rate of ground-water movement between the subsea outcrop (karst of the Miami Terrace) in the Straits of Florida and site 9 at Fort Lauderdale is about 10.5 mi in about 3,200 yr, or about 17.3 ft/yr; the rate between the subsea outcrop and site 10 is about 55.0 mi in about 7,500 yr, or about 38.7 ft/yr. The relative increase in rates of movement with distance inland from the source suggests that inland movement of seawater through the highly permeable zones of the Lower Floridan aquifer could be related in part to the rapid rise of sea level during the Holocene transgression. The effects of changing sea level on ground-water movement and hydraulic gradients in the Lower Floridan aquifer are discussed in a later section of this report.

URANIUM ISOTOPES

Dissolved uranium (U) isotopes have been used with varying degrees of success to relate samples of ground water to aquifers and to deduce ground-water flow patterns. Dissolved uranium in ground water from the Floridan aquifer system ranges widely, from several micrograms per liter (µg/L) to a trace. Generally, uranium concentrations are relatively high in areas where the aquifer is unconfined (oxidizing environment) and relatively low in areas where it is confined (reducing environment). Also, concentrations are relatively high in areas where the ground water represents a mixture of seawater, and anomalously high concentrations of dissolved uranium have been found in dolomitized parts of the aquifer system. Uranium concentrations in the ground water of the karst in west-central Florida (oxidizing environment) are generally one or two orders of magnitude higher than concentrations in the ground water of central and southern Florida (reducing environment). Concentrations are relatively high in oxidizing environments (unconfined aquifer) because the uranyl ion (UO_2^{+2}) forms strong bicarbonate, tricarbonate, and phosphate complexes, and concentrations in reducing environments (confined aquifer) are relatively low because the complex uranium ions are either precipitated or adsorbed.

The relative abundance of ^{234}U (uranium-234) to ^{238}U (uranium-238) in the ground water is attributed to the selected accumulation of ^{234}U in the liquid phase by either selective leaching of ^{234}U or by direct-recoil trans-

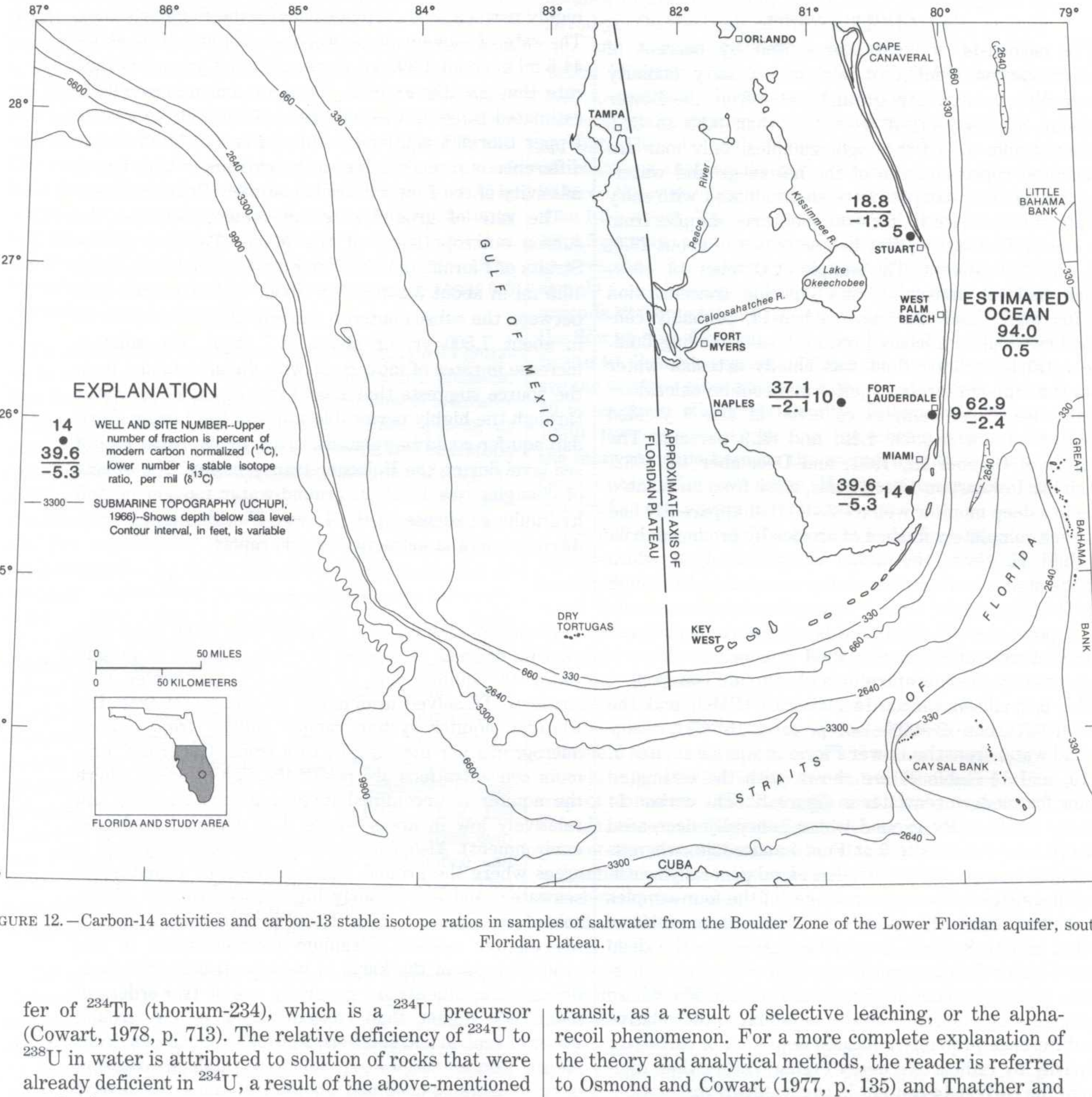

FIGURE 12.—Carbon-14 activities and carbon-13 stable isotope ratios in samples of saltwater from the Boulder Zone of the Lower Floridan aquifer, south Floridan Plateau.

fer of ^{234}Th (thorium-234), which is a ^{234}U precursor (Cowart, 1978, p. 713). The relative deficiency of ^{234}U to ^{238}U in water is attributed to solution of rocks that were already deficient in ^{234}U, a result of the above-mentioned mechanisms.

The relative abundance of ^{234}U to ^{238}U is theoretically about 1.00 (unity at equilibrium) within eight half-lives of ^{234}U, or about 2 million yr. The ratio of ^{234}U to ^{238}U in a sample of ground water is determined by measurements of alpha activity, and the results are expressed in terms of the alpha-activity ratio (AR). AR values for the ground water in the Floridan aquifer system generally increase downgradient, and hence with increased time in transit, as a result of selective leaching, or the alpha-recoil phenomenon. For a more complete explanation of the theory and analytical methods, the reader is referred to Osmond and Cowart (1977, p. 135) and Thatcher and others (1977, p. 8).

The uranium concentrations and AR values for 62 samples of ground water from the Floridan aquifer system are presented with the corresponding worldwide average values for seawater (Ku and others, 1974) in table 5. Eight of the samples represent salty, seawater-like ground water from the Lower Floridan aquifer (chiefly the Boulder Zone), and 54 samples represent ground water ranging in salinity from that of freshwater

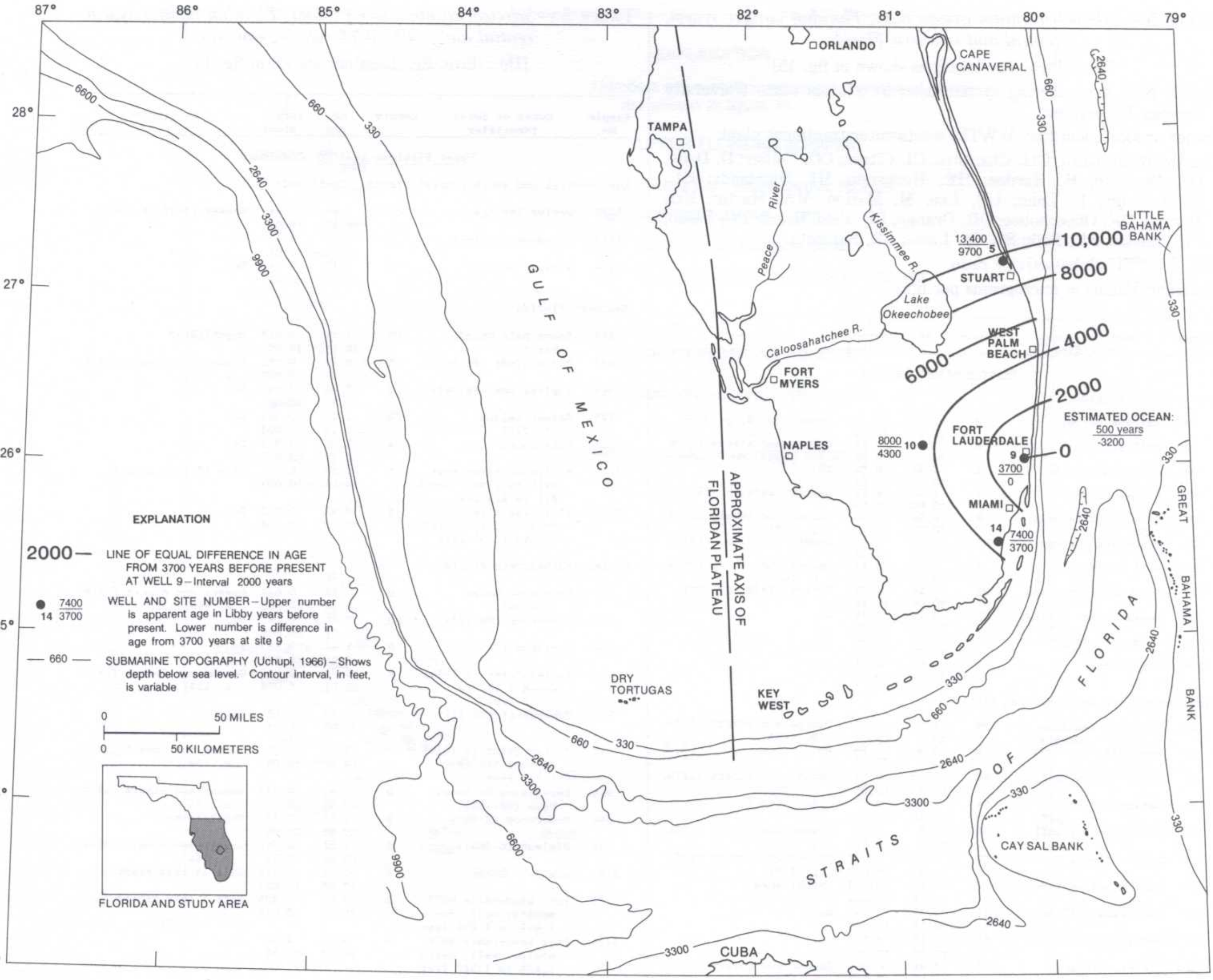

FIGURE 13.—Apparent carbon-14 ages and relative ages of saltwater in the Boulder Zone of the Lower Floridan aquifer, south Floridan Plateau.

to that of seawater from the Upper Floridan aquifer. The data are shown graphically in figure 14 by geographic location and hydrogeologic environment (that is, an unconfined aquifer generally represents an oxidizing environment and a confined aquifer generally represents a reducing environment).

The uranium concentrations for the 62 samples ranged from about 7.97 µg/L in sample 3605 (table 5) to 0.003 µg/L in sample 525, and the AR values ranged from 3.9 in sample 13 to about 0.46 in sample 3773. For the 62 samples, the average AR value is 1.40 and the average uranium concentration is 0.653 µg/L. The geographic-hydrologic distribution of the data (fig. 14) suggests that (1) a general relation exists between samples of seawater-like ground water from the confined Lower Floridan aquifer (Boulder Zone) in southeastern Florida, samples of fresh ground water from the unconfined Upper Floridan aquifer in west-central Florida, and samples of brackish ground water from the confined Upper Floridan aquifer in distal southeastern Florida, and (2) a general relation exists between samples of fresh ground water from the confined Upper Floridan aquifer in central Florida and samples of brackish ground water from the confined Upper Floridan aquifer in southern Florida.

The first relation suggests that the shared characteristics of the samples are indicative of their close proximity to sources of recharge (that is, direct infiltration of

TABLE 5.—*Selected uranium isotope data, Floridan aquifer system, central and southern Florida*

[Do., ditto. Site locations shown in fig. 15]

Sample No.: A numbering system used by Florida State University Geology Department.

Owner or local identifier: WWTP, wastewater treatment plant.

County: B, Broward; CH, Charlotte; CI, Citrus; CO, Collier; D, Dade; DS, De Soto; H, Hardee; HE, Hernando; HI, Highlands; HL, Hillsborough; L, Lake; LE, Lee; M, Marion; MA, Martin; MO, Monroe; OK, Okeechobee; OR, Orange; PB, Palm Beach; PC, Pasco; PI, Pinellas; PK, Polk; SL, St. Lucie; SR, Sarasota.

AR: $^{234}U/^{238}U$ alpha-activity ratio.

Uranium: Values in micrograms per liter.

Sample No.	Owner or local identifier	County	AR	U (uranium)	Reference
	Upper Floridan aquifer				
West-central Florida:					
91	Rainbow Springs	M	1.02 ±0.05	0.15 ±0.02	Cowart (1978, p. 715)
95	Well SCE 170	M	1.08 ±0.06	0.10 ±0.03	Osmond and others (1974, p. 1089).
96	Dunellon well No. 2	M	0.92 ±0.06	0.95 ±0.03	Do.
99	Silver Springs	M	1.03 ±0.03	0.79 ±0.03	Cowart (1978, p. 715)
105	City of Ocala well No. 3.	M	0.94 ±0.02	1.08 ±0.10	Osmond and others (1974, p. 1092).
121	Homosassa Springs	CI	0.93 ±0.07	0.58 ±0.06	Cowart (1978, p. 715)
151	Well CE 30A	M	1.47 ±0.06	0.71 ±0.03	Osmond and others (1974, p. 1092).
439	Sulphur Springs spa	HL	0.88 ±0.04	1.91 ±0.12	Cowart (1978, p. 715)
913	Weeki Wachee Springs	HE	0.73 ±0.04	1.16 ±0.07	Do.
956	Crystal Springs	PC	0.72 ±0.05	0.50 ±0.03	Do.
1118	Bug Springs	L	1.01 ±0.06	0.28 ±0.01	Do.
East-central and south-central Florida:					
12	Brewster American Cyanide Company.	PK	2.8 ±0.3	0.05 ±0.02	Osmond and others (1974, p. 1096)
13	Wauchula City well	H	3.9 ±0.6	0.04 ±0.01	Do.
15	Winter Haven well No. 2.	PK	1.40 ±0.3	0.03 ±0.01	Osmond and others (1974, p. 1096)
39	Carlton (M-186)	MA	1.59 ±0.26	0.05 ±0.01	Rydell (1969)
44	Mulberry City well	PK	1.8 ±0.3	0.04 ±0.01	Osmond and others (1974, p. 1096).
440	Lakeland well No. 10	PK	2.38 ±0.37	0.015 ±0.002	Osmond and Cowart (1977 p. 139).
443	Lake Wales well No. 3	PK	1.20 ±0.18	0.038 ±0.004	Unpublished
444	Avon Park well No. 2	HI	1.31 ±0.16	0.045 ±0.004	Do.
445	Sebring well No. 3	HI	1.10 ±0.08	0.073 ±0.084	Do.
448	Big Pine Island	LE	2.98 ±0.87	0.004 ±0.001	Osmond and Cowart (1977 p. 139).
450	Alva	LE	1.41 ±0.21	0.016 ±0.002	Do.
481	Hot Springs (Humble-Lowndes-Treadwell)	CH	0.94 ±0.07	0.024 ±0.002	Osmond and Cowart (1977 p. 139); site 1 this report.
491	Sarasota disposal No. 1.	SR	1.40 ±0.04	0.338 ±0.001	Osmond and Cowart (1977, p. 139).
654	McKay Creek Monitor No. 1.	PI	2.06 ±0.28	0.043 ±0.007	Cowart and others (1978, p. 166).
699	Zolfo Springs City well.	H	2.92 ±0.67	0.020 ±0.006	Do.
703	Northeast of Arcadia	DS	1.61 ±0.29	0.044 ±0.007	Do.
708	Deep Creek ROMP 10	CH	0.94 ±0.18	0.040 ±0.005	Do.
712	Sun City well No. 5	HL	1.57 ±0.35	0.011 ±0.002	Do.
719	General Development Corporation.	DS	2.00 ±0.24	0.020 ±0.002	Do.
727	Williamson	OK	2.75	0.18	Unpublished
890	L. H. Avant	DS	1.82 ±0.24	0.039 ±0.004	Osmond and Cowart (1977 p. 139).

TABLE 5.—*Selected uranium isotope data, Floridan aquifer system, central and southern Florida*—Continued

[Do., ditto. Site locations shown in fig. 15]

Sample No.	Owner or local identifier	County	AR	U (uranium)	Reference
	Upper Floridan aquifer--Continued				
East-central and south-central Florida--Continued:					
1120	Wekiwa Springs	OR	1.46 ±0.10	0.41 ±0.03	Cowart (1978, p. 715)
1123	Alexander Springs	L	1.40 ±0.09	0.15 ±0.01	Do.
1124	Juniper Springs	M	1.19 ±0.08	0.14 ±0.01	Do.
Southern Florida:					
452	Snook Hole Motel, Marco.	CO	1.94 ±0.11	0.018 ±0.003	Unpublished
457	Belle Glade (PB-203)	PB	0.92 ±0.04	0.051 ±0.002	Cowart and others (1978, p. 166).
524	Jupiter DNR (PB-747)	PB	0.66 ±0.03	0.065 ±0.003	Do.
525	Peanut Island (PB-216).	PB	1.45 ±0.18	0.003 ±0.003	Do.
726	Hobe Sound	MA	1.06 ±0.19	0.055 ±0.007	Do.
3771	Alligator Alley test well (G-2296), depth 811 to 816 feet.	B	1.73 ±0.15	0.071 ±0.005	Site 10 this report.
3772	Alligator Alley test well (G-2296), depth 895 to 1,150 feet.	B	0.92 ±0.13	0.072 ±0.008	Do.
Distal southeastern Florida:					
454	Hurricane Lodge (S-1354).	D	2.12 ±0.14	0.034 ±0.002	Cowart and others (1978, p. 166).
455	Pennekamp (MO-127)	MO	0.84 ±0.02	0.147 ±0.003	Do.
456	Grossman (S-524)	D	1.47 ±0.05	0.093 ±0.008	Do.
505	Turkey Point (S-1534), depth 1,132 to 1,412 feet.	D	0.76 ±0.01	0.455 ±0.005	Osmond and Cowart (1977, p. 139).
512	Ocean Reef (MO-133)	MO	0.99 ±0.03	0.30 ±0.02	Do.
513	Turkey Point (S-1534), depth 1,544 to 1,930 feet.	D	1.30 ±0.10	0.24 ±0.08	Osmond and Cowart (1977, p. 139).
521	Everglades National Park (NP-100).	D	1.41 ±0.05	0.093 ±0.005	Cowart and others (1978, p. 166).
544	Underwood (S-993)	D	1.12 ±0.05	0.33 ±0.04	Unpublished
545	Hialeah (G-3061)	D	1.51 ±0.06	0.049 ±0.03	Cowart and others (1978, p. 166).
2183	MDWSI-5	D	0.53 ±0.08	0.076 ±0.007	Site 14 this report.
3773	Fort Lauderdale WWTP monitor well, depth 1,021 to 1,072 feet.	B	0.46 ±0.03	0.305 ±0.014	Site 9 this report.
3774	Fort Lauderdale WWTP monitor well, depth 1,466 to 1,562 feet.	B	0.78 ±0.02	4.70 ±0.30	Do.
	Lower Floridan aquifer				
Southeastern Florida:					
508	Margate WWTP (G-2292)	B	1.15 ±0.01	3.42 ±0.06	Cowart and others (1978, p. 166); site 8 this report.
520	Stuart WWTP (M-1034)	MA	1.50 ±0.15	0.45 ±0.03	Cowart and others (1978, p. 166); site 6 this report.
678	West Palm Beach WWTP (PB-965).	PB	1.21 ±0.06	1.42 ±0.04	Cowart and others (1978, p. 166); site 7 this report.
935	Quaker Oats IW-3 (PB-1141).	PB	1.25 ±0.05	1.95 ±0.12	Site 3 this report.
2186	Miami-Dade WWTP (MDWSI-5).	D	1.22 ±0.04	2.50 ±0.09	Site 14 this report.
3605	Port St. Lucie WWTP (STL-254).	SL	1.26 ±0.03	7.97 ±0.57	Site 5 this report.
3680	Fort Lauderdale WWTP (G-2333).	B	1.14 ±0.04	3.04 ±0.14	Site 9 this report.
3681	Alligator Alley test well (G-2296).	B	1.20 ±0.03	2.44 ±0.07	Site 10 this report.
Worldwide seawater			1.140 ±0.016	3.30 ±0.14	Ku and others (1974, p. 314).

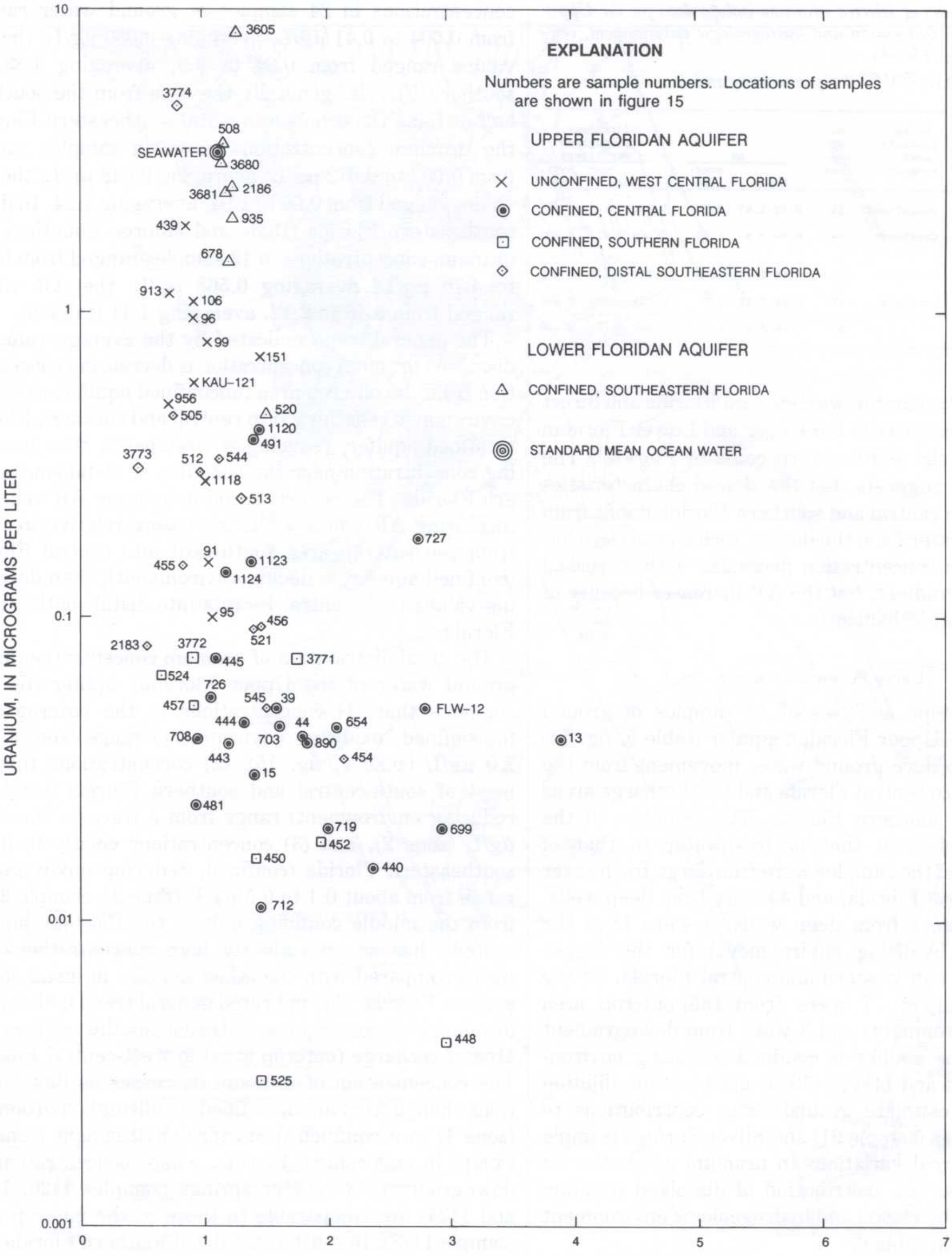

FIGURE 14.—Relation of uranium-234/uranium-238 alpha-activity ratio and uranium concentration for selected samples of ground water from the Florida aquifer system and seawater worldwide.

TABLE 6.—*Summary of selected uranium isotope data for the Upper Floridan aquifer by location and hydrogeologic environment, central and southern Florida*

[AR, $^{234}U/^{238}U$ alpha-activity ratio]

Location	Hydrogeologic environment	No. of samples	AR		U (uranium) (micrograms per liter)	
			Range	Average	Range	Average
West-central	Unconfined	11	0.72-1.47	0.98	0.10-1.91	0.75
East-central and south-central.	Confined	24	0.94-3.9	1.83	0.004-0.41	0.080
Southern	Confined	7	0.66-1.94	1.24	0.003-0.072	0.048
Distal southeastern	Confined	12	0.46-2.12	1.11	0.034-4.70	0.568
Total area		54	0.46-3.9	1.42	0.003-4.70	0.320

freshwater in the karst of west-central Florida and direct infiltration of seawater in the Upper and Lower Floridan aquifers along the southeastern coast of Florida). The second relation suggests that the shared characteristics of samples from central and southern Florida result from transit of the water from the distant recharge areas (that is, the uranium concentration decreases with increased distance downgradient, but the AR increases because of the alpha-recoil mechanism).

UPPER FLORIDAN AQUIFER

Uranium isotope analyses of 54 samples of ground water from the Upper Floridan aquifer (table 5, fig. 14) were used to deduce ground-water movement from the recharge areas in central Florida and the discharge areas in central and southern Florida. The salinities of the samples ranged from that of freshwater to that of seawater. Ten of the samples were from large freshwater springs in central Florida, and 44 were from deep wells. Of the 44 samples from deep wells, 4 were from the outcrop area (oxidizing environment) for the Upper Floridan aquifer in western and central Florida. Of the 10 springs sampled, 7 were from the outcrop area (oxidizing environment) and 3 were from downgradient areas where the aquifer is confined (reducing environment). Osmond and others (1974) used isotope dilution techniques to estimate ground-water contributions to Rainbow Springs (sample 91) and Silver Springs (sample 99) based on areal variations in uranium concentration and AR values. The distribution of dissolved uranium and AR values by region and hydrogeologic environment is summarized in table 6.

In west-central Florida, the area where the aquifer is unconfined, the uranium concentrations in 11 samples of ground water ranged from 0.10 to 1.91 μg/L, averaging 0.75 μg/L; the AR values ranged from 0.72 to 1.47, averaging 0.98. In east-central and south-central Florida, generally the area south and east of the outcrop area to the northern half of Lake Okeechobee, the uranium concentrations in 24 samples of ground water ranged from 0.004 to 0.41 μg/L, averaging 0.080 μg/L; the AR values ranged from 0.94 to 3.9, averaging 1.83. In southern Florida, generally the area from the southern half of Lake Okeechobee to distal southeastern Florida, the uranium concentrations in seven samples ranged from 0.003 to 0.072 μg/L, averaging 0.048 μg/L; the AR values ranged from 0.66 to 1.94, averaging 1.24. In distal southeastern Florida (Dade and Monroe Counties), the uranium concentrations in 12 samples ranged from 0.034 to 4.70 μg/L, averaging 0.568 μg/L; the AR values ranged from 0.46 to 2.12, averaging 1.11 (table 6).

The general trend indicated by the average values of dissolved uranium concentration is decreasing concentration from the outcrop area (unconfined aquifer, oxidizing environment) southward to central and southern Florida (confined aquifer, reducing environment), then increasing concentration near the coastline in distal southeastern Florida. The general trend in average AR values is increasing AR values (^{234}U increasing relative to ^{238}U) from the outcrop area southward into central Florida (confined aquifer, reducing environment), then decreasing values from central Florida into distal southeastern Florida.

The areal distribution of uranium concentration in the ground water of the Upper Floridan aquifer (fig. 15) suggests that (1) concentrations in the outcrop area (unconfined, oxidizing environment) range from 0.1 to 2.0 μg/L (zone 1, fig. 15), (2) concentrations through most of south-central and southern Florida (confined, reducing environment) range from a trace to about 0.1 μg/L (zone 2), and (3) concentrations chiefly in distal southeastern Florida (confined, reducing environment) range from about 0.1 to 0.5 μg/L (zone 3). Sample 3774, from the middle confining unit of the Floridan aquifer system, has an anomalously high concentration (4.70 μg/L) compared with the other samples in distal southeastern Florida. The indicated general trend in dissolved uranium is decreasing concentration southward from the area of recharge (outcrop area) in west-central Florida. The concentration of uranium decreases as flow conditions change from an unconfined (oxidizing) environment (zone 1) to a confined (reducing) environment (zone 2), except in east-central Florida, where concentrations in downgradient freshwater springs (samples 1120, 1123, and 1124) are comparable to those in the outcrop area (sample 1118). In south-central and southern Florida, the concentrations are mixed but generally less than 0.1 μg/L. The lowest concentrations are on coastlines in southern Florida (samples 448 and 525), suggesting (subtly at best) that concentrations generally decrease southward. Scattered within the broad expanse of low concentrations in central and southern Florida (zone 2) are areas of anomalously higher concentrations (zone 3).

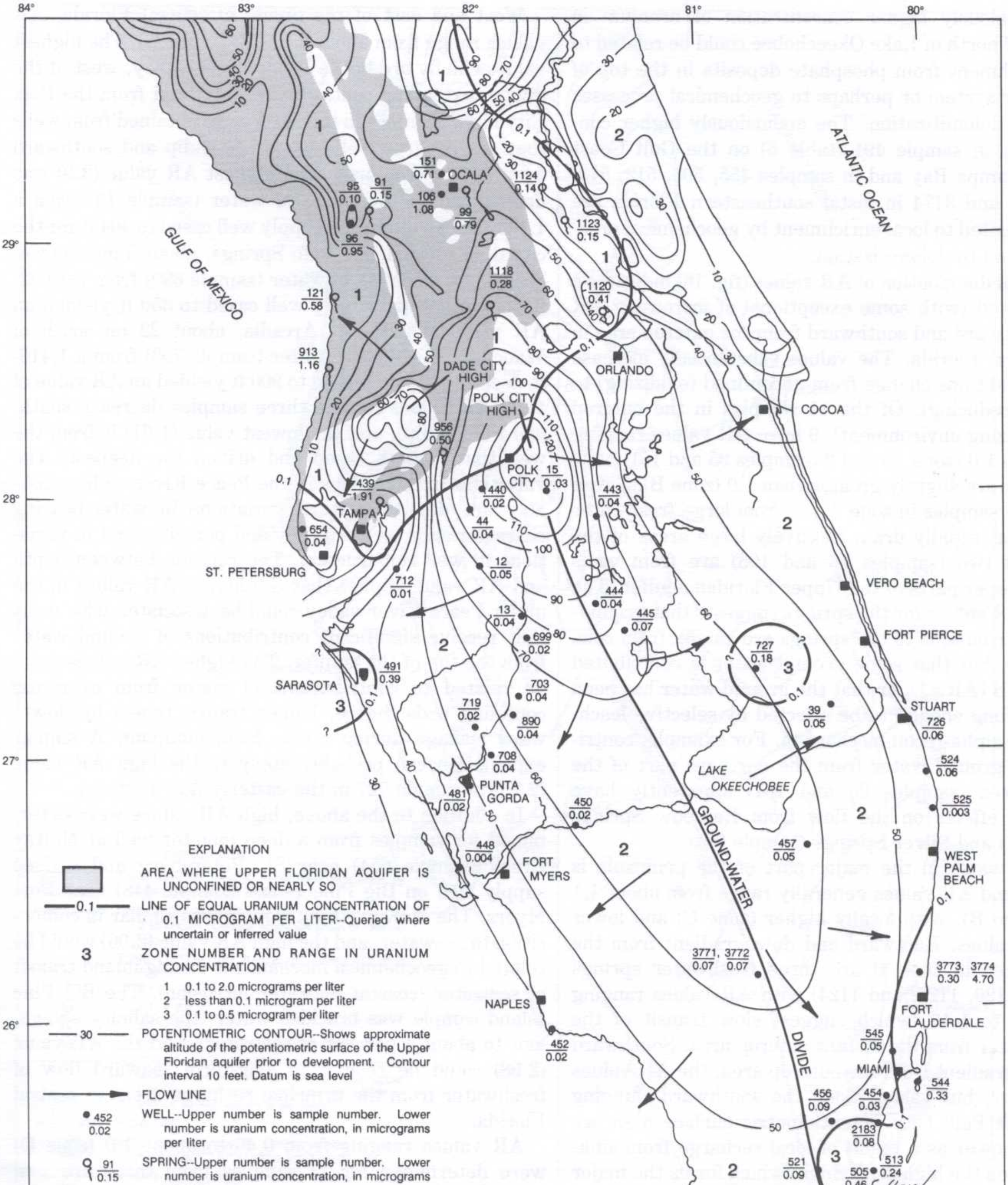

FIGURE 15.—Uranium concentration and predevelopment potentiometric surface, Upper Floridan aquifer, peninsular Florida.

The anomalously higher concentration of uranium in sample 727 north of Lake Okeechobee could be related to local enrichment from phosphate deposits in the top of the aquifer system or perhaps to geochemical processes related to dolomitization. The anomalously higher concentrations in sample 491 (table 5) on the Gulf Coast south of Tampa Bay and in samples 455, 505, 512, 513, 544, 3773, and 3774 in distal southeastern Florida are perhaps related to local enrichment by geochemical processes related to dolomitization.

The areal distribution of AR values (fig. 16) indicates a general trend (with some exceptions) of increasing AR values eastward and southward from the outcrop area in west-central Florida. The values substantially increase as flow conditions change from unconfined (oxidizing) to confined (reducing). Of the 11 samples in the outcrop area (oxidizing environment), 9 have AR values ranging from 0.7 to 1.0 (zone A) and 2 (samples 95 and 151) have values that are slightly greater than 1.0 (zone B). Seven of the nine samples in zone A are from large freshwater springs that rapidly drain relatively large areas of the karst, and two (samples 96 and 106) are from wells tapping deeper parts of the Upper Floridan aquifer. The range in AR values for the springs suggests that ground-water contributions to the springs are chiefly from zone A (AR≤1), but that some ground water is contributed from zone B (AR>1), or that the ground water has been in transit long enough to be affected by selective leaching, or the alpha-recoil mechanism. For example, contributions of ground water from the northern part of the outcrop area (samples 95 and 151) apparently have significant effects on the flow from Rainbow Springs (sample 91) and Silver Springs (sample 99).

Ground water in the major part of the peninsula is confined, and AR values generally range from about 1.1 to 2.0 (zone B), with locally higher (zone C) and lower (zone D) values. Eastward and downgradient from the outcrop area in zone B are three freshwater springs (samples 1120, 1123, and 1124) with AR values ranging from 1.19 to 1.46, which suggest slow transit of the ground water from the distant outcrop area. Southward and downgradient from the outcrop area, the AR values vary widely, but values along the southward-plunging nose of the Polk City potentiometric surface high are relatively lower as a result of local recharge from sinkhole lakes on the high sand ridge, which forms the major axis of the present-day peninsula to a point about 25 mi northwest of Lake Okeechobee. Coincident with the sand ridge is the ground-water divide that extends to the southern terminus of the peninsula and separates flow to the east and to the west. In central Florida, there is subtle but reasonable evidence that AR values increase downgradient (east and west) from this ground-water divide.

West and east of the divide in central Florida, AR values range from about 2.1 to 3.0 (zone C). The highest values chiefly are in the Peace River valley, west of the divide, extending southward about 70 mi from the Polk City high. Samples in this area were obtained from wells that are progressively deeper downdip and southward from the outcrop area. The highest AR value (3.9) was determined for a sample of water (sample 13) from a 1,103-ft-deep municipal supply well cased to 404 ft for the city of Wauchula. At Zolfo Springs, about 5 mi south of Wauchula, a sample of water (sample 699) from a 1,002-ft-deep municipal supply well cased to 350 ft yielded an AR value of 2.92. At Arcadia, about 22 mi south of Wauchula, a sample of water (sample 703) from a 1,410-ft-deep supply well cased to 900 ft yielded an AR value of 1.61. AR values for the three samples decrease southward (downdip), and the lowest value (1.61) is from the well that is both cased and drilled the deepest. The variations in AR values in the Peace River valley probably are due to vertical variations in water-bearing characteristics (permeability and porosity) and to variations in well construction. The relation between depth and AR value implies that the higher AR values in the upper Peace River valley could be associated with wells that receive significant contributions of ground water from the top of the aquifer. The higher AR values could be related to contributions of water from overlying confining beds (hence, longer transit times) by downward leakage during stress from pumping. A similar explanation can probably apply to the high AR value (2.75) in sample 727 in the easterly flow regimen.

In addition to the above, high AR values were determined for samples from a deep monitor well at McKay Creek (sample 654) near St. Petersburg and a deep supply well on Big Pine Island (sample 448) near Fort Myers. The McKay Creek sample was similar in composition to seawater, and the high AR value (2.06) would be related to geochemical mechanisms during inland transit of seawater (coastal seawater intrusion). The Big Pine Island sample was brackish water (the salinity equivalent to about 4 percent of seawater), and the AR value (2.98) could be related to long-term seaward flow of freshwater from the principal recharge areas in central Florida.

AR values ranging from 0.46 to about 1.0 (zone D) were determined for 11 samples from three areas in central and southern Florida where the aquifer is confined. As previously stated, values of about 1.0 or less are mostly found in unconfined oxidizing environments; therefore, the occurrence of values of less than unity in the confined reducing environment is considered to be anomalous. Samples 481 and 708 near the Peace River estuary have identical AR values (0.94) although the sources are vastly different. Sample 481 is from a 1,640-

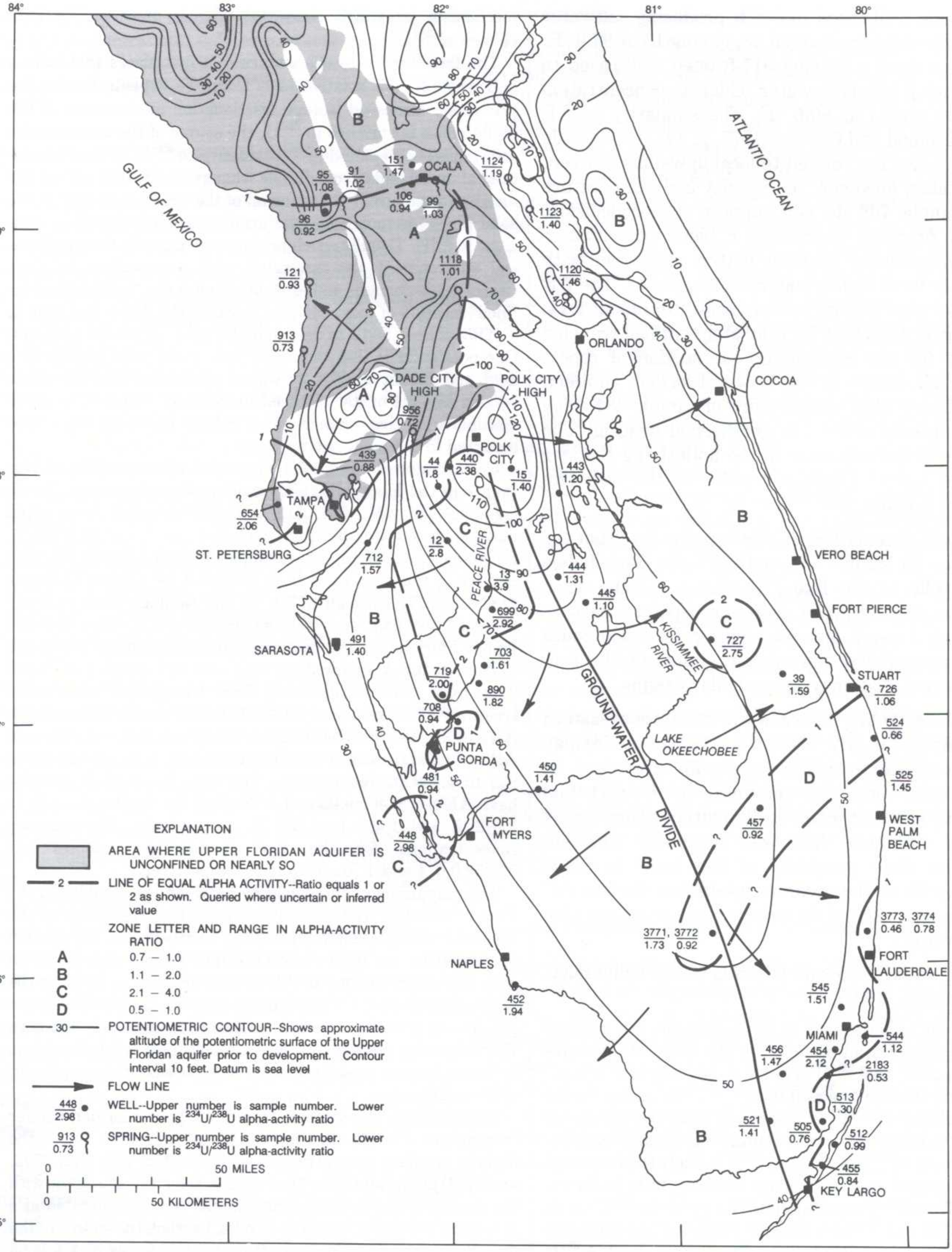

FIGURE 16.—Uranium-234/uranium-238 alpha-activity ratio and predevelopment potentiometric surface, Upper Floridan aquifer, peninsular Florida.

ft-deep flowing well cased to 648 ft producing saltwater (chloride concentration of about 18,400 mg/L) at 96.0 °F. Sample 708 is from a flowing 917-ft-deep well cased to 595 ft producing brackish water (chloride concentration of about 380 mg/L) at 80.6 °F. The similarity in AR values led Osmond and Cowart (1977, p. 145) to conclude that both samples are related to local upwelling of deep, warm saltwater; however, the salinity and temperature data for sample 708 do not support that conclusion. Sample 481 probably represents a blend of saltwater (seawater-like salinity) from the bottom of the well with fresher water from higher water-bearing zones. The AR value is lower than that for modern seawater (about 1.14) and much lower than that for seawater that had traveled significantly far (for comparison see section of report concerning AR values in the Lower Floridan aquifer). The anomalously high temperature of sample 481 (96.0 °F) is undoubtedly related to geothermal heating. The temperature of the saltwater in the underlying Boulder Zone of the Lower Floridan aquifer at the well site (sample 481) is about 110 °F (see fig. 7).

Cowart and others (1978, p. 169) hypothesized that the low AR value for sample 457 south of Lake Okeechobee may be a relic of the late Pleistocene Epoch, when oxidized waters ($AR \leqq 1.0$) were transported farther downgradient through discrete solution features (zones of high transmissivity) during low stands of the sea. Samples 524 and 3772 may have similar origins.

The anomalously low AR values in distal southeastern Florida (samples 455, 512, 505, 2183, 3773, and 3774) may have origins similar to that of sample 457. However, an alternate explanation was proposed by Cowart and others (1978), one that involves dissolution of previously precipitated uranium that was originally deficient in ^{234}U. The close proximity of the wells in distal southern Florida to the ocean suggests that the low AR values there are related to geochemical reactions that involve seawater.

According to J.B. Cowart (Florida State University, written commun., 1984),

> the mechanisms hypothesized to be responsible for uranium isotope disequilibrium all assume (on the basis of extensive radiochemical data) that ^{234}U is likely to be more mobile (and, thus, end up in the liquid phase) than ^{238}U. The reason for the increased mobility of ^{234}U is associated with the radiogenic origin of the isotope. The formation of ^{234}U results from the radioactive decay of ^{238}U so that (1) ^{234}U is likely to be situated in a lattice-damaged site (the damage resulting from its formation from ^{234}Th and ^{234}Pa (palladium-234)), or (2) the ^{234}U (or its precursors ^{234}Th and ^{234}Pa) is directly propelled into the liquid phase surrounding the solid phase by direct alpha recoil. A ^{234}U atom in a lattice-damaged site is less tightly bound to the solid and is, therefore, more likely to be leached from the solid than is the ^{238}U situated in an undamaged site. There is no known mechanism by which elemental ^{238}U is more mobile than elemental ^{234}U.
>
> The fact that there are waters in a few places that have a deficiency of ^{234}U relative to ^{238}U can be explained using the previously discussed isotope fractionation mechanisms. If the liquid phase is enriched in ^{234}U, the source of the uranium (the solid) must be depleted in ^{234}U relative to ^{238}U. If the environmental geochemical conditions change such that all of the uranium in the solid phase (or all of the uranium in part of the solid phase) is mobilized, the uranium entrained will be deficient in ^{234}U. Usually, such profound changes in the geochemical environment are associated with near-surface locations (water-table changes and erosion)—hence the "oxidized unconfined" location of most samples in which the AR is less than 1.
>
> AR's of less than 1 in deep samples pose a different problem. One possibility is that the water was transported rapidly to a deep and distant location by way of conduits so that the water retains aspects of its "oxidized unconfined" origin. The other possibility is that changes of a rather profound type have occurred in the deep environment.
>
> Cowart and others (1978) suggested that the AR's of less than 1 in the Upper Floridan aquifer of southeastern Florida (samples 455, 457, 505, 512, and 524) resulted from rapid movement of water from the recharge area to south Florida. Since that publication, other samples from the Upper Floridan aquifer in the area have been analyzed by Cowart (samples 2183 and 3771 through 3774). Of the samples more recently collected, two pairs representing vertical sets of water from the Upper Floridan aquifer have been analyzed (samples 3771 and 3772 from the Alligator Alley test well and samples 3773 and 3774 from Fort Lauderdale's Port Everglades wastewater treatment plant monitor wells). Of the four samples, three have AR's of less than 1. The Alligator Alley test well samples have AR's of 1.73 ± 0.15 and 0.92 ± 0.13 for depths of 811 to 816 ft and 895 to 1,150 ft, respectively. The Fort Lauderdale samples have AR's of 0.46 ± 0.03 and 0.78 ± 0.02 for depths of 1,021 to 1,072 ft and 1,466 to 1,562 ft, respectively. The uranium concentrations for the Fort Lauderdale samples are 0.305 ± 0.014 and 4.70 ± 0.30 µg/L, respectively.
>
> The magnitude of the disparity between the samples in the Fort Lauderdale well strongly suggests that the source of the <1-AR uranium is relatively nearby. Furthermore, the dilution or mixing of the higher concentration sample (sample 3774) with any water having an AR of 0.46 or more to produce the uranium concentration and isotope ratio of sample 3773 is not possible. It is not known whether the other samples in southern Florida having AR's of less than 1 result from relict circulation or from changes in environment; it is possible they represent some combination.
>
> Interestingly, the samples from the Upper Floridan aquifer in southern Florida that have AR's of less than 1 and the highest uranium concentrations (samples 455, 505, 512, 3773, and 3774) are located near the coast. A scenario consistent with the results is one in which uranium has been precipitated at a geochemical barrier, possibly a redox barrier, the source of the dissolved uranium being seawater. With changes in sea level and hydraulic head, the precipitated uranium was isolated in a reducing environment, wherein by the process of alpha recoil it became depleted in ^{234}U. With the advent of geochemical-redox

changes, the precipitated uranium became mobile (thus, the relatively high concentration), and it was, of course, deficient in ^{234}U (AR of less than 1). Such a scenario is unlikely for the more inland samples (samples 481, 708, 457, and 3772) that have AR's of less than 1.

The explanation for the apparent AR anomalies are, therefore, many and diverse and could involve several processes. Dolomitization, for example, may be important in the selective precipitation of elemental uranium. An investigation of high gamma-ray emissions from dolostone in the Lower Floridan aquifer at Stuart (fig. 2, site 6) in 1974 by borehole spectrometry indicated that uranium was the probable source (W.S. Keyes, U.S. Geological Survey, written commun., 1974). The low AR anomaly in distal southeastern Florida could be linked to the mixing of magnesium-rich seawater with brackish bicarbonate-type ground water (Hanshaw and Back, 1971) to yield dolomite that perhaps has excess ^{234}U. Lowered temperatures (less than 77 °F) along the southeastern coast may enhance the dolomitization process. In other areas, upwelling of warm, magnesium-rich, relatively young seawater from the Boulder Zone may also produce uranium-rich dolomite and AR anomalies. Also, some of the AR anomalies may be due to experimental error since the uranium concentration in the brackish artesian water of southern Florida is generally very low.

The trends in dissolved uranium concentration and AR values suggest that flow originated from the outcrop area (figs. 15, 16); however, predevelopment heads in the Upper Floridan aquifer, as indicated by the potentiometric surface map, suggest that flow in the outcrop area is chiefly westward toward the Gulf of Mexico. This discrepancy could be related to changes in flow patterns as a result of sea-level fluctuations, and perhaps climatic changes, during the Holocene transgression. Plummer (1977, p. 811) estimated that the ground water at Polk City (the highest heads)—the northernmost source of flow to central and southern Florida—is about 3,200 to 8,000 yr old (water samples contain about 67 percent of modern carbon) and that the average southward velocity was about 32 ft/yr. Therefore, the present-day concentration gradients are perhaps, to a large degree, a relic of antecedent flow patterns when the principal recharge area was perhaps 20 mi north of the Polk City potentiometric surface high.

To date, the uranium isotope data for the Upper Floridan aquifer are meager and present a complex picture of the regional flow system. Data from discrete water-bearing zones in the Upper Floridan aquifer are necessary prerequisites for correct interpretation, and further investigation is needed into the possible causes of the apparent anomalies.

Lower Floridan Aquifer

Uranium isotope analyses of eight samples of salty ground water from the Lower Floridan aquifer (chiefly the Boulder Zone) in southeastern Florida were used to evaluate the potential for inland circulation of seawater from the Straits of Florida (tables 4, 5; fig. 14). A sample from a deep monitor well at site 9 (well G–2331) was not included because the sample was contaminated with drilling fluid. The uranium concentration in the eight samples ranged from 0.45 μg/L in sample 520 to 7.97 μg/L in sample 3605, averaging 2.90 μg/L. The AR values ranged from 1.14 to 1.50, averaging 1.24. The uranium concentrations in six samples are less than that of worldwide seawater (U=3.30±0.14 μg/L). The anomalously high uranium concentration (7.97 μg/L) in sample 3605 is unexplained. The areal distribution of uranium (fig. 17) shows that concentrations generally decrease radially inland from site 9 in the Fort Lauderdale area, where the concentration compares best to that of seawater. The inland concentration gradient suggests that uranium is either precipitated or adsorbed during transit from a source in the Straits of Florida. A similar flow was indicated by the radiocarbon data.

The AR values for the samples from the Lower Floridan aquifer generally increase radially inland from site 9 in the Fort Lauderdale area, where the AR value is identical to that in seawater (fig. 17). The inverse gradient suggests that ^{234}U increases relative to ^{238}U, probably by the alpha-recoil phenomenon during transit inland of seawater from a source area in the Straits of Florida, east of Fort Lauderdale. Therefore, the increase in AR values is an indication of time in transit through the Boulder Zone, and the AR data correspond with both the uranium concentration data and the radiocarbon data.

FLOW PATTERNS BASED ON HYDRAULIC GRADIENTS

The maximum hydraulic gradient (dh/dl) along a flow path indicates the direction of ground-water movement, whereas the rate of movement is dependent on the hydraulic gradient and the hydraulic properties of an aquifer—specifically, hydraulic conductivity and porosity. The average effective linear velocity of ground water ($\bar{v}$) in a homogeneous and isotropic porous medium is explained by Darcy's law, which is expressed by the following equation:

$$\bar{v}=\frac{K\,(dh/dl)}{\phi} \qquad (6)$$

where

$\bar{v}$ = average effective linear velocity, in feet per day;
K = hydraulic conductivity, in feet per day;

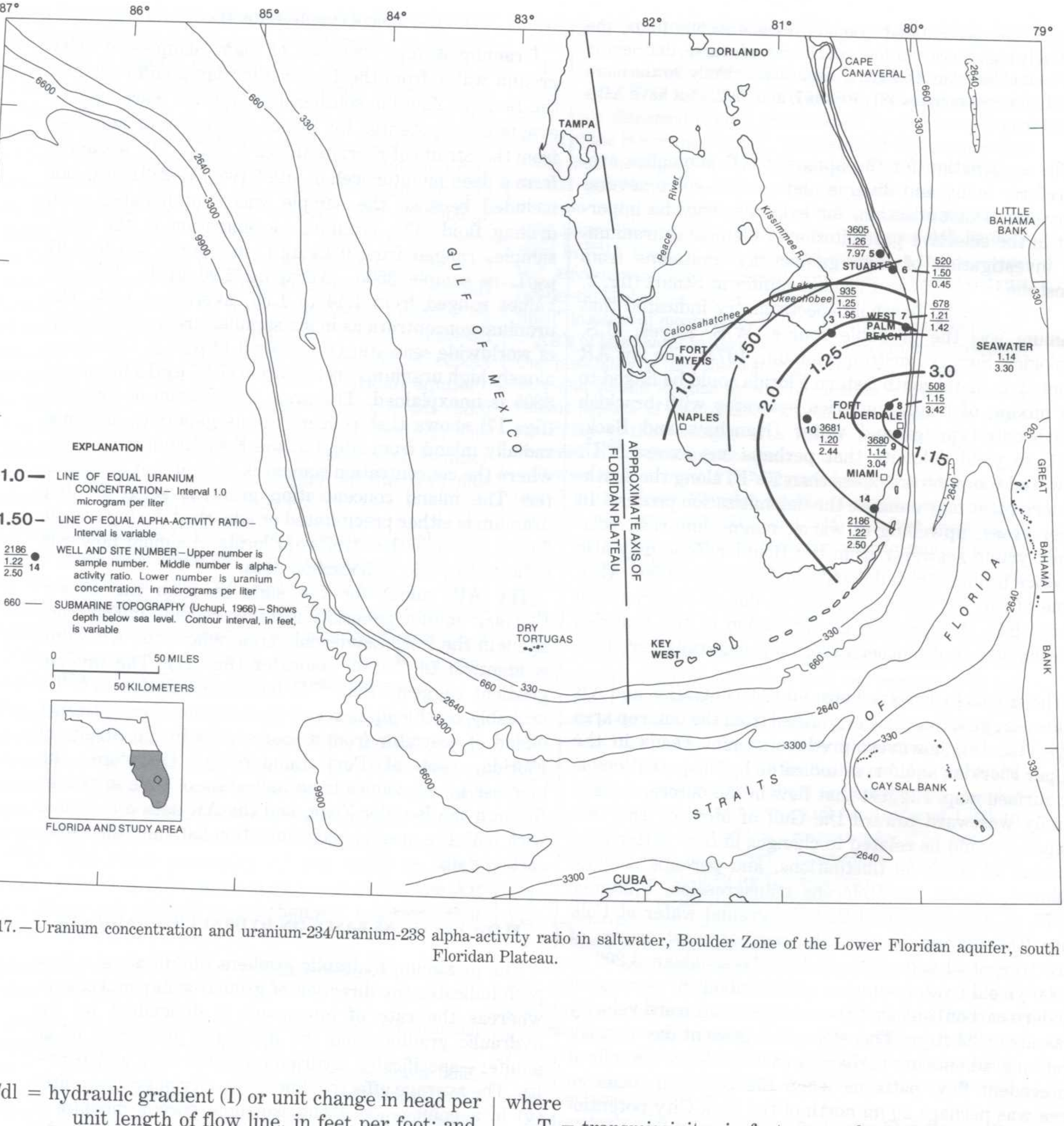

FIGURE 17.—Uranium concentration and uranium-234/uranium-238 alpha-activity ratio in saltwater, Boulder Zone of the Lower Floridan aquifer, south Floridan Plateau.

dh/dl = hydraulic gradient (I) or unit change in head per unit length of flow line, in feet per foot; and

ϕ = effective porosity.

Where hydraulic conductivity and effective porosity are constant, changes in hydraulic gradient indicate relative changes in velocity. Velocity can also be determined by the equation

$$\bar{v}=\frac{T\times I}{m\times \phi} \quad (7)$$

where

T = transmissivity, in feet squared per day;

m = aquifer thickness, in feet; and

I = hydraulic gradient (dh/dl), in feet per foot.

UPPER FLORIDAN AQUIFER

Measurements of head in the Floridan aquifer system are chiefly confined to the upper part of the aquifer system, where most wells were constructed. Maps of the

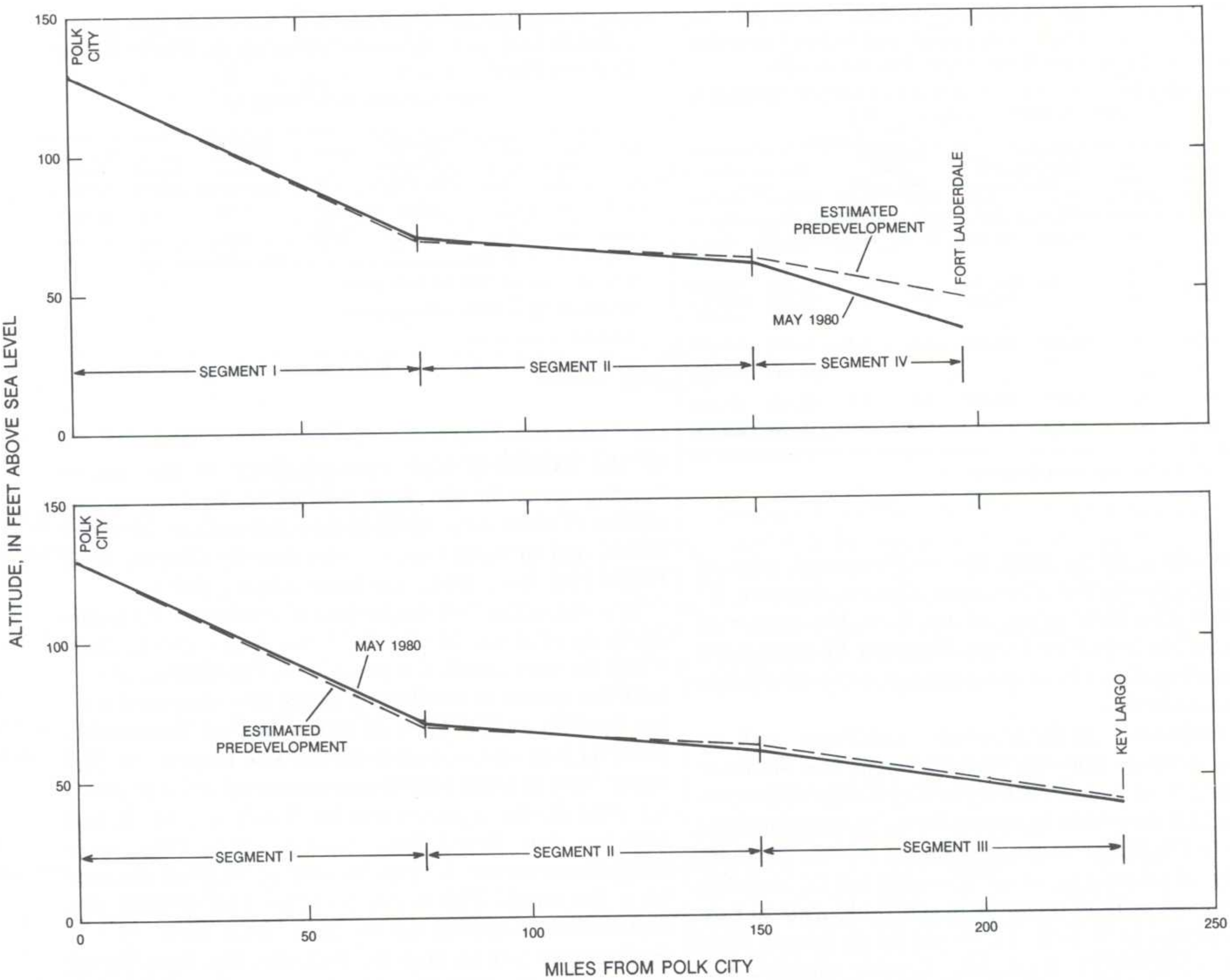

FIGURE 18.—Estimated predevelopment and May 1980 hydraulic gradients along flow lines from Polk City to Key Largo and Fort Lauderdale, Upper Floridan aquifer. (Location of segments shown in fig. 11.)

potentiometric surface of the Upper Floridan aquifer (see map for 1980, fig. 4) are periodically prepared by the U.S. Geological Survey and other government agencies from measurements of water levels in many wells throughout the State. The maps show the configuration of the contours representing the prevailing isopotentials, and ground-water movement is downgradient (that is, from areas of high potential to areas of low potential) and approximately normal to the contours if the aquifer system is assumed to be isotropic. Movement of ground water in the Upper Floridan aquifer is shown by flow lines radiating generally from the area of highest head in central Florida near Polk City (fig. 4). South of the Polk City potentiometric surface high, the head in the aquifer declines gradually along a flow line that divides flow to the Atlantic Ocean on the east and the Gulf of Mexico on the west.

To gain insight into the rate of ground-water movement southward from the Polk City potentiometric surface high in central Florida, estimates of velocities and transit times were calculated for estimated predevelopment hydraulic gradients along selected segments of flow lines from Polk City to Key Largo and to Fort Lauderdale (fig. 18).

The estimates are further based on the assumptions that (1) predevelopment hydraulic gradients were unaffected by changes in sea level and climate, (2) the transmissivity (T) of the Upper Floridan aquifer is distributed according to Bush (1982, fig. 6), (3) the thickness of the aquifer (m) is 500 ft, and (4) the effective porosity (ϕ) is 0.30 (table 7) and vertical flow is negligible. Segment I represents the flow along 75 mi from Polk City to about the southernmost point of recharge by sinkhole lakes in central Florida. Segment II represents

TABLE 7.—*Estimated transit times along flow lines from the Polk City potentiometric surface high to Key Largo and to Fort Lauderdale under predevelopment gradients, Upper Floridan aquifer*

[Based on aquifer thickness of 500 feet and porosity of 0.30. Location of flow segments shown in fig. 11]

Flow segment	Head difference (feet)	Distance (miles)	Transmissivity (feet squared per day) Minimum	Transmissivity (feet squared per day) Maximum	Velocity (feet per year) Minimum	Velocity (feet per year) Maximum	Transit time (years) Minimum	Transit time (years) Maximum
I	60.5	75	100,000	250,000	37	93	4,300	11,000
II	8.2	72						
	[1]4.1	[1]36	[1]100,000	[1]250,000	[1]5.2	[1]13	[1]15,000	[1]36,000
	[1]4.1	[1]36	[1]10,000	[1]50,000	[1]0.5	[1]2.6	[1]73,000	[1]380,000
							88,000	416,000
III	21.8	80	10,000	50,000	1.2	6.3	67,000	352,000
I-III	90.5	227					159,000	779,000
IV	14.3	47	10,000	50,000	1.4	7.0	35,000	177,000
I,II,IV	83.0	194					127,000	604,000

[1]Segment II divided into two subsegments.

the flow along 72 mi from the southernmost point of recharge to the center of southern Florida. Segment III represents the flow along 80 mi from the center of southern Florida to Key Largo. Segment IV represents the flow along 47 mi from the center of southern Florida to Fort Lauderdale.

For estimated predevelopment gradients and an assumed average porosity of 0.30, a particle of water traveling 227 mi from Polk City to Key Largo (segments I through III) would be in transit for a time ranging from 159,000 to 779,000 yr, depending on the estimated transmissivity. A particle of water traveling 152 mi from the southernmost point of recharge in central Florida to Key Largo (segments II and III) would be in transit from 155,000 to 768,000 yr. A particle of water traveling 119 mi from the southernmost point of recharge to Fort Lauderdale (segments II and IV) would be in transit from 123,000 to 593,000 yr. Locally, a particle of water traveling 47 mi (segment IV) from the center of southern Florida (site 10) to Fort Lauderdale (site 9) would be in transit from 35,000 to 177,000 yr. Only the transit time between sites 10 and 9 (segment IV) is within the 40,000-yr useful range of carbon-14 dating. Therefore, the occurrence of measurable carbon-14 activity in the brackish ground water in southern Florida strongly suggests that infiltrating freshwater in central Florida is not the only source.

LOWER FLORIDAN AQUIFER

Estimates of movement of ground water in the Lower Floridan aquifer have chiefly been based on indirect evidence because measurements of representative head are difficult to obtain. Attempts to calculate hydraulic gradients between a few closely spaced wells for which data are available have largely been unsuccessful owing

TABLE 8.—*Comparison of pressure head and related data between well G-2334 at site 9 and well G-2296 at site 10, Boulder Zone of the Lower Floridan aquifer*

[Site locations shown in fig. 2]

Well No.	Site No.	Average temperature (°F)	Dissolved solids[1] (milligrams per liter)	Salinity (per mil)	Density[2] (grams per cubic centimeter)	Water level[3] (feet)	Pressure head[4] (feet)
G-2334	9	62.2	37,500	36.62	1.02683	0.2	2,875.3
G-2296	10	78.8	37,500	36.62	1.02427	7.0	2,875.1

[1]Assumed to be the same for both wells.

[2]At prevailing salinity and temperature.

[3]Referred to sea level.

[4]At 2,800 feet below sea level; density equals 1.00000 g/cm^3 (gram per cubic centimeter).

to the extremely high transmissivity of the water-bearing zones in the Lower Floridan aquifer, to the effects of short-term tidal-caused fluctuations in water levels, and to variations in water density (Meyer, 1974; CH_2M Hill, Inc., 1981; Singh and others, 1983).

In recognition that the hydraulic gradient for a transmissivity of about 2.5×10^7 ft^2/d (Singh and others, 1983) would be very small, the head in well G–2296 at site 10 near the center of southern Florida was compared with the head in well G–2334 at site 9 in Fort Lauderdale about 44.5 mi east of well G–2296 at site 10 (table 8). The water level in well G–2296 was measured at 7.0 ft above sea level during a packer test on March 4, 1981. It was assumed that fluctuations resulting from tides were insignificant at well G–2296 because of its great distance from the coast. The water level in well G–2334 was continuously recorded during May 16–20, 1983, after a performance test on May 10, 1983 (fig. 19). Semidiurnal tides caused the water level to fluctuate about 0.5 ft, but the daily mean water level rose about 0.6 ft during the period as the density of the water column decreased owing to heating. The water level was about 0.2 ft above sea level on May 26, 1981, when a temperature survey (log) of the water column was obtained (fig. 6).

The density of the borehole fluid in each well was calculated from oceanographic tables (U.S. Navy, 1962) based on measurements of salinity (dissolved solids) and temperature, and the pressure heads were calculated for each well at a common depth of 2,800 ft below sea level for a common fluid density of 1.0000 gram per cubic centimeter (g/cm^3). Salinity was based on the dissolved solids residue upon evaporation at 180 °C in a sample of water from well G–2334 at site 9. The lack of precision in the dissolved solids analyses required an assumption of uniform salinity. The average temperature of the borehole fluid (salinity comparable to seawater) in each well was determined from temperature logs.

The pressure head at well G–2334, site 9, was about 0.2 ft higher than that at well G–2296, site 10. The apparent

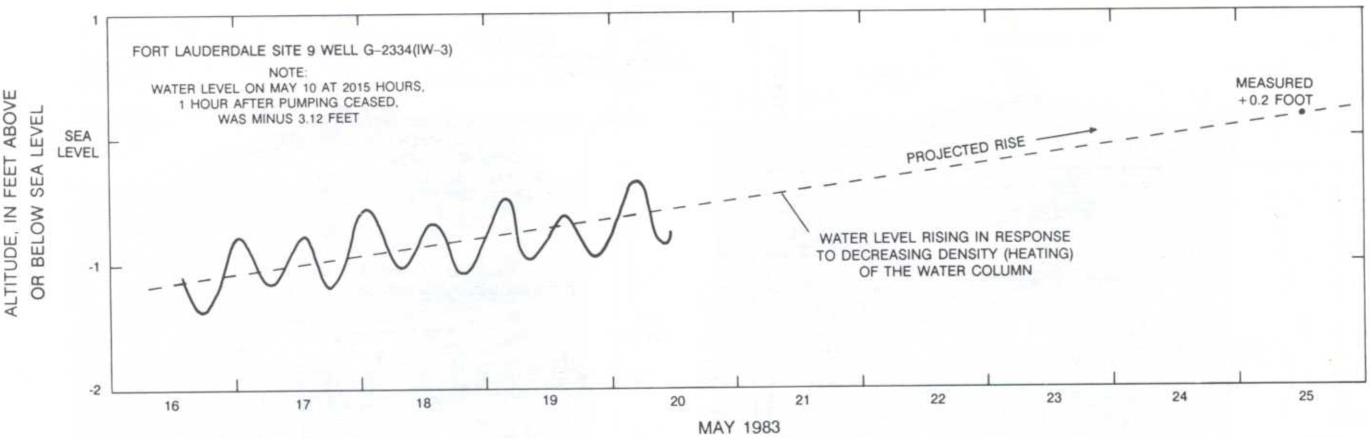

FIGURE 19.—Hydrograph of water level (saltwater) in well G-2334 at site 9 near Fort Lauderdale, Boulder Zone of the Lower Floridan aquifer. (Location of site 9 shown in fig. 2.)

inland hydraulic gradient, I, was estimated by the equation

$$I=\frac{0.2\text{ foot}}{44.5\text{ miles}}\times\frac{1\text{ mile}}{5{,}280\text{ feet}} \quad (8)$$
$$=8.5\times10^{-7}$$

The average water velocity, $\bar{v}$, was estimated by the equation

$$\bar{v}=\frac{T\times I}{m\times\phi}\times365 \quad (9)$$

where
$\bar{v}$ = average water velocity, in feet per year;
T = 2.5×10^{7} ft^2/d;
m = 650 ft;
I = 8.5×10^{-7}; and
ϕ = porosity, ranging from 0.2 to 0.4.

Based on the estimated hydraulic gradient (8.5×10^{-7}), the average velocity of ground-water flow through the Boulder Zone from site 9 to site 10 ranges between 59.7 and 29.8 ft/yr for porosities ranging from 0.2 to 0.4, and the transit time ranges from 3,900 to 7,900 yr.

A comparison of the estimated hydraulic gradient, velocity, and transit time from water-level measurements at sites 9 and 10 with those estimated by radiocarbon dating suggests that the calculated difference in head may be too high (table 9, measurement 1). The estimated gradients and velocities based on transit time from radiocarbon dating suggest a gradual decrease in gradient and velocity during the past 7,500 yr. The present-day gradient and velocity would probably be closer to 3.8×10^{-7} and 17 ft/yr, respectively. The difference in head between the wells, located 44.5 mi apart, would then be only 0.09 ft—a relatively small value compared with the range of tidal fluctuations at the coast and with the corrections in head for differences in fluid density. Another possibility is that the ground-water velocity calculated by equation 9 is on the basis of porous-medium concept. However, ground-water flows through the Boulder Zone may be best described by conduit or fracture flow, which normally is faster than flow in porous media. No acceptable fracture flow equations are available to calculate such velocity.

EFFECTS OF RISING SEA LEVEL ON GROUND-WATER MOVEMENT

Sea level is generally accepted as the lower limit for hydraulic gradients in natural surface-water and ground-water flow systems. During periods of constant climate (no changes in rainfall and temperature) and rising sea level, freshwater in aquifer storage would gradually be displaced by seawater. During periods of constant climate and falling sea level, seawater in aquifer storage would gradually be displaced by freshwater.

TABLE 9.—*Estimated hydraulic gradients and related hydraulic data based on measured water levels and radiocarbon dating, Boulder Zone of the Lower Floridan aquifer*

[Based on transmissivity of 2.46×10^{7} feet squared per day, thickness of 650 feet, and porosity of 0.30. Site locations shown in fig. 2]

Measurement No.	Referenced segment	Distance (miles)	Head difference (feet)	Hydraulic gradient (feet per foot)	Average velocity (feet per year)	Transit time (years)
1	Site 9 to site 10[1]	44.5	0.2	8.5×10^{-7}	39.0	6,025
2	Site 9 to site 10[2]	44.5	.28	1.2×10^{-6}	54.6	4,300
3	Subsea outcrop to site 9[2].	10.5	.021	3.8×10^{-7}	17.3	3,200
4	Subsea outcrop to site 10[2].	55.0	.24	8.4×10^{-7}	38.7	7,500

[1]Calculation based on fluid density, water-level measurements, and assumed aquifer characteristics.
[2]Calculation based on radiocarbon age and assumed aquifer characteristics.

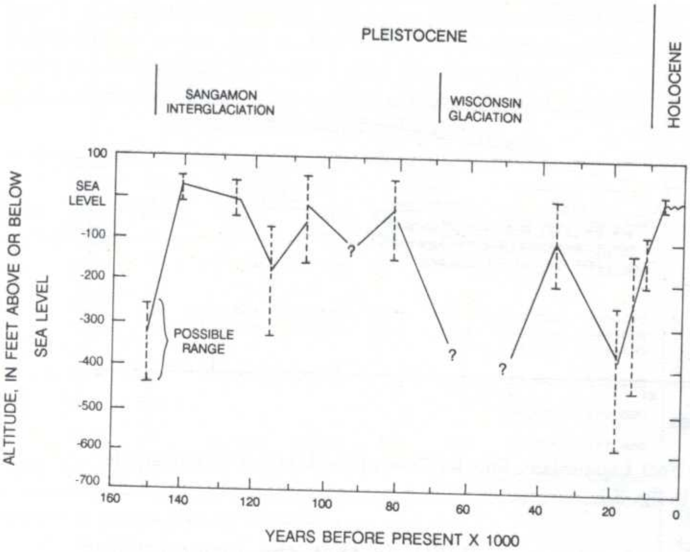

FIGURE 20.—Sea-level fluctuations during the late Pleistocene and Holocene Epochs.

Sea-level fluctuations during the past 150,000 yr (Cronin, 1983) range from about 23 ft above present sea level at about 140,000 yr B.P. (before present) to about 330 ft below present sea level at about 18,000 yr B.P. (fig. 20). High stands of sea level represent interglacial stages, and low stands represent glacial stages. The last rise in sea level, called the Holocene transgression, began about 18,000 yr ago and is continuing, although at a much slower rate. Predevelopment hydraulic gradients of the Floridan aquifer system in the late 1800's were, therefore, temporary and do not relate directly to antecedent flow conditions. However, flow rates based on radiocarbon dating (or the relative carbon-14 ages of water) reflect average antecedent hydraulic gradients. Therefore, estimates of hydraulic gradients, velocities, and transit times based on carbon-14 dating should consider the effects of changes in sea level, climate, topography, and perhaps permeability.

Data on paleoclimates, paleohydraulic gradients, paleotopography, and paleopermeability are generally lacking; however, data on changes in vegetative types during the past 8,500 yr in central Florida and southern Georgia (Watts, 1971) suggest that changes in forest types probably relate to rising sea level. Watts (1971, p. 676) reported that pollen studies of bottom sediments in upland lakes in central Florida and southern Georgia showed that from about 8,500 to 5,000 yr B.P. (based on radiocarbon age) the vegetation was chiefly oak (*Quercus*) and that for the past 5,000 yr, the vegetation has chiefly been pine (*Pinus*). Prior to 8,500 yr B.P., a long hiatus occurred in sedimentation (about 27,000 yr) which probably resulted from greatly lowered water levels during the Wisconsin glaciation. Watts (1971, p. 686)

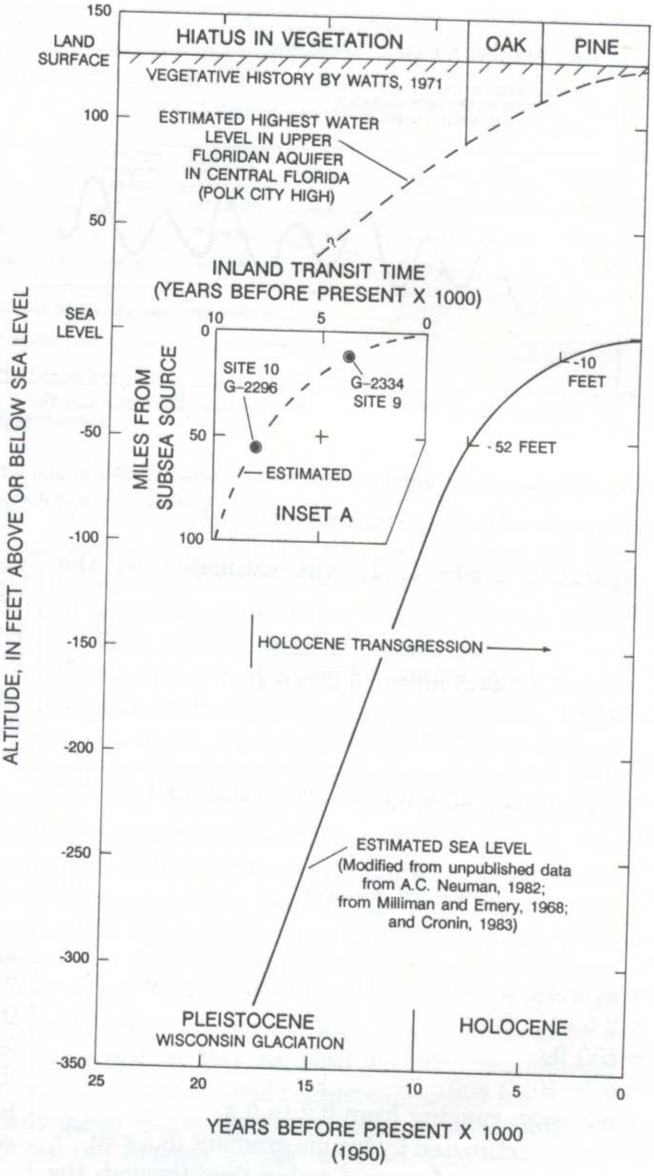

FIGURE 21.—Comparisons of water level in central Florida, vegetation, and transit distance from subsea outcrop with sea level during the Holocene transgression. (Location of sites shown in fig. 2.)

estimated that during the hiatus, the water table was probably at least 40 ft below that of today, and he concluded that the changes in vegetation were chiefly caused by rising water tables and sea level rather than by increased rainfall.

The estimated rise in sea level during the Holocene transgression is shown in the conceptual cross section (fig. 21), along with the hypothetical rise of the water level in the Upper Floridan aquifer at the center of the Polk City high and the changes in forest vegetation according to Watts (1971). The hypothetical relationships suggest that at the beginning of the Holocene transgres-

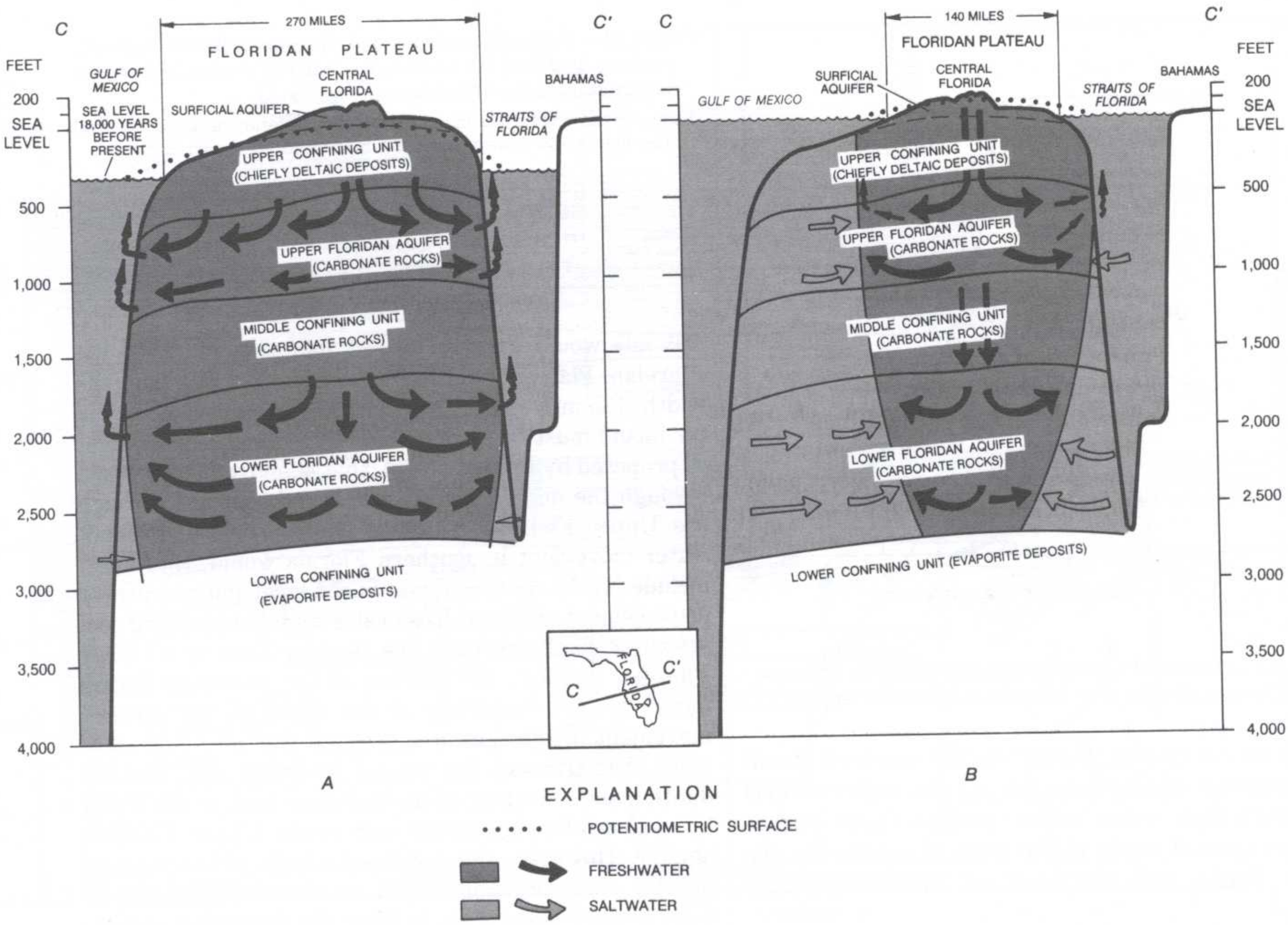

FIGURE 22.—Hypothetical hydrogeologic sections through the Floridan Plateau for (*A*) 18,000 years B.P. and (*B*) present.

sion, ground-water levels in central Florida were relatively high above sea level but low with respect to land surface. From 18,000 to 9,800 yr B.P., sea level was estimated to have risen about 0.03 ft/yr and water levels in central Florida were estimated to have risen about 0.008 ft/yr; water levels during this period in central Florida were too far below land surface for appreciable forest growth. From 9,000 to 5,000 yr B.P., sea level probably rose about 0.01 ft/yr and ground-water levels in central Florida rose about 0.006 ft/yr; water levels during this period in central Florida were sufficiently near land surface (within 20 to 40 ft) to sustain growth of oak forests. From 5,000 yr B.P. to the present, both sea level and water level in central Florida probably rose at the same rate, about 0.004 ft/yr; water levels in central Florida were sufficiently near land surface (within 20 ft or less) to sustain growth of pine forests. Dissolution of limestone during the Holocene transgression probably resulted in a slight increase in the permeability of the Floridan aquifer system.

The retreat of the glaciers (and hence the rise in sea level) during the Holocene transgression probably lagged behind the change (global warming) in worldwide climate, and rainfall over the Floridan Plateau probably was subtropical. Drainage in central peninsular Florida was chiefly subsurface through the Floridan aquifer system, and the part beneath the exposed land mass probably was filled with freshwater (fig. 22*A*). As sea level rose (rapidly at first), seawater moved inland through the Floridan aquifer system and displaced the stored freshwater (fig. 22*B*). Freshwater discharge to the Atlantic Ocean and the Gulf of Mexico by submarine springs decreased (principal discharge probably confined to the Straits of Florida). Continued subtropical rainfall maintained high water levels in central Florida so that the freshwater head was above land surface over most of the coastal areas. Circulation of freshwater in the Floridan aquifer system was restricted both laterally and vertically, and shallow circulation patterns developed in which karst features that earlier were sources of

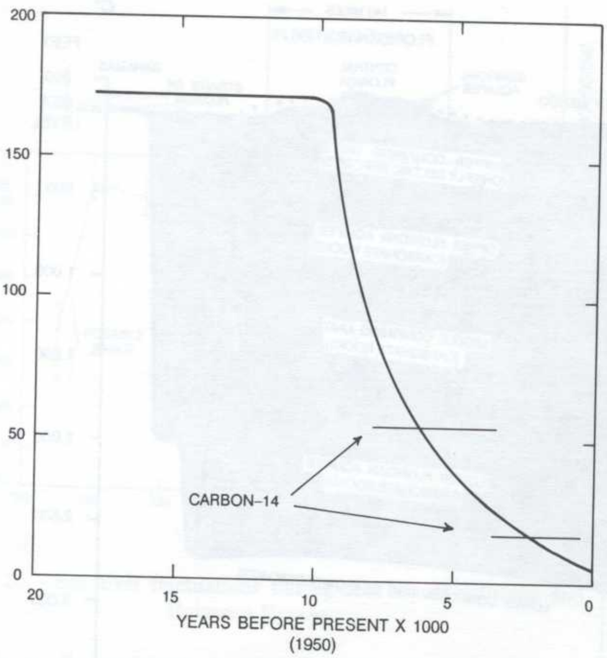

FIGURE 23.—Theoretical velocity distribution during the Holocene transgression, Boulder Zone of the Lower Floridan aquifer.

recharge to the system (during the low sea-level stand) became sources of discharge during the high sea-level stand. With high water tables, outflow (both surface water and ground water in the surficial aquifer) to the Atlantic Ocean and the Gulf of Mexico probably increased.

Results of radiocarbon dating of seawater from the Boulder Zone (in the Lower Floridan aquifer) suggest that the rise of movement inland may be directly related to the rise in sea level. Comparison of the estimated inland transit curve based on apparent carbon-14 ages of samples at sites 9 and 10 (see inset A in fig. 21) with the sea-level curve (fig. 21) suggests that seawater moved inland about 1 mi for each 1-ft rise in sea level. The velocity of seawater moving inland in south Florida probably was greatest at the beginning of the Holocene transgression and least at the end (present). The velocities, based on assumed aquifer characteristics ($T=2.5 \times 10^7$ ft^2/d, m=650 ft, and $\phi=0.3$) ranged from about 172 to 5 ft/yr (fig. 23). The corresponding hydraulic gradients would, therefore, range from 3.7×10^{-6} to 1.1×10^{-7} (table 10), and the corresponding differences in head between sites 9 and 10 (44.5 mi apart) would be about 0.87 and 0.026 ft. Again, these values are relatively small compared with transient effects of tides and changes in fluid density.

The distance traveled by a water particle moving inland through the Lower Floridan aquifer from the Straits of Florida during the Holocene transgression (330-ft rise × inland movement of 1 mi per 1 ft of rise = 330 mi) would greatly exceed half the width of the Floridan Plateau (width (fig. 22A), 270 mi; half the width, 135 mi), suggesting that the movement of seawater inland must be accompanied by a circulation system, as proposed by Kohout (1965) (that is, movement upward through the middle confining unit and seaward through the Upper Floridan aquifer). The scenario of groundwater movement in southern Florida would, therefore, include (1) the continued rise in sea level and concurrent displacement of stored freshwater by inland-moving cool seawater chiefly through the Boulder Zone (the Lower Floridan aquifer), (2) heating of the seawater during inland transit (lowering of the density), (3) upward movement of the seawater through fractures and sinkholes that transect the middle confining unit, and (4) dilution and transport of the seawater back to the ocean by seaward-flowing freshwater in the Upper Floridan aquifer. However, the combined effects of heating and dilution alone probably would provide sufficient loss of head in the Boulder Zone to drive the circulation regardless of changes in sea level.

TABLE 10.—*Estimated maximum and minimum velocities, hydraulic gradients, and head loss between sites 9 and 10 during the Holocene transgression, Lower Floridan aquifer*

[Based on radiocarbon dating and theoretical relation between sea level rise and inland transit in fig. 23. Site locations shown in fig. 2]

	Velocity (feet per year)	Hydraulic gradient (feet per foot)	Hydraulic gradient (feet per mile)	Distance (miles)	Head loss (feet)
Maximum	172	3.7×10^{-6}	1.9×10^{-2}	44.5	0.87
Minimum	5	1.1×10^{-7}	5.8×10^{-4}	44.5	0.026

The time involved in the circulation is short by geologic standards but extremely long by man's standards. The circulation is best shown by flow lines in figure 24. Fractures and sinkholes, which transect the middle confining unit, hydraulically connect the Upper Floridan aquifer with the Boulder Zone (Lower Floridan aquifer) near the coastline. Relatively young, cold seawater flows into the Boulder Zone through the sinkholes and fractures, then is heated as it flows inland. Some saltwater moves upward into the Upper Floridan aquifer through sinkholes and fractures, where it is diluted and carried seaward by the flowing freshwater. The relative carbon-14 activities and apparent ages of the ground waters in the Floridan aquifer system support the theory of this circulation, as does the uranium isotope data and the occurrence of anomalously cool saltwater in the Lower Floridan aquifer. Oxygen isotope data (table 4) show enrichment of oxygen-18 with respect to oxygen-16 ($\delta^{18}O$) in the saltwater in the Lower Floridan aquifer and a possible relation between oxygen-18 concentration and radiocarbon age. However, the data are insufficient to draw conclusions on paleotemperatures of the ocean during the Holocene transgression. The role that rising

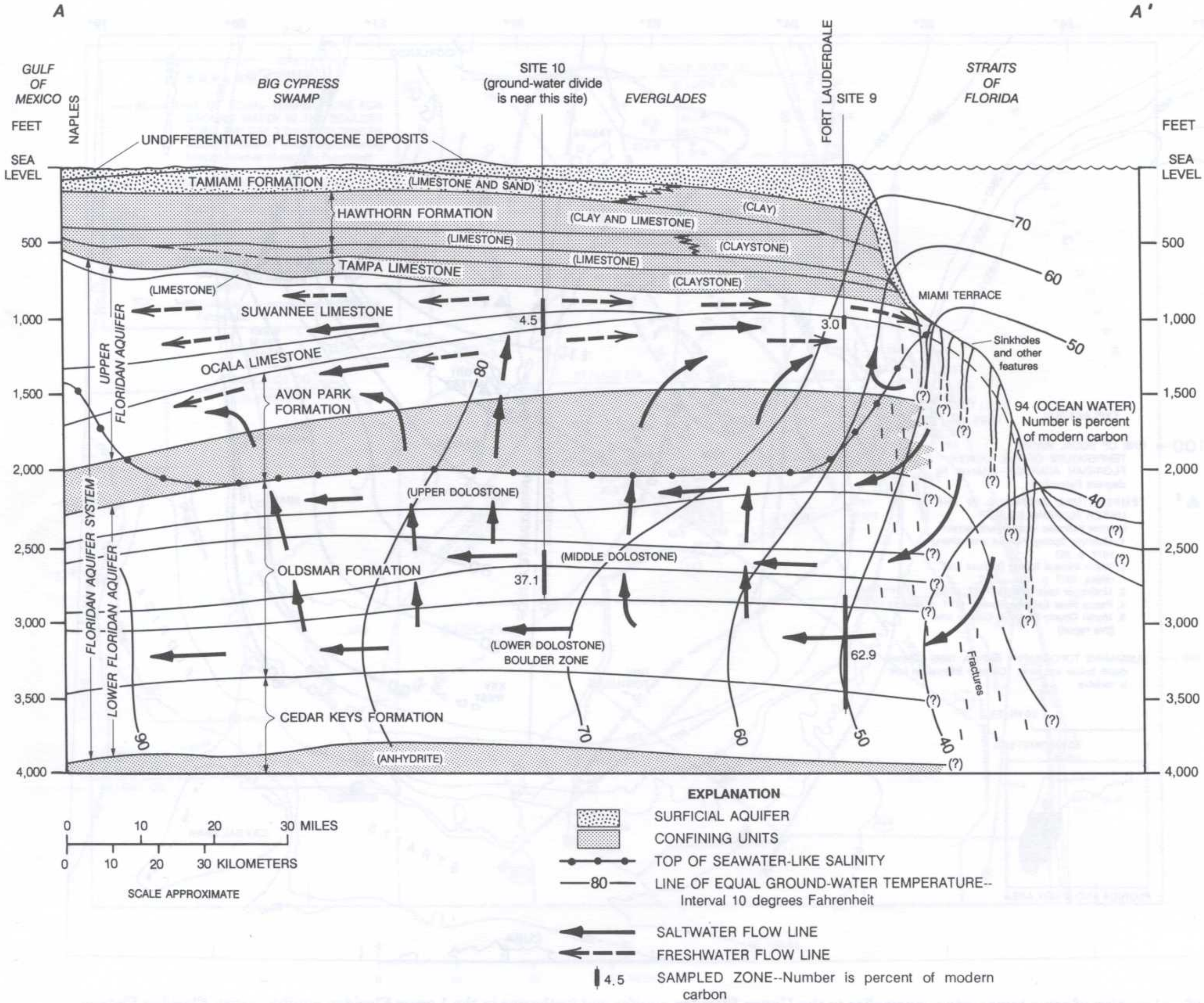

FIGURE 24.—Idealized cross section *A-A'* through southern Florida showing ground-water circulation and carbon-14 activities, Floridan aquifer system. (Line of section shown in fig. 2.)

sea level plays in circulation is not well documented, and more research is needed to fully evaluate such an effect.

UPWELLING GROUND WATER AS EVIDENCE OF CIRCULATION

The existence of upwelling warm, salty ground water in the Upper Floridan aquifer in southern Florida is further evidence that vertical circulation does occur. At least five temperature anomalies in southern Florida have been identified and discussed by various investigators (fig. 25). Most of the reported anomalies are on the southwestern coast of Florida, where the Upper Floridan aquifer is an important source of supply (and consequently there is a higher density of deep artesian wells) and where temperatures in the underlying Lower Floridan aquifer are highest. On the southeastern coast, temperature anomalies in Martin County were first reported by Lichtler (1960, p. 62) and expanded on by Sproul (1977, p. 84); data on temperature and salinity anomalies in St. Lucie County were later reported by Reece and others (1980).

The temperature anomalies in the Upper Floridan aquifer in the Martin County-St. Lucie County area (fig. 26) are indicated by composite temperatures of ground

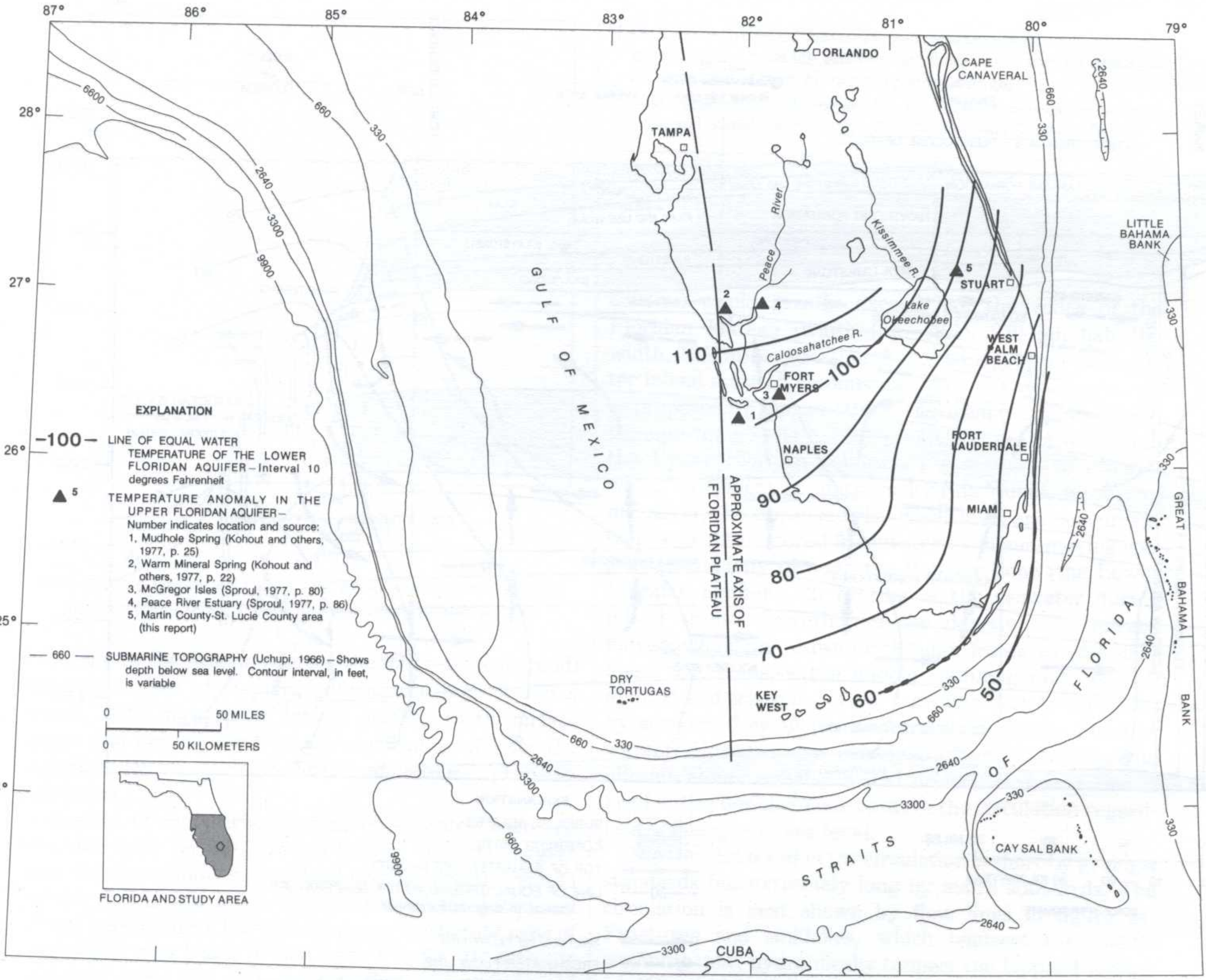

FIGURE 25.—Location of some temperature anomalies in the Upper Floridan aquifer and isotherms in the Lower Floridan aquifer, south Floridan Plateau.

water from wells ranging in depth from about 800 to 1,200 ft, exceeding the background temperature of about 80 °F by as much as 10 °F. Temperatures that are above normal occur in wells aligned generally in a northwesterly-southeasterly trend, extending from the northwestern corner of St. Lucie County to the southeastern corner of Martin County. Above-normal temperatures also occur in the vicinity of south-central Martin County. The temperatures of the anomalies compare closely with the temperatures of saltwater in the underlying Boulder Zone of the Lower Floridan aquifer. Also, the salinity (dissolved solids) of the ground water in the Upper Floridan aquifer near the temperature anomalies is locally higher (fig. 27), thereby providing additional evidence of upwelling from the Boulder Zone. The northwesterly-southeasterly trend of the salinity and temperature anomalies suggests that the source likely is water upwelling through sinkholes or vertical solution pipes, which are associated with major linears (fractures or perhaps faults) in the Tertiary limestone. During low stands of sea level, the same features probably facilitated recharge to the underlying Boulder Zone. The presence of brackish ground water with anomalously high carbon-14 activity in the Upper Floridan aquifer in southern Florida also is evidence that upwelling is widespread. The theory of inland circulation of seawater and subsequent mixing with seaward-flowing freshwater is preferred to the theory that saltwater in the Floridan

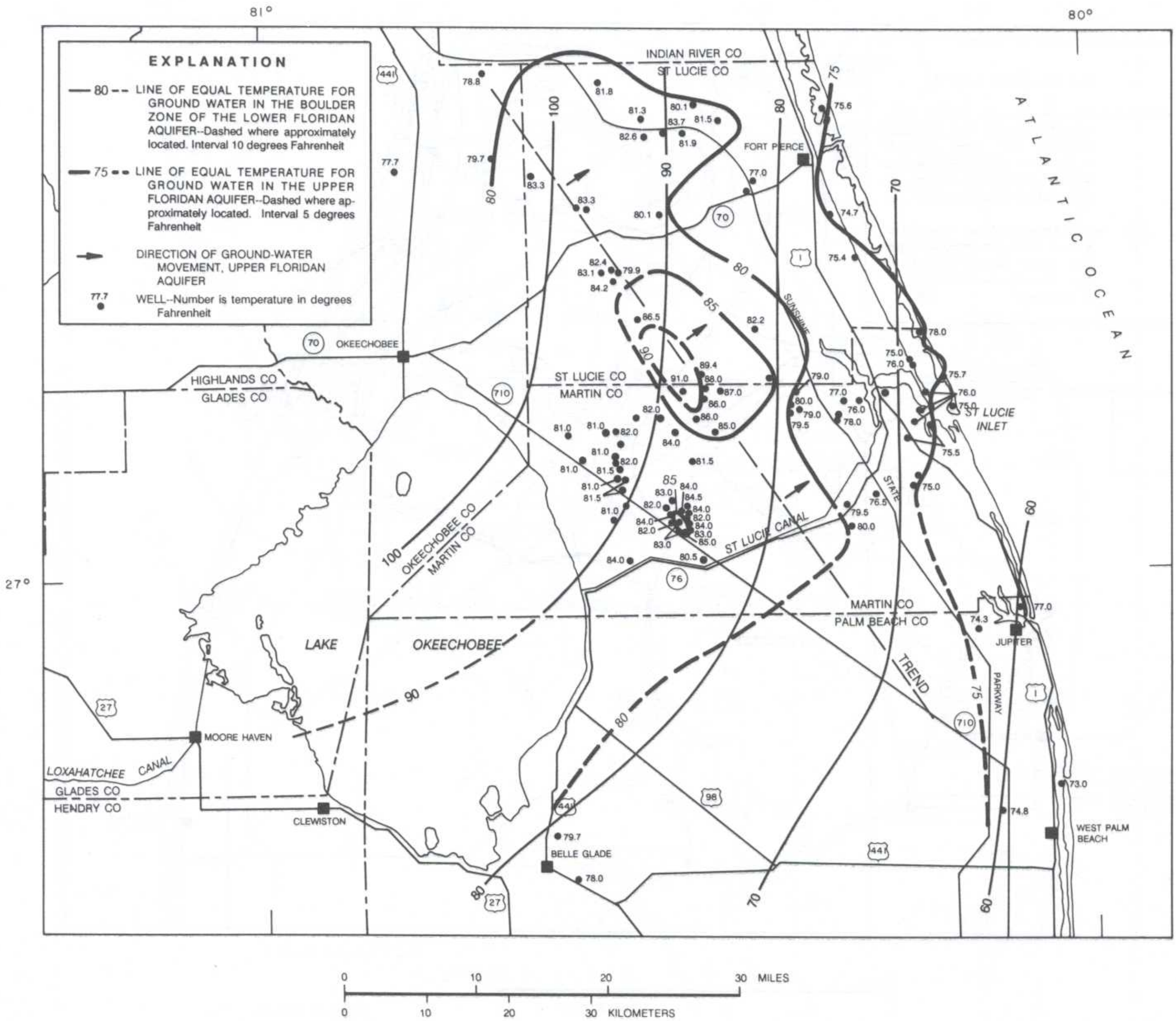

FIGURE 26.—Temperature of ground water in the Upper and Lower Floridan aquifers, Martin County-St. Lucie County area.

aquifer system in southern Florida is connate or residual seawater from high stands of sea level.

SUBSURFACE STORAGE IN THE FLORIDAN AQUIFER SYSTEM IN SOUTHERN FLORIDA

Subsurface storage is the practice of emplacing fluids in permeable underground rocks (aquifers) by gravity flow or pressure-induced injection through wells. The receiving rocks must have sufficient confinement, porosity, and permeability to accept the fluids without endangering underground sources of drinking water. In most cases, the fluids are nontoxic liquid wastes that cannot easily be disposed of at the surface. In some cases, however, the fluids are valuable and are temporarily emplaced underground for later recovery. The subsurface storage practice is commonly referred to as "underground injection," "deep disposal," and "deep-well injection."

The practice of injecting nontoxic liquid wastes into saline parts of the Floridan aquifer system began in 1943 at an oil field in Collier County (fig. 28, site 1); oil field brine was injected into the cavernous, saltwater-filled Boulder Zone of the Lower Floridan aquifer (Vernon, 1970). The injection of treated municipal wastewater into brackish zones of the Upper Floridan aquifer began in 1959 at a wastewater-treatment plant (fig. 28, site 14) in

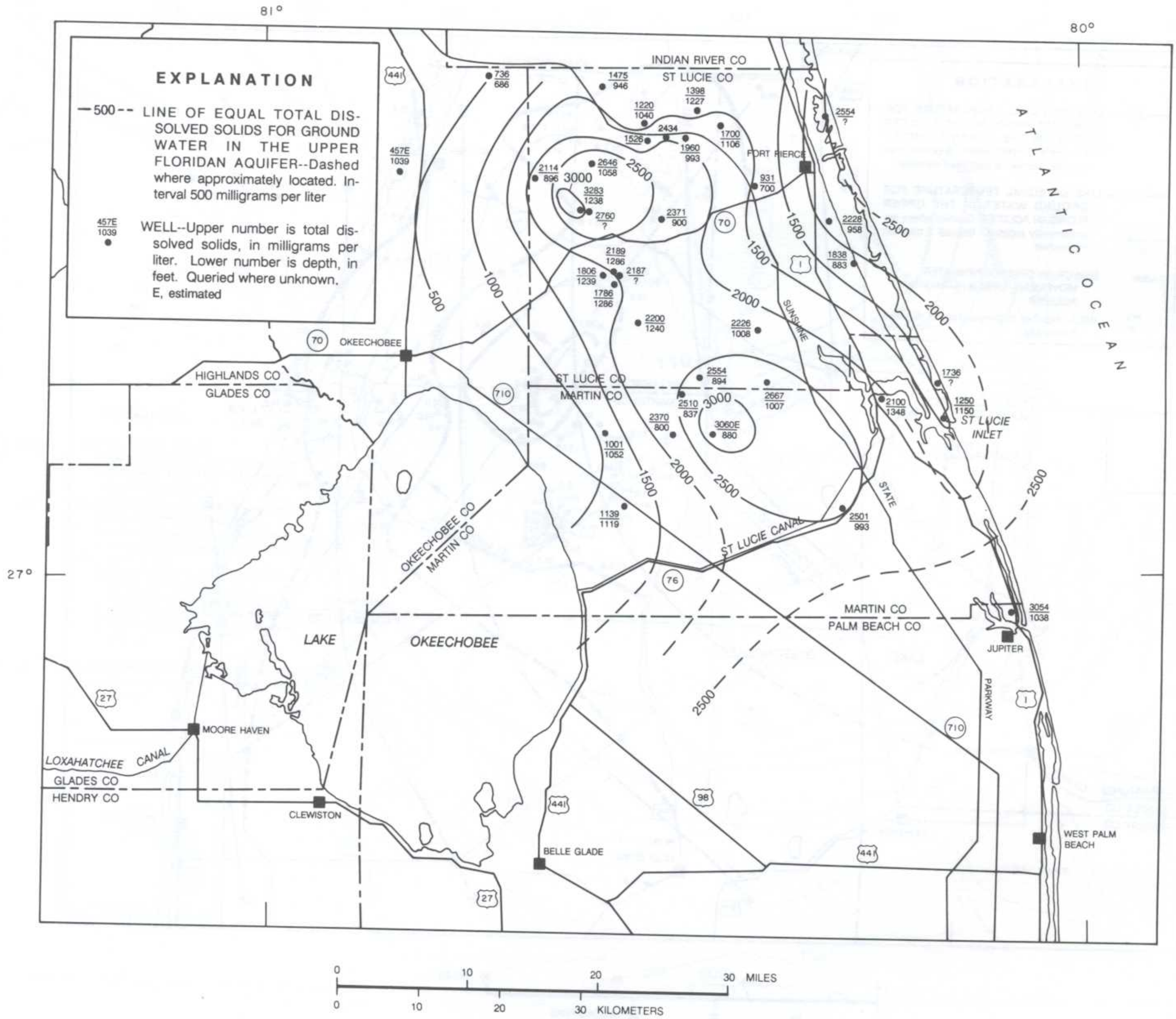

FIGURE 27.—Dissolved solids in ground water from the Upper Floridan aquifer, Martin County-St. Lucie County area.

Broward County (McKenzie and Irwin, 1984). Injection of treated municipal wastewater into the saltwater-filled Boulder Zone began in 1971 at a wastewater-treatment plant (fig. 28, site 16) in Dade County (Meyer, 1974). Injection of industrial liquid wastes (chiefly acetic acid) into brackish zones of the Upper Floridan aquifer began in 1966 at a furfural plant (fig. 28, site 15) in Palm Beach County (Kaufman and McKenzie, 1975).

Prior to 1970, regulation of injection wells was a principal function of the Florida State Board of Health (chapter 170C-3, Florida Administrative Code), and permits were issued as though the injection well were a drainage well. The criterion for issuing the permit was that the receiving rocks contain water that was nonpotable and salty (water having a chloride concentration of 1,500 mg/L or more). Subsequent assignment of the permitting function to the Florida Department of Pollution Control in about 1970 led to more stringent regulation, and permits were issued only after thorough review by the Florida Department of Natural Resources, the State Board of Health, and the local Water Management District in consultation with the U.S. Geological Survey.

As injection wells proliferated in the early 1970's, the Federal Government became increasingly concerned about the impact of deep-well disposal practices on drinking-water supplies. In 1974, Congress passed the Safe Drinking Water Act (Public Law 93–523, as amended by Public Law 95–190), which required the

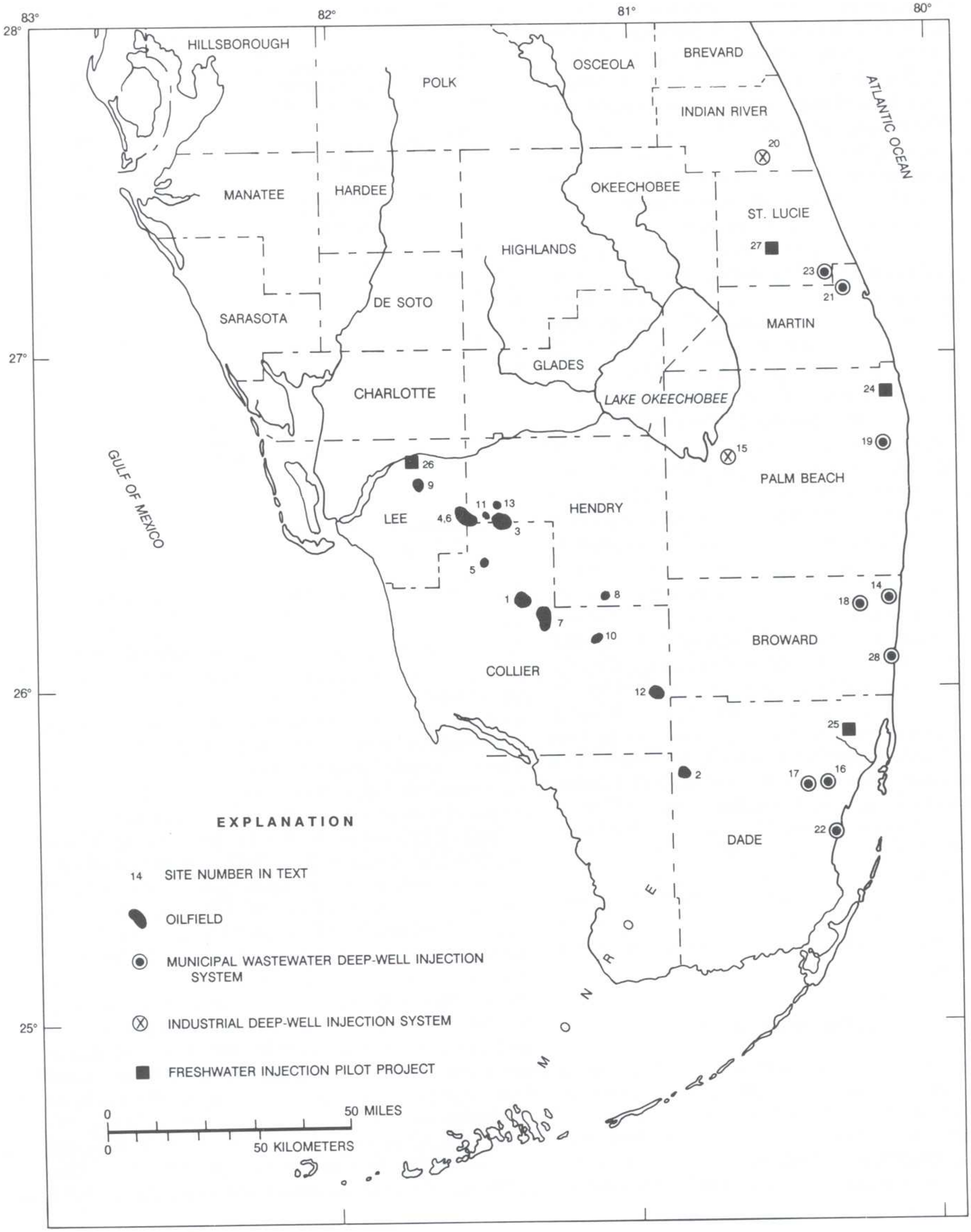

FIGURE 28.—Location of oil fields, municipal and industrial deep-well injection systems, and freshwater injection pilot projects, southern Florida.

U.S. Environmental Protection Agency (EPA) to develop and publish regulatory and minimum requirements to control underground injection. The regulations, called UIC (underground injection control) regulations, were published in the Congressional Federal Register on June 24, 1980 (chapter 40, parts 122 and 146). Responsibility for development and enforcement of the UIC regulations along the lines established by the EPA, for all but Class II injection wells, was delegated to the Florida Department of Environmental Regulation in 1983. The regulation of injection wells associated with oil and gas production, Class II injection wells, is administered by the Florida Bureau of Geology, Florida Department of Natural Resources (chapter 377, Florida Statutes and Rules 16C–2 and 16C–26 through 16C–30, Florida Administrative Code), and by the EPA.

All injection wells other than those associated with oil and gas production are regulated by the Florida Department of Environmental Regulation (chapter 17–28, Florida Administrative Code). The purposes of the UIC regulations are to protect the quality of the State's underground sources of drinking water and to prevent degradation of the quality of other aquifers adjacent to the injection zone. They regulate the location, construction, operation, and monitoring of injection wells so that the injection does not interfere with any designated use of ground water or cause violations of water-quality standards for underground sources of drinking water. An underground source of drinking water is defined by the State as an aquifer or its portion that supplies drinking water for human consumption, or is classified by rule 17–3.403, Florida Administrative Code, as Class G–I or G–II water, and is not an exempted aquifer. In general, ground water having a dissolved solids concentration of 10,000 mg/L or less is protected by the UIC regulations.

This section of the report is concerned with Class I injection wells, those that are used to inject municipal and industrial wastewater, Class II injection wells, those that are used to inject oil field brine, and Class V, Group 2, injection wells, those that are used to inject freshwater for storage.

OIL FIELD BRINE

Since the discovery of oil in southern Florida in 1943 at a field in Collier County, 12 other oil fields have been discovered that have produced commercial amounts of crude oil (fig. 28). Oil is chiefly produced from the Lower Cretaceous limestone, called the Sunniland Zone by drillers, that underlies the region at depths ranging from 11,000 to 12,000 ft. Along with the crude oil produced are large quantities of saltwater, called brine. The brines are several times saltier than seawater, and small amounts spilled on the surface can render a potable water supply useless for many years. Analyses of selected oil field brine are shown in table 11. Chloride concentrations range from 108,000 to 164,570 mg/L, compared with about 19,200 mg/L for seawater.

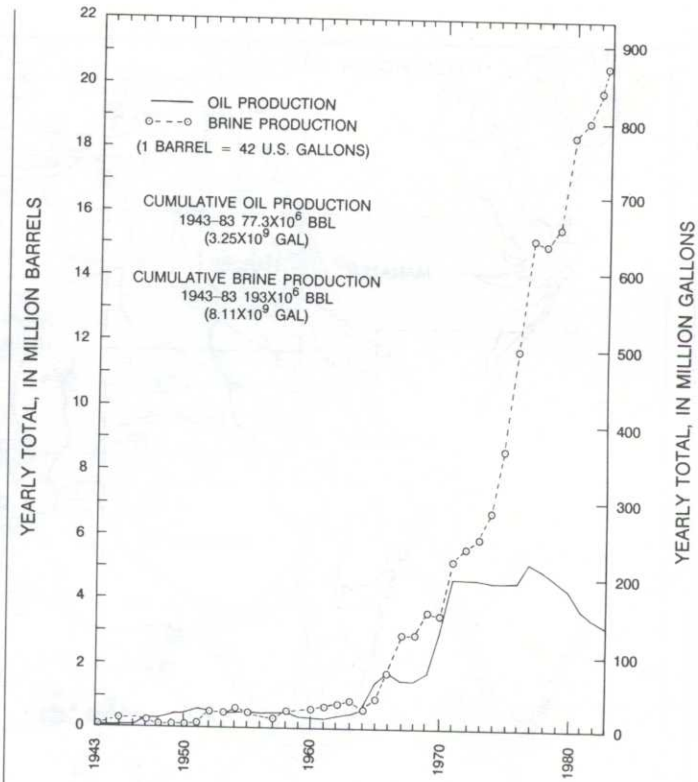

FIGURE 29.—Brine and oil production for southern Florida oil fields, 1943–83.

Total oil production for the 13 fields during 1943–83 was 77.3 million barrels (bbl) (3.2 billion gallons (Ggal)), and brine production was 193.2 million bbl (8.1 Ggal). The largest producer of oil and brine (fig. 28, site 4) yielded 35 million bbl of oil and 73 million bbl of brine during 1966–83. The next largest producer (fig. 28, site 1) yielded 18 million bbl of oil and 52 million bbl of brine during 1943–83. During 1943–66, the ratio of brine to oil was relatively stable, as production was mostly from the field shown as site 1 in figure 28. Subsequent oil production at site 4 resulted in significantly greater amounts of brine, and in 1971 oil production leveled off while brine production continued to increase exponentially (fig. 29). Ultimately, oil production began to decline in 1977, and brine production continued to rise. The brine-to-oil ratio in 1983 was 6.4 to 1.0 compared with a 1 to 1 ratio in 1964.

TABLE 11.—*Selected analyses of oil field brine, southern Florida*

[Concentrations in milligrams per liter. Remarks: BM, U.S. Bureau of Mines; GS, U.S. Geological Survey; PL, private laboratory; SDS, saltwater disposal system. Site locations shown in fig. 28. Dashes indicate no data]

Site No.	Date	Calcium	Magnesium	Sodium	Potassium	Chloride
1	12/43	25,204	3,110	58,491	4,700	143,601
	12/77	31,700	4,070	65,600	--	164,570
	6/55	23,800	3,400	48,300	3,150	129,000
2	11/7/55	6,910	3,010	53,500	2,030	108,000
	6/19/59	27,730	4,080	50,980	350	140,000
	8/1/65	27,700	4,770	56,900	3,950	152,000
3	11/64	21,100	2,880	55,600	2,850	131,000
	11/13/64	21,600	2,970	51,500	2,920	129,000
4	2/1/78	23,165	3,699	65,154	--	152,000
	2/1/78	23,165	3,946	62,730	--	149,000
7	12/29/77	28,448	4,439	60,292	--	156,000
	12/29/77	27,635	5,425	57,445	--	153,000
9	12/29/77	26,010	4,192	62,896	--	155,000

Site No.	Date	Sulfate	Dissolved solids	Remarks
1	12/43	275	230,827	Specific gravity 1.162 at 60.1°F. Drill stem test for discovery well. Permit 42. Analysis by BM. References: Gunter (1945, p. 18); Babcock (1962, p. 20).
	12/77	215	--	Composite injection into SDS No. 1, well 2. Permit 102. Analysis by PL. Source: Exxon Co.
	6/55	139	>207,000	Density 1.16 g/cm³ (grams per cubic centimeter) at 68.0°F. Drill stem test for nonproducing wildcat. Permit 222. Analysis by GS, No. 8655.
2	11/7/55	1,380	>175,000	Density 1.134 g/cm³ at 68.0°F. Pumped sample. Permit 167. Analysis by GS, No. 8016.
	6/19/59	408	246,000	Drill stem test. Permit 278. Analysis by GS, No. 17682.
	8/1/65	665	>254,000	Density 1.204 g/cm³ at 68.0°F. Drill stem test. Permit 331. Analysis by GS, No. MSF-546.
3	11/64	1,030	271,000	Drill stem test. Permit 314. Analysis by GS, No. MSF-170.
	11/13/64	415	>209,000	Pumped sample. Permit 315. Analysis by GS, No. OKE-19.
4	2/1/78	140	>244,000	Specific gravity 1.171 at 68.0°F. Composite injected into SDS No. 1, well 1. Permit 491. Analysis by PL. Source: Exxon Co.
	2/1/78	140	>239,000	Specific gravity 1.170 at 68.0°F. Composite injected into SDS No. 2, well 1. Permit 748. Analysis by PL. Source: Exxon Co.
7	12/29/77	130	>249,600	Specific gravity 1.177 at 73.0°F. Composite injected into SDS No. 2, well 1. Permit 856. Analysis by PL. Source: Exxon Co.
	12/29/77	140	>244,000	Specific gravity 1.176 at 73.0°F. Composite injected into SDS No. 1, well 1. Permit 761. Analysis by PL. Source: Exxon Co.
9	12/29/77	140	>248,500	Specific gravity 1.176 at 73.0°F. Composite injected into SDS No. 1, well 1. Permit 812. Analysis by PL. Source: Exxon Co.

TABLE 12.—*Summary of brine production and disposal for oil fields in southern Florida, 1943–83*

[Volume of brine in barrels. Operator: B. Burns; C, Commonwealth; E, Exxon; G, Gulf; K, Kanaba; NRM, Natural Resources Management; S, Sun; W, Weiner. No. of injection wells: B, Boulder Zone; P, Paleocene or older rocks; S, Sunniland Zone in Lower Cretaceous limestone. Dashes indicate no data. Site locations shown in fig. 28]

Site No.	Operator	Period	Brine production	No. of injection wells	Brine disposal: Boulder Zone	Brine disposal: Sunniland Zone
1	E	1943-73	51,879,210	3B	51,879,210	0
2	C/G	1954-55	98,700	--	98,700	0
3	S	1964-83	29,963,400	1B,9S	13,862,112	16,101,288
4	S/E	1966-83	72,722,755	3B,1S	69,428,463	3,294,292
5	K[1]	1969-83	0	--	0	0
[2]6	E	1970-75	1,118,625	--	1,118,625	0
7	E	1972-83	18,369,565	2B,8S	14,215,772	4,153,793
8	W/K	1973-78	289,106	--	289,106	0
9	E	1974-83	17,658,580	2B	17,658,580	0
10	E	1977-78	19,458	--	19,485	0
11	B	1977-83	1,000,222	1B	1,000,222	0
12	E	1977-83	13,880	1B	13,880	0
13	NRM	1982-83	60,396	1P	0	[3]60,396
Total[4]			193,193,924 (8,114)		169,584,155 (7,122)	23,609,769 (992)

[1]Formerly owned by Mobil.

[2]This site was included in site 4 in 1975.

[3]Injection occurs below the Boulder Zone in the open hole between 3,835 and 11,074 feet.

[4]Total in parentheses is shown in million gallons.

Some of the produced brine was used to repressure the oil-producing zone during 1966–83 to enhance oil recovery. This process is termed "water flooding" or "secondary recovery" and generally involves injection of the brine back into an abandoned oil well. About 23.6 million bbl (991 million gallons; Mgal) of brine were reinjected into the producing zone for water flooding.

A summary of brine production, by oil field, is presented in table 12. During 1943–83, about 193.2 million bbl (8.1 Ggal) of brine were produced, of which 169.6 million bbl (7.1 Ggal) were injected into the Boulder Zone (Lower Floridan aquifer) and 23.6 million bbl (1.0 Ggal) were injected back into the oil-producing zone.

Figure 30 shows the hydrogeology and construction details of typical oil field brine disposal wells at two oil fields (sites 12 and 1). The injection well at site 12 was constructed since establishment of the UIC regulations and incorporates current design criteria. The injection well at site 1 is a converted oil-production well with a cement plug in the lower confining unit of the Floridan aquifer system. Both wells, however, inject brine through perforations into the Boulder Zone (Lower Floridan aquifer). The main difference between the injection wells is that the injection well at site 12 has two strings of casing that extend from land surface to the middle confining unit of the Floridan aquifer system, whereas the well at site 1 has only one string of casing to

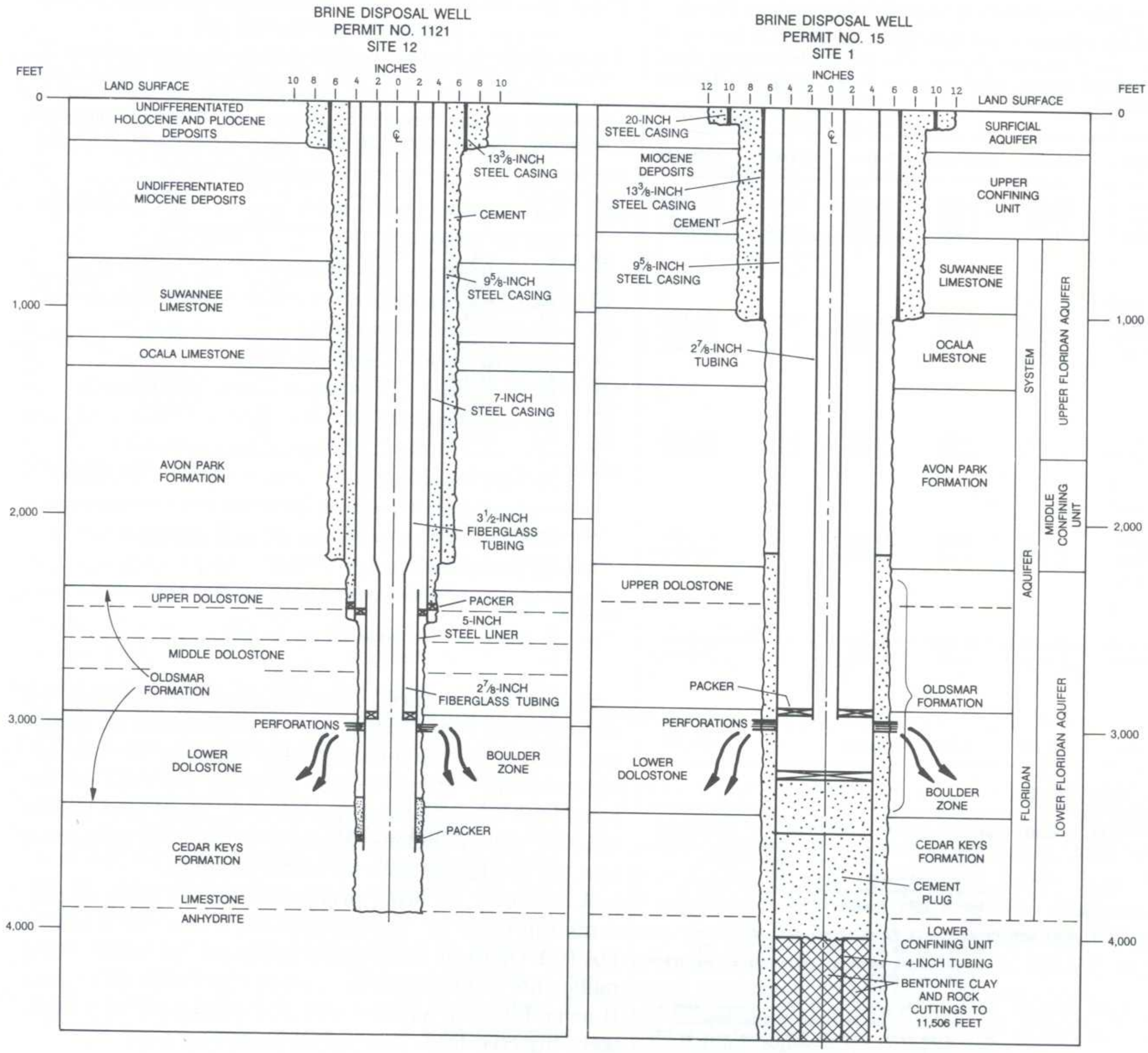

FIGURE 30.—Hydrogeology and typical construction of oil field brine disposal wells.

protect brackish ground water in the Upper Floridan aquifer. Also, the injection well at site 12 has associated with it a separate monitoring well (not shown in fig. 30) used to provide an early warning for leaks and upward migration of saltwater.

MUNICIPAL AND INDUSTRIAL LIQUID WASTES

Injection of municipal and industrial liquid wastes through wells into the Floridan aquifer system is prevalent in the southeastern part of the Florida peninsula (fig. 28). The start of this practice was mentioned previously in the report. Liquid wastes from both sources were injected into brackish water-bearing zones of the Upper Floridan aquifer because the criteria at that time required only that the receiving rocks contain water having a chloride concentration of at least 1,500 mg/L. Problems ultimately developed with the operation of both systems. In the municipal wastewater injection system (site 14), the low transmissivity of the aquifer and the high suspended solids in the injectant caused frequent plugging of the wellbore and excessive injection pressure (McKenzie and Irwin, 1984). In the furfural plant system (site 15), the hot acid waste migrated upward from the lower part of the Floridan aquifer to appear in a monitored zone near the top (Kaufman and McKenzie, 1975; McKenzie, 1976; Vecchioli and others, 1979).

The practice of deep-well injection of liquid wastes became increasingly attractive in 1969 when a test injection well drilled at a wastewater-treatment plant (fig. 28, site 16) tapped the highly transmissive saltwater-filled Boulder Zone of the Lower Floridan aquifer. An evaluation of the natural water-level fluctuations in the well by Meyer (1974) suggested that the transmissivity of the Boulder Zone was about 3.2×10^6 ft^2/d; however, a later pumping test at a wastewater-treatment plant (fig. 28, site 22) suggested that the transmissivity was about 2.5×10^7 ft^2/d (Singh and others, 1983). The success of the injection well at site 16 soon led to rapid exploitation of the Boulder Zone as a receptacle for nonhazardous municipal and industrial liquid wastes.

The characteristics of the Boulder Zone meet the current criteria for Class I injection wells as required by the Florida Department of Environmental Regulation (that is, the receiving zone is deep, confined, thick, porous, and highly transmissive and contains ground water whose dissolved solids concentration exceeds 10,000 mg/L).

During 1959–70, the volume of liquid wastes injected into the Floridan aquifer system increased gradually from 98 to 465.6 Mgal/yr (fig. 31, table 13). In 1971, the volume of liquid wastes injected began to increase exponentially, and in 1983 it reached 26.8 billion gallons per year (Ggal/yr). The total amount injected for the 25-yr period (1959–83) was 112 Ggal. Of that, 4 Ggal were industrial liquid wastes (sites 15 and 20) and 108 Ggal were treated municipal wastewater.

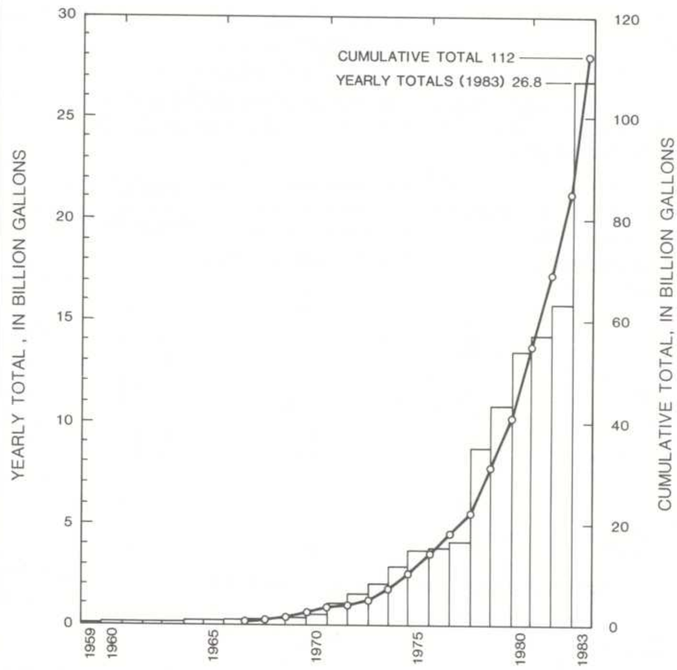

FIGURE 31.—Annual and cumulative volumes of municipal and industrial liquid wastes injected, 1959–83.

The injected industrial liquid waste at site 15 is chiefly acetic acid, a byproduct of the production of furfural. Neutralization of the acid waste takes place in the receiving zone by dissolution of the carbonate rocks and release of carbon dioxide. High concentrations of biogenic hydrogen sulfide and methane also result from reaction in the receiving zone. Characteristics of the

TABLE 13.—*Summary of municipal and industrial injection of liquid wastes in southern Florida, 1959–83*

[In million gallons. Site locations shown in fig. 28]

Year	Site 14[1]	Site 15	Site 16	Site 17	Site 18	Site 19	Site 20	Site 21	Site 22	Site 23	Yearly total	Cumulative
1959	98										98	98
1960	182										182	280
1961	182										182	462
1962	182										182	644
1963	182										182	826
1964	219										219	1,045
1965	219										219	1,264
1966	219	2.0									221	1,485
1967	182	45.4									227.4	1,712.4
1968	219	104.6									323.6	2,036.0
1969	219	121.8									340.8	2,376.8
1970	265	200.6									465.6	2,842.4
1971	223	213.4	577.0								1,013.4	3,855.8
1972	248	246.5	1,046.0								1,540.5	5,396.3
1973	293	307.5	1,275.0	179.5							2,055.0	7,451.3
1974	259	284.3	1,341.0	483.9	570.6						2,938.8	10,390.1
1975	10	311.1	1,537.0	582.3	1,299.4						3,739.8	14,129.9
1976		317.6	1,732.0	531.4	1,284.0						3,865.0	17,994.9
1977		157.6	1,715.5	646.8	1,415.1	175.7					4,110.7	22,105.6
1978		187.8	1,734.8	902.1	1,671.3	4,253.3					8,749.3	30,854.9
1979		272.1	1,957.7	1,134.5	1,816.6	5,673.7	0.2				10,854.8	41,709.7
1980		375.6	1,723.5	1,006.5	1,756.7	8,531.5	20.4				13,414.2	55,123.9
1981		358.4	1,754.8	1,277.9	1,850.6	8,910.2	44.2				14,196.1	69,320.0
1982		201.3	1,856.0	1,022.0	1,993.6	10,639.3	66.8	81.2			15,860.2	85,180.2
1983		161.1	139.3	82.3	2,001.3	11,125.1	55.3	742.5	12,376.9	144.6	26,828.4	112,008.6
Total	3,401	3,868.7	18,389.6	7,849.2	15,659.2	49,308.8	186.9	823.7	12,376.9	144.6	112,008.6	

[1]Estimated except for 1969 through 1974.

TABLE 14.—*Selected water-quality characteristics of injectant of industrial liquid wastes, local water supply, and native ground water in the Boulder Zone at site 15, Palm Beach County*

[Concentrations in milligrams per liter, except where noted; analyses by U.S. Geological Survey. Location of site 15 shown in fig. 28. Dashes indicate no data]

Characteristic	Injectant[1]	Water supply[2]	Ground water in the Boulder Zone[3]
Major inorganics and related physical characteristics			
Acidity, as H^+	208	0	0
Bicarbonate (HCO_3)	0	150	200
Calcium (Ca)	140	44	430
Chloride (Cl)	160	99	19,000
Dissolved solids (residue at 180°C).	9,720	>380	36,100
Magnesium (Mg)	63	21	1,300
pH (units)	2.9	8.6	7.9
Potassium (K)	310	5	410
Sodium (Na)	110	60	12,000
Specific conductance (microsiemens per centimeter).	2,400	700	51,500
Sulfate (SO_4)	290	66	2,400
Suspended solids (residue at 110°C).	1,500	--	--
Temperature (°C)	[4]75.0	26.5	--
Selected nutrients and related characteristics			
Carbon, total organic	7,500	20	
Nitrogen, ammonia as N	19	.03	
Nitrogen, total as N	138	1.6	
Phosphorus, total as P	47	.02	

[1]Sample of plant effluent was collected on July 8, 1974.

[2]Sample was collected at North New River Canal below hurricane gate and pump station on April 18, 1974.

[3]Sample was collected from injection well 3 at 3,130 feet on June 29, 1976.

[4]Temperature of effluent is reduced to about 50.0°C prior to injection.

TABLE 15.—*Selected water-quality characteristics of injectant of secondary-treated wastewater, local water supply, and native ground water in the Boulder Zone at site 19, Palm Beach County*

[Concentrations in milligrams per liter, except where noted; analyses by U.S. Geological Survey. Location of site 19 shown in fig. 28. Dashes indicate no data]

Characteristic	Injectant[1]	Water supply[2]	Ground water in the Boulder Zone[3]
Major inorganics and related physical characteristics			
Bicarbonate (HCO_3)	120	150	180
Calcium (Ca)	50	40	390
Chloride (Cl)	240	78	21,000
Dissolved solids (residue at 180°C).	1,060	330	37,400
Magnesium (Mg)	16	8.9	1,300
pH (units)	6.7	8.3	7.6
Potassium (K)	15	3.1	450
Sodium (Na)	160	45	12,000
Specific conductance (microsiemens per centimeter).	1,220	550	>50,000
Sulfate (SO_4)	110	33	2,800
Suspended solids (residue at 110°C).	12	--	43
Temperature (°F)	78.8	79.7	<17.5
Selected nutrients and related characteristics			
Carbon, total organic	15	--	8.2
Nitrogen, ammonia as N	.03	--	<.01
Nitrogen, total as N	1.6	>.02	.00
Phosphorus, total as P	.08	--	.02

[1]Sample of effluent from site 19 collected on April 18, 1978.

[2]Sample of raw surface-water supply (Clear Lake) for site 19 collected on May 9, 1979.

[3]Sample of native ground water collected from injection well 2 at site 19 on May 30, 1972. Density was 1.022 g/mL (grams per milliliter) at 68°F and hydrogen sulfide was 2.4 mg/L (milligrams per liter).

TABLE 16.—*Selected water-quality characteristics of injectant of secondary-treated wastewater, local water supply, and native ground water in the Boulder Zone at site 22, Dade County*

[Concentrations in milligrams per liter, except where noted. Location of site 22 shown in fig. 28. Dashes indicate no data]

Characteristic	Injectant[1]	Water supply[2]	Ground water in the Boulder Zone[3]
Major inorganics and related physical characteristics			
Acidity, as H^+	--	0	0
Bicarbonate (HCO_3)	--	260	146
Calcium (Ca)	--	92	430
Chloride (Cl)	65	25	19,000
Dissolved solids (residue at 180°C).	360	322	37,900
Magnesium (Mg)	--	3.2	1,200
pH (units)	6.0	7.5	7.1
Potassium (K)	--	1.7	200
Sodium (Na)	--	16	1,100
Specific conductance (microsiemens per centimeter).	700	540	52,900
Sulfate (SO_4)	--	28	2,600
Temperature (°F)	87.8	82.4	<19.0
Selected nutrients and related characteristics			
Carbon, total organic	7.65	2.0	3.9
Nitrogen, ammonia as N	17.5	.01	.12
Nitrogen, total as N	18.6	.36	.24
Phosphorus, total as P	1.56	<.01	<.01

[1]Sample of treated effluent collected on August 14, 1984. Analyses by the Miami-Dade Water and Sewer Authority.

[2]Sample of raw water from the Biscayne aquifer collected on June 6, 1975, at site 22. Analyses by the U.S. Geological Survey.

[3]Sample of native ground water collected from monitor well BZ-1 between depth of 2,689 and 2,960 feet on October 22, 1981. Sample contained high metal concentrations due to pipe erosion. Analyses by the U.S. Geological Survey.

injected industrial liquid wastes (site 15) are compared with those of the local water supply and the native ground water in the Boulder Zone in table 14.

At site 20, the industrial liquid waste is caustic (chiefly aluminum hydroxide and sodium chloride), a byproduct of the production of pectin. Analyses of the injectant from site 20 were unavailable.

The injected municipal liquid waste is secondary-treated wastewater (that is, wastewater that has had at least 90 percent of the suspended solids and biochemical oxygen demand removed by treatment). The characteristics of the treated wastewater vary from plant to plant, but the wastewaters are distinguished from local water supply by high concentrations of nutrients. The characteristics of the injected wastewater at two wastewater-treatment plants (sites 19 and 22) are compared with those of the local water supply and native ground water in the Boulder Zone in tables 15 and 16.

Injection into the brackish water-bearing zones of the Upper Floridan aquifer occurred only at sites 14 and 15. The combined amount (municipal and industrial) for both sites during 1959–75 was 5 Ggal.

Injection into the middle confining unit and perhaps the upper unit of the Lower Floridan aquifer occurred only at site 15, where about 656.7 Mgal were injected during 1972–75.

Injection into the Boulder Zone of the Lower Floridan aquifer occurred at the eight remaining sites during

1971–83 and at site 15 during 1977–83. The total amount injected into the Boulder Zone during 1971–83 was 106.4 Ggal.

Injection rates have increased exponentially since 1971, when the injection well at site 16 became operational and injection was directed to the Boulder Zone. The rate in 1983 was 73.5 Mgal/d, and the estimated rate in 1984 was 112 Mgal/d (table 17).

In 1983, two injection wells (fig. 28, sites 16 and 17) were removed from service because of small leaks in uncemented (conductor) inner casings, and the effluent from the plant was directed to other treatment facilities of the Miami-Dade Water and Sewer Authority. Also in 1983, a small leak was detected in the uncemented inner casing of a third injection well (fig. 28, site 18), and construction of a replacement well was required by the Florida Department of Environmental Regulation before remedial work could be performed on the leaking well. Despite these minor problems, which have been resolved by enforcement of the UIC regulations, the outlook for deep-well injection in southern Florida is for continued expansion. The outlook, however, should include caution because the injected liquid waste will ultimately conform to the regional ground-water circulation system. The injected waste, thus, will move with the hypothesized inland and upward flow of seawater from the Florida Straits.

Typical construction characteristics of nontoxic municipal and industrial liquid wastes disposal wells are shown in figures 32 and 33 along with the local hydrogeology. The construction of the municipal liquid wastes disposal well (fig. 32) is based on that of well 3 at the city of Fort Lauderdale's Port Everglades wastewater-treatment plant (fig. 28, site 28). The well is constructed with

TABLE 17.—*Average rate of municipal and industrial liquid wastes injection, 1959–84*

[In million gallons per day; e, estimated]

Year	Rate	Year	Rate
1959	0.268	1972	4.221
1960	.499	1973	5.630
1961	.499	1974	8.052
1962	.499	1975	10.520
1963	.499	1976	10.589
1964	.600	1977	11.262
1965	.600	1978	23.971
1966	.605	1979	29.739
1967	.623	1980	36.751
1968	.887	1981	38.894
1969	.934	1982	43.453
1970	1.276	1983	73.502
1971	2.776	1984	112e

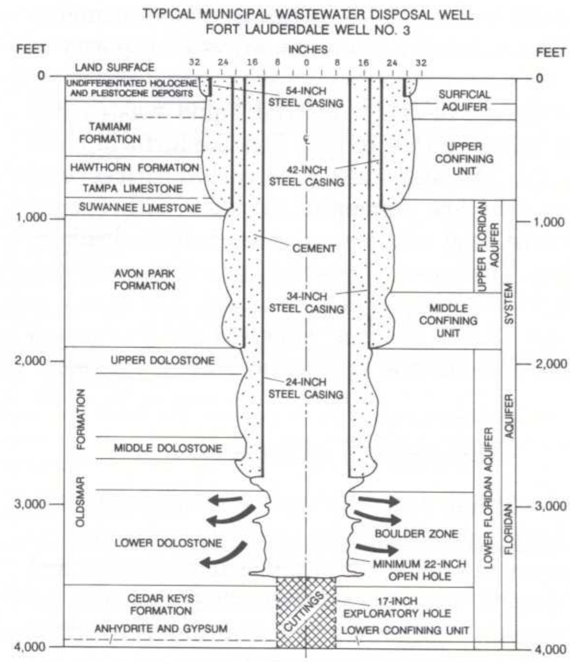

FIGURE 32.—Hydrogeology and typical construction characteristics of a municipal wastewater disposal well.

telescoping steel casings to protect drinking water resources in the surficial aquifer and the Upper Floridan aquifer. The casings are cemented in place from top to bottom with special sulfate-resistant cement. The steel

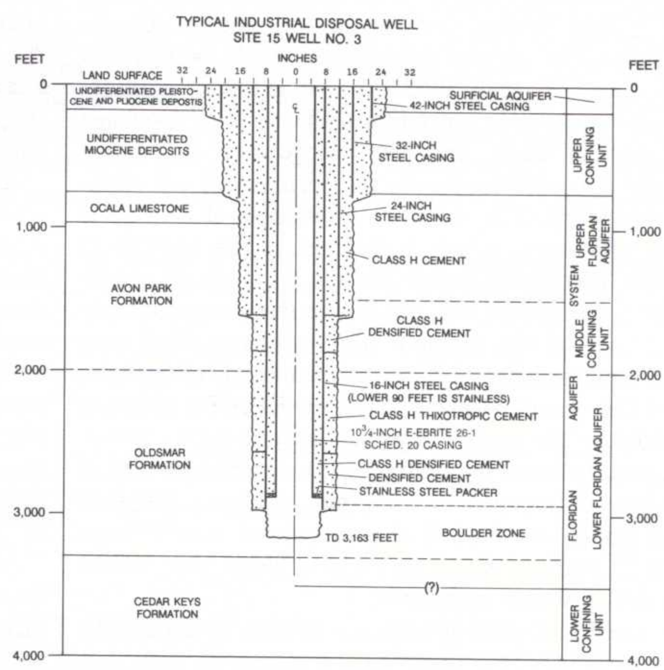

FIGURE 33.—Hydrogeology and typical construction characteristics of an industrial liquid wastes disposal well.

inner (conductor) casing is 24 inches in diameter and 1/2 inch thick. The well has a minimum injection capacity of 15 Mgal/d.

The construction of the industrial liquid wastes disposal well is based on that of well 3 at the furfural plant (fig. 28, site 15). The well is also constructed with several steel casings that are cemented in place with special cement to resist heat and corrosion to protect drinking water sources. The inner (conductor) casing is made of a special alloy that is acid and heat resistant. Not shown in figures 32 and 33 are monitor wells, which are located nearby to detect leaks and upward-migrating wastes.

FRESHWATER STORAGE

Subsurface storage of freshwater as an alternative to surface storage has become increasingly attractive to water managers in southern Florida as urbanization and population growth have placed increasing demands on the water supply. The advantages of the subsurface storage concept are that subsurface space is free, water loss by evapotranspiration is nonexistent, and the site may be located at the point of greatest need (provided hydrogeologic conditions are favorable). The concept is particularly desirable in southern Florida, where real estate has become very expensive, the availability of water is seasonal, and underlying artesian aquifers in the intermediate (Miocene) aquifer system and Floridan aquifer system contain nonpotable saline ground water.

The source of freshwater for injection might be surplus within the surface-water storage system or the surficial aquifer system during the annual wet season. On an annual basis, the surplus freshwater would be injected through Class V wells into suitable artesian aquifers during the wet season, stored for a short period (perhaps 3 to 6 months (mo)), and then withdrawn as needed during the dry season—hence the term cyclic injection-storage-recovery. The measure of success of a cycle is recovery efficiency, which is defined as the volume of freshwater recovered before it fails to meet an established (or a prescribed) chemical standard, expressed as a percentage of the volume of freshwater that was injected. Pilot studies to date in southern Florida have assumed the standard established by EPA for chloride concentration (250 mg/L) in public water supply. Other criteria may be used depending on the particular use of the recovered water. For example, a higher chloride standard could be used if the recovered water were mixed with surface water to yield a blend that would meet drinking water standards.

Theoretical and pilot-operational studies to date indicate that recovery efficiency usually improves with successive cycles, provided that recovery ceases when the recovered water reaches the standard and that the storage period is sufficiently short to prevent significant migration of the injectant away from the point of recovery.

TABLE 18.—*Results of Florida Department of Natural Resources and Florida Department of Environmental Regulation injection, storage, and recovery tests of freshwater at site 24 in Palm Beach County, 1975–76*

[Quantities in million gallons and rates in gallons per minute. From J.J. Plappert, Florida Department of Environmental Regulation, written commun., 1977. Location of site 24 shown in fig. 28]

Test	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Quantity injected	20.5	100	306	102
Storage period (days)	15	30	30	120
Quantity of potable water recovered[1]	0	4.7	55.5	36.1
Percent of recovery	0	4.7	18.0	35.2
Injection rate	2,000	2,000	2,000	2,000
Withdrawal rate	1,000	1,000	1,000	1,000

Transmissivity and storage coefficient: Unknown
Injected water chloride concentration: 65 mg/L (milligrams per liter)
Resident water chloride concentration: 1,980 mg/L
Open hole: 990 to 1,280 feet (Ocala Limestone and Avon Park Formation)

[1]Recovery was terminated when the chloride concentration of the recovered water reached 250 mg/L.

Pilot studies have been conducted at four sites (fig. 28) in southern Florida, with varying degrees of success (Merritt and others, 1983; Wedderburn and Knapp, 1983). Also, data on the recovery of injected wastewater (freshwater) from Class I injection wells during repairs, testing, and abandonment have yielded valuable information on recovery efficiency (McKenzie and Irwin, 1984). Aspects of the existing pilot studies are summarized in tables 18 through 21. Of the four studies, three (sites 24, 25, and 27) involved injection into water-bearing zones of the Upper Floridan aquifer and one (site 26) involved injection into water-bearing zones of the intermediate aquifer system. Plugging of the wellbore by suspended solids in the injectant was a significant problem in all four studies.

At site 24 in Palm Beach County (table 18), injection was chiefly into water-bearing zones of the Ocala Limestone and Avon Park Formation (units of the Upper Floridan aquifer). The study involved four injection-storage-recovery cycles (J.J. Plappert, Florida Department of Environmental Regulation, written commun., 1977). Recovery efficiencies ranged from 0 to 35.2 percent. The transmissivity of the injection zone(s) is probably on the order of 10,000 to 20,000 ft^2/d, although data are lacking to support that assumption. The injection zones are apparently associated with zones of dissolution at or near unconformities that separate formations.

At site 25 in Dade County (table 19), injection of freshwater chiefly was into water-bearing zones of the Suwannee Limestone although the injection well tapped parts of the Tampa Limestone and Avon Park Formation (all units of the Upper Floridan aquifer). The study involved three injection-storage-recovery cycles. Recov-

TABLE 19.—*Results of U.S. Geological Survey injection, storage, and recovery tests of freshwater at site 25 in Dade County, 1975–80*

[Quantities in million gallons and rates in gallons per minute. Location of site 25 shown in fig. 28]

Test	Cycle 1	Cycle 2	Cycle 3
Quantity injected	41.9	85	208
Storage period (days)	2	54	181
Quantity of potable water recovered	13.8	40.7	80.1
Percent of recovery	32.9	47.8	38.5
Injection rate	[1]440-780	854	800
Withdrawal rate [2]	330	494	450

Transmissivity[3]: 10,950 ft^2/d (feet squared per day)
Storage coefficient[3]: 8.4×10^{-5}
Injected water chloride concentration: 65 mg/L (milligrams per liter)
Resident water chloride concentration[4]: 1,200 mg/L
Open-hole: 955 to 1,105 feet (Tampa Limestone, Suwannee Limestone, and Avon Park Formation).

[1]Progressive decline due to wellbore plugging.

[2]Natural artesian flow.

[3]Estimated by computer simulation of well G-3062 pumping test.

[4]Multilevel composite, range from 800 to 2,000 mg/L.

ery efficiencies ranged from 32.9 to 47.8 percent. A decline in efficiency was recorded for the third cycle which probably was related to migration of the injectant downgradient from the injection recovery well during the 181 days (d) of storage. The transmissivity of the injection zone(s) is 10,950 ft^2/d. The results of the tests at this site were the basis for theoretical studies that used a mathematical model to evaluate the effects of varying aquifer characteristics, fluid density, regional flow, well arrays, and operating schedules on recovery efficiency (Merritt, 1985).

At site 26 in Lee County (table 20), injection of freshwater was into water-bearing zones in limestone of the Hawthorn Formation (unit of the intermediate aquifer system). The study involved three injection-storage-recovery cycles. Recovery efficiencies ranged from 9.7 to 38.7 percent. The efficiency of the first cycle, which had the greatest efficiency value, is probably not representative of the true efficiency because of the small amount injected and the short storage period. The value for the third cycle (30.4 percent) probably represents the efficiency and the storage capability of the aquifer. The transmissivity of the injection zone(s) is about 750 ft^2/d.

At site 27 in St. Lucie County (table 21), injection of freshwater chiefly was into water-bearing zones of the Ocala Limestone and the Avon Park Formation of the Upper Floridan aquifer. The water-bearing zones are associated with zones of dissolution near formation contacts. The study involved one injection-storage-recovery cycle, for which the recovery efficiency was only 3 percent. The low efficiency was due to the high chloride concentration (200 mg/L) of the injectant. The 3-percent recovery efficiency represented a 79-percent blend of the injectant (chloride concentration of 200 mg/L) with native ground water (chloride concentration of 1,000 mg/L). A recovery efficiency of 33 percent would have been realized had the chloride concentration of the injectant been 50 mg/L (based on the indicated rate of mixing and the limit of 250 mg/L for chloride in drinking water). The transmissivity of the injection zone(s) is about 6,000 ft^2/d.

TABLE 20.—*Results of U.S. Geological Survey injection, storage, and recovery tests of freshwater at site 26 in Lee County, 1980–82*

[Quantities in million gallons and rates in gallons per minute. From Fitzpatrick, 1985. Location of site 26 shown in fig. 28]

Test	Cycle 1	Cycle 2	Cycle 3
Quantity injected	0.571	[1]6.831	[2]29.026
Storage period (days)	0	47	99
Quantity of potable water recovered	.221	.663	8.819
Percent of recovery	38.7	[3]9.7	30.4
Injection rate	170-350	300	300
Withdrawal rate[4]	95-110	165-175	150

Transmissivity: 700 to 800 ft^2/d (feet squared per day)
Storage coefficient: About 1×10^{-4}
Injected water chloride concentration: Cycle 1, 60 mg/L (milligrams per liter); cycle 2, 150 to 350 mg/L[5]; cycle 3, 80 to 100 mg/L (finished water) and 60 mg/L (raw water).
Resident water chloride concentration: 550 mg/L
Open hole: 447 to 600 feet (limestone of the Hawthorn Formation)

[1]Estimated after loss of water due to equipment failure.

[2]8.548×10^6 gallons of finished water, followed by 20.873×10^6 gallons of raw river water.

[3]Low due to relatively high chloride concentration of injected water. Purpose was to test well after acidification.

[4]Natural artesian flow; improvement in cycle 2 due to acidification of well.

[5]Abnormally high due to record low flows in Caloosahatchee River source; decreased during injection.

During 1975–77, the U.S. Geological Survey, in cooperation with the Florida Department of Environmental Regulation, conducted a study of the quality of recovered secondary-treated wastewater from subsurface storage in the Upper Floridan aquifer at site 14 in Broward County (table 22). The injection system consisted of two wells that were in operation from 1959 to 1975. Injection ceased in January 1975 when the plant's function was transferred to the Broward County North Regional wastewater treatment plant. Recovery of the injected

TABLE 21. *Results of South Florida Water Management District injection, storage, and recovery tests of freshwater at site 27 in St. Lucie County, 1982–83*

[Quantities in million gallons and rates in gallons per minute. From Wedderburn and Knapp, 1983. Location of site 27 shown in fig. 28]

Test	Cycle
Quantity injected	1.488
Storage period (days)	37.5
Quantity of potable water recovered	.041
Percent of recovery[1]	2.76
Injection rate	331
Withdrawal rate	140-190

Transmissivity: 6,000 ft^2/d (feet squared per day)
Storage coefficient: 1.6×10^{-4}
Injected water chloride concentration: 200 mg/L (milligrams per liter)
Resident water chloride concentration: 1,000 mg/L
Open hole: 600 to 775 feet (limestone of the Hawthorn Formation, Ocala Limestone, and Avon Park Formation).

[1]Percent of recovery would have been 33 percent if the chloride concentration of the injected water were 50 mg/L.

TABLE 22.—*Results of U.S. Geological Survey wastewater recovery tests of freshwater at site 14 in Broward County, 1975–77*

[Quantities in million gallons and rates in gallons per minute. From McKenzie and Irwin, 1984. Location of site 14 shown in fig. 28]

Test	Cycle
Quantity injected	3,401
Storage period (years)	16
Quantity of potable water recovered	69.2
Percent of recovery	2
Injection rate	400
Withdrawal rate	
	4-132

Transmissivity and storage coefficient: Not determined
Injected water chloride concentration: 84 mg/L (milligrams per liter)
Resident water chloride concentration: 2,360 mg/L
Open hole: 995 to about 1,250 feet (Avon Park Formation)

treated wastewater began in April 1975 and ended in March 1977, when the chloride concentration reached 250 mg/L. The recovery efficiency based on reaching a chloride concentration of 250 mg/L was only 2 percent, which was much less than expected for the great volume (3.4 Ggal) that was injected during the 16 yr of operation. The transmissivity of the injection zone was not determined but was probably greater than for previously discussed freshwater storage pilot studies. Records of the construction of one injection well suggest that injection occurred to a greater depth (perhaps as deep as 1,600 ft) than previously reported. The low recovery efficiency is probably a result of higher aquifer transmissivity, higher chloride concentration (and, hence, higher density) of the resident water, and construction problems. As with the previous pilot studies, plugging of the wellbore by suspended solids was a significant problem.

Unpublished data collected by the Florida Department of Environmental Regulation on the amount of freshwater effluent from abandoned injection wells at sites 16 and 17 in Dade County suggest that recovery efficiency for wells that tap the Boulder Zone of the Lower Floridan aquifer is virtually nonexistent. The injection well at site 16 was abandoned in 1983 after 13 yr of operation and after 18.4 Ggal of effluent were injected; the injection well at site 17, also abandoned in 1983, was operated for 11 yr, during which time 7.8 Ggal of effluent were injected. At both sites, the chloride concentration of the injectant was about 60 mg/L, and the chloride concentration of the resident water was about 19,200 mg/L. For both sites, the amount of effluent recovered before the chloride concentration exceeded 250 mg/L did not exceed 1 Mgal. The recovery tests indicate that there is no potential for recovering freshwater stored in the highly transmissive Boulder Zone.

Dissolution zones at erosional unconformities between the Suwannee and Ocala Limestones and the Avon Park Formation probably offer the best opportunity for large-scale storage of freshwater in the subsurface of southern Florida. Detailed maps of the dissolution zones are unavailable, but maps showing the configuration of the top of the middle and upper Eocene rocks are shown in chapter B (Miller, 1986, pls. 6, 8) of this professional paper. The surface is irregular and shows the effects of large-scale erosion at the close of the Eocene Epoch. Erosion removed the Ocala Limestone from much of southeastern Florida and exposed the underlying (older) Avon Park Formation. Zones of dissolution are prominent near this erosion surface; therefore, the maps in Miller (1986) may be used to estimate the depth at which favorable injection zones may be present.

SUMMARY AND CONCLUSIONS

In southern Florida, the Floridan aquifer system is divided into three general hydrogeologic units: (1) the Upper Floridan aquifer, which contains brackish ground water, (2) the middle confining unit, which contains salty ground water, and (3) the Lower Floridan aquifer, which contains ground water whose chemical composition compares closely with that of seawater. The aquifer system is about 3,000 ft thick and is composed chiefly of carbonate rocks that range in age from early Miocene to Paleocene. Zones of high permeability are present in the Upper Floridan aquifer at the unconformable contacts of the Suwannee Limestone with the Ocala Limestone and the Ocala Limestone with the Avon Park Formation. Zones of high permeability in the Lower Floridan aquifer are present in three dolostones in the Oldsmar Formation; the lowermost, locally called the Boulder Zone, is perhaps one of the most permeable units in the world. The transmissivity of the Upper Floridan aquifer is estimated to range from 10,000 to 60,000 ft^2/d, whereas that of the Lower Floridan aquifer (Boulder Zone unit) is as much as 2.5×10^7 ft^2/d. The porosity of both aquifers is estimated at 0.3. In southeastern Florida, the salinity of the ground water in the aquifer system generally increases with increasing depth, whereas water temperature decreases with increasing depth. Temperatures of salty ground water in the Lower Floridan aquifer (Boulder Zone) range from 50.0 °F at Fort Lauderdale on the southeastern coast to about 110.0 °F near Punta Gorda on the southwestern coast.

Seismic reflection profiles in the western Straits of Florida show submerged karst on the Miami Terrace at about a 1,000-ft depth and in deeper parts of the straits. Ground-water movement in the Upper Floridan aquifer is generally southward to the Gulf of Mexico and the Atlantic Ocean from recharge areas in central Florida. Hydraulic gradients in the Upper Floridan aquifer in southeastern Florida suggest that eastward-flowing, brackish ground water is actively discharging through unfilled sinkholes on the Miami Terrace as submarine springs. The middle confining unit is relatively less permeable than the Upper and Lower Floridan aquifers, and it separates the two flow systems. However, hydraulic connection between the aquifers is inferred from the presence of sinkholes and fractures and from local temperature and salinity anomalies in the Upper Floridan aquifer.

Samples of ground water from the Upper and Lower Floridan aquifers were analyzed for natural carbon and uranium isotopes to determine rates of ground-water movement. Analyses of principal anions and cations were also performed. Tritium was determined in selected samples to check for contamination by modern water, and oxygen isotopes were determined in selected samples to assess their use as climate indicators.

Vertical variations in carbon-14 activity were indicated earlier by samples of ground water from selected depths in the Alligator Alley test well (site 10), and areal variations in carbon-14 activity were reported by Hanshaw and others (1965). Carbon-14 activity in the ground water in the Upper Floridan aquifer decreases southward and downgradient from the principal recharge area in central Florida to site 5 near Lake Okeechobee, where the activity is hardly detectable (apparent age, 50,000 Libby yr), and increases slightly downgradient from the lake to the coastal area of Dade and Broward Counties. The apparent reversal in the carbon-14 activity gradient at site 5 near Lake Okeechobee is coincident with the area where the southward-flowing fresh ground water becomes brackish and is no longer potable. Southward and downgradient from the Lake Okeechobee area, the increase in salinity and in carbon-14 activity is probably related to upwelling of relatively young seawater (with relatively higher carbon-14 activity) from the Lower Floridan aquifer. Carbon-14 activity in ground water in the Lower Floridan aquifer is highest at Fort Lauderdale (which is closest to the source area in the Straits of Florida) and decreases radially inland. Carbon-14 activity in the ocean is estimated at 94 percent of modern carbon, the activity at Fort Lauderdale (well G–2333) was 62.9 percent, and the activity at well G–2296 (site 10) about 44.5 mi west of Fort Lauderdale was 37.1 percent. The apparent carbon-14 ages of the samples suggest that the past rate of inland flow was decreasing and may have been affected by the rise in sea level during the Holocene transgression. The average rate of movement between Fort Lauderdale (site 9) and well G–2296 (44.5 mi west of Fort Lauderdale) is estimated at 54.6 ft/yr, and the average rate between Fort Lauderdale and the subsea source (about 10.5 mi east of Fort Lauderdale) is estimated at 17.3 ft/yr.

The results of the uranium isotope analyses of ground water from the Upper Floridan aquifer show a relation that apparently parallels the carbon-14 data. The uranium concentration gradient generally decreases down the hydraulic gradient to about the latitude of Lake Okeechobee and then increases slightly along the southeastern coast, again implying upwelling of uranium-rich saltwater from the Lower Floridan aquifer and (or) lateral encroachment of seawater from the Straits of Florida. Concentrations of dissolved uranium averaged 0.75 μg/L in the outcrop area of west-central Florida, 0.080 μg/L in central Florida, 0.048 μg/L in southern Florida, and 0.568 μg/L in distal southeastern Florida. The alpha-activity ratios for the Upper Floridan aquifer generally showed an inverse relation to the dissolved uranium. Ratios generally increased downgradient from the outcrop area in west-central Florida but decreased in southern and distal southeastern Florida. Increasing ratios indicate enrichment of uranium-234 with respect to uranium-238, and decreasing ratios indicate depletion of uranium-238 with respect to uranium-234. Ratios averaged 0.98 in the outcrop area of west-central Florida, 1.83 in central Florida, 1.24 in southern Florida, and 1.11 in distal southeastern Florida.

In the Lower Floridan aquifer, the uranium concentration gradient parallels the carbon-14 gradient. The dissolved uranium concentration at Fort Lauderdale is almost identical to that for seawater, and the concentration decreases radially inland as did the carbon-14. The alpha-activity ratio decreased radially inland, suggesting enrichment of uranium-234 with respect to uranium-238 during transit. Therefore, the concentration gradients for both carbon-14 and uranium indicate inland flow of seawater from the Straits of Florida; the relative carbon-14 ages of the seawater in the Lower Floridan aquifer imply that velocity is greatest toward the center of the Floridan Plateau, where temperatures are highest.

Measurements of water levels in the Upper and Lower Floridan aquifers were used to estimate hydraulic gradients, which were then used to estimate rates of ground-water movement. The hydraulic rates were then compared with estimates of rates based on relative carbon-14 ages of the ground water. Rates and transit times were calculated for segments of the flow lines from Polk City to Key Largo (227 mi) and from Polk City to Fort Lauderdale (194 mi) based on estimated predevelopment hydraulic gradients and assumed aquifer characteristics. Although predevelopment gradients represent a relatively short transient event compared with long-term averages represented by the carbon-14 data, the estimated rates and transit times for predevelopment conditions are considered an indication of the long-term flow pattern. For the predevelopment gradient, a particle of water traveling 227 mi from Polk City to Key Largo would be in transit from 159,000 to 779,000 yr, and a particle of water traveling 152 mi from the southernmost sinkhole lakes in central Florida to Key Largo would be in transit from 155,000 to 768,000 yr. Both estimates of transit time exceed the maximum dating capability of carbon-14. Only the transit time between site 9 (Fort Lauderdale) and site 10 (well G–2296, 44.5 mi west of Fort Lauderdale) is within the dating capability of carbon-14. Therefore, the occurrence of measurable carbon-14 activity in the brackish ground water of the Upper Floridan aquifer in southern Florida strongly suggests that infiltrating freshwater in central Florida is not the only source.

For the Lower Floridan aquifer, water-level measurements and estimates of fluid density at site 9 (well G–2334 at Fort Lauderdale) and site 10 (well G–2296, 44.5 mi west of Fort Lauderdale) were used to calculate the difference in head and the apparent hydraulic gradient. The head at site 9 (in terms of equivalent density) is about 0.2 ft higher than the head at site 10, thereby indicating an inland hydraulic gradient of about 8.5×10^{-7}. The transit time between wells is from 3,900 to 7,900 yr based on the estimated hydraulic gradient and assumed aquifer characteristics. Comparison of the hydraulically derived rates and transit times with those based on relative carbon-14 ages suggests that the estimated hydraulic gradient based on the water-level measurements may be too high. The particle velocities, transit times, and hydraulic gradients based on relative carbon-14 ages of the seawater in the Straits of Florida and ground water at sites 9 and 10 probably represent average values for the period represented by the differences in apparent age of the water samples.

Changing sea level, and perhaps changing climate, had significant effects on hydraulic gradients in the Floridan aquifer system. During periods of rising sea level and constant climate, freshwater in aquifer storage would gradually be displaced by seawater. Estimates of sea-level fluctuation during the past 150,000 yr suggest that sea level ranged from about 23 ft above present sea level to about 330 ft below present sea level. The last rise in sea level, called the Holocene transgression, began about 18,000 yr ago. Sea level rose about 330 ft during this period, and it is still rising, although at a slower rate. The rise of freshwater levels in the Florida peninsula during the past 9,000 yr was recorded by changes in vegetative types. Pollen studies of bottom sediments in lakes by Watts (1971) indicated a change from oak forest to pine forest as water tables in central Florida rose in response to rising sea level about 5,000 yr ago. A hypothetical relation between sea level and the water table in central Florida resulted from the pollen studies. The apparent carbon-14 ages of samples of saltwater from the Lower Floridan aquifer at sites 9 and 10 in southern Florida suggest that the inland transit of seawater from the Straits of Florida is also related to the rise in sea level during the Holocene transgression. Estimates of the rates based on assumed aquifer characteristics and relations between sea-level rise and the apparent carbon-14 ages of the samples ranged from about 172 ft/yr at the beginning of the Holocene transgression to about 5 ft/yr at present. The estimated differences in the head between sites 9 and 10 (44.5 mi apart) associated with these rates are 0.87 and 0.026 ft, respectively.

The present-day scenario of circulation proposed for the Floridan aquifer system of southern Florida is, therefore, (1) continuing rise in sea level and concurrent displacement of stored fresh ground water by inland-moving cold seawater chiefly through the Lower Floridan aquifer, (2) heating of the seawater in the Lower Floridan aquifer during inland transit, which results in lowered fluid density, (3) upwelling of seawater from the Lower Floridan aquifer through sinkholes and fractures that transect the middle confining unit, and (4) dilution of the seawater (again reducing the fluid density) and transport of the seawater back to the ocean by seaward-flowing freshwater in the Upper Floridan aquifer. This circulation theory is generally similar to that proposed earlier by Kohout (1965). The inland circulation of seawater is an argument against the theory that the saltwater in the Floridan aquifer system in southern Florida is connate or residual from former high stands of sea level.

Evidence of the upwelling phenomenon is indicated by salinity and temperature anomalies (also by anomalous carbon-14 activity) in the ground water of the Upper Floridan aquifer. In the Martin County-St. Lucie County area of southern Florida, wells ranging from 800 to 1,200 ft in depth produce brackish water that exceeds the background temperature of 80.0 °F by 10.0 °F. Associated with the local temperature anomalies are salinity anomalies. Beneath the temperature and salinity anomalies, at a depth of about 3,000 ft in the Lower Floridan aquifer, is saltwater having temperatures that compare with anomalous temperatures in the Upper Floridan aquifer. The temperature-salinity anomalies generally trend northwestward to southeastward and seem to originate from sinkholes or vertical solution pipes that are aligned with the major system of fractures or joints in the Tertiary limestone.

The Floridan aquifer system has been used as a receptacle for oil field brines since 1943. During 1943–83, 8.1 Ggal of brine were produced with 3.2 Ggal of oil. Of the 8.1 Ggal of brine, about 7.1 Ggal were injected into the Florida aquifer system. During 1959–83, 112 Ggal of nontoxic liquid waste were injected into the Floridan by municipal wastewater-treatment systems and industry. The average rate of injection increased from 268,000 gal/d in 1959 to 73.75 Mgal/d in 1983. In 1984, the estimated rate of injection was 112 Mgal/d. Injection of nontoxic liquid wastes is chiefly into the Boulder Zone of the Lower Floridan aquifer, although small amounts have been injected into the Upper Floridan aquifer.

Pilot studies indicate that the Upper Floridan aquifer can be used for temporal storage of freshwater. However, storage of freshwater in the Lower Floridan aquifer is not feasible.

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