SECOND AFFIDAVIT OF MARK A. QUARLES

BEFORE ME, the undersigned authority, personally came and appeared, Mark A. Quarles, who, after being duly sworn, did depose and say:

Qualifications

1. My name is Mark A. Quarles. I am an expert in the field of investigating planned and accidental releases of environmental pollutants to the environment and evaluating the risks associated with those releases.

2. I have specific education and experience performing environmental investigations in fractured sedimentary bedrock such as limestone and have specific education and experience in karst geologic bedrock conditions.

3. I have reviewed and assessed the Florida Power & Light Company's Response to Joint Intervenor's Motion to Amend Contention 2.1, February 10, 2012 prepared by Florida Power & Light Company (FP&L) relative to the potential for wastewater injection operations to contaminate the groundwater and drinking water aquifers.

4. I have also reviewed and assessed the NRC Staff's Answer to Joint Intervenors' Motion to Amend Contention NEPA 2.1, February 10, 2012 prepared by the Nuclear Regulatory Commission (NRC) relative to Miami-Dade County wastewater discharges and its characteristics and the potential for that wastewater to contaminate drinking water aquifers.

5. This Affidavit contains my expert opinions, which I hold to a reasonable degree of scientific certainty. My opinions are based on my application of professional judgment and expertise to sufficient facts or data, consisting specifically of documents related to this matter. These are facts and data typically and reasonably relied upon by experts in my field.

6. In my expert opinion, FP&L has still not adequately analyzed and discussed the site conditions, the risks associated with wastewater injection activities, and the potential of certain constituents – including heptachlor, ethylbenzene, toluene, and tetrachloroethylene – to contaminate underground aquifers. FP&L concluded in their ER that the potential impact to the groundwater quality in both the underground source of drinking water (USDW) and the Boulder Zone injection formation beneath the Turkey Point plant is "SMALL". ER, Section 5.2.3.2.4 at 5.2-25. This determination relied upon incomplete, inaccurate, and unsupported data.

Summary of Opinions

FP&L has failed to provide any information regarding the sources of its data and methods of data collection used to produce the list of chemical concentrations presented in Table 3.6-2. The data presented is likely to be inaccurate given the variability of these chemical concentrations.

7. FP&L has not provided any documentation of the data set forth in Table 3.6-2 relative to the date of sample(s), which plant(s) were used to develop the list, whether or not the concentrations were based on a single sampling event, when the sample(s) were collected, if the values represent arithmetic or geometric means, or the maximum/minimum concentrations of the constituents. FP&L failed to respond to the Intervenors' request for that information. FP&L, Motion to Amend.

8. The constituents and their concentrations can vary seasonally during the year and can depend on such variables as age of the collection system, the degree of infiltration and inflow into the collection system, the treatment methods used, the compliance history of the treatment plant, the compliance history of commercial and industrial dischargers to the plant, the presence of agricultural operations that use herbicides and pesticides, and the types of industrial and commercial users connected to the wastewater collection system for each plant, as examples. Wastewater treatment plants that have more commercial and industrial fruit and vegetable washing operations, as an example, would be expected to have more herbicides and pesticides in the wastewater. Further, if one geographic area has more mosquito spraying operations where those chemicals could enter the collection system, that variable would also be relevant for wastewater constituents. Lastly, industrial users that discharge organic chemicals, such as degreasers, and their pre-treatment compliance history all would play a role in what chemicals might be present and require treatment at the treatment plant. Not all wastewater treatment operations can remove or effectively treat recalcitrant chemicals such as tetrachloroethylene and heptachlor.

9. This seasonal variability necessitates the use of long-term sampling to achieve an accurate indication of actual chemical concentrations in wastewater.

10. For these reasons, FP&L cannot accurately estimate chemical concentrations, and the risks associated with aquifer contamination, without a long-term study of constituents from the South District Wastewater Treatment Plant site.

FP&L disputes that deep well injection of South District wastewater that is planned for injection at the Turkey Point site has already contaminated the Upper Floridan Aquifer. That argument is not supported by the ER prepared by FP&L or actual data collected from the South District site.

11. FPL&L disputes the previous assertion that the upper portions of the Floridan Aquifer have already been contaminated by the Miami-Dade Water and Sewer Department (MDWASD) South District Wastewater Treatment Plant site – located just 9 miles away

from the Turkey Point site. FP&L Response at 10. Their dispute against the assertion was based on the Walsh and Price report and their definition of what geologic formations are actually included as the "Upper Floridan Aquifer".

12. According to the United States Geologic Survey (USGS), the Avon Park Formation (also known as the Avon Park Permeable Zone, APPZ) is considered to be an aquifer within the Upper Floridan Aquifer system. USGS at G7. According to the Walsh and Price investigation, 10 of 12 wells drilled in the APPZ at the South District plant site are contaminated with wastewater that was injected into the Boulder Zone approximately 1,250 feet deeper than the APPZ. Walsh and Price at 4 and 7.

13. The Idaho National Engineering and Environmental Laboratory (INEEL) has also concluded that the Avon Park Permeable Zone is within the Upper Floridan Aquifer. INEEL at 4.

14. The ER prepared by FP&L described the "Upper Floridan Aquifer" as including the Avon Park Formation / APPZ. ER, Revision 3 at 2.3-18.

15. The ER prepared by FP&L, the INEEL, and the Walsh and Price review of data support the assertion that the Upper Floridan Aquifer has already been contaminated by wastewater. That same wastewater (90 million gallons per day according to the ER) is planned for deep well injection at the Turkey Point site.

No detailed, extensive investigation has ever been completed at the Turkey Point site to determine the presence or absence of geologic confining layers or horizontal and vertical bedrock fractures that can be contaminant migration pathways.

16. The only information that FP&L submitted in the ER to support the suitability of the Turkey Point site is generalized data from various published reports that generalize regional, South Florida geologic conditions - as opposed to determining actual geological subsurface data from the Turkey Point site.

17. The only completed investigation of the subsurface near the Turkey Point site to evaluate the presence of key geologic and hydrogeologic conditions necessary to protect drinking water aquifers comes the Miami-Dade Water and Sewer Department (MDWASD) South District Wastewater Treatment Plant – the proposed source of 90 million gallons a day of wastewater to be injected at the Turkey Point site. Groundwater at that site has already been contaminated by deep well injection activities. Walsh and Price at 1. EPA RA at 4-13. INEEL at iv.

18. Walsh and Price concluded - based upon actual groundwater monitoring results from wells from data collected from 1991 to 2007 for the nearest deep well injection site for wastewater that will be injected at the Turkey Point plant - that wastewater has already contaminated shallower groundwater. Key conclusions include:

- Density-driven buoyant and rapid vertical migration occurred because in part, wastewater was less dense than the salty water in the Boulder Zone. As a result, wastewater has a natural tendency to rise. Walsh and Price at 14.
- Injected wastewater will rise upward through bedrock as a distinct water body, with little mixing of native waters as it migrates upwards. Walsh and Price at 15.
- Injected wastewater will migrate upwards through discrete vertical pathways. Walsh and Price at 15.
- Groundwater data illustrated that the injected water has a "direct pathway to the APPZ" – completely bypassing the lower Middle confining Unit (MCU2). Walsh and Price at 14.
- Contaminant concentrations in the more permeable, shallow APPZ over the MCU2 increased over time and correlated well with the concentrations that were injected into the Boulder Zone. Walsh and Price at 7.
- Rapid vertical migration pathways can be due to "structural anomalies such as fracturing and karst features that would vertically connect aquifers and provide high hydraulic conductivity transport pathways through confining layers". Walsh and Price at 13.
- Contaminated water that reaches the higher aquifer levels above the confining unit is then able to flow horizontally away from the site along the regional direction of groundwater flow. Walsh and Price at 15.

19. The South District Wastewater Treatment Plant is located approximately 9 miles north of the Turkey Point plant. ER at 2.3-47.

20. A report published in 2010 by Walsh and Price on behalf of the MDWASD, concluded after reviewing 16 years (from 1991 to 2007) of groundwater data that widespread groundwater contamination exists at that injection site because of unfavorable geologic conditions – conditions that are contrary to the assumptions made by FP&L in the ER. Walsh and Price at 7, 14, and 15.

21. Nine deep well injection wells were drilled at the South District plant from 1995 to 1996. Walsh and Price at 4. The Walsh and Price investigation of historical groundwater data showed that contamination of the Well 6U drilled into the Upper Floridan Aquifer, as defined by the USGS, began almost immediately after injection began in 1995. In fact, the investigation concluded "Well 6U showed an increased trend of NH_3 (ammonia nitrogen, the marker compound used by Walsh and Price to identify wastewater in groundwater) that was observed to be similar to the increasing trend of NH_3 in the injectate". Walsh and Price at 7. That trend was also seen in other Upper Floridan Aquifer wells when Walsh and Price concluded "almost all of the wells showed variation of NH_3 concentrations over time". Walsh and Price at 7 and 8.

22. An evaluation of the data reviewed by Walsh and Price indicates that the lower Middle Confining Unit (MCU2) does virtually nothing to prohibit the rapid vertical migration of the more buoyant wastewater that is injected. The study concluded that four (4) different contamination plumes already exist in the Avon Park Permeable Zone (APPZ), which is a zone of very permeable limestone bedrock of the Upper Floridan Aquifer that is

sandwiched between the lower MCU2 (deeper layer) and the upper MCU1 confining layer (more shallow). According to that study, 10 of 12 wells (83%) drilled to monitor for unintended contamination in the APPZ drinking water are already contaminated with wastewater. Walsh and Price at 7.

23. The ER prepared by FP&L relied on an assumed 1,000-foot thickness (at least) of the Middle Confining Unit to separate the Boulder Zone from the Upper Floridan Aquifer and to protect drinking water. FP&L Motion to Amend at 11.

24. According to Walsh and Price, the base of the APPZ is situated 378 meters (1,240 feet) above the top of the Boulder Zone. Walsh and Price at 4. As a result, contaminated groundwater at the South District site has migrated vertically a minimum of approximately 1,250 feet.

25. FP&L estimated in the ER that the vertical hydraulic conductivity (rate that groundwater will travel upwards) of the important middle confining unit that separates the Boulder Zone from the upper drinking water aquifer ranged between 1.3×10^{-4} feet per day (0.0026-inch) to no more than 0.24 feet per day (around 3 inches). ER at 2.3-33. That estimate was based upon generalized data for southern Florida published in the ER, not from the specific site in question. ER, Revision 3 at 2.3-33. This estimate is a gross underestimate for the same generalized geologic conditions at the South District plant where groundwater migrated *at least* 1,240 feet upward into the drinking water aquifer almost immediately after injection of the same wastewater planned for Turkey Point began at that plant, according to Walsh and Price.

26. Of the 32 groundwater monitoring wells installed at the South District plant, only four (4) wells monitor the "Upper Floridan Aquifer" (as defined by Walsh and Price); 12 wells monitor the Avon Park Permeable Zone (APPZ), which the USGS has defined as part of the "Upper Floridan Aquifer", and 16 wells monitor groundwater within the lower MCU2. None are installed into the upper Middle Confining Unit (MCU1) to know whether or not groundwater within that bedrock formation is also contaminated. As a result, there is no data to show whether or not the upper MCU1 is actually confining any contaminated groundwater at the South Plant.

27. The Walsh and Price conclusion that vertical pathways "did not appear to extend up to the UFA" (Upper Floridan Aquifer) seems to be based on the absence of groundwater contamination in one or more wells drilled within the UFA zone, as defined by Walsh and Price. That conclusion cannot be supported by groundwater data because no wells are even drilled into the upper MCU1 that lies just below the Upper Floridan Aquifer.

28. Further, of the four (4) wells drilled into the UFA (according to Walsh and Price) at the South Plant, only one (1) of four (4) wells is even capable of detecting a release of contaminants because only one well (Well 1U) is located hydraulically downgradient (in the regional direction of flow) from a plume (Plume 2 of 4), as illustrated by Walsh and Price. The remaining wells (2U, 3U, and BZ1) are located hydraulically *upgradient* from the nearest of three other contaminant plumes (plumes 1, 3, and 4).

29. The Walsh and Price investigation does not support the FP&L conclusions in the ER relative the effectiveness of the middle confining unit layers to prevent upward migration and contamination of more shallow drinking water aquifer zones.

30. Vertical pathways across multiple layers of fractured bedrock can be just a few (e.g. 2 to 3 feet) feet wide and be extremely difficult to identify. Without a very detailed subsurface investigation at the Turkey Point site to identify those features, an injection well program will risk rapid migration of contaminants into drinking water aquifers, based on the results at the South District plant.

The single exploratory well currently being drilled by FP&L to determine suitability of the Turkey Point site for deep well injection is grossly inadequate to characterize the site and define the risk to human health.

31. Apparently, there is only one subsurface boring or well that will be drilled by FP&L deeper than 615 feet at the Turkey Point site. FP&L, Response at 12. According FP&L's response, "from this well, FPL will be able to determine the confining characteristics of the intervals overlying the Boulder Zone" and not until and unless confinement is confirmed, will injection wells be drilled. In summary, FP&L is drilling a *single* exploratory well to define confinement conditions that 32 wells at the South District plant have been unable to define. That single well cannot possibly define subsurface geologic conditions to either determine the suitability of the confining layers to confine vertical migration of wastes into drinking water aquifers or to determine the true risks to the drinking water aquifer.

32. According to Walsh and Price, 32 groundwater monitoring wells and borings have been installed at the South District plant. According to the INEEL, the data produced from those 32 wells have proven insufficient to determine subsurface geologic conditions, requiring the installation of even three (3) to four (4) *more wells* and conducting more extensive monitoring activities. This degree of investigation required to understand the localized geology and hydrogeology makes the single well currently being drilled by FP&L at the Turkey Point site seem grossly inadequate.

33. Unless and until a thorough subsurface investigation is performed at the Turkey Point site to determine actual conditions before deep well injections begin, FP&L cannot possibly ensure protection of overlying drinking water aquifers. Without such a thorough investigation and given the shear volume of water to be injected in unknown geologic conditions, FP&L risks widespread contamination of drinking water aquifers with contamination - possibly lasting for the foreseeable future should that occur. The INEEL recommended these additional investigative measures be performed at the South District plant, at a minimum, to calculate the net thickness of the confining layer:

Recommended Additional Geologic Investigative Activities

• Install 3 to 4 new wells	• Test for borehole temperature logs
• Obtain gamma-ray log	• Test for electrical conductivity of the mud filtrate
• Obtain lateral logs	• Collect whole core samples
• Obtain compensated density / neutron logs	• Determine log-derived porosity
• Obtain deep resistivity logs	• Determine bedrock porosity
• Obtain micro resistivity logs	• Determine compatibility of waste with the bedrock
• Obtain spontaneous potential logs	• Test for electrical conductivity of the wastewater injected
• Develop core permeability / density cross plots	• Determine formation fluid conductivity

Recommended Additional Hydrogeologic Investigative Activities

• Collect geophysical data from new wells	• Calculate actual equivalent hydraulic conductivity of the Upper and Lower Floridan Aquifer formations
• Conduct flow meter logging from wells	• Calculate vertical flux and time of travel
• Conduct a series of packer tests	• Assess the vertical time of travel effects

In my expert opinion, wastewater injected via deep well injection into the Boulder Zone at the Turkey Point site may migrate into the Upper Floridan Aquifer, contaminating the groundwater with four constituents -- heptachlor, ethylbenzene, toluene, and tetrachloroethylene.

34. A report prepared by the Idaho National Engineering and Environmental Laboratory (INEEL) supports the conclusions of the Walsh and Price report that groundwater contamination exists; contamination of the Upper Floridan Aquifer has already occurred; that vertical bedrock fractures and conduits are likely migration pathway(s); and that an extensive investigation is needed to further understand the site conditions.

35. The INEEL report concluded that deep well injection activities at the South District plant have already contaminated the Upper Floridan Aquifer. INEEL at 38. Further, the INEEL concluded that "the geochemical data sets indicate that groundwater at some locations in the Upper Floridan Aquifer is contaminated with treated wastewater, which implies that contaminants are migrating through the Middle Confining Layer". INEEL at 39.

36. Calculations made by the INEEL using actual data collected from the South District plant site to determine the vertical rate between the Boulder Zone and the Upper Floridan Aquifer shows that "approximately 5 to 36 millions gallons per day could move from the Boulder Zone to the Upper Floridan Aquifer. For comparison, approximately 100 million gallons per day are injected". INEEL at 25. Simply put and assuming that 90 million gallons per day are injected (according to FP&L in the ER), the INEEL believes that up to 40 percent of the injected fluids could contaminate the Upper Floridan Aquifer.

37. The INEEL calculated that the travel time from the Boulder Zone to the Upper Floridan Aquifer would be rapid, with a conservative estimate being approximately 1 to 6 years. INEEL at 25.

38. The EPA Relative Risk Assessment that FP&L relied upon in their ER concluded "it would take between 30 and 1,100 years for wastewater injected via underground wells to migrate up to current Underground Source of Drinking Water (USDWs)". FP&L Response at 14. This estimate grossly underestimates the travel time that was actually experienced and / or calculated by both INEEL and Walsh and Price.

39. FP&L relies on that 30 to 1,100 years to decrease the concentrations of contaminants in the groundwater "to lower levels by the time the effluent water reached the drinking water receptors". FP&L Response at 14. Given the lower travel times actually seen and reported by Walsh and Price and the INEEL, this implies that there would be insufficient time for concentrations to be reduced before reaching drinking water receptors (humans) should the aquifer be used as a source of drinking water. Moreover, FPL provides no calculations of the rate to which the contaminants at issue here would actually degrade

40. The INEEL study for the South District plant concluded that a pattern of point-source contamination of the Upper Floridan aquifer exists at the South District plant; however, the available data to determine what exactly the "point sources" are "were not sufficient to differentiate between inadequately sealed wells or natural features as the point source features". INEEL at 36. The INEEL recommended an extensive investigation to determine what the exact sources are. INEEL at 9, 10, 26, 27, 36, 38, 39, and 40. As such, both leaky wells and geologic conditions are suspects for the contamination. INEEL at 40.

41. The EPA Relative Risk Assessment determined that there were 18 documented instances where injection well sites have contaminated drinking water aquifers.

42. The EPA concluded in their Relative Risk Assessment that 18 deep well injection activities in Florida have resulted in unintended contamination of underground sources of drinking water (USDW) due to fluid migration from the targeted injection zone. EA at 4-12. By design, fluid migration through an injection well is not supposed to migrate into an underground drinking water aquifer. The fact that the EPA specifically identified the South District plant as one of the confirmed sites that has in fact contaminated a drinking

water aquifer, supports the conclusions made by Walsh and Price and the INEEL. EA at 4-13.

43. Given that the EPA has determined that deep well injection at the South District plant has contaminated a drinking water aquifer and given that the USGS and the INEEL both consider the APPZ to be within the "Upper Floridan Aquifer", there is sufficient information to infer that wastewater injected into the Boulder Zone has migrated upward - resulting in contamination of the Upper Floridan Aquifer at the South District plant for the actual wastewater planned for injection at Turkey Point.

Sources:

1. Environmental Report (ER), Revision 3, Part 3, COL Application, Turkey Point Plant, Units 6 & 7, Florida Power and Light Company.
2. *Determination of vertical and horizontal pathways of injected fresh wastewater into a deep saline aquifer (Florida, USA) using natural chemical traces*, Hydrogeology Journal, by Walsh, Virginia and Price, Rene, published online February 2010.
3. *Evaluation of Confining Later Integrity Beneath the South District Wastewater Treatment Plant, Miami-Dade Water and Sewer Department, Dade County, Florida*, by the Idaho National Engineering and Environmental Laboratory, INEEL / EXT-01-00046, February 2001.
4. *Florida Power & Light Company's Response to Joint Intervenors' Motion to Amend Contention 2.1,* Florida Power & Light Company, February 10, 2012.
5. *Hydrogeology, Ground-Water Movement, and Subsurface Storage in the Floridan Aquifer System in Southern Florida, Professional Paper 1403-G,* U.S. Geological Survey, 1989.
6. *NRC Staff's Answer to Joint Intervenors' Motion to Amend Contention NEPA 2.1,* Nuclear Regulatory Commission, February 10, 2012.
7. *Relative Risk Assessment of Management Options for Treated Wastewater in South Florida,* US EPA Office of Water, EPA 816-R-03-010, April 2003.

Dated: February 17, 2012

MARK A. QUARLES

SWORN TO AND ASCRIBED BEFORE ME, THIS 17th DAY OF Feb., 2012.

NOTARY PUBLIC

MARSHALL W. BUTLER
STATE OF TENNESSEE NOTARY PUBLIC
DAVIDSON COUNTY
My Commission Expires 09-08-2013

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403–G

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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, Cob., 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 elastics (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 and 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

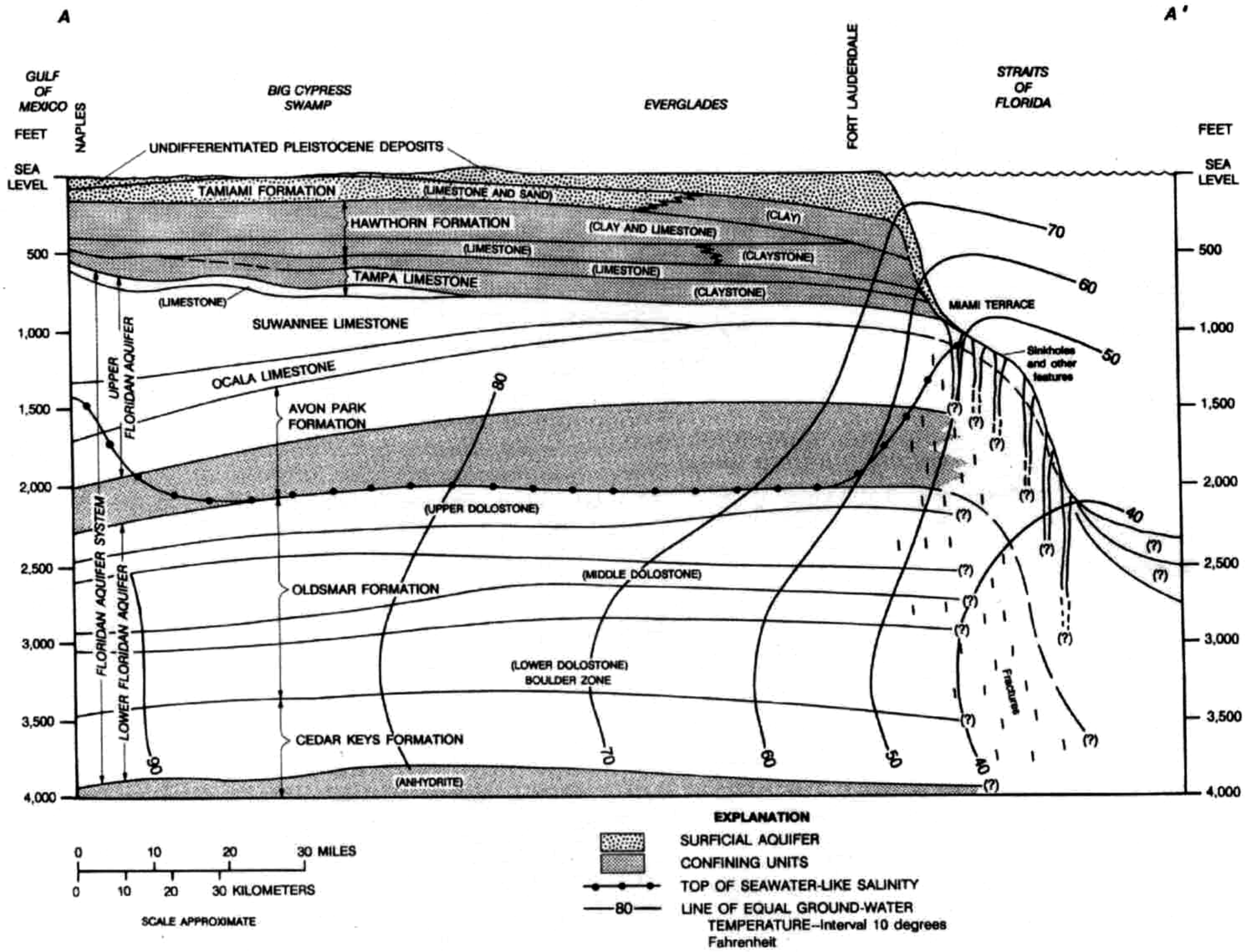

FIGURE 3. –Generalized hydrogeologic section A-A' through southern Florida showing isotherms and top of saltwater in the Floridan aquifer system. (line of section shown in fig 2.)

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

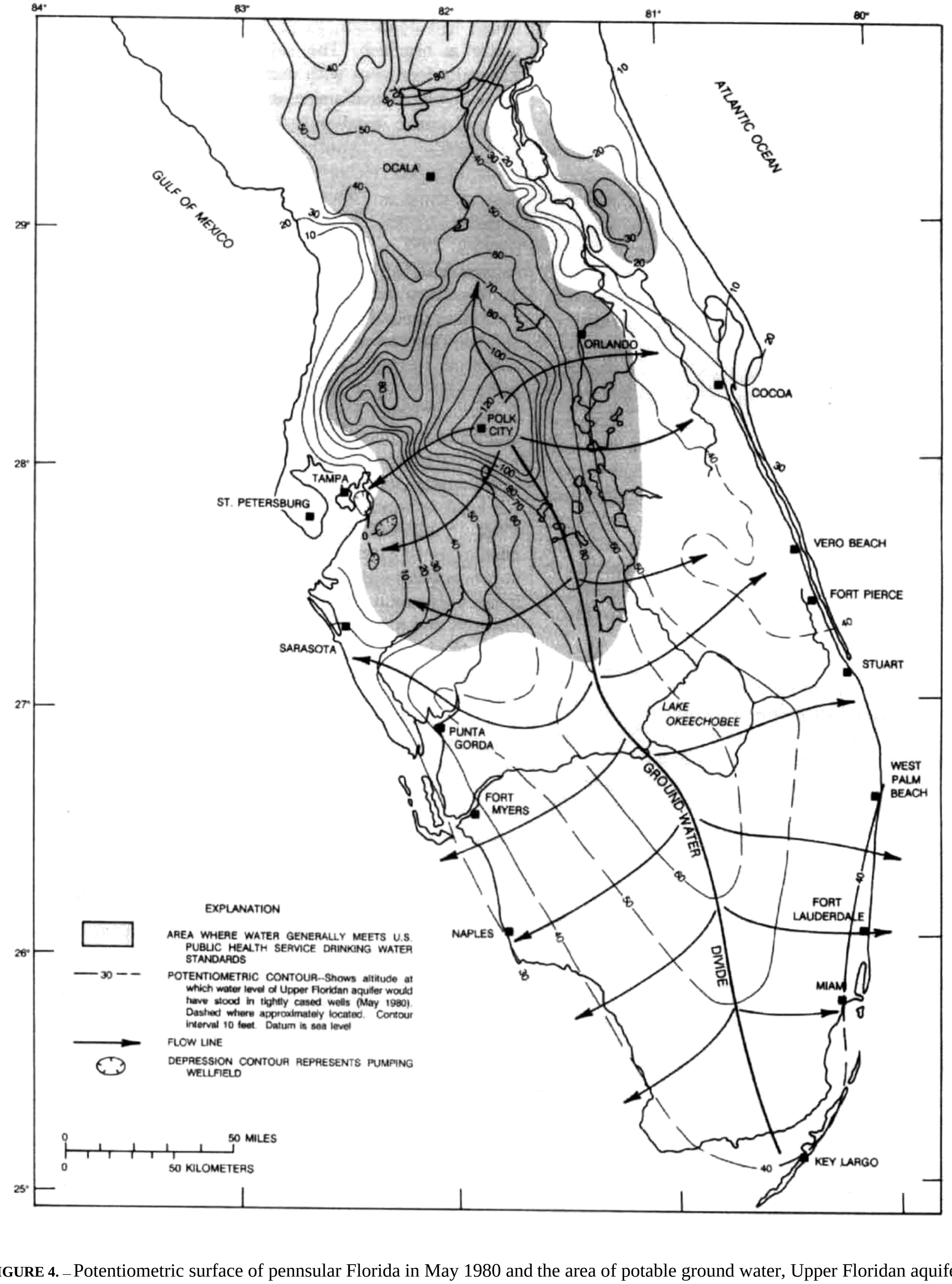

FIGURE 4. – Potentiometric surface of pennsular Florida in May 1980 and the area of potable ground water, Upper Floridan aquifer (revised from Johnston and others, 1981 and Healy, 1982).

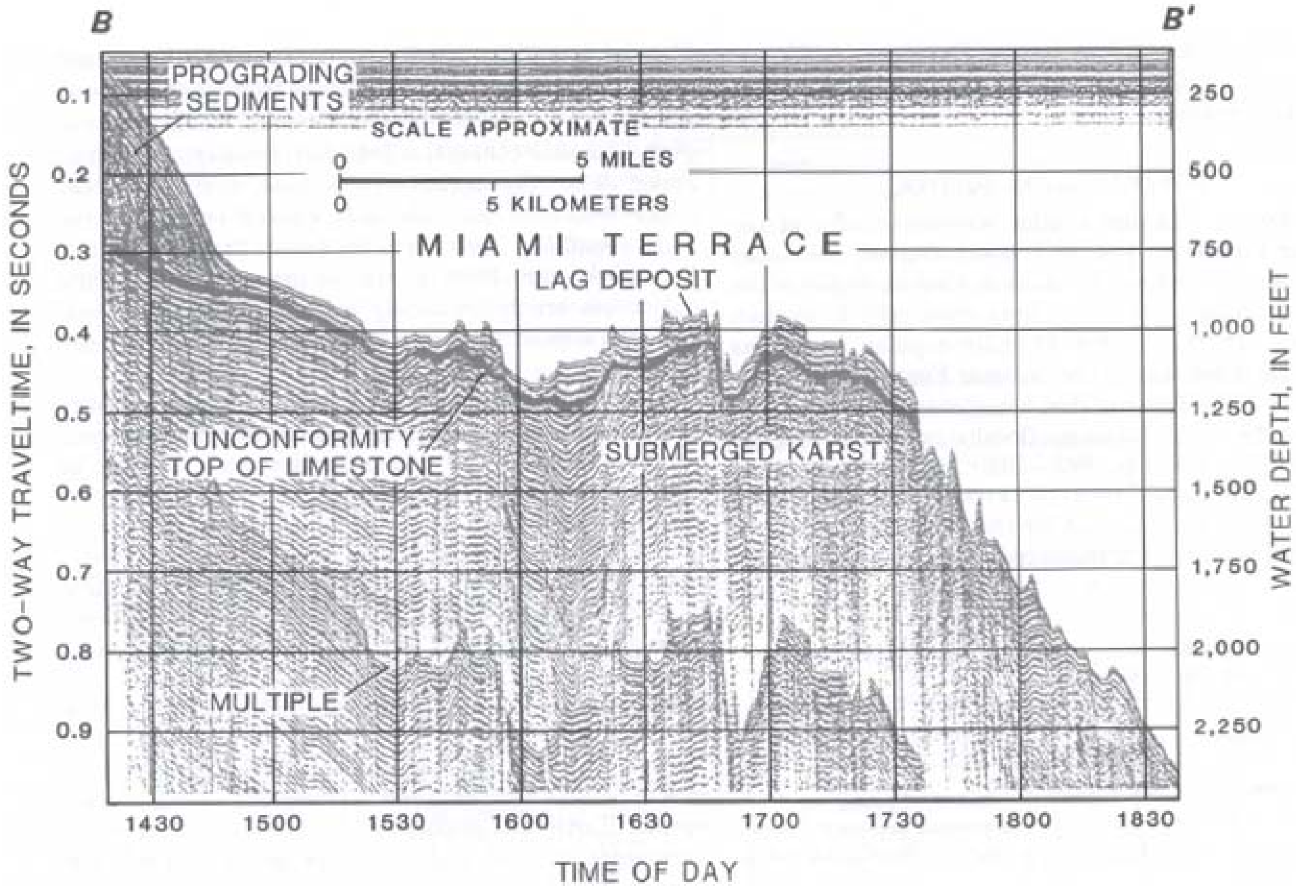

FIGURE 5. – Seismic reflection profile ***B-B'*** in the western Straits of Florida showing submarine karst on the Miami Terrace. (Line of section shown in fig 2.)

composed of fossiliferous phosphatic limestone that contains numerous foraminifers, chiefly *Miogypsina* sp., *Giobigerina* 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 3.2x 10^6 ft^2/d (Meyer, 1974) to 24.6x 10^6 ft^2/d (Singh and others, 1983), whereas that for the overlying dolostones is probably an order of magnitude less. In southeastern

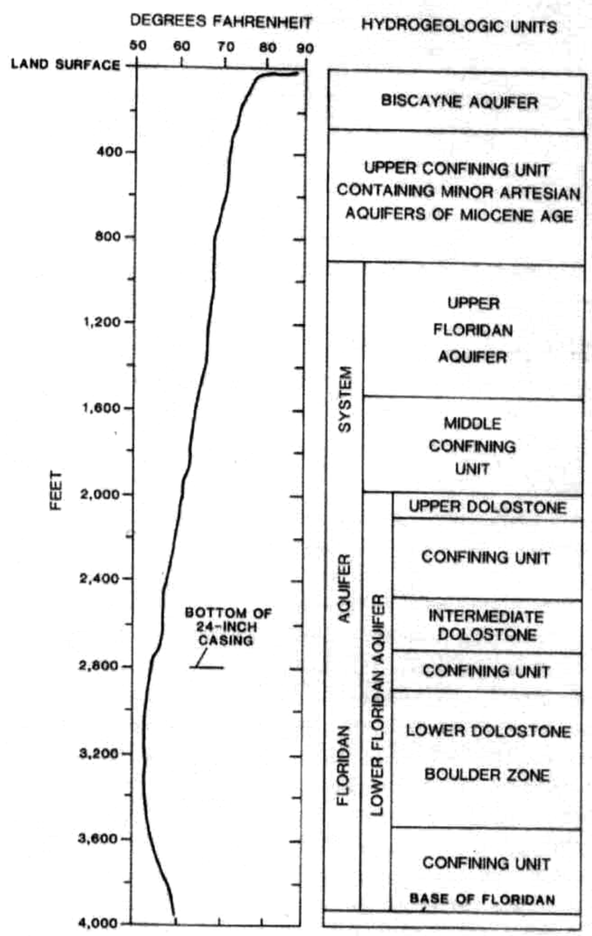

FIGURE 4. – Fluid temperature and hydrogeologic units in well G-2334 at site 9, Fort Lauderdale (see fig 2.)

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.

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

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$_2$M Hill, Inc.
5	3,180	Temperature log shows 72.0°F from 3,180 to 3,424 feet. Source, CH$_2$M Hill, Inc. Local well STL-254.
6	3,290	Temperature log shows coolest from 3,140 to 3,290 feet. Source, CH$_2$M 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$_2$M 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.

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/mm) 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.

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

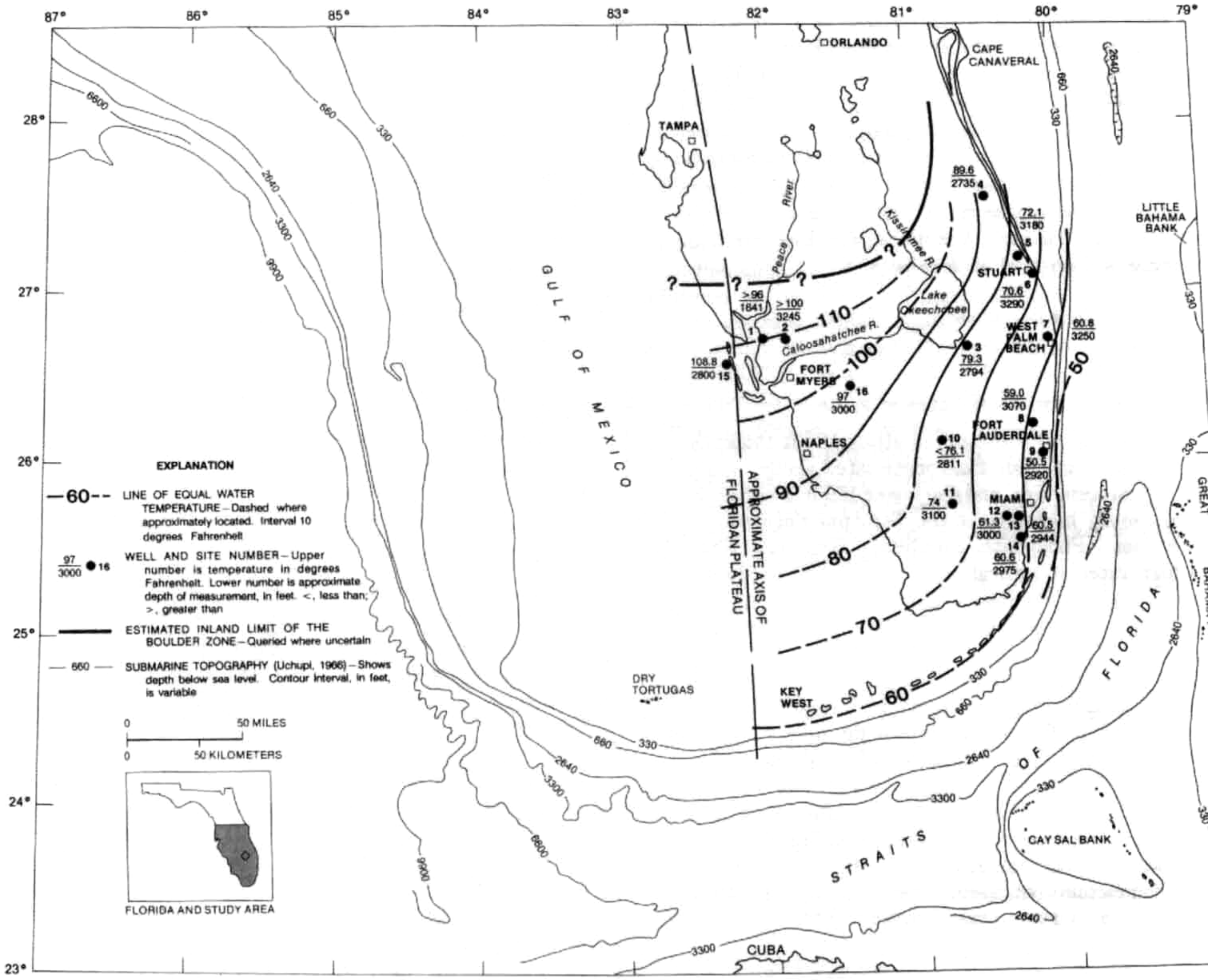

FIGURE 7. – Temperature of salt water in the boulder zone of the Lower Floridan Aquifer, south Floridan plateau

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

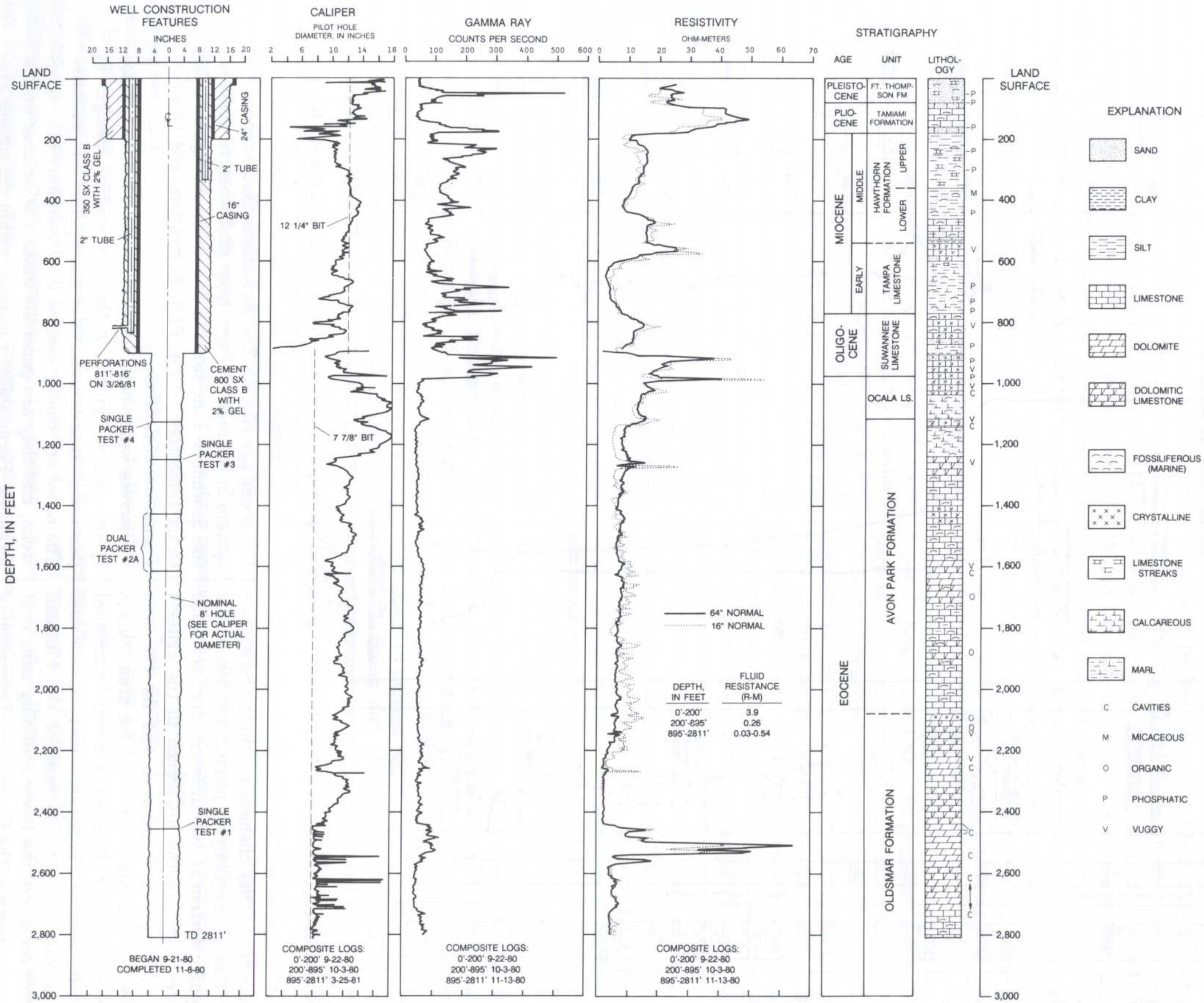

FIGURE 8.—Construction features, selected geophysical logs, and stratigraphy for the Alligator Alley test well (well G-2296 at site 10, fig. 2).

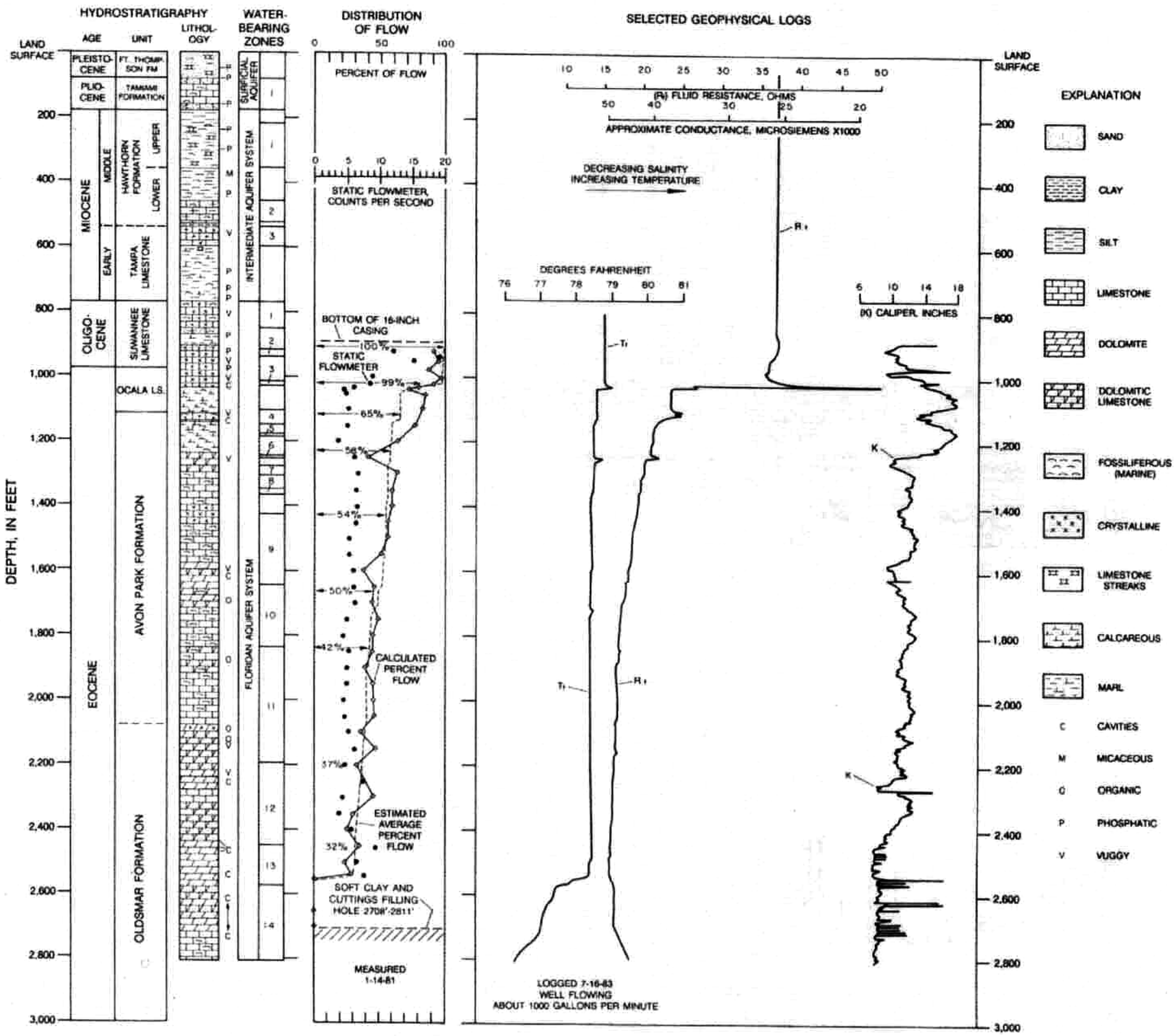

FIGURE 9. – Hydrostratigraphy, distribution of flow, and selected geophysical logs for the Alligator Alley test well (well G-2296 at site 10 fig. 2.)

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 sys

tem 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 2,811ft 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 (micro siemens 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.

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:

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.

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

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:

$$PG_{SW}(D\text{-}8.4) \qquad (2)$$

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

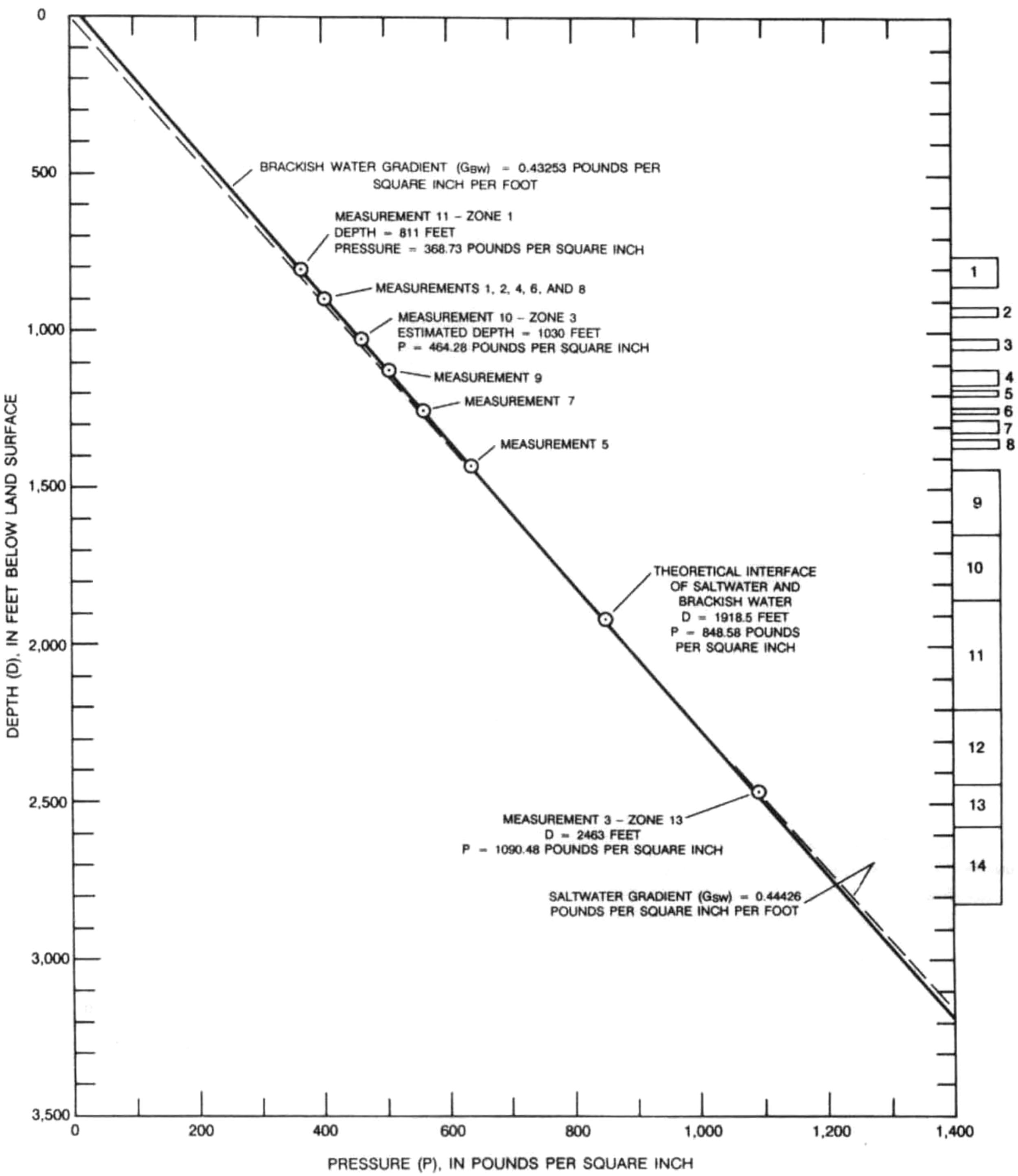

FIGURE 10. – Pressure-depth relation for water level measurements in the Floridan aquifer system in the Alligator Alley test well (well G-2296 at site 10, fig. 2)

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. ^3H 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 Belenmita).

R: Relative activity of sample with respect to standard x 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	^3H 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.