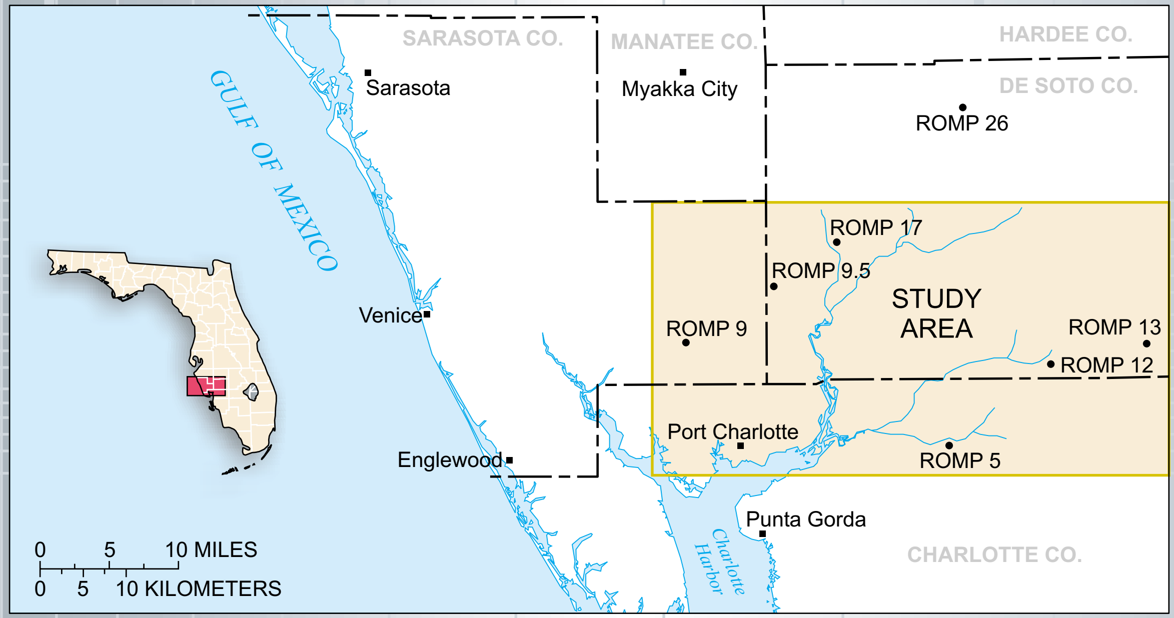
Hydrogeologic Framework and Geochemistry of the Intermediate Aquifer System in Parts of Charlotte, De Soto, and Sarasota Counties, Florida

Water-Resources Investigations Report 01-4015

Prepared in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT



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

Hydrogeologic Framework and Geochemistry of the Intermediate Aquifer System in Parts of Charlotte, De Soto, and Sarasota Counties, Florida

By A.E. Torres, L.A. Sacks, D.K. Yobbi, L.A. Knochenmus,
and B.G. Katz

U.S. Geological Survey

Water-Resources Investigations Report 01–4015

Prepared in cooperation with the

SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

Tallahassee, Florida
2001

science for a changing world

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 3015
227 N. Bronough Street
Tallahassee, FL 32301

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225
888-ASK-USGS

Additional information about water resources in Florida is available on the World Wide Web at **http://fl.water.usgs.gov**

CONTENTS

Figures

Tables

Conversion Factors, Vertical Datum, Acronyms, and Additional Abbreviations

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch per month (in/mo)	2.54	centimeter per month
inch per year (in/yr)	2.54	centimeter per year

Temperature in degrees Celsius (ºC) can be converted to degrees Fahrenheit (ºF) as follows:
$^oF = (1.8 \times {}^oC) + 32$

Temperature in degrees Fahrenheit (ºF) can be converted to degrees Celsius (ºC) as follows:
$^oC = ({}^oF - 32) / 1.8$

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

Acronyms and Additional Abbreviations

Ca	calcium
$CaCO_3$	calcium carbonate
Cl	chloride
^{14}C	carbon-14 isotope
CH_2O	organic matter
CO_2	carbon dioxide
CU	confining unit
δ	delta
$\delta^{13}C$	delta carbon-13
$\delta^{13}C_{DIC}$	δ carbon-13 isotope of dissolved inorganic carbon
$\delta^{18}O$	delta oxygen-18
δD	delta deuterium
FeS_2	pyrite
ft/d	foot per day
FGS	Florida Geological Survey
gal/min/ft	gallons per minute per foot
GMWL	global meteoric water line
K'/S's	hydraulic diffusivity
K_r	equilibrium reaction constant
K_v	vertical hydraulic conductivity
in/yr	inches per year
m	meter
meq/L	milliequivalent per liter
µS/cm	microsiemens per centimeter
Mg	magnesium
mg/L	milligrams per liter
mmol/L	millimoles per liter
mL	milliliter
MW	monitor well
N	nitrogen
Na	sodium
^{16}O	oxygen-16 isotope
^{18}O	oxygen-18 isotope
pmc	percent modern carbon (analyzed)
PMC	Percent Modern Carbon (normalized)
P	phosphorus
PCO_2	partial pressure of carbon dioxide
PZ	permeable zone
PZ1	Tamiami/Peace River permeable zone 1
PZ2	Upper Arcadia permeable zone 2
PZ3	Lower Arcadia permeable zone 3
RMSE	root-mean-square error
ROMP	Regional Observation and Monitor-Well Program
SAS	surficial aquifer system
SI	saturation index
SO_4	sulfate
SO_{4ex}	excess sulfate concentration
SS	sum of squared residuals
SWFWMD	Southwest Florida Water Management District
t_d	dimensionless time factor
TU	tritium units
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey

Hydrogeologic Framework and Geochemistry of the Intermediate Aquifer System in Parts of Charlotte, De Soto, and Sarasota Counties, Florida

By A.E. Torres, L.A. Sacks, D.K. Yobbi, L.A. Knochenmus, *and* B.G. Katz

Abstract

The hydrogeologic framework underlying the 600-square-mile study area in Charlotte, De Soto, and Sarasota Counties, Florida, consists of the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. The hydrogeologic framework and the geochemical processes controlling ground-water composition were evaluated for the study area. Particular emphasis was given to the analysis of hydrogeologic and geochemical data for the intermediate aquifer system. Flow regimes are not well understood in the intermediate aquifer system; therefore, hydrogeologic and geochemical information were used to evaluate connections between permeable zones within the intermediate aquifer system and between overlying and underlying aquifer systems. Knowledge of these connections will ultimately help to protect ground-water quality in the intermediate aquifer system. The hydrogeology was interpreted from lithologic and geophysical logs, water levels, hydraulic properties, and water quality from six separate well sites. Water-quality samples were collected from wells located along six ground-water flow paths and finished at different depth intervals. The selection of flow paths was based on current potentiometric-surface maps. Ground-water samples were analyzed for major ions; field parameters (temperature, pH, specific conductance, and alkalinity); stable isotopes (deuterium, oxygen-18, and carbon-13); and radioactive isotopes (tritium and carbon-14).

The surficial aquifer system is the uppermost aquifer, is unconfined, relatively thin, and consists of unconsolidated sand, shell, and limestone. The intermediate aquifer system underlies the surficial aquifer system and is composed of clastic sediments interbedded with carbonate rocks. The intermediate aquifer system is divided into three permeable zones, the Tamiami/Peace River zone (PZ1), the Upper Arcadia zone (PZ2), and the Lower Arcadia zone (PZ3). The Tamiami/Peace River zone (PZ1) is the uppermost zone and is the thinnest and generally, the least productive zone in the intermediate aquifer system. The Upper Arcadia zone (PZ2) is the middle zone and productivity is generally higher than the overlying permeable zone. The Lower Arcadia zone (PZ3) is the lowermost permeable zone and is the most productive zone in the intermediate aquifer system. The intermediate aquifer system is underlain by the Upper Floridan aquifer, which consists of a thick, stratified sequence of limestone and dolomite. The Upper Floridan aquifer is the most productive aquifer in the study area; however, its use is generally restricted because of poor water quality. Interbedded clays and fine-grained clastics separate the aquifer systems and permeable zones.

The hydraulic properties of the three aquifer systems are spatially variable. Estimated transmissivity and horizontal hydraulic conductivity varies from 752 to 32,900 feet squared per day and from 33 to 1,490 feet per day, respectively, for the surficial aquifer system; from 47 to 5,420 feet squared per day and from 2 to 102 feet per day,

respectively, for the Tamiami/Peace River zone (PZ1); from 258 to 24,633 feet squared per day and from 2 to 14 feet per day, respectively, for the Upper Arcadia zone (PZ2); from 766 to 44,900 feet squared per day and from 10 to 201 feet per day, respectively, for the Lower Arcadia zone (PZ3); and from 2,350 to 7,640 feet squared per day and from 10 to 41 feet per day, respectively, for the Upper Floridan aquifer. Confining units separating the aquifer systems have leakance coefficients estimated to range from 2.3×10^{-5} to 5.6×10^{-3} feet per day per foot. Strata composing the confining unit separating the Upper Floridan aquifer from the intermediate aquifer system are substantially more permeable than confining units separating the permeable zones in the intermediate aquifer system or separating the surficial aquifer and intermediate aquifer systems.

In Charlotte, Sarasota, and western De Soto Counties, hydraulic head generally increases with depth indicating an upward flow potential. Elsewhere, head decreases with depth indicating a downward flow potential. During September 1998, relatively small head differences occurred between the Upper Floridan aquifer and Lower Arcadia zone (PZ3) in the intermediate aquifer system (up to 5 feet) whereas relatively larger head differences occurred between permeable zones of the intermediate aquifer system and the surficial aquifer system (as much as 8 feet).

The hydraulic connection between the surficial aquifer system, the intermediate aquifer system and associated permeable units, and the Upper Floridan aquifer is variable in the study area. Clay beds within the confining units can limit the degree of hydraulic connection between aquifer systems and permeable zones; however, facies changes within the units may result in local hydraulic connection with overlying and underlying aquifers. Generally, better hydraulic connection exists between the Upper Floridan aquifer and the Lower Arcadia zone (PZ3) than exists between the permeable zones of the intermediate aquifer system and the surficial aquifer system.

Several important findings about flow patterns in the intermediate aquifer system have been supported by combining geochemical modeling with hydraulic head data. Vertical flow from underlying aquifers is significant in the chemical evolution of water in the intermediate aquifer system. Flow patterns derived only from potentiometric-surface maps may be misleading because flow paths are presumed to be lateral. Recent flow patterns delineated strictly based on potentiometric-surface maps do not represent predevelopment ground-water flow paths. The chemical composition of intermediate aquifer waters most likely reflects predevelopment conditions. Areas where geochemical models indicate large amounts of upward flow may actually be areas where discontinuity of the permeable zone exists, thereby limiting lateral flow.

Water in the intermediate aquifer system varies widely in chemical composition, but generally fits into one of two categories. At inland sites, water is a mixed ion or mixed cation-bicarbonate type. Sites closer to the coast have a sodium-chloride or mixed cation-chloride type water. Water within the same permeable zone of the intermediate aquifer system does not have a distinct chemical composition throughout the study area. Water in the surficial aquifer system, which is a calcium bicarbonate type, is more dilute than water from underlying aquifers. The chemical composition of water from the Upper Floridan aquifer is variable in the study area with no dominant cation present.

Most water from the surficial aquifer system has isotopically lighter deuterium and oxygen-18 values than water from the intermediate aquifer system or the Upper Floridan aquifer. Water from the surficial aquifer system most likely represents a mixture of meteoric water, with an isotopically light composition, and ground water that has been recharged by water that has undergone evaporation, with an enriched isotopic composition. Water from the intermediate aquifer system and the Upper Floridan aquifer may be the result of recharge that occurred under different climatic conditions than present conditions. Water from the three aquifer systems have isotopically distinct carbon-13 signatures of dissolved inorganic carbon, which is related to the evolution of inorganic carbon.

Water from the intermediate aquifer system and Upper Floridan aquifer is probably greater than 10,000 years old. Age dating indicates that water in some parts of these aquifers may be greater than 20,000 years old. Thus, the aquifer systems may have been recharged under different hydraulic conditions than currently observed.

INTRODUCTION

Ground-water withdrawals in southwest Florida are expected to increase and may result in water-level declines and water-quality degradation. The sources of ground water in southwest Florida are the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. The ground-water resources in this area are geographically limited by the quantity or quality of water in each aquifer. Generally, ground-water resources are small to moderate in the surficial aquifer system, moderate in the intermediate aquifer system, and abundant in the Upper Floridan aquifer. In parts of southwest Florida, the ground-water resources of the surficial aquifer system and the intermediate aquifer system are in greater demand because the ambient quality of the water is typically less mineralized than water in the Upper Floridan aquifer.

The intermediate aquifer system is an interbedded group of permeable zones and confining units deposited under highly varied environmental conditions that form a complex, heterogeneous aquifer system. Several major permeable zones exist within the intermediate aquifer system, however, the regional distribution, areal extent, and hydraulic character of permeable zones and confining units and their occurrences have not been well defined due to the complexity of the system. For ground-water resources in the intermediate aquifer system to be adequately protected from water-quality degradation, it is essential to understand the hydrogeologic framework, ground-water flow patterns, and variations in water quality. As demand for water increases in southwest Florida, more information is needed to efficiently develop and manage the intermediate aquifer system as a water-supply source.

In 1996, the U.S. Geological Survey (USGS) in cooperation with the Southwest Florida Water Management District (SWFWMD) initiated an investigation to evaluate the hydrogeology and geochemistry of the intermediate aquifer system in parts of Charlotte, De Soto, and Sarasota Counties in southwest Florida (fig. 1). Although the majority of this study is focused on the intermediate aquifer system, data were collected from the surficial aquifer system and the Upper Floridan aquifer to provide an understanding of the interaction between aquifers overlying and underlying the intermediate aquifer system.

Purpose and Scope

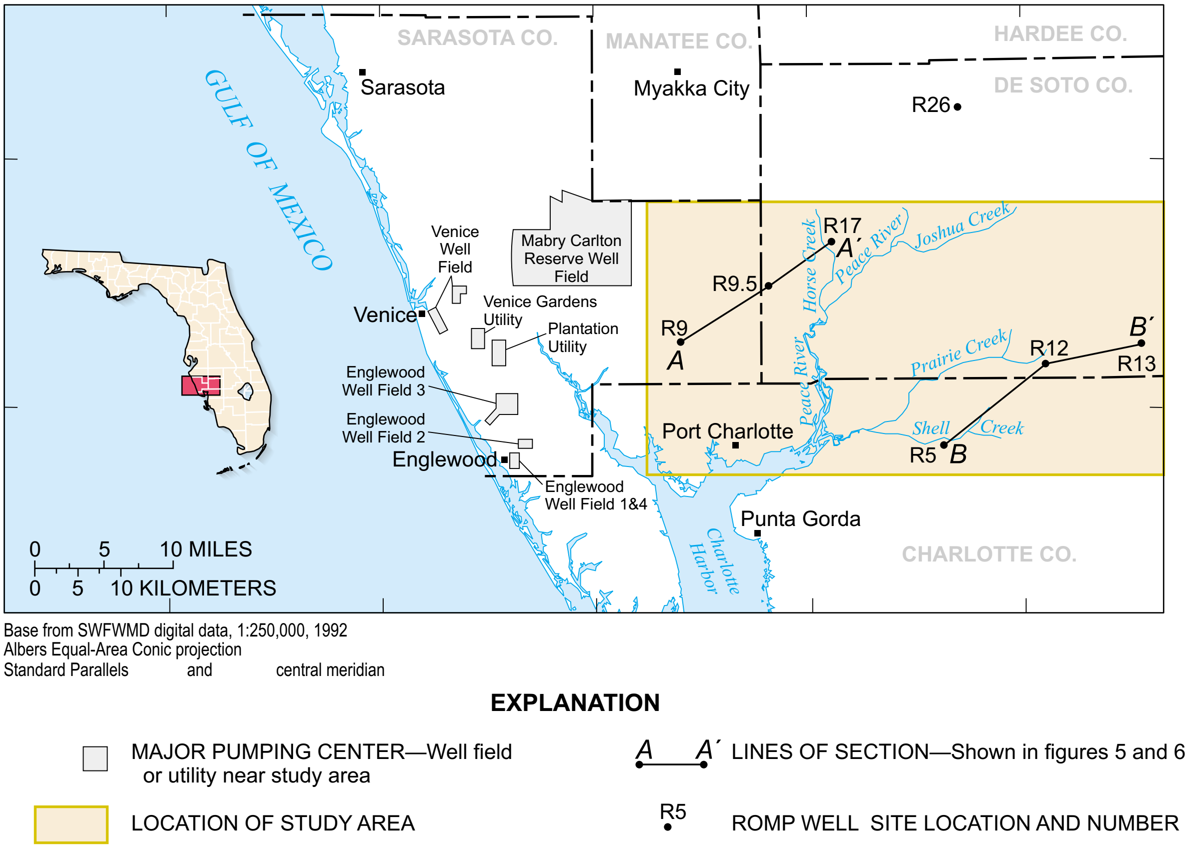
The purpose of this report is threefold: (1) to describe the hydrogeologic framework and geochemistry of the aquifer systems (particularly the intermediate aquifer system) in the study area (fig. 1), (2) to evaluate the geochemical evolution of ground water to understand the flow regimes in the intermediate aquifer system, and (3) to determine the lateral continuity of flow within permeable zones of the intermediate aquifer system and the vertical connection between the intermediate aquifer system and overlying and underlying aquifer systems. Hydrogeologic and geochemical characteristics of the intermediate aquifer system were determined at six Regional Observation and Monitor-Well Program (ROMP) sites in Charlotte, De Soto, and Sarasota Counties. Information presented in this report was obtained from data collected during this study and from published USGS, Florida Geological Survey (FGS), and SWFWMD reports. The stratigraphic and hydraulic units composing the hydrogeologic framework were delineated using lithologic and geophysical logs, water levels, water quality, and hydraulic characteristics from five existing ROMP sites and one new ROMP test site constructed in De Soto County during this study. Each ROMP site consists of numerous monitor wells that penetrate various depth intervals in the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. The geochemical composition of water was determined from water-quality samples collected at five of the ROMP sites. Water was sampled for major ions, field parameters (temperature, pH, specific conductance, dissolved oxygen, and alkalinity), stable isotopes (deuterium, oxygen-18, and carbon-13), and radioactive isotopes (tritium and carbon-14). The water-quality data provided the input for geochemical mass-balance modeling. The geochemical evolution of ground water was simulated for six apparent flow paths. The flow paths were delineated using September 1998 potentiometric-surface maps of the intermediate aquifer system.

Description of the Study Area

The study area encompasses about 600 square miles (mi^2) and includes parts of Charlotte, De Soto, and Sarasota Counties (fig. 1). The study area lies within the physiographic subdivisions of the De Soto Plain, the Gulf Coast Lowlands, and the Caloosahatchee Incline (White, 1970). The gently sloping De Soto Plain has land surface elevations ranging between about 30 and 100 feet (ft). The Gulf Coast Lowlands is low with land surface elevations less than 40 ft. The Caloosahatchee Incline has land elevations ranging from about 50 to 60 ft. All three subdivisions are poorly drained broad flatlands containing many sloughs and marshes, including some that have been drained by ditches and canals. The study area is bisected by the Peace River (fig. 1), one of the largest rivers in southwest Florida. Four smaller streams, Horse Creek, Joshua Creek, Prairie Creek, and Shell Creek drain the eastern and north-central parts of the study area.

Previous Investigations

Although many reports describe the ground-water resources of southwest Florida, few reports focus predominantly on the hydrogeology of the intermediate aquifer system. Current conceptualization of the intermediate aquifer system is based on data compiled from numerous small area or site specific investigations published in USGS, SWFWMD, other government agencies, and consultants' reports. Reports by SWFWMD have been particularly informative because they provide detailed lithologic, hydraulic, and chemical data from the intermediate aquifer system at specific sites in southwest Florida. Reports by Clark (1964), Sutcliffe (1975), Joyner and Sutcliffe (1976), Sutcliffe and Thompson (1983), Wolansky (1983), Gilboy (1985), Duerr and others (1988), Duerr and Enos (1991), Hutchinson (1992), Broska and Knochenmus (1996), Barr (1996), and Knochenmus and Bowman (1998) have helped



Base from SWFWMD digital data, 1:250,000, 1992
Albers Equal-Area Conic projection
Standard Parallels and central meridian

Figure 1. Location of study area, Regional Observation and Monitor-Well Program (ROMP) sites, and hydrogeologic sections, west-central Florida.

improve the current state-of-knowledge concerning the intermediate aquifer system regional hydrogeology.

The chemical and isotopic composition of intermediate aquifer system water and the interaction and mixing of waters among aquifer systems have been described in various reports. Berndt and Katz (1992) related differences in major-ion composition of waters in the intermediate aquifer system to variations in the chemical composition and amount of water leaking downward from the surficial aquifer system and upward from the Upper Floridan aquifer. Sacks and Tihansky (1996) characterized the chemical and stable isotopic composition of water from the intermediate aquifer system in parts of southwest Florida, focusing on wells with discrete open-hole intervals; waters in the intermediate aquifer system influenced by upward flow from the Upper Floridan aquifer were chemically and isotopically distinct from areas not so influenced. Water quality of the discrete production zones of the intermediate aquifer system in Sarasota County was reported by Knochenmus and Bowman (1998). Kauffman and others (1998) and Hobbie (1993) attributed vertical differences in the chemical composition of water in permeable zones of the intermediate aquifer system to the influence of confining units and upward flow from the Upper Floridan aquifer.

Acknowledgments

The authors are extremely grateful for the cooperation of SWFWMD, especially the Geohydrologic Data Section personnel and Michael T. Gates who provided invaluable help with data collection at the ROMP 9.5 site. The authors thank Paulette Bond of the Florida Geological Survey (FGS) for extracting rock material from cores, and Edward T. Furlong and Ronald W. Brenton of the USGS for modifying analytical protocols to determine the carbon content of cores. Thanks also to Tyler B. Coplen of the USGS for analysis of stable isotopes. The authors also thank Blair F. Jones and Daniel M. Webster of the USGS for providing mineralogic identifications and clay-fraction determinations of cores. Finally, the authors would like to express their appreciation to Lynn Barr of the USGS for all of his contributions during the course of the investigation.

METHODS OF STUDY

Hydrogeologic and geochemical data were collected from test holes at six ROMP sites (5, 9, 9.5, 12, 13, and 17) in Charlotte, De Soto, and Sarasota Counties. The ROMP 9.5 site was established during this study with a total of 18 monitor wells constructed at discrete depths. Hydrogeologic data were collected by SWFWMD personnel in accordance with ROMP sampling protocol.

Hydrogeology

Hollow-stem auger, wire-line coring, and mud rotary drilling methods were used to collect lithologic and water samples at depth. At each ROMP site, a test hole was drilled and continuous cores were collected from land surface to variable depths in the Upper Floridan aquifer. Data collected during the coring of the test hole included water levels, water quality, geophysical logs, and specific capacities. Water levels were measured while coring and during packer testing. A qualitative measure of permeability obtained by the visual inspection of cores was used to test discrete borehole intervals for hydraulic properties. Specific capacity of discrete intervals was determined during packer tests. The hydraulic properties of discrete stratigraphic units from the intermediate aquifer system and Upper Floridan aquifer were determined from falling-head permeameter tests. The hydraulic properties of permeable zones and confining units were determined from aquifer test analysis by SWFWMD and USGS personnel. Aquifer tests were evaluated using analytical methods (Jacob, 1946; Hantush, 1960; and Neuman and Witherspoon, 1972). Aquifer tests also were evaluated using numerical methods at the ROMP 9.5 site (McDonald and Harbaugh, 1988; and Halford, 1992). The delineation of the stratigraphic units composing the geologic framework was based on stratigraphic picks by SWFWMD and FGS personnel. The hydrogeologic framework was delineated using a qualitative evaluation of core permeability conducted by SWFWMD personnel and by concurrent evaluation of borehole data. The geologic and hydrogeologic frameworks were linked using water-level, water-quality, geophysical logs, and specific-capacity data (apps. A through C). It should be recognized that, for hydraulically complex carbonate strata, all hydrogeologic identifications are tentative until detailed flowmeter measurements can be collected.

Geochemistry

Water and rock samples were collected for chemical and isotopic analysis. Results from the chemical and isotopic analysis were used to evaluate geochemical processes influencing the chemical and isotopic composition of ground water in the study area. Rock mineralogy from selected cores was analyzed using x-ray diffraction. The age of ground water in different aquifer systems was estimated from isotopic signatures. Geochemical models were used to examine reactions and mixing along apparent flow paths in the intermediate aquifer system.

Water Sampling

Vertical variability in the composition of ground water was determined from water-quality samples collected by SWFWMD personnel during exploratory drilling of test holes at ROMP sites. Typically, samples were collected every 20 to 40 ft from a discrete interval at the base of the borehole, with the drill stem acting as a temporary casing. Because upper zones were not effectively sealed, mixing with water from overlying sediments was possible. At the ROMP 9.5 site, samples were collected less frequently and only from the uppermost part of the Upper Floridan aquifer. An inflatable packer was used to isolate the bottom of the test hole, allowing samples to be collected from discrete zones.

Water was collected from wells completed at different depth intervals in the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. Existing water-quality data collected from the ROMP 17 site for a previous study also was utilized (Sacks and Tihansky, 1996). Standard techniques were used to collect water-quality samples (Wood, 1976) and to conduct water-quality analyses (Skougstad and others, eds., 1979). Water samples were collected from the wells using a submersible or peristaltic pump, or by using discharge tubes from flowing wells. Field measurements of pH, specific conductance, temperature, and dissolved oxygen were made using a closed flow chamber to prevent atmospheric contact with water samples.

Water samples were collected after three well casing volumes had been removed and field measurements of pH, specific conductance, and temperature had stabilized. Alkalinity was measured in the field by incremental titration using sulfuric acid. Sulfide concentrations were measured at the ROMP 9.5 site using a field spectrophotometer and reagent solutions (Hach Company, 1989). Major ions and selected trace element concentrations were determined by the USGS Water Quality Laboratory in Ocala, Florida.

Isotope ratios of deuterium (D/H) and oxygen-18 ($^{18}O/^{16}O$) were determined by the USGS stable isotope laboratory in Reston, Virginia, using techniques described by Coplen and others (1991) and Coplen (1994). Tritium (^{3}H), carbon-14 (^{14}C), and carbon-13 ($^{13}C/^{12}C$) were determined by USGS contract laboratories. Standard δ (delta) notation (Gonfiantini, 1981) was used to express concentrations of the stable isotopes (deuterium, oxygen-18, and carbon-13), in units of parts per thousand (per mil). Standards are Vienna Standard Mean Ocean Water (VSMOW) for deuterium and oxygen-18 and Pee Dee Belemnite (PDB) for carbon-13 (Coplen, 1994). Oxygen and hydrogen isotope results are normalized on scales such that the oxygen and hydrogen isotopic values of Standard Light Antarctic Precipitation (SLAP) are -55.5 and -428 parts per thousand (per mil), respectively (Coplen and others, 1991, and Coplen, 1994); the 2σ (standard deviation) precision for $\delta^{18}O$, δD, and $\delta^{13}C$ are 0.2, 2.0, and 0.2 per mil, respectively. Water samples for tritium were collected and analyzed according to methods described by Michel (1989). Tritium activity is reported in tritium units (TU; 1 TU is equal to 1 tritium atom in 10^{18} hydrogen atoms, and 7.1 disintegrations per minute per gram of water), with a 1σ precision of less than 10 percent for waters containing more than 2 TU (Michel, 1989). Carbon-14 was analyzed using gas-stripping and accelerator mass spectrometry methods (Beukens, 1992). All ^{14}C determinations are reported in Percent Modern Carbon (PMC) normalized to a $\delta^{13}C$ value of -25 per mil and the 1950 oxalic acid standard from the National Institute of Standards and Technology (Stuiver and Polach, 1977; Wigley and Muller, 1981). The reported analytical precision is 1 PMC for ^{14}C values less than 10 PMC and 2 PMC for values greater than 10 PMC (A. Mullin, USGS, written commun., 1998).

Rock Sampling

Analysis of rock mineralogy was performed on eight cores collected from the test hole at the ROMP 9.5 site. Cores were selected to represent permeable zones and confining units of the intermediate aquifer system and the upper part of the Upper Floridan aquifer. Bulk sediments and ultra fine (less than 1 millimeter (mm)) clays from these zones were analyzed using X-ray diffraction techniques (Brindley and Brown, eds., 1980; Moore and Reynolds, 1989). Bulk samples were scanned as amyl acetate smear mounts. The clays were analyzed untreated, glycol solvated, and heated at 550 ^{o}C for 1 hour or longer. Clay minerals were identified based on the response of their (001) reflections following the established procedure described above.

Additionally, selected cores from the ROMP 9.5 test hole were analyzed to estimate the fraction of organic carbon in the rock material and the δ^{13}C content of the inorganic and organic carbon. Two methods were used to estimate the fraction of organic carbon: traditional combustion/gasometric methods and a persulfate-oxidation method. For δ^{13}C of organic carbon, the inorganic carbon fraction was removed by dissolving the sample in hydrochloric acid (Barrie and Prosser, 1996). For δ^{13}C of inorganic carbon, 20 milligrams (mg) of carbonate material was reacted with 2 milliliter (mL) of 100-percent phosphoric acid. The liberated carbon dioxide was dried and its ^{13}C content was determined using a dual-inlet isotope ratio mass spectrometer (Barrie and Prosser, 1996).

Geochemical Modeling

The geochemical model NETPATH (Plummer and others, 1994) was used to determine the dominant processes (including chemical reactions and mixing of waters) controlling ground-water evolution along six apparent flow paths. Input to the model included the chemical and isotopic composition of the ground water, the saturation state of ground water with respect to mineral phases, the known mineralogy of the aquifer systems, and the isotopic composition of solid phase materials. Input also required defining flow paths within the aquifer system and knowledge of vertical head differences between aquifers so that likely mixing scenarios between aquifers could be hypothesized.

NETPATH also was used to calculate plausible ages for ground water using ^{14}C. In the calculations, the analyzed ^{14}C values, in percent modern carbon (pmc), rather than the normalized values reported by the laboratory, in PMC, were used (L.N. Plummer, USGS, written commun., 1998). The Fontes and Garnier (1979) adjustment model was used to calculate the initial ^{14}C activity (A_o) in ground water at each site by considering a two-stage evolution of recharge waters that includes dissolution and isotopic exchange of carbonate minerals with CO_2 in the unsaturated zone and isotopic exchange with the carbonate rocks in the saturated zone. The inorganic carbon system was used for computing age corrections; dissolved organic carbon and methane were not analyzed for this study, and thus, the assumption was made that their concentrations were negligible or their ^{14}C concentrations were 0 pmc. All models with ^{14}C parameters used the following constraints to calculate A_o:

1. a user-defined δ^{13}C of soil gas CO_2 of -20 to -25 per mil (Deines and others, 1974),
2. ^{14}C soil gas = 100 pmc,
3. ^{14}C of calcite and dolomite = 0 pmc, and
4. the δ^{13}C value used is the δ^{13}C composition of the dissolved inorganic carbon of the initial water.

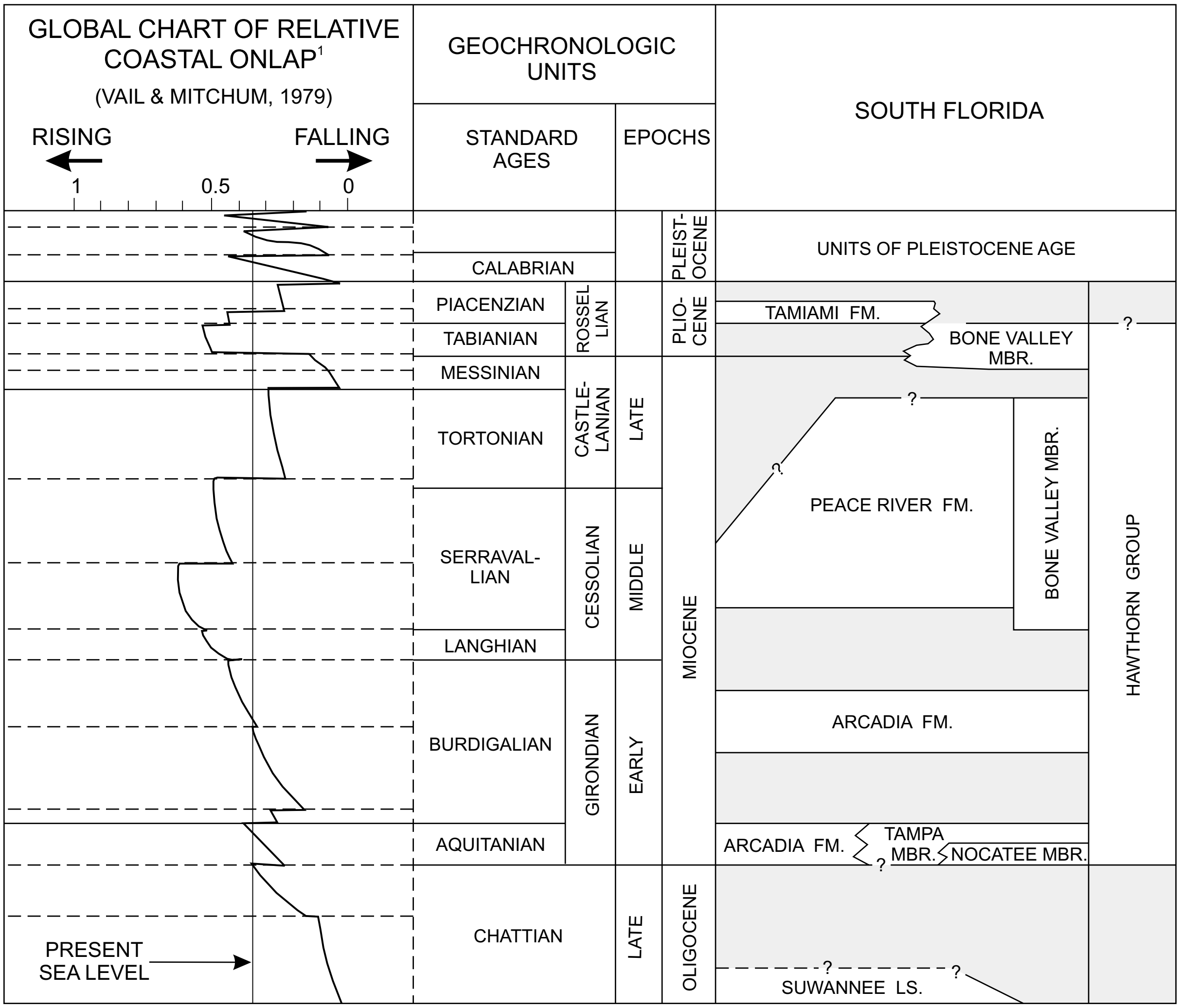
The sensitivity of analytical uncertainties in the ^{14}C value on the computed ages also was evaluated.

GEOLOGIC FRAMEWORK

Defining the geologic framework in the study area is problematic. The stratigraphy comprising the geologic framework is mired in contradictory and confusing nomenclature because of inconsistent application of the North American Stratigraphic Code (code) and the limitations of the code with respect to Florida’s rock record (Randazzo, 1997, p. 49). The code relies upon definition of lithostratigraphic units to name formations. Carbonate rocks in Florida do not easily lend themselves to lithostratigraphic definition because of limited exposures in outcrops; as a result, scientists rely on key fossils to name stratigraphic units. The code, however, does not recognize the practice of using fossils to name formations. Furthermore, identification of stratigraphic units is complicated by complex sediment facies patterns and phosphorite sedimentation and diagenetic alteration of sediments obliterating fossils. In addition, correlating geologic units with hydrogeologic units is difficult because of wide variations in depositional environment occurring simultaneously within the study area. Complex facies changes can occur at the boundaries of predominately carbonate rocks and siliciclastic rock deposition. Additionally, the same rock type may recur at several horizons in the lithostratigraphic (geologic) section because the exact depositional and diagenetic conditions that produced the rocks were repeated several times (Miller, 1986, p. B7). The formation names used in this report are based upon the geologic definitions of Scott (1988) and those used by the FGS.

Depositional History

The depositional history of the Florida Platform resulted in a thick sequence of evaporite, carbonate and siliciclastic facies. These sediments began to accumulate on the Florida Platform with the development of the Gulf of Mexico Basin, probably during the middle Jurassic (Randazzo, 1997, p. 39). Beginning in the late Cretaceous, a stable tectonic period allowed the accumulation of a thick sequence of sedimentary rocks in peninsular Florida. The primary force affecting the type of sediments deposited was changing sea levels throughout the Cenozoic Era and especially during the Tertiary. Throughout the Tertiary, the Florida Platform was subjected to numerous sea-level fluctuations, and variations in sea level were most dramatic from the late Oligocene through Pliocene Epochs (Scott, 1988, p.112). Periods of rising levels are defined as transgressions and falling sea levels are defined as regressions. Sea-level fluctuations, relative to the present sea-level stand since the Oligocene Epoch are shown in figure 2. On the Florida Platform, transgressions or high sea-level stands, indicated as rising water levels (fig. 2), resulted in carbonate and evaporite deposition whereas regressions or low sea-level stands, indicated as falling water levels (fig. 2), resulted in increased siliciclastic sedimentation that suppressed carbonate sedimentation. The depositional history of the Hawthorn Group is directly related to the Miocene-age sea-level fluctuations and can be observed in the rock record as episodes of cyclic sedimentation that resulted in interbedded layers of peloidal and skeletal limestone, mudstone



Notes: 1. The horizontal scale showing amplitude of relative rises and falls is calibrated to a relative scale normalized on the maximum range of sea level positions of the curve. The highest position of sea level, occurring at the end of the Cretaceous, is set at 1.0 and the lowest position, at the mid-Oligocene, is set at 0.0

2. Shaded areas schematically show unconformities between formations

Figure 2. Sea-level fluctuations in South Florida (modified from Vail and Mitchum, 1979).

(carbonate mud), clay (siliciclastic) and quartz sand. In addition to influencing the type of sediments deposited, sea-level changes interrupted sediment deposition, removed sedimentary units by erosion, and altered the units post depositionally. Subaerial exposure resulted in karstification and erosional sequence-boundary surface development (Randazzo, 1997, p. 47).

The Avon Park Formation is a carbonate mud-dominated peritidal sequence. Open-marine, shallow water, and shelf deposits prevailed during the late Eocene, which was a period of restricted-flow and open marine deposition. During the Oligocene, deposition was predominately open-marine. Sea-level fluctuations after the Oligocene were a primary factor controlling the distribution of depositional environments during the Miocene and Pliocene. The frequent sea-level fluctuations during the Miocene spread sediments over the Florida Platform but left an intermittent stratigraphic record. Carbonate deposition on the southern part of the platform persisted until the middle to late Miocene. In the southernmost peninsula, deposition of the Arcadia Formation continued until the Pliocene. Thin beds of siliciclastic sediments were deposited nearly platform-wide (Scott, 1997, p. 61) throughout the early (lower) Miocene. A major eustatic regression occurred during the middle Pliocene (Vail and others, 1977) creating a disconformity separating younger Pliocene- and Pleistocene-age sediments from the underlying older Pliocene- and Miocene-age sediments.

Stratigraphy Underlying the Study Area

The stratigraphy underlying the study area was determined from cores collected at the six ROMP sites and reported by SWFWMD and FGS (Decker, 1988; Gates, 1997a,b; Peterman, 1997; Thompson, 1997; Baldini, 1998; Gates, 1998a; Baldini, 1999; Clayton, 1999; and Jon Arthur, FGS, written commun., 2000). Where formation (or member) boundaries differed between the reporting sources of geologic data, the FGS designations were used. The stratigraphy and dominant lithology for the six sites are presented in figure 3 and appendices A through C. Test wells penetrated the undifferentiated surficial deposits, the heterogeneous marine deposits comprising the Tamiami Formation and Hawthorn Group, and the persistent carbonates comprising the Suwannee Limestone, Ocala Limestone, and Avon Park Formation.

Avon Park Formation, Ocala Limestone, and Suwannee Limestone

The 1,200-ft thick, middle Eocene-age Avon Park Formation is the oldest stratigraphic unit exposed in Florida (Miller, 1986). The Avon Park Formation is a carbonate mud, pervasively dolomitized in places and undolomitized in others with mostly benthic fossils indicating a lack of faunal diversity (Randazzo, 1997, p. 50). Lithologically, the formation consists predominately of cream, tan, or light-brown, soft to well-indurated limestone that is mostly pelletal but is locally micritic. The limestone may be interbedded with dark-brown, highly fractured sucrosic dolostone. The top of the Avon Park ranges from about 1,000 to 1,230 ft below sea level in the study area.

Overlying the Avon Park Formation is the 200- to 300-ft thick, late Eocene-age Ocala Limestone. The Ocala can contain two distinct lithologic units that include a basal dense dolostone and an upper relatively pure, porous limestone. The basal dense dolostone is similar to the Avon Park dolostone described above. The limestone unit has been described as fossiliferous, white, soft, friable, and porous, and includes fossils of foraminifera, bryozoan fragments, and echinoid remains loosely bound by a matrix of micritic cement. The basal dense dolostone unit occurs in the Ocala Limestone at the ROMP 5, 9, 12, and 17 sites. The top of the Ocala ranges from about 700 to about 1,100 ft below sea level.

The boundary between the Ocala and Suwannee Limestone can be difficult to identify because of their similar lithologic appearance (Randazzo, 1997, p. 50). The 70- to 400-ft thick, Oligocene-age Suwannee Limestone is a granular, fossilifereous limestone that occurs about 600 ft below sea level. The limestone can be interbedded with calcilutite (calcareous mud, greater than 50-percent silt or clay-size limestone) and calcarenite (calcareous sand, greater than 50-percent sand-size limestone) units, and the basal unit can be a fine-grained dolosilt. Beds of unconsolidated quartz sand were noted at the ROMP 5 site. The Suwannee Limestone generally is distinguished from the overlying Hawthorn Group by the lack of phosphatic sand content, however, the contact becomes obscure in Charlotte and Lee Counties (Randazzo, 1997).

Hawthorn Group

Based on the work of Scott (1988), the Miocene- and early Pliocene-age sediments were reclassified as a group. The reclassification of the Hawthorn to group status is justified by the presence of areally extensive and mappable lithologic units (Scott, 1988, p. xii). In the study area, the 400- to 600-ft thick, Miocene- and early Pliocene-age Hawthorn Group contains multiple distinct lithologic units. Sea-level fluctuations during the Miocene are reflected in the interbedded layering of the siliciclastic and carbonate units that compose the Hawthorn Group. The sediments consist of highly variable mixtures of clay, silt, sand, and carbonate. Limestone is the dominant carbonate phase in southern Florida. Additionally, the Hawthorn Group sediments contain unique minerals including phosphorite ranging from trace amounts to about 50 percent. Phosphogenic episodes typically occur during the transition from carbonate to siliciclastic deposition. Associated with phosphogenesis is the formation of palygorskite and sepiolite (magnesium-rich clay) and dolomite. Apatite (phosphate grains) is virtually ubiquitous in the Hawthorn sediments underlying peninsular Florida. Palygorskite, sepiolite, and dolomite can occur statewide. In southern peninsula Florida, the Hawthorn Group includes, in ascending order, the Arcadia and Peace River Formations (Scott, 1988, p. 17).

Arcadia Formation

The Arcadia Formation is the basal unit of the Hawthorn Group. The Arcadia Formation may contain up to two named members, in ascending order, the Nocatee and Tampa Members. Where both of the named members cannot be identified, the Arcadia

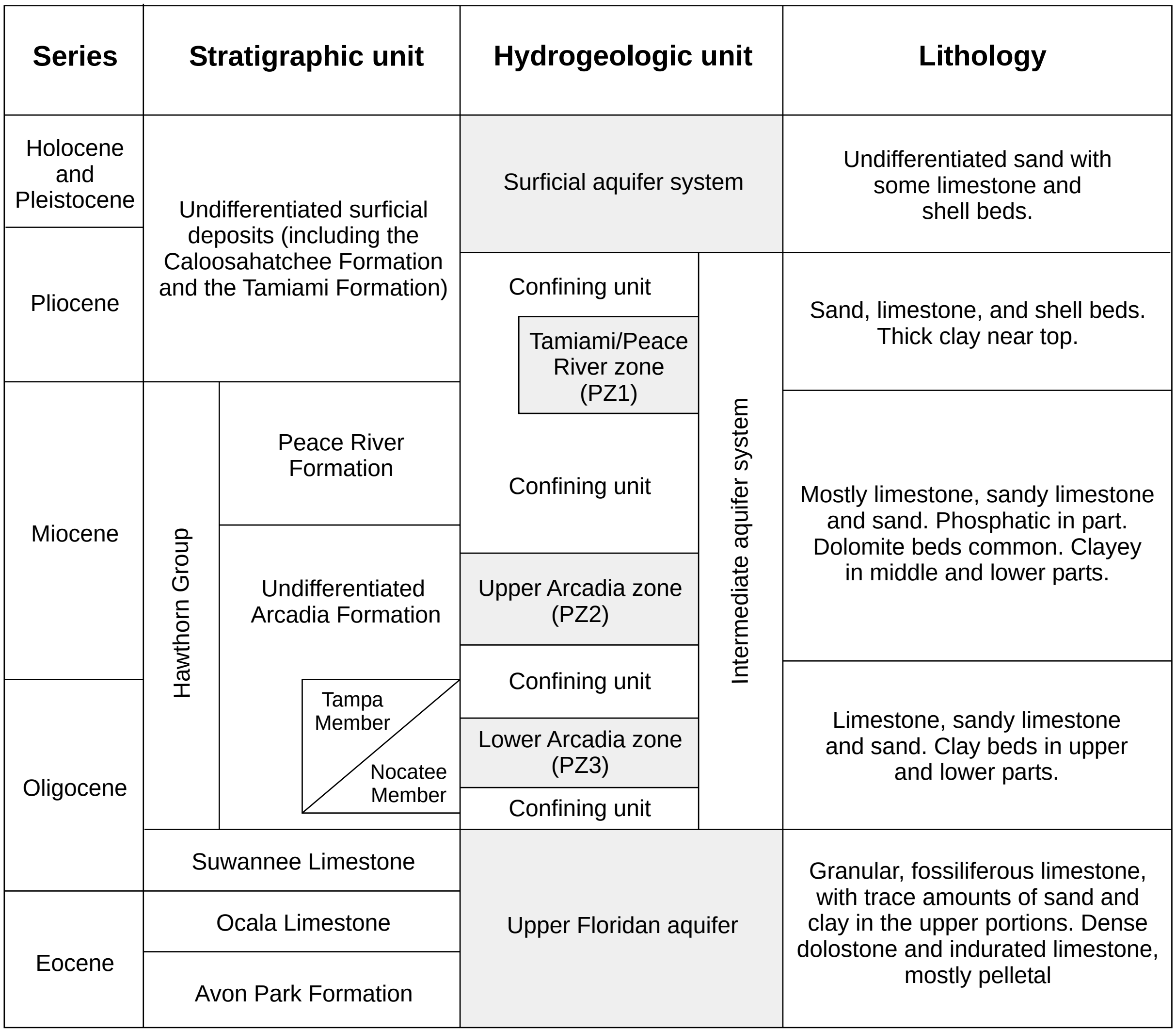


Figure 3. Relation of stratigraphic and hydrogeologic units (modified from Duerr and Wolansky 1986; Southeastern Geological Society 1986; Scott 1988; Barr 1996; and Knochenmus and Bowman, 1998).

Formation is designated the undifferentiated Arcadia Formation. The Arcadia Formation is composed predominately of carbonate rocks with varying amounts of included and interbedded siliciclastics. The predominate carbonate rock type is dolostone. The undifferentiated Arcadia Formation consists predominantly of limestone and dolostone containing varying amounts of quartz sand, clay, and phosphate grains. Thin beds of quartz sand and clay are present sporadically throughout the section. These thin sand and clay beds are generally dolomitic and phosphatic, less than 5 ft thick, and of limited areal extent (Scott, 1988, p. 58). Chert, which can occur in updip areas, such as in parts of Hardee, Hillsborough, Manatee, and Polk Counties, and appears to be silicified clays and dolosilts.

Nocatee and Tampa Members

The basal Nocatee Member has the highest content of siliciclastic sediments in the Arcadia Formation. The Nocatee Member is a complexly interbedded sequence of quartz sands, clays, phosphates, and minor carbonates. The Nocatee Member has been designated previously as the sand and clay unit of the Tampa Formation. The Nocatee Member ranges in thickness from about 50 to 200 ft in the study area.

The Tampa Member of the Arcadia Formation was formerly referred to as the Tampa Limestone or Tampa Formation. The new name reflects a change in nomenclature and status of the Tampa lithologic unit, which has long been a problematic unit due to facies changes and apparent gradational contacts with overlying and underlying units. In areas where the intermediate aquifer system is absent, the Tampa Member directly overlies the Suwannee Limestone and is considered part of the Upper Floridan aquifer. Where both the Tampa and Nocatee Members are present in the stratigraphic section, the Tampa Member overlies the Nocatee Member in the study area. The Tampa Member occurs between the upper and lower parts of the undifferentiated Arcadia Formation. A diagnostic characteristic that can be used to separate the Tampa Member from the rest of the Arcadia Formation is the lack of phosphate content in the Tampa Member. The Tampa Member of the Arcadia Formation consists predominantly of limestone with subordinate dolostone, sand, and clay and contains little or no phosphate. The Tampa Member ranges from zero to less than 200 ft thick in the study area.

Peace River Formation

The Peace River Formation is the upper unit of the Hawthorn Group and unconformably overlies the Arcadia Formation. Siliciclastics are the predominate lithology in the Peace River Formation, comprising greater than 66 percent of the rock material. Clay beds are common in the formation and phosphate, in varying amounts, generally is present. The carbonate content increases near the base of the formation. In some areas, the contact of the Peace River Formation with the underlying Arcadia Formation is delineated by a phosphatic rubble zone (Scott, 1988).

Bone Valley Member of the Peace River Formation

The Bone Valley Formation of former usage has been reclassified to member status within the Peace River Formation. The reduction in status is due to the limited areal extent, gradational relations with supra- and subjacent units, and lithologic similarities to the undifferentiated Peace River Formation. The Bone Valley Member is a clastic unit consisting of pebble- to gravel-size phosphate fragments and grains in a matrix of quartz sand and clay (Scott, 1988, p. 86-87). Phosphate concentrations are highest in the Bone Valley Member. Clays can occur as matrix material but also as discrete beds of relatively pure clay referred to as “bed clay” by the phosphate industry. These clay beds delineate the base of the Bone Valley Member. A carbonate rubble, consisting of basal gravels below the bed clay, has been described as delineating the contact between the Bone Valley Member and the undifferentiated Peace River Formation. When the basal gravels are absent, locating the contact with the Peace River Formation becomes arbitrary (Scott, 1988, p. 88). The Bone Valley Member has not been identified in the study area.

Tamiami Formation

The Tamiami Formation occurs over much of southern Florida and consists of sand, clay, carbonate, and reef facies. At least nine subsurface facies of the Tamiami Formation have been mapped by various investigators in southwest Florida but only one to four of the facies occur in the stratigraphic section at a given locality (Missimer, 1992, p. 69). The formation contains thick carbonate sequences in southwestern Florida and grades into siliciclastic sediments to the north and east. In Charlotte, Sarasota, and most of Lee Counties, the base of the Tamiami Formation occurs at the top of the first major green dolosilt/sand unit that marks the top of the Peace River Formation (Missimer, 1992, p. 65). In the study area, the middle to late Pliocene-age Tamiami Formation is thin and is designated stratigraphically as part of the undifferentiated surficial deposits (Jon Arthur, FGS, oral commun., 2000).

Surficial Deposits

The stratigraphy of the deposits overlying the Hawthorn Group (or Tamiami Formation where present) is a complex of Plio-Pleistocene to Holocene-age, highly fossiliferous siliciclastics designated the undifferentiated surficial deposits. The surficial deposits generally have been separated into three units: 1) the Caloosahatchee Marl of Pliocene and Pleistocene age consisting of shell beds, shelly, sandy, or silty marl, marl, and sandy limestone, 2) Pleistocene-age deposits consisting of medium yellow-orange sand with clay and shell, and 3) Holocene-age deposits consisting of fine-grained quartz sand referred to as undifferentiated or surficial sand. Surficial deposits occur throughout De Soto and Hardee Counties but thin greatly near creeks and rivers. The upper sand unit is composed of a fine sand that blankets the area and is about 25 ft thick in the study area (Wilson, 1977, p.25). In most of De Soto County, the underlying shell and sand unit comprises the Caloosahatchee Marl. In southern and southeastern De Soto County, the marl contains fine sand with clay and large marine shells. Along Prairie Creek near the ROMP 12 site (fig. 1), the unit is almost entirely composed of marine shells. In northern De Soto and Hardee Counties, the basal unit of the undifferentiated surficial deposits consists of phosphate deposits. In the study area, the middle to late Pliocene-age Caloosahatchee Formation is thin and is designated stratigraphically as part of the undifferentiated surficial deposits (Jon Arthur, FGS, oral commun., 2000).

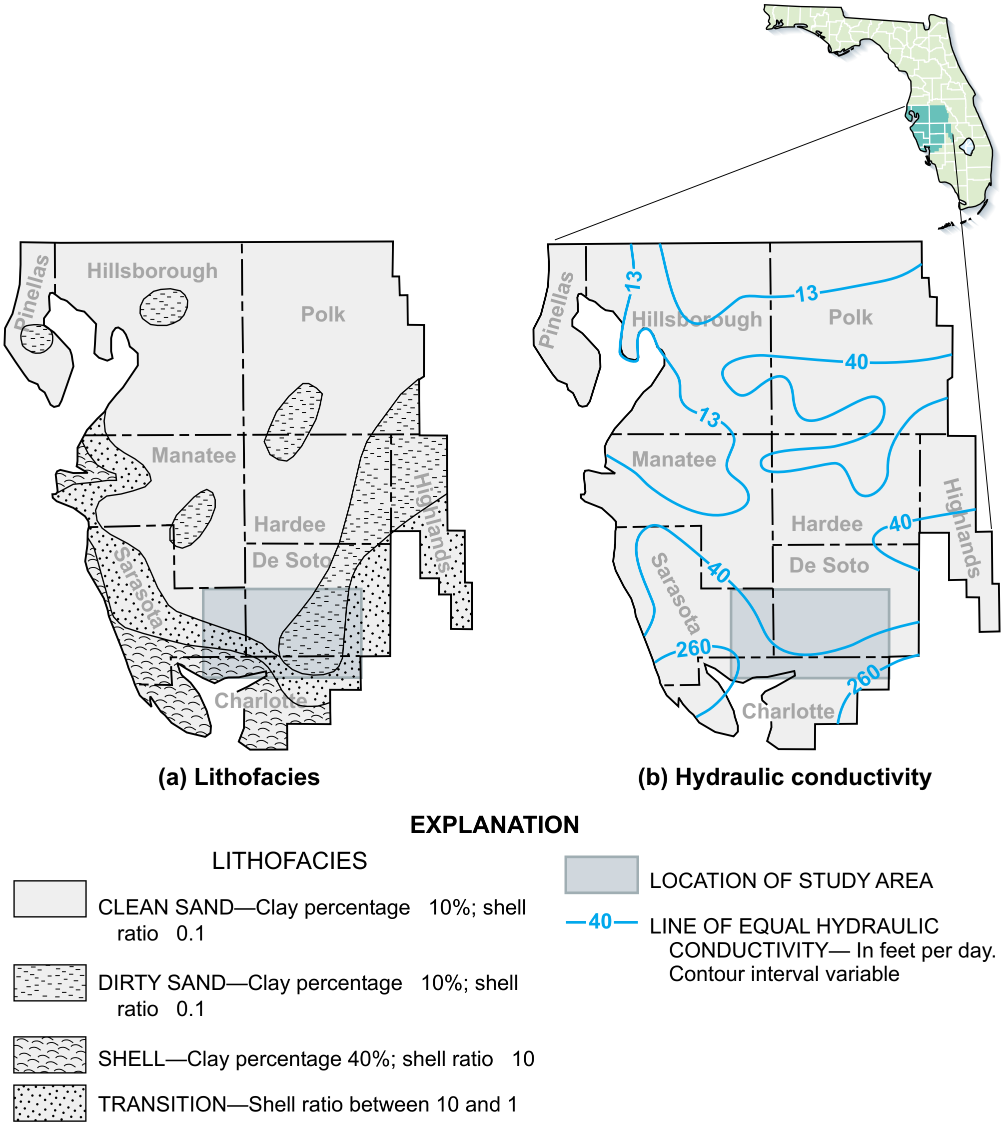
HYDROGEOLOGIC UNITS AND HYDRAULIC PROPERTIES

The hydrogeologic units underlying the study area consist of the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. The corresponding chronostratigraphic, lithostratigraphic, and hydrogeologic units underlying the study area are shown in figure 3. Deposits overlying the Tamiami Formation or the Hawthorn Group comprise the surficial aquifer system. Deposits of the Hawthorn Group and the Tamiami Formation form the intermediate aquifer system, and the underlying Oligocene and older carbonate rocks compose the Floridan aquifer system. The Floridan aquifer system consists of the Upper and Lower Floridan aquifers that are separated by a middle confining unit (Miller, 1986). Each of these aquifer systems include one or more water-producing zones separated by less-permeable units. The hydrogeologic framework described in this report is based on data from the six ROMP sites located in the study area (fig.1).

Surficial Aquifer System

The surficial aquifer system comprises Pliocene to Holocene-age, unconsolidated to poorly indurated, clastic sediments, and is defined as a permeable unit contiguous with land surface (Southeastern Geological Society, 1986, p.4). Because of the interbedded nature of the clastics forming the surficial aquifer system, more than one water-producing zone separated by beds of lower permeability may occur in the surficial aquifer system. The water-bearing capacity of the surficial aquifer system is largely dependent on the grain size, sorting, and saturated thickness of the sediments. Results by Vacher and others (1992), indicate a relation between sediment type and hydraulic properties in the surficial aquifer system based on mapped regional distribution of selected lithofacies and published hydraulic properties for the surficial aquifer system (fig. 4). The lithofacies map was constructed from trilinear analysis of three general lithologies (end members) that include (1) clay (clayey sand), (2) shell (limestone, shelly sand), and (3) sand (fig. 4a). In the study area, the surficial aquifer system consists of relatively thin, unconsolidated sand, shell, and limestone that generally yield small volumes of water to wells. The thickness of the surficial aquifer system ranges from 19 ft at the ROMP 13 site to 69 ft at the ROMP 5 site (apps. A through C). The lithofacies in the study area span the range from dirty sand (substantial clay content/low water yield) in parts of De Soto County to clean sand (moderate water yield) in southeastern and southwestern De Soto County to transition (interbedded/wide range water yield) to shell bed (substantial limestone and shell content/high water yield) in southwestern Sarasota and most of Charlotte Counties where significant shell facies occur (Vacher and others, 1992). A map of published hydraulic conductivities (fig. 4b) shows an increase in hydraulic conductivities from north to south (Vacher and others, 1992).

Hydraulic properties of the surficial aquifer system have been estimated from aquifer tests conducted at three of the ROMP sites in the study area. The aquifer tests were conducted at the ROMP 5 site in north-central Charlotte County, at the ROMP 9 site in southeastern Sarasota County, and at the ROMP 12 site in south-central De Soto County. The test at the ROMP 5 site evaluated an 85-ft thick sequence of unconsolidated material including interbedded sand, silt, clay, shell, and limestone (Gates, 1997a). At the ROMP 9 site a 20-ft thick sequence of sand and shell was tested (Thompson, 1997), and at the ROMP 12 site a 15-ft thick sequence of sand and shell was tested. The reported values for transmissivity, horizontal hydraulic conductivity, and specific capacity were 2,780, 32,900, and 752 feet squared per day (ft^2/d); 33, 1,490, and 50 feet per day (ft/d); and 14, 160, and 2 gallons per minute per foot of drawdown (gal/min/ft) for ROMP 5, 9, and 12, respectively. These hydraulic property values for the surficial aquifer system generally agree with the lithofacies/hydraulic properties delineated by Vacher and others (1992) (fig. 4).



(a) Lithofacies

(b) Hydraulic conductivity

Figure 4. Lithofacies (a) and hydraulic conductivity (b) of the surficial aquifer system, west-central Florida (modified from Vacher and others, 1992).

Intermediate Aquifer System

The intermediate aquifer system includes all rock units that lie between the overlying surficial aquifer system and underlying Upper Floridan aquifer, and generally coincide with the stratigraphic unit designated as the Hawthorn Group. Additionally, the stratigraphy that corresponds to the Tamiami Formation is included in the intermediate aquifer system either as the upper confining unit or as part of the uppermost water-producing zone. Generally, the intermediate aquifer system consists of (a) an upper sandy clay, clay, and marl confining unit that separates the upper permeable zones in the Tamiami and Peace River Formations from the surficial aquifer system; (b) a group of up to three water-producing zones separated by confining units and composed primarily of carbonate and sandy carbonate rocks (Tamiami, Peace River and Arcadia Formations); and (c) a lower sandy clay to clayey sand confining unit overlying the Upper Floridan aquifer (Nocatee Member or Undifferentiated Arcadia Formation).

The occurrence of multiple, discrete permeable zones within the stratigraphy composing the intermediate aquifer system has been documented by previous investigators (Sutcliffe, 1975; Joyner and Sutcliffe, 1976; Wilson, 1977; Wolansky, 1983; Duerr and Wolansky, 1986; Miller, 1997; Barr, 1996; and Knochenmus and Bowman, 1998). The hydraulic properties of these zones vary depending on (1) the original texture of the sediments and (2) post-depositional processes such as dolomitization, recrystallization, fracturing, and dissolution. Additionally, interpretations of borehole geophysical-log data indicate that water-producing zones are of limited vertical extent and occur at different depths in adjacent boreholes (Broska and Knochenmus, 1996). On a regional scale, the heterogeneous distribution of carbonate and siliciclastic sediments makes delineation of water-producing zones within the intermediate aquifer system difficult to characterize, both in quality and quantity. In the past, the zones have been numbered in descending order, however, problems arise because equivalent water-bearing lithologies may not be areally persistent. In this report the stratigraphic name, as well as permeable zone (PZ) number will be used to designate the discrete zones in the intermediate aquifer system because the stratigraphic name helps to locate the zone vertically in the geologic section.

Currently, the delineation of the permeable zones (apparent water-producing zones) and lower-permeability units separating these zones has been based predominately on visual inspection of rock cores collected during test drilling of test holes at the ROMP sites. Additional data collected during test drilling including water levels, water quality, and specific capacity have been used to characterize the hydraulic characteristics of the intermediate aquifer system. Based on interpretation from test-hole data, two apparent water-producing zones were delineated at the ROMP 5 and 9.5 sites and three apparent water-producing zones were delineated at the ROMP 9, 12, 13, and 17 sites (apps. B and C). These zones occur in the (a) Tamiami/Peace River Formations, referred herein as the Tamiami/Peace River zone (PZ1), (b) Upper Arcadia Formation, referred herein as the Upper Arcadia zone (PZ2), and (c) Tampa Member or Nocatee Member of the Lower Arcadia Formation, referred herein as the Lower Arcadia zone (PZ3). The Tampa Member exists in the northern section (ROMP 9, 9.5 and 17 sites) but not in the southern section (ROMP 5, 12, and 13 sites) (figs. 5 and 6). Generally, the carbonate units yield substantial volumes of water to wells compared to the siliciclastic units. The water-bearing capacity ranges over several orders of magnitude. Values for transmissivity, horizontal hydraulic conductivity, storage, leakance, and specific capacity, are reported in Gates (1997b), Thompson (1997), Baldini (1999), Clayton (1999), and Gates (SWFWMD, written commun., 2000), and listed in table 1.

The Tamiami Formation is present in much of southern Florida. The Tamiami Formation is an important hydrostratigraphic unit where carbonate rocks are the dominant lithology and comprise all or part of the Tamiami/Peace River zone (PZ1). Generally, PZ1 is the thinnest and least productive zone of the intermediate aquifer system. The thickness of PZ1 (where it exists) ranges from 24 ft at the ROMP 9 site to 49 ft at the ROMP 12 site (apps. B and C). Hydraulic properties of PZ1 have been estimated from aquifer tests conducted at two of the ROMP sites in the study area. The aquifer tests were conducted at the ROMP 9 site in southeastern Sarasota County and at the ROMP 12 site in south-central De Soto County. The test at the ROMP 9 site evaluated a 24-ft thick sequence of sand and limestone (Thompson, 1997), and the test at the ROMP 12 site evaluated a 49-ft thick sequence of unconsolidated material including interbedded dolosilt and dolostone (Clayton, 1999). Reported values for transmissivity, horizontal hydraulic conductivity, and specific capacity were 47 and 5,420 ft^2/d; 2 and 102 ft/d; and 2 and 160 gal/min/ft for ROMP 9 and 12, respectively (Thompson, 1997, Clayton, 1999) (table 1).

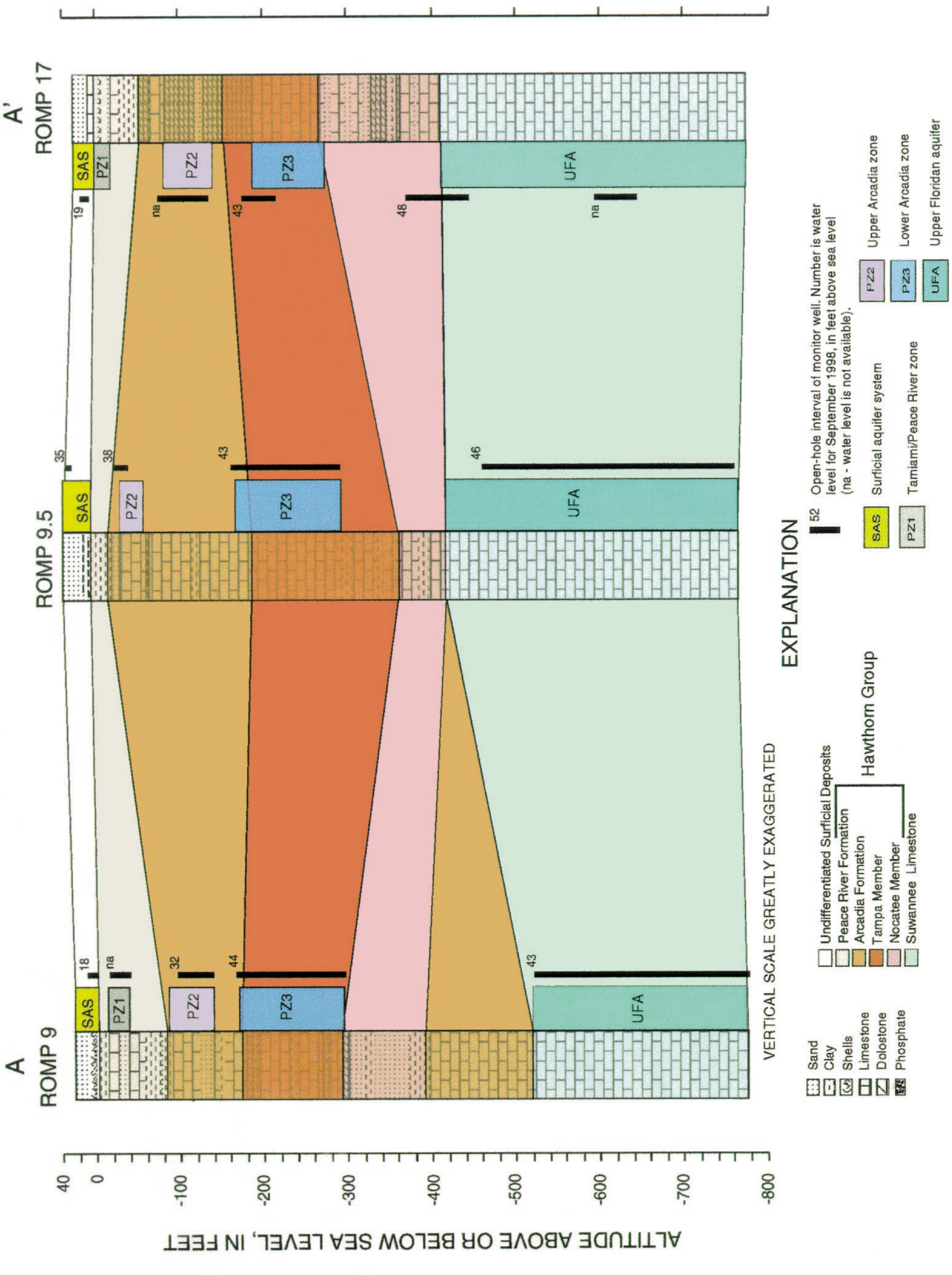


Figure 5. Hydrogeologic and lithostratigraphic cross section A-A' through ROMP sites 9, 9.5, and 17.

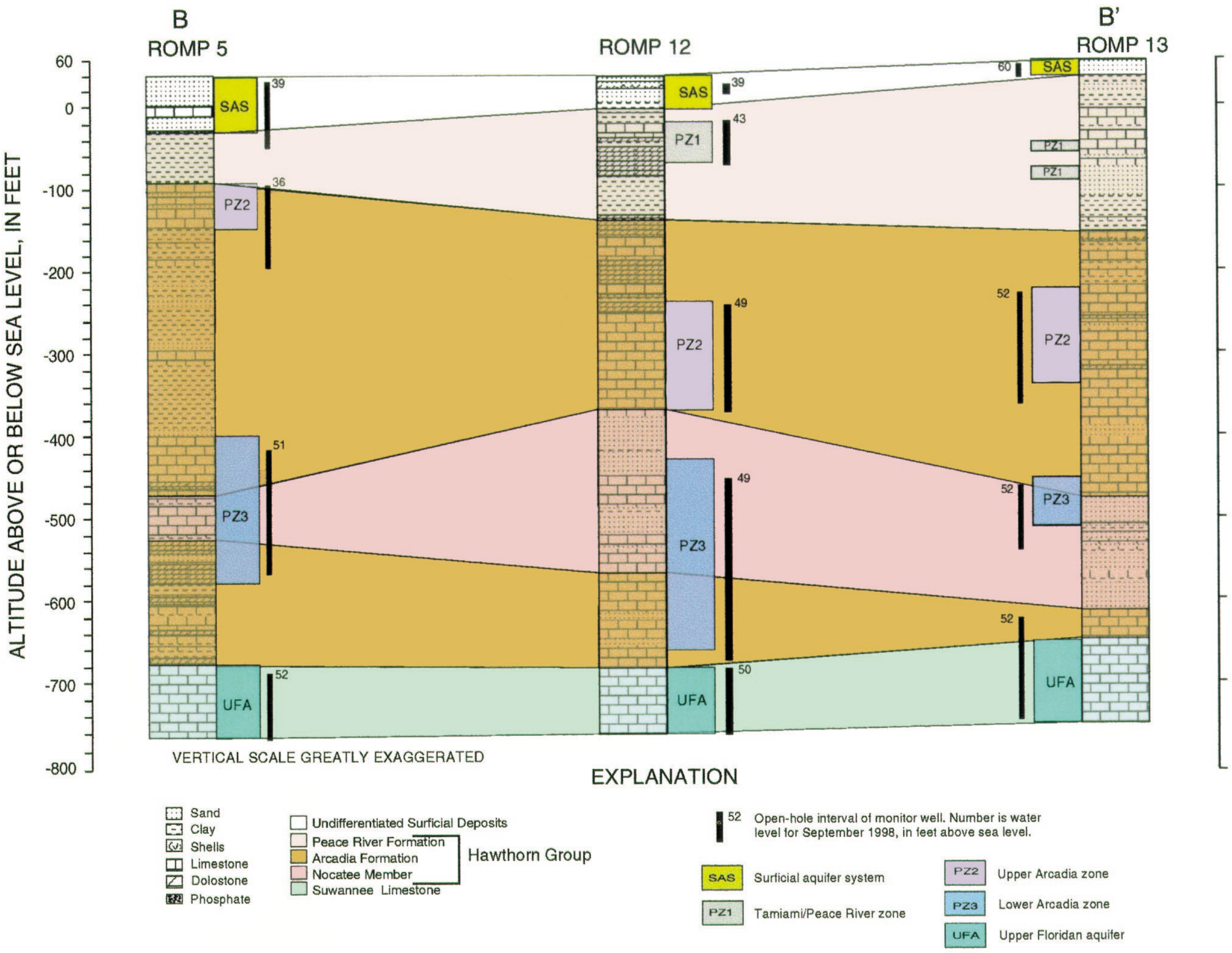


Figure 6. Hydrogeologic and lithostratigraphic cross section B-B' through ROMP sites 5, 12, and 13.

Table 1. Summary of aquifer test results from selected ROMP sites

[From Gates, 1997; Thompson, 1997; Baldini, 1999; Clayton, 1999; and Gates, SWFWMD, written commun., 2000][SAS, surficial aquifer system; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; K_h, horizontal hydraulic conductivity; T, transmissivity; S, storage coefficient; L, leakance; Q/s, specific capacity; ft, feet; bls, below land surface; ft/d, feet per day; ft^2/d, feet squared per day; gpm, gallons per minute; --, not determined]

ROMP site	Hydrogeologic unit	Interval tested (ft bls)	T (ft^2/d)	K_h (ft/d)	S	L (ft/d/ft)	Q/s (gal/min/ft)
ROMP 5	SAS	5 - 85	2,780	33	--	--	14
	PZ2	130 - 230	2,789	14	2.1×10^{-3}	3.7×10^{-4}	6
	PZ3	450 - 600	2,970	20	--	--	49
	UFA	720 - 970	2,610	10	4.1×10^{-1}	1.8×10^{-3}	6
ROMP 9	SAS	7 - 27	32,900	1,490	--	--	160
	PZ1	40 - 65	47	2	--	2.3×10^{-5}	2
	PZ2	122 - 165	24,633	5	2.6×10^{-4}	8.2×10^{-4}	42
	PZ3	190 - 320	6,374	23	2.8×10^{-4}	1.7×10^{-3}	3
	UFA	545 - 860	7,260	23	2.8×10^{-4}	5.6×10^{-3}	24
ROMP 9.5	PZ3	205 - 331	14,000	111	2.2×10^{-4}	3.7×10^{-5}	21
	UFA	505 - 801	4,870	16	3.0×10^{-4}	1.2×10^{-3}	12
ROMP 12	SAS	12 - 27	752	50	2.5×10^{-4}	2.2×10^{-2}	2
	PZ1	60 - 110	5,420	102	8.0×10^{-5}	5.8×10^{-4}	160
	PZ2	280 - 409	5,420	9	2.3×10^{-5}	1.4×10^{-3}	47
	PZ3	487 - 710	44,900	201	5.4×10^{-5}	--	32
	UFA	725 - 909	7,640	41	3.2×10^{-4}	--	15
ROMP 13	PZ2	282 - 417	258	2	7.6×10^{-5}	--	1
	PZ3	510 - 592	766	10	1.1×10^{-4}	--	5
	UFA	671 - 786	2,350	21	8.6×10^{-2}	--	3

The Upper Arcadia zone (PZ2) occurs throughout the study area and consists predominately of limestone and dolostone. The thickness of PZ2 ranges from 27 at the ROMP 9.5 site to 131 ft at the ROMP 12 site (apps. B and C). PZ2 is separated from PZ1 by a clay bed within the Peace River Formation. The clay bed is thinner in the northern part of the study area (fig. 5) than in the southern part (fig. 6). The clay ranges in thickness from about 20 to about 60 ft (app. B and C). Hydraulic properties of PZ2 vary accordingly with lithology and with solution development within the limestone and dolomite, more so than to variation in thickness (Wolansky, 1983). Hydraulic properties of PZ2 were estimated from aquifer tests conducted at four of the ROMP sites in the study area (ROMP 5, 9, 12, and 13). The reported ranges for transmissivity, horizontal hydraulic conductivity, and specific capacity were 258 to 24,633 ft^2/d; 2 to 14 ft/d; and 1 to 47 gal/min/ft, respectively (table 1).

The third and lowermost water-producing zone, the Tampa Member or Nocatee Member of the Lower Arcadia Formation, occurs throughout the study area and consists of limestone and dolostone with varying amounts of interbedded siliciclastics. Both the Tampa and Nocatee Members occur stratigraphically below the first occurrence of the Arcadia Formation. The thickness of the Lower Arcadia zone (PZ3) ranges from 57 at the ROMP 13 site to 234 ft at the ROMP 12 site (apps. B and C). The hydraulic properties of PZ3 are more variable than overlying zones, and probably are related to the degree of solution development within the limestone and dolomite beds. Typically, PZ3 is the most productive zone in the intermediate aquifer system. Hydraulic properties of PZ3 were estimated from aquifer tests conducted at five of the ROMP sites. The reported ranges for transmissivity, horizontal hydraulic conductivity, and specific capacity were 766 to 44,900 ft^2/d; 10 to 201 ft/d; and 3 to 49 gal/min/ft, respectively (table 1.)

Upper Floridan Aquifer

The Upper Floridan aquifer consists of a thick carbonate sequence that includes all or part of the Paleocene- to Oligocene-age rocks. The Upper Floridan aquifer contains one or more water-producing zones separated by less-permeable units. Generally, the permeability of the Upper Floridan aquifer is very high in parts of the Avon Park Formation, somewhat lower in the Suwannee Limestone, and lowest in the Ocala Limestone. Hydraulic properties have been estimated from aquifer tests conducted at five of the ROMP sites

(ROMP 5, 9, 9.5, 12, and 13). Aquifer test data are presented for wells that penetrated only the Suwannee Limestone. Reported ranges for transmissivity, horizontal hydraulic conductivity, and specific capacity were 2,350 to 7,640 ft^2/d; 10 to 41 ft/d; and 3 to 24 gal/min/ft, respectively (table 1). The relatively low hydraulic property values reported for the Suwannee Limestone indicate that a substantial water-producing zone was not penetrated in the Suwannee Limestone.

Confining Units

In the study area, confining units separating water-producing zones and aquifers consist of clay and low permeability carbonates (app. C). Hydraulic properties of the confining units range more than two orders of magnitude and vary with lithology and thickness. Leakance of the confining units was estimated from aquifer tests conducted by SWFWMD at the ROMP 5, 9, 9.5, and 12 sites, and is affected by heterogeneity and anisotropy of the aquifer system. The leakance values published by SWFWMD (Gates, 1997; Thompson, 1997; Baldini, 1999; Clayton, 1999; and Gates, SWFWMD, written commun., 2000), expressed in units of feet per day per foot (ft/d/ft) are:

	[1]UFA:PZ3 (ft/d/ft)	[2]PZ3:PZ2 (ft/d/ft)	[3]PZ2:PZ1 (ft/d/ft)	[4]PZ1:SAS (ft/d/ft)
ROMP 5	1.8×10^{-3}	na	na	3.7×10^{-4}
ROMP 9	5.6×10^{-3}	1.7×10^{-3}	8.2×10^{-4}	2.3×10^{-5}
ROMP 9.5	1.2×10^{-3}	3.7×10^{-5}	1.4×10^{-3}	5.5×10^{-4}
ROMP 12	na	1.4×10^{-3}	5.8×10^{-4}	2.2×10^{-2}

[1] Confining unit between Upper Floridan aquifer (UFA) and Lower Arcadia zone (PZ3)

[2] Confining unit between Lower Arcadia zone (PZ3) and Upper Arcadia zone (PZ2)

[3] Confining unit between Upper Arcadia zone (PZ2) and Tamiami/Peace River zone (PZ1)

[4] Confining unit between Tamiami/Peace River zone (PZ1) and surficial aquifer system (SAS)

na - not available

Generally, the largest and smallest values of leakance are for the confining unit separating the Upper Floridan aquifer from the lowermost permeable zone in the intermediate aquifer system, and the confining unit separating the surficial aquifer system from the uppermost permeable zone in the intermediate aquifer system, respectively. Leakance of the confining units was calculated using analytical models with limiting assumptions. Many of these assumptions may be violated when applied to the heterogeneous aquifer systems. Therefore, reported leakance values may not accurately quantify flow across confining units, especially where the aquifer is known to receive leakage from underlying, overlying, and/or internal sources.

A check was made using a form of Darcy’s Law to test the reasonableness of the leakance values for the confining units computed from analytical analysis of aquifer test data. Darcy’s Law was formulated as:

$$L = (q/365)/h,$$

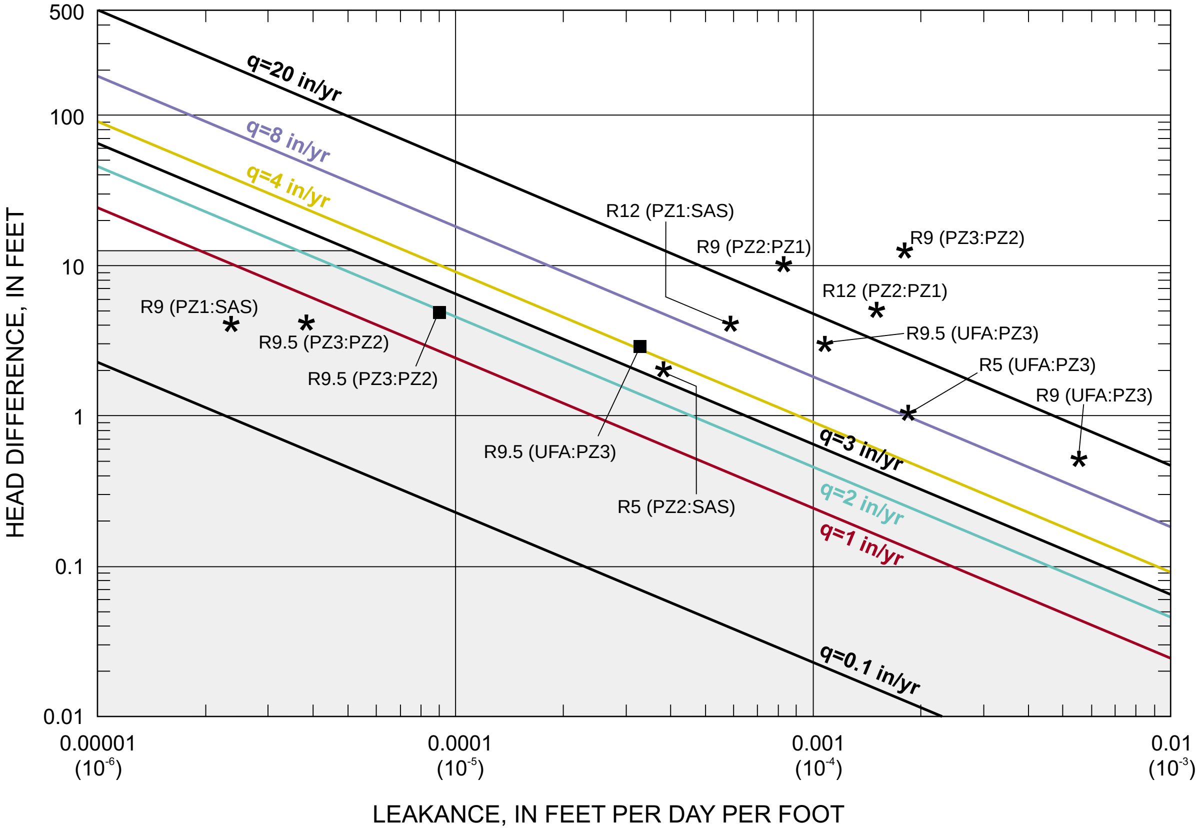
where

L is leakance of the confining bed, in feet per day per foot (ft/d/ft),
q is annual leakage across confining bed, in feet per year (ft/yr), and
h is head difference across confining bed, in feet (ft).

Figure 7 shows a graph of the empirical relations between leakance, head differences, and annual leakage (leakage values expressed in units of inches per year (in/yr)). The shaded area of the graph corresponds to the observed head differences in September 1998 (less than 1 to 12 ft) and the range in leakage (less than 1 to 3 in/yr) between hydrogeologic units derived from numerical simulations of ground-water flow of the study area (Wolansky, 1983, Ryder, 1985, and SWFWMD, 1994). Also shown on figure 7 are the leakance values of the confining units derived for each ROMP site using analytical methods and the leakance values derived for ROMP 9.5 using numerical analysis. The graph shows that most of the leakance values derived from analytical analysis of aquifer test data are in excess of 8 in/yr and more than twice the rate (less than 1 to 3 in/yr) indicated from numerical simulation results. This test using Darcy’s Law indicates that most of the analytically derived leakance values are probably too high.

Ground-Water Flow Patterns

Ground-water flow patterns in the intermediate aquifer system were evaluated using water-level data collected from a network of wells distributed across the study area and adjacent areas. Ground-water levels are measured and mapped semi-annually in May and September, to depict the seasonal changes in head distribution and ground-water flow patterns in the intermediate aquifer system and the Upper Floridan aquifer. Vertical flow potentials were evaluated using water-level data collected from wells open to discrete depths at a single monitor well site. Generally, lateral head differences are relatively small compared to vertical head differences.

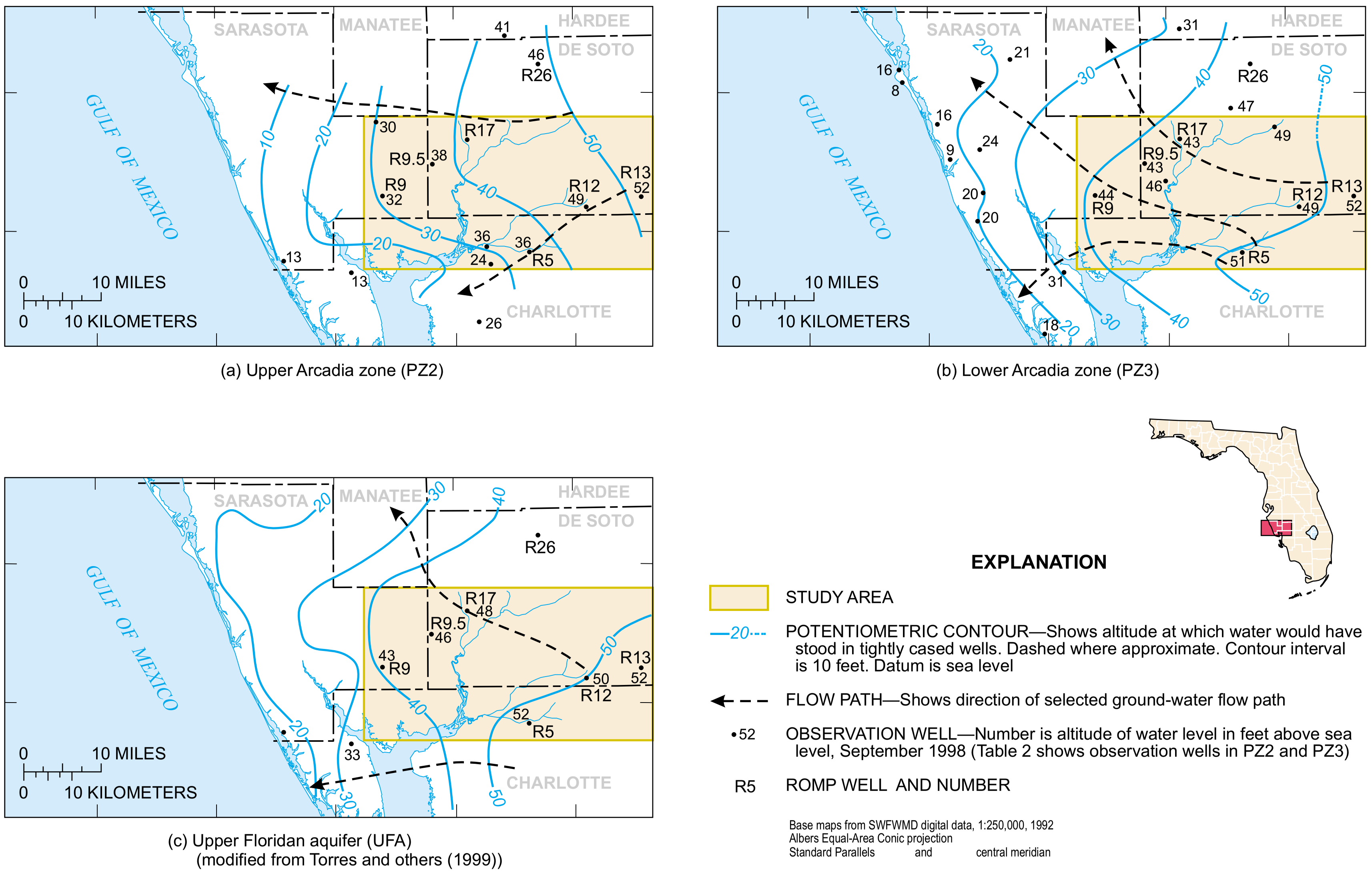


EXPLANATION

▢	Range of leakance computed assuming a leakage (q) of less than 3 inches per year (in/yr) and head differences of less than 12 feet
R5	ROMP site number
■	Leakance value reported by U.S. Geological Survey (USGS) using numerical solutions
*	Leakance value reported by Southwest Florida Water Management District (SWFWMD) using analytical solutions
q	Leakage across confining units, in inches per year (in/yr)
SAS:PZ1	Confining unit between the surficial aquifer system (SAS) and the Tamiami/Peace River zone (PZ1)
PZ1:PZ2	Confining unit between the Tamiami/Peace River zone (PZ1) and the Upper Arcadia zone (PZ2)
PZ3:PZ2	Confining unit between the Lower Arcadia zone (PZ3) and the Upper Arcadia zone (PZ2)
UFA:PZ3	Confining unit between the Upper Floridan aquifer (UFA) and the Lower Arcadia zone (PZ3)

Figure 7. Range of leakance values estimated for confining units at the ROMP 5, 9, 9.5, and 12 sites.

Potentiometric-surface maps of the Upper Arcadia zone (PZ2) and the Lower Arcadia zone (PZ3) (figs. 8a, b; table 2), and the Upper Floridan aquifer (fig. 8c) were prepared using data collected in September 1998. Regional ground-water flow in the intermediate aquifer system is generally westerly toward the Gulf of Mexico. Regional flow patterns in PZ3 of the intermediate aquifer system are similar to patterns in the Upper Floridan aquifer (fig. 8). Flow patterns in PZ2 of the intermediate aquifer are generalized due to a lack of spatial resolution and are more westerly than those in PZ3 or the Upper Floridan aquifer. In the study area, ground-water inflow to the intermediate aquifer system primarily occurs as upward leakage from the underlying Upper Floridan aquifer rather than lateral flow through the intermediate aquifer system or recharge from the surficial aquifer system. The relative contribution of water from each of the aquifer systems is supported by geochemical data and discussed in later sections of this report. Only minor quantities of inflow are contributed from upgradient inland areas, and little if any ground-water inflow to the intermediate aquifer system is contributed from the surficial aquifer system.



(a) Upper Arcadia zone (PZ2)

(b) Lower Arcadia zone (PZ3)

(c) Upper Floridan aquifer (UFA)
(modified from Torres and others (1999))

Base maps from SWFWMD digital data, 1:250,000, 1992
Albers Equal-Area Conic projection
Standard Parallels and central meridian

Figure 8. Potentiometric surface of the (a) Upper Arcadia zone (PZ2) and (b) Lower Arcadia zone (PZ3) of the intermediate aquifer system, and (c) Upper Floridan aquifer, southwest Florida, September 1998.

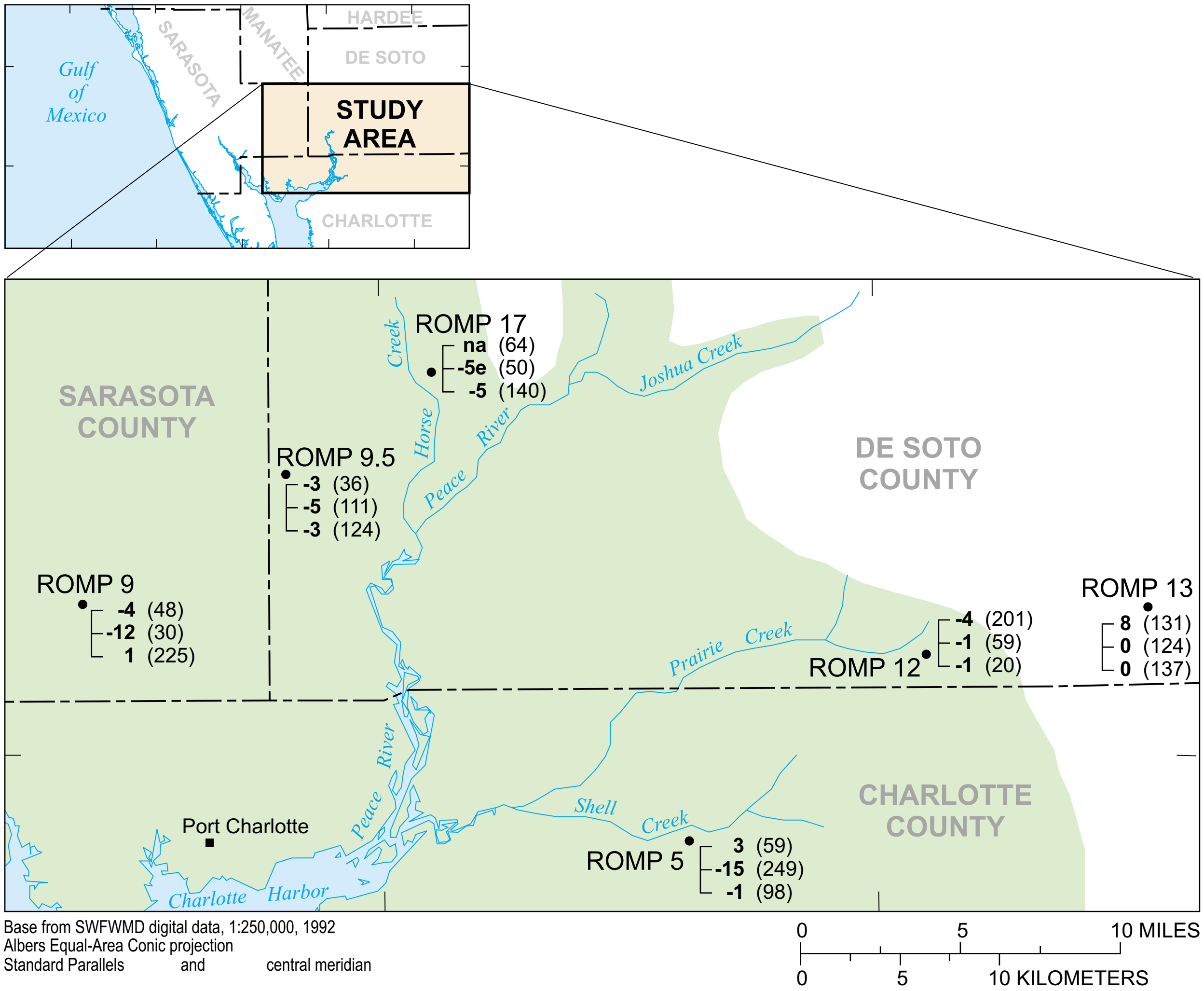
Table 2. Information on selected observation wells open to the Upper Arcadia zone (PZ2) and Lower Arcadia zone (PZ3) within the intermediate aquifer system

[PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; CHA, Charlotte; DES, De Soto; HAR, Hardee; SAR, Sarasota; --, unknown]

Site identification number	Name	Hydrogeologic unit	County	Casing (feet)	Depth (feet)	Water level September 98 (feet)[1]
265004081581901	Ch-311 Mid Htrn Well	PZ2	CHA	--	220	26.08
265017082153701	USGS Htrn Well 8 At Placida	PZ3	CHA	346	413	17.90
265531082194804	Romp TR 3-3 Htrn Well Nr Englewood	PZ3	CHA	370	410	20.00
265531082194805	Romp TR 3-3 Upper Hawthorn Nr Lemon High School	PZ2	CHA	155	175	13.00
265638082130705	Romp TR 3-1 Htrn Well Nr El Jobean	PZ3	CHA	380	400	30.81
265644081483303	Romp 5-MW 3-IAS-LPZ	PZ3	CHA	450	600	50.86
265644081483304	Romp 5-MW2-IAS-UPZ	PZ2	CHA	130	230	35.53
265646081554501	USGS Tuh Well C-5 Nr Punta Gorda	PZ2	CHA	194	280	23.80
265837081561101	Romp 11 Htrn Well Nr Punta Gorda	PZ2	CHA	220	335	35.90
271757081493003	Romp 26 Htrn Well Nr Gardner	PZ2	DES	140	180	46.09
270225081443304	Romp 12-INT-L Arcadia Well near Arcadia (Well #4)	PZ2	DES	280	409	48.65
270225081443304	Romp 12-INT-L Nocatee Well #5 near Arcadia	PZ3	DES	505	705	49.40
270418081365803	ROMP 13-MW3 IAS LPZ	PZ3	DES	514	592	52.27
270418081365804	ROMP 13-MW2 - INT-UPZ	PZ2	DES	282	417	51.47
270540082001102	Gen. Dev. Htrn Well T-2 Nr Ft, Ogden	PZ3	DES	393	496	45.61
270737082025001	ROMP 9.5 - MW18	PZ2	DES	60	77	38.17
270737082025002	ROMP 9.5 - MW2	PZ3	DES	205	330	43.43
271026081583604	Romp 17 Htrn Well Nr Arcadia	PZ3	DES	200	240	43.15
271115081462702	Romp 16 Htrn Well Nr Arcadia	PZ3	DES	300	340	49.13
271308081522601	City Of Arcadia Htrn Well 2 At Arcadia	PZ3	DES	263	372	46.97
272038081530701	Limestone Land Int Well At Limestone	PZ2	HAR	126	235	41.02
272108081582601	Hollingsworth Int Well Nr Limestone	PZ3	HAR	146	335	31.17
272714081545902	Romp 31 Htrn Well Nr Ona	PZ3	HAR	130	350	43.19
272728081474702	Romp 30 Tamp Well Nr Zolfo Springs	PZ3	HAR	280	316	47.86
273435081444001	R. Henderson Htrn Well Nr Wauchula	PZ3	HAR	105	293	64.26
273555081403001	John White Htrn Well Nr Wauchula	PZ3	HAR	63	270	89.19
265710082205101	Englewood Wd HTRN	PZ2	SAR	152	310	12.86
270137082235301	Manasota Deep Well 14 Nr Englewood	PZ3	SAR	263	305	20.02
270420082230503	Venice Gardens Htrn Well Nr Venice	PZ3	SAR	200	400	20.11
270432082085709	Romp 9 (MW4) - Lower Intermediate Monitor, near Northport, Sarasota	PZ3	SAR	194	320	43.65
270808082270503	Romp TR 5-1 Htrn Well At Laurel	PZ3	SAR	275	289	9.20
270919082234203	Romp TR 5-2 Lower Htrn Well Nr Laurel	PZ3	SAR	245	365	23.93
271134082092201	Big Slough Tuh Well Nr Arcadia	PZ2	SAR	78	100	29.69
271137082284502	Romp 20 LHtrn Well At Osprey	PZ3	SAR	50	370	16.15
271137082284503	Romp 20 TUH Well	PZ2	SAR	75	125	0.40
271601082330501	Romp TR 6-1 Htrn Well Nr Sarasota	PZ3	SAR	300	315	8.15
271813082201303	Romp 22 - Lower INT Well ,Hi Hat Ranch near Fruitville	PZ3	SAR	230	260	20.62

[1] Altitude above mean sea level.

The study area is primarily an area of upward-flow potential except near the ROMP 13 site in the southeastern part of De Soto County (fig. 9), where a downward head difference occurs between the aquifer systems. Areas of discharge from the Upper Floridan aquifer occur in the river valleys and in areas of low topographic relief. In river valleys, upward discharge is the result of decreased heads in the shallower aquifers. In areas of low topographic relief, upward discharge is affected by subsurface stratigraphy. Five of the six ROMP sites are located in discharge areas where water levels increase with depth and the flow potential is upward from the Upper Floridan aquifer, through the intermediate aquifer system, to the surficial aquifer system. At the ROMP 5 site, an anomalous condition was observed where a downward head difference



Base from SWFWMD digital data, 1:250,000, 1992
Albers Equal-Area Conic projection
Standard Parallels and central meridian

EXPLANATION

🟩 AREA OF ARTESIAN FLOW–Estimated using topographic and potentiometric surface altitudes

ROMP 5 ● WELL LOCATION AND NAME

HEAD DIFFERENCE AND CONFINING UNIT THICKNESS—Bold number is head difference between adjacent aquifers, in feet. Parenthetic number is thickness of the intervening confining unit, in feet. An "e" means value was estimated, "na" means value is not available

3 (59)	Head difference and thickness between the surficial aquifer system and the Tamiami/Peace River zone (PZ1) or the Upper Arcadia zone (PZ2)
-15 (249)	Head difference and thickness between the Upper Arcadia zone (PZ2) and the Lower Arcadia zone (PZ3)
-1 (98)	Head difference and thickness between the Lower Arcadia zone (PZ3) and the Upper Floridan aquifer

Note: Negative numbers indicate an upward head gradient and positive numbers indicate a downward head gradient.

Figure 9. Head differences among aquifers, area of artesian flow, and thickness of confining units, September 1998.

occurs between the surficial aquifer system and PZ2, while an upward head difference occurs for the other hydrogeologic units.

Head differences generally were small between the Upper Floridan aquifer and PZ3, and moderate between PZ3 and PZ2, and between PZ2 or PZ1 and the surficial aquifer system (fig. 9). Localized head-difference reversals, however, can occur in response to local ground-water withdrawals. Aquifer test data collected at the ROMP sites indicate that relatively large drawdowns in pumped wells (20 to 50 ft) can occur when the intermediate aquifer system is stressed, resulting in localized head-difference reversals between the Upper Floridan aquifer and the intermediate aquifer system.

Although a regional flow system can be mapped for the intermediate aquifer system, the depth and extent of ground-water flow paths within each of the permeable zones in the intermediate aquifer system are not well understood or known, and locally, flow may be opposite of the regional flow pattern. The juxtaposition of heterogeneous sediments within the intermediate aquifer system results in lateral discontinuities (permeable zone pinches out or is discontinuous) and variable locations of water-producing zones that probably produce multi-scale flow fields within the aquifer system. For example, at the same geographic location, water levels in wells penetrating the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer may reflect different hydrologic conditions such as recharge, flow through, or discharge conditions. Freeze and Cherry (1979) have shown that stratigraphic layering of sediments with permeability contrasts (geologic heterogeneity) can have profound effects on the regional flow system. Subsurface variations in horizontal hydraulic conductivity can create multi-scale flow fields and affect the relation between local and regional ground-water flow, areas of recharge and discharge, and the quantities of flow discharged through the aquifer systems (Freeze and Cherry, 1979, p. 197).

Hydraulic Connection Between Hydrogeologic Units

Drilling and testing indicate that the hydraulic connection between the surficial aquifer system, permeable zones of the intermediate aquifer system, and the Upper Floridan aquifer is variable in the study area. Water levels in some wells respond rapidly to pumping from overlying and underlying aquifers whereas other wells seem to have little or no response to pumping when one or more aquifers are stressed. The degree of hydraulic connection is related to the presence and thickness of clay and dolosilt beds composing the confining units; however, facies changes and karstification may result in local hydraulic connection with overlying and underlying aquifers. Effective hydraulic coupling is indicated by small head differences among aquifers, high leakance values, and rapid drawdowns in adjacent aquifers when one or the other is stressed.

Generally, a hydraulic connection exists between the Upper Floridan aquifer and the Lower Arcadia zone (PZ3). The two zones are probably connected locally by fractures or other zones of preferential flow. Thickness of the intervening confining unit averages about 125 ft and ranges from 20 ft at the ROMP 12 site to 225 ft at the ROMP 9 site (fig. 9; apps. B and C). Relatively small head differences are observed between the two zones (fig. 10). Head differences between the two hydrogeologic units averaged about 2 ft in September 1998 and ranged from less than 1 ft at the ROMP 5, 9, and 13 sites to 5 ft at the ROMP 17 site (fig. 10). Leakage across the intervening confining unit is low and ranges from less than 1 to 3 in/yr (Wolanksy, 1983, Ryder, 1985, and Southwest Florida Water Management District, 1994). Aquifer testing conducted on PZ3 and on the Suwannee Limestone of the Upper Floridan aquifer indicated, generally, a hydraulic response when either unit was stressed, indicating hydraulic connection between units. One exception is at the ROMP 9 site, where no water-level response was recorded in observation wells in the overlying or underlying unit when one or the other unit was stressed. The confining unit separating these units is thickest at the ROMP 9 site and consists of a sequence of low-permeability units (apps. B and C) that probably restrict the hydraulic connection between zones at this site. A second exception is at ROMP 9.5, where no water-level response was recorded in the Upper Floridan aquifer observation wells when PZ3 was pumped; however, a delayed response was recorded in the PZ3 observation wells when the Upper Floridan aquifer was stressed. At the ROMP 12, 13, and 17 sites, monitor wells are open to both the intermediate aquifer system and the Upper Floridan aquifer (figs. 5 and 6). The open-hole intervals penetrate a contiguous sequence of carbonates that comprises the Nocatee Member/Lower Arcadia Formation and Suwannee Limestone, and the hydrogeologic units are probably hydraulically coupled at these sites.

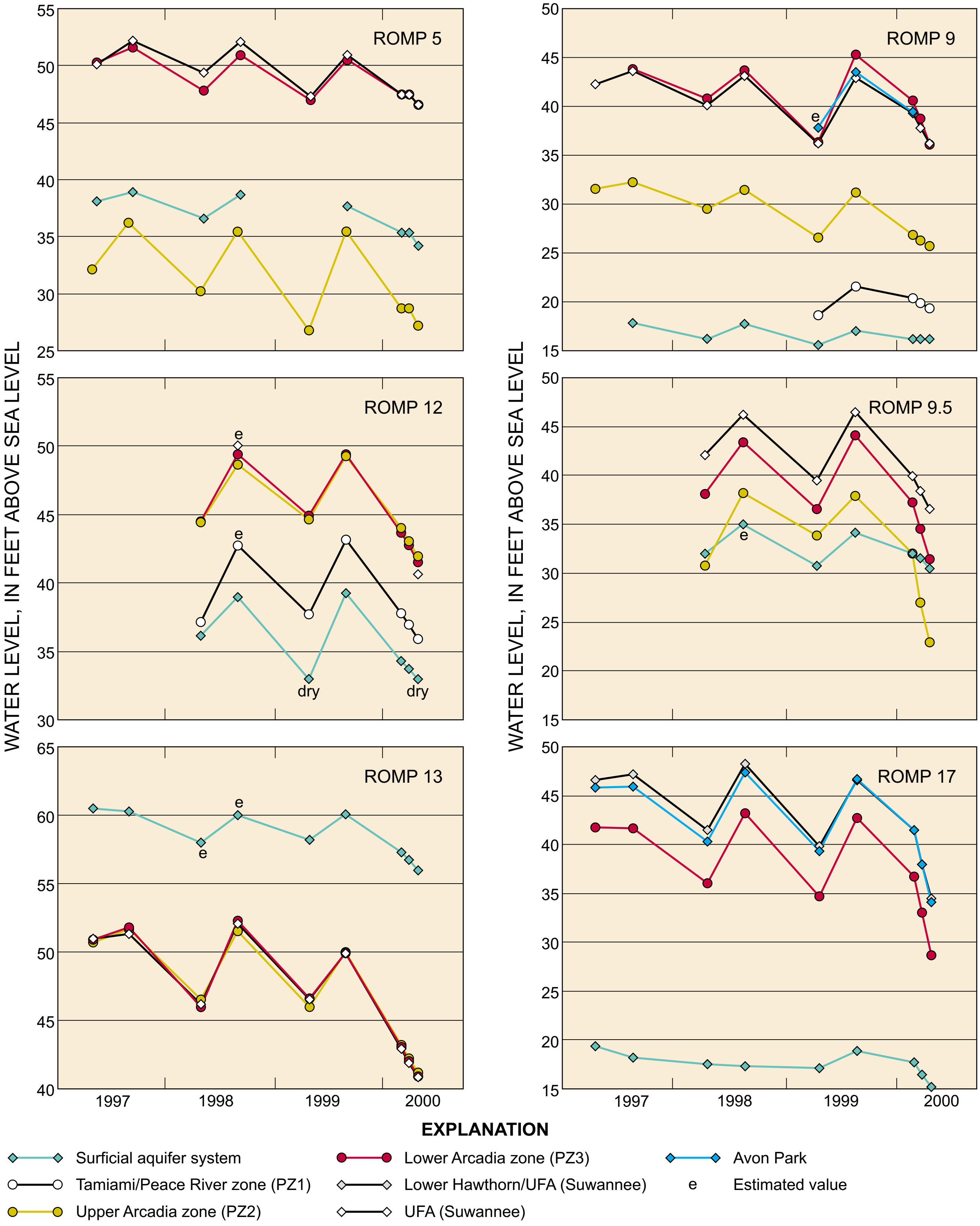


Figure 10. Water levels in wells at the ROMP 5, 9, 9.5, 12, 13, and 17 sites from May 1997 through May 2000.

Hydraulic data indicate little hydraulic connection between PZ3 and PZ2, probably due to the thickness and low permeability of sediments separating the two zones. Thickness of the intervening confining unit averages more than 100 ft and ranges from 30 ft at the ROMP 9 site to 249 ft at the ROMP 5 site (fig. 9; apps. B and C). Moderate head differences are observed between the two units (fig. 10). Head differences between the two hydrogeologic units averaged about 5 ft in September 1998 and ranged from less than 1 ft at the ROMP 13 site to 12 ft at the ROMP 9 site (fig. 10). Leakage across the intervening confining unit is low, about 1 in/yr (Wolanksy, 1983). Aquifer testing conducted on PZ3 and PZ2 indicated little or no water-level response when one or the other zone is stressed, suggesting hydraulic separation between the units.

Little hydraulic connection exists between the surficial aquifer system and either PZ1 or PZ2, probably because of a relatively thick clay unit separating the two zones. Thickness of the intervening confining unit averages about 100 ft, ranging from 36 ft at the ROMP 9.5 site to 201 ft at the ROMP 12 site (fig. 9; apps. B and C). Head differences between the two hydrogeologic units averaged about 4 ft in September 1998, ranging from about 3 ft at the ROMP 5 and 9.5 sites to about 8 ft at the ROMP 13 site (fig. 10). Leakage across the intervening confining unit is low, in the range of 1 in/yr (Wolanksy, 1983). Aquifer test results indicated no water-level response in the monitored unit when the surficial aquifer system, PZ1 or PZ2 were pumped, suggesting hydraulic separation between the units.

HYDRAULIC CHARACTERISTICS AT THE ROMP 9.5 SITE

Hydraulic characteristics of permeable zones and confining units at the ROMP 9.5 site were quantified using permeameter tests on cores, short-term withdrawal tests (specific-capacity tests), and long-term withdrawal tests (aquifer tests). In addition, an initial quantification of permeability was determined from visual inspection of core samples. In consolidated materials and/or rock cores, low porosity is presumed to be an indicator of low permeability whereas high porosity is presumed to be associated with high permeability. This qualitative indication is consistent with observations of the core. Most cores obtained from the ROMP 9.5 site exhibit some visual degree of permeability.

Core Analysis

Based on visual inspection, 10 cores, each 3-6 inches long, were selected for laboratory testing of hydraulic properties. The cores were selected to be representative of both permeable and confining units within the intermediate aquifer system and the Upper Floridan aquifer (Gates, 1998a). Values for porosity and vertical hydraulic conductivity (K_v) were determined by the FGS and are shown in figure 11 and table 3.

Laboratory analyses indicate that hydraulic properties determined from cores are highly variable, indicative of the variable nature of the sedimentary units. The vertical hydraulic conductivities and porosity values are generally highest in the confining units and lowest in the permeable units. Bulk porosity values were highly variable within confining materials in selected hydrogeologic units ranging from 28 to 52 percent (fig. 11, table 3). K_v ranged from 1.124×10^{-4} to 3.818×10^{-2} feet per day (ft/d) (fig. 11; table 3).

The vertical hydraulic conductivity values determined from cores are much lower than values determined from standard aquifer tests, and are related to the difference in scale between core samples and aquifer matrix. Fractures, cavities, and preferential pathways play a major role in conducting water to a pumped well, whereas only the properties of the rock for a discrete interval itself were measured in the laboratory. Therefore, the vertical hydraulic conductivity determined from the laboratory data should be used cautiously and only in a relative sense.

Specific-Capacity Tests

Specific capacities of selected intervals of the intermediate aquifer system and the Upper Floridan aquifer at the ROMP 9.5 site were determined during drilling of the test hole. Specific capacity can be used to evaluate the productivity of various intervals. Packer equipment was used to isolate and pump 12 bottom-hole intervals as drilling progressed. Values of specific capacity ranged from 0.02 to 0.55 (gal/min)/ft (table 4), indicating that productivity of specific zones within the intermediate aquifer system is relatively low and highly variable. Generally, the highest specific capacity is associated with producing zones and the lowest specific capacity is associated with confining units.

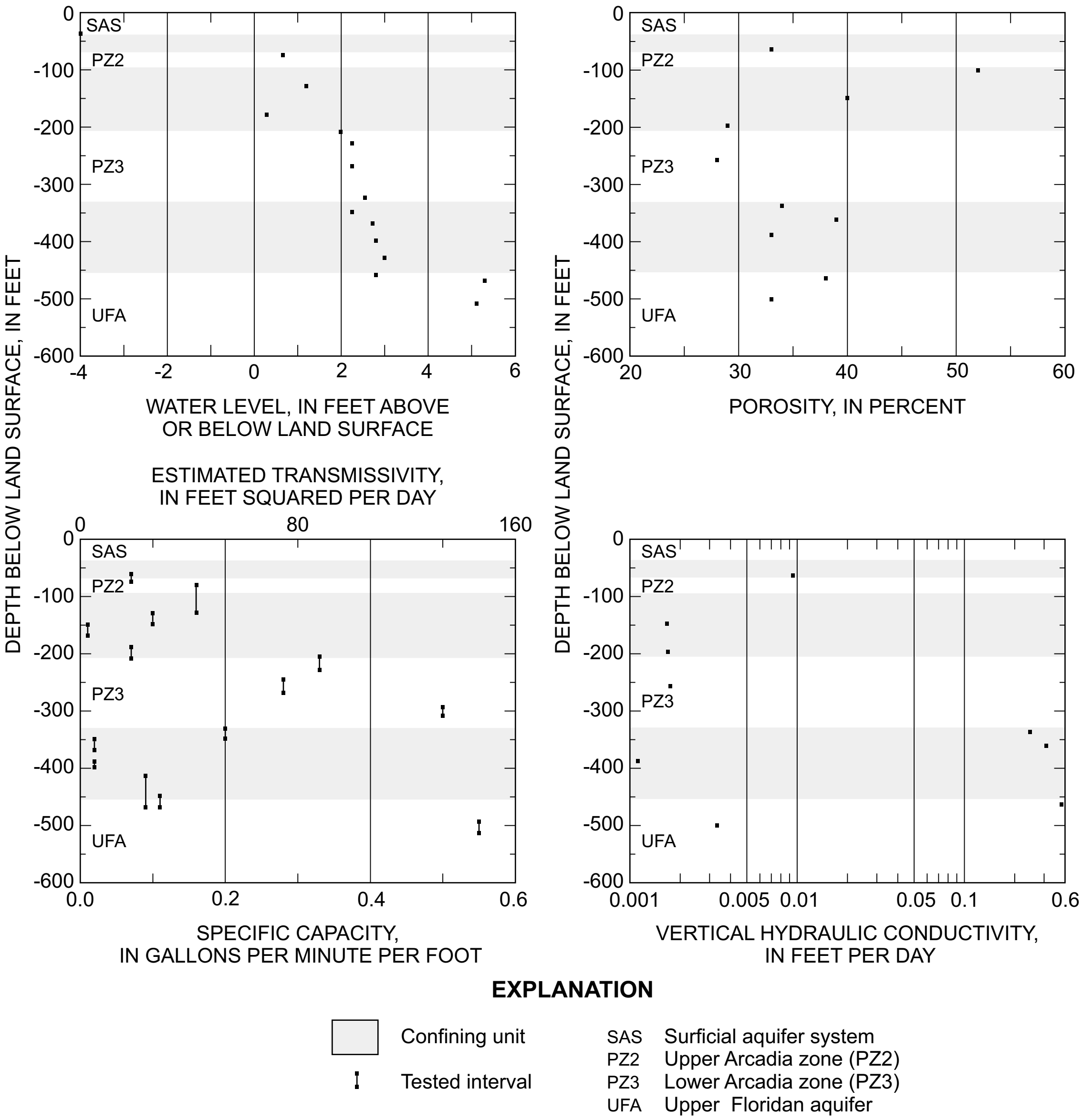


Figure 11. Hydraulic data collected during coring and testing at the ROMP 9.5 site.

Aquifer Tests

Two aquifer tests were conducted at the ROMP 9.5 site to estimate hydraulic properties of the intermediate aquifer system and the Upper Floridan aquifer. The first test was conducted on the Lower Arcadia zone (PZ3) from January 12-15, 1998, for 2.77 days (3,990 minutes). The second test was conducted on the Suwannee Limestone (Upper Floridan aquifer) from February 2-3, 1998, for 1 day (1,440 minutes). Aquifer test data were analyzed using both analytical and numerical techniques.

Test Design and Implementation

A plan view and construction records of the production and observation wells for the aquifer tests conducted at the ROMP 9.5 site are shown in figure 12. Water levels were measured continuously in selected wells for background, withdrawal, and recovery periods of the tests. The data were collected using pressure transducers connected to a digital data logger. Additional water-level measurements were made manually to verify data logger water-level data.

Table 3. Porosity and hydraulic conductivity of confining material in selected hydrogeologic units at the ROMP 9.5 exploratory borehole, De Soto County, Florida

[Bulk porosity calculations and falling-head permeameter tests were conducted on cores collected from the exploration borehole between June and August, 1997, by the Florida Geological Survey, Tallahassee, Florida; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; --, no data]

Core interval below land surface (feet)	Hydrogeologic unit	Porosity, bulk (percent)	Hydraulic conductivity (feet/day)	Comments for permeameter tests (hydraulic conductivity)
64.0 - 64.8	Upper Arcadia zone (PZ2), confining material	33	9.402×10^{-4}	Average of three tests
100.7 - 101.2	Confining unit between PZ2 and PZ3	52	--	Sample fractured. Test not run
148.7 - 149.1	Confining unit between PZ2 and PZ3	40	1.672×10^{-4}	One test. No flow
195.7 - 198.0	Confining unit between PZ2 and PZ3	29	1.682×10^{-4}	One test. Saturated, but no flow
257.6 - 258.0	Lower Arcadia zone (PZ3), confining material	28	1.751×10^{-4}	One test. No flow
337.3 - 337.7	Confining unit between PZ3 and UFA	34	2.474×10^{-2}	Average of three tests
361.5 - 361.9	Confining unit between PZ3 and UFA	39	3.095×10^{-2}	Average of three tests
388.3 - 388.7	Confining unit between PZ3 and UFA	33	1.124×10^{-4}	One test. No flow
464.2 - 464.6	Confining unit between PZ3 and UFA	38	3.818×10^{-2}	Average of three tests. Minor fractures developed. About 1-centimeter thick core broken off
500.8 - 501.1	Upper Floridan aquifer, confining material	33	3.333×10^{-4}	One test. No flow

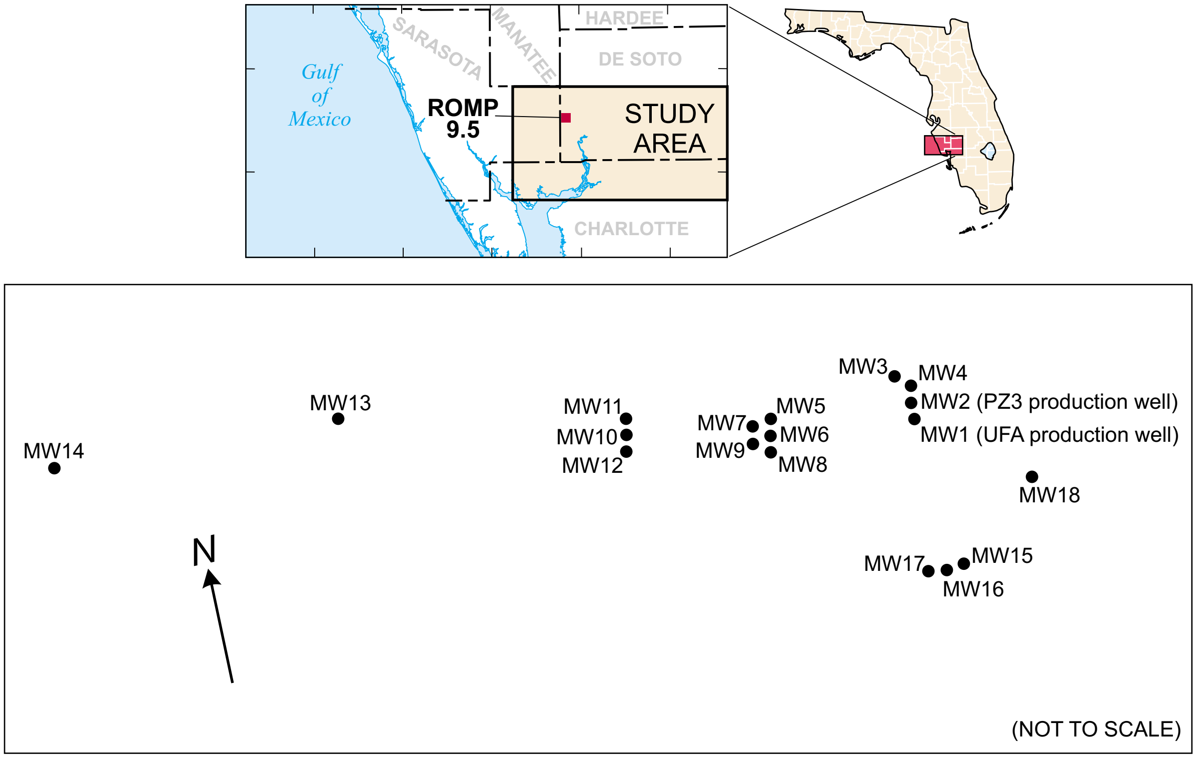
Table 4. Specific capacity of selected hydrogeologic units estimated by packer tests at the ROMP 9.5 exploratory borehole, De Soto County, Florida

[PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer]

Open-hole interval below land surface (feet)	Hydrogeologic unit	Specific capacity (gallons per minute/foot)	Discharge (gallons per minute)/ drawdown (feet) [1]	Duration of test (minutes)
80 - 128	Confining unit between PZ2 and PZ3	0.16	5/31	60
148 - 168	Confining unit between PZ2 and PZ3	[2] 0.10	1/90	28
188 - 208	Confining unit between PZ2 and PZ3	0.07	5/70	20
205 - 228	Lower Arcadia zone (PZ3)	0.33	5/15	10
245 - 268	Lower Arcadia zone (PZ3)	0.28	4/14	10
293 - 308	Lower Arcadia zone (PZ3)	0.50	5/10	8
331 - 348	Confining unit between PZ3 and UFA	0.12	3/25	8
348 - 368	Confining unit between PZ3 and UFA	0.02	3/140	50
388 - 398	Confining unit between PZ3 and UFA	0.02	3/108	50
413 - 468	Confining unit between PZ3 and UFA	0.09	4/42	20
448 - 468	Confining unit between PZ3 and UFA	0.11	5/42	15
493 - 513	Upper Floridan aquifer	0.55	5/9	5

[1] Discharge decreased during pumping; estimated value is maximum discharge at start of pumping.

[2] Specific capacity unreliable, but low permeability is estimated.



Relative position of wells at ROMP 9.5 site

Well name	Station identification	Hydrogeologic unit	Casing depth/ well depth (feet)	Casing diameter (inches)	Distance from production well MW1 (feet)	Distance from production well MW2 (feet)
MW1	270737082025101	Upper Floridan aquifer	500/800	12	--	11.7
MW2	270737082025102	Lower Arcadia zone (PZ3)	205/330	8	11.7	--
MW3	270737082025103	Surficial aquifer system	10/38	4	32.3	20.7
MW4	270737082025104	Surficial aquifer system	2/8	4	28.6	16.8
MW5	270737082025201	Upper Floridan aquifer	500/800	2	98.7	98.5
MW6	270737082025202	Upper Floridan aquifer	470/475	2	98.9	99.9
MW7	270737082025203	Confining unit	340/350	2	109.3	109.5
MW8	270737082025204	Lower Arcadia zone (PZ3)	205/330	2	100.6	102.5
MW9	270737082025205	Confining unit	180/190	2	109.2	110.3
MW10	270737082025301	Confining unit	340/350	2	199.1	199.2
MW11	270737082025302	Lower Arcadia zone (PZ3)	205/330	2	198.5	198.1
MW12	270737082025303	Confining unit	180/190	2	199.9	200.5
MW13	270737082025501	Lower Arcadia zone (PZ3)	205/330	2	398.2	397.7
MW14	270737082025901	Lower Arcadia zone (PZ3)	205/330	2	798.1	798.4
MW15	270736082025101	Confining unit	340/350	2	87.7	99.1
MW16	270736082025102	Lower Arcadia zone (PZ3)	205/330	2	85.6	97.2
MW17	270736082025103	Confining unit	180/190	2	87.3	99.1
MW18	270737082025001	Upper Arcadia zone (PZ2)	60/77	4	97.5	104.9

Figure 12. Location of study area, plan view, and description of wells at the ROMP 9.5 test site.

The production wells were pumped using a shaft-driven turbine pump powered by a diesel engine. Water from the production wells was discharged to connecting PVC piping through a totalizing flow-thru meter, collapsible hose, and finally through a pipe-orifice plate manometer apparatus. All water was discharged into a shallow ditch about 100 ft from the production wells. Flow rates were recorded using a flow-thru meter and orifice-plate manometer apparatus.

The Lower Arcadia zone (PZ3) was stressed at an average discharge rate of 425 gallons per minute (gal/min) and water levels were measured in the production well and 16 observation wells during the test and during a 7-day recovery period. Water levels for background, withdrawal, and recovery periods of the test for 7 of the 16 observation wells (MW1, MW3, MW4, MW6, MW7, MW8, and MW9) are shown in figure 13. Diurnal water-level fluctuations of less than 0.2 foot were observed in the production and observation wells leading into both the PZ3 and Upper Floridan aquifer tests. The diurnal fluctuations were considered negligible and no water-level corrections were made.

The Suwannee Limestone of the Upper Floridan aquifer was stressed at an average discharge rate of 797 gal/min, and water levels were measured in the production well and seven observation wells during the test and during a recovery period. Water levels for background, withdrawal, and recovery periods of the test for the pumped well (MW1) and the seven observation wells (MW2, MW5, MW6, MW7, MW15, MW17, and MW18) are shown in figure 14. At about 110 minutes after pumping began, a discharge control valve briefly closed and a temporary recovery of about 40 ft occurred in the production well. Also,

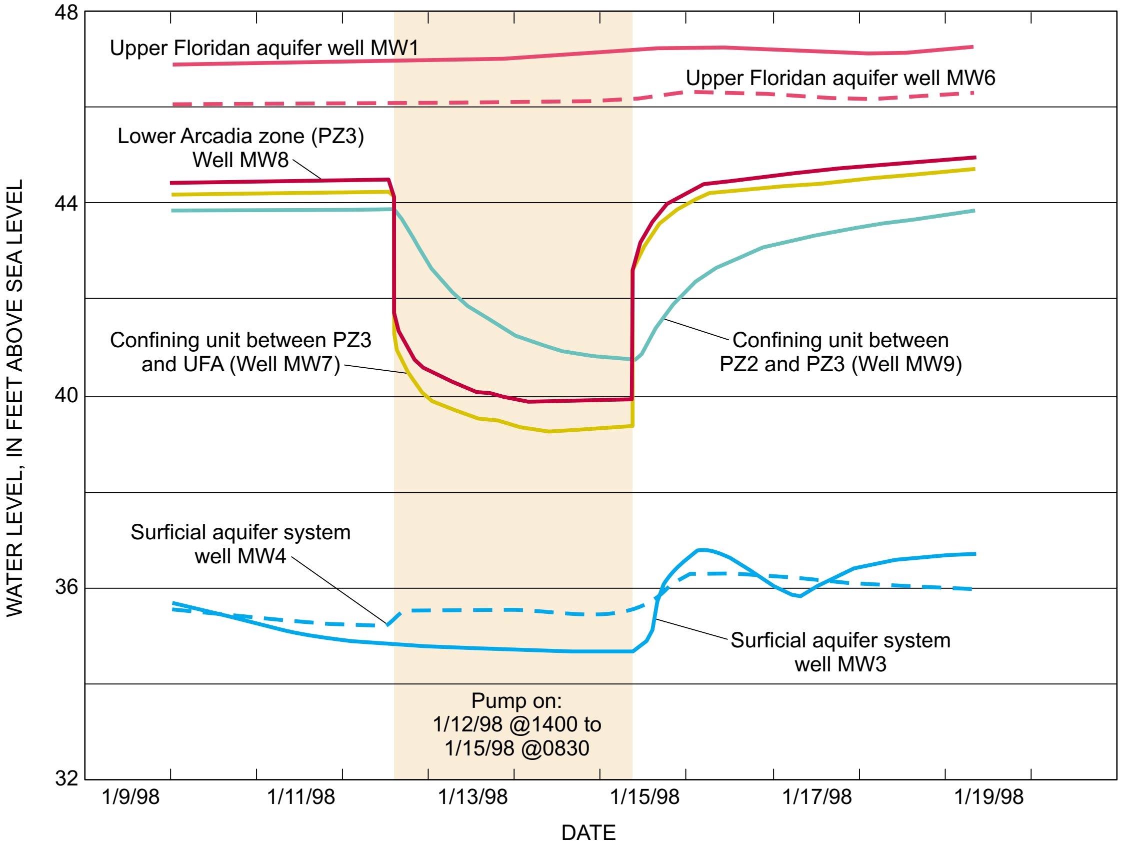


Figure 13. Water levels in selected observation wells for background, withdrawal, and recovery periods for the Lower Arcadia zone (PZ3) aquifer test at the ROMP 9.5 site.

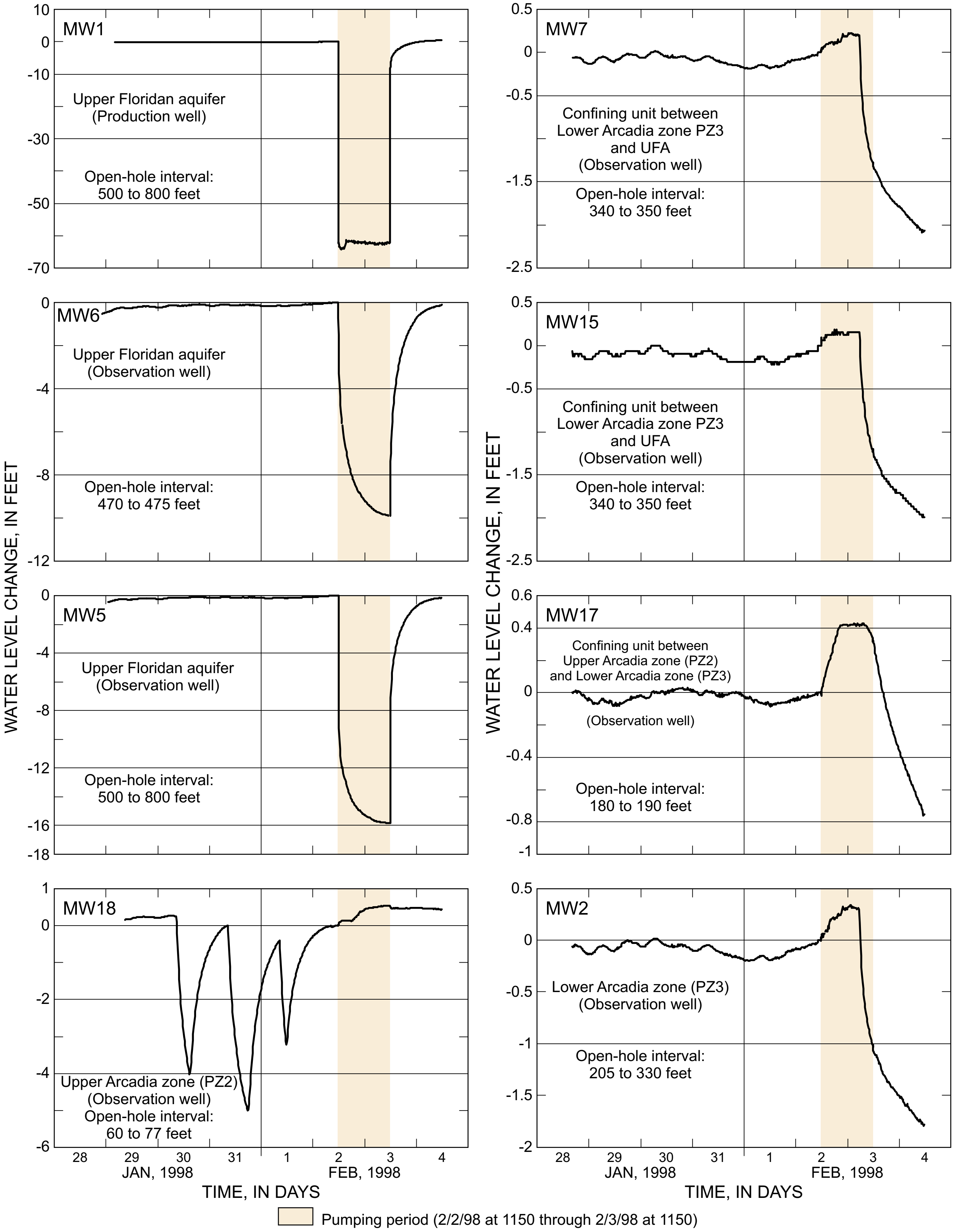


Figure 14. Water levels in selected wells for background, withdrawal, and recovery periods of the Upper Floridan aquifer test at the ROMP 9.5 site.

offsite pumpage apparently affected water levels in PZ2 well MW18, in PZ3 well MW2, and in the confining unit wells MW7, MW15, and MW17. The location and pumping rate of the offsite well or wells are unknown, and therefore, estimation of the hydraulic properties of the confining units was not attempted for this test. This unknown pumpage from an offsite well(s) did not produce drawdowns in the Upper Floridan aquifer observation wells.

Analytical Analysis of Aquifer Tests

Three analytical methods were used to analyze the tests conducted at the ROMP 9.5 site. The methods selected to analyze the tests are: (1) the Hantush (1960) modified leaky method, (2) the Jacob (1946) steady-state method, and (3) the Neuman and Witherspoon (1972) ratio method. The methods use the concept of an artesian aquifer overlain by leaky confining units and assume a homogeneous isotropic aquifer of uniform thickness and infinite areal extent. Many of the inherent assumptions of the methods are not met, or were only partially satisfied at the ROMP 9.5 site because the aquifer system at this site is heterogeneous and anisotropic. All of the methods apply curve-matching techniques. Detailed procedures for application of the analytical methods are described in Kruseman and de Ridder (1991). Even though aquifer test data can be fit to a type curve from one of the idealized models, there is no guarantee that the aquifer system satisfies the assumption on which the type curve was developed (Wolansky and Corral, 1985).

Hantush (1960) Modified Leaky Method

The Hantush (1960) modified leaky method can be applied to aquifers with leaky confining units. The analytical solution accounts for water leaking into the aquifer being pumped from confining beds, and for the effects of water coming out of storage in the confining beds. Mass plots of drawdown data are plotted on logarithmic paper in relation to time since pumping started divided by the square of the radial distance between the observation well and the pumped well (fig.15). The resulting drawdown curves are superimposed on the family of type curves of the function W (u, B) verses 1/u. Parameter estimation was facilitated by the use of an automatic curve matching program AQTESOLV (HydroSOLVE, Inc., 1996). The program uses a nonlinear weighted least-squares parameter estimation algorithm to match type curves to time-drawdown data. Results of the test analysis are shown in figure 15 and listed in table 5.

Jacob (1946) Leaky Artesian Method

The Jacob (1946) leaky artesian method also can be applied to aquifers with leaky confining units. The application of the method assumes steady-state flow near a well discharging at a constant rate for a leaky confined aquifer, and uses a graphical method for determining transmissivity of the aquifer and the leakance of the confining bed. Data from the Lower Arcadia zone (PZ3) test indicate that a relatively steady-state condition had been reached by the end of the withdrawal phase of the test. For this test, the steady-state drawdown in each observation well is plotted on logarithmic paper in relation to distance of the observation well to the pumped well (fig. 16). The data then are matched to the Bessel function logarithmic type curve K_o (x) versus x with its tabular values given in Ferris and others (1962, table 4). The common match points and resulting aquifer and confining unit hydraulic coefficients are shown in figure 16 and listed in table 5.

Table 5. Summary of aquifer test results for the ROMP 9.5 site using analytical analysis

[PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; T, transmissivity; S, storage coefficient; $K'S_s'$, leakance characteristic of confining bed; K'/b', leakance coefficient of confining bed; K'/S_s', vertical hydraulic diffusivity of confining beds; d, days; ft, feet; ft/d, feet per day; ft^2/d, feet squared per day; --, not determined

Method of analysis	Aquifer characteristics		Confining unit characteristics		
	T (ft^2/d)	S	[1]$K'S_s'$ (d^{-1})	[1]K'/b' (ft/d/ft)	K'/S_s' (ft^2/d)
Hantush (1960)					
PZ3	10,000	1.3×10^{-4}	1.1×10^{-6}	--	--
UFA	4,300	2.8×10^{-4}	4.6×10^{-6}	--	--
Jacob (1946)					
PZ3	11,800	--	--	1.9×10^{-4}	--
UFA	--	--	--	--	
Neuman and Witherspoon (1972)	--	--	--	--	[2]130 to 274

[1] Leakance values, derived from the PZ3 aquifer test, incorporate the effects of upward and downward leakage.

[2] Value is for the interval from 190 to 206 feet below land surface.

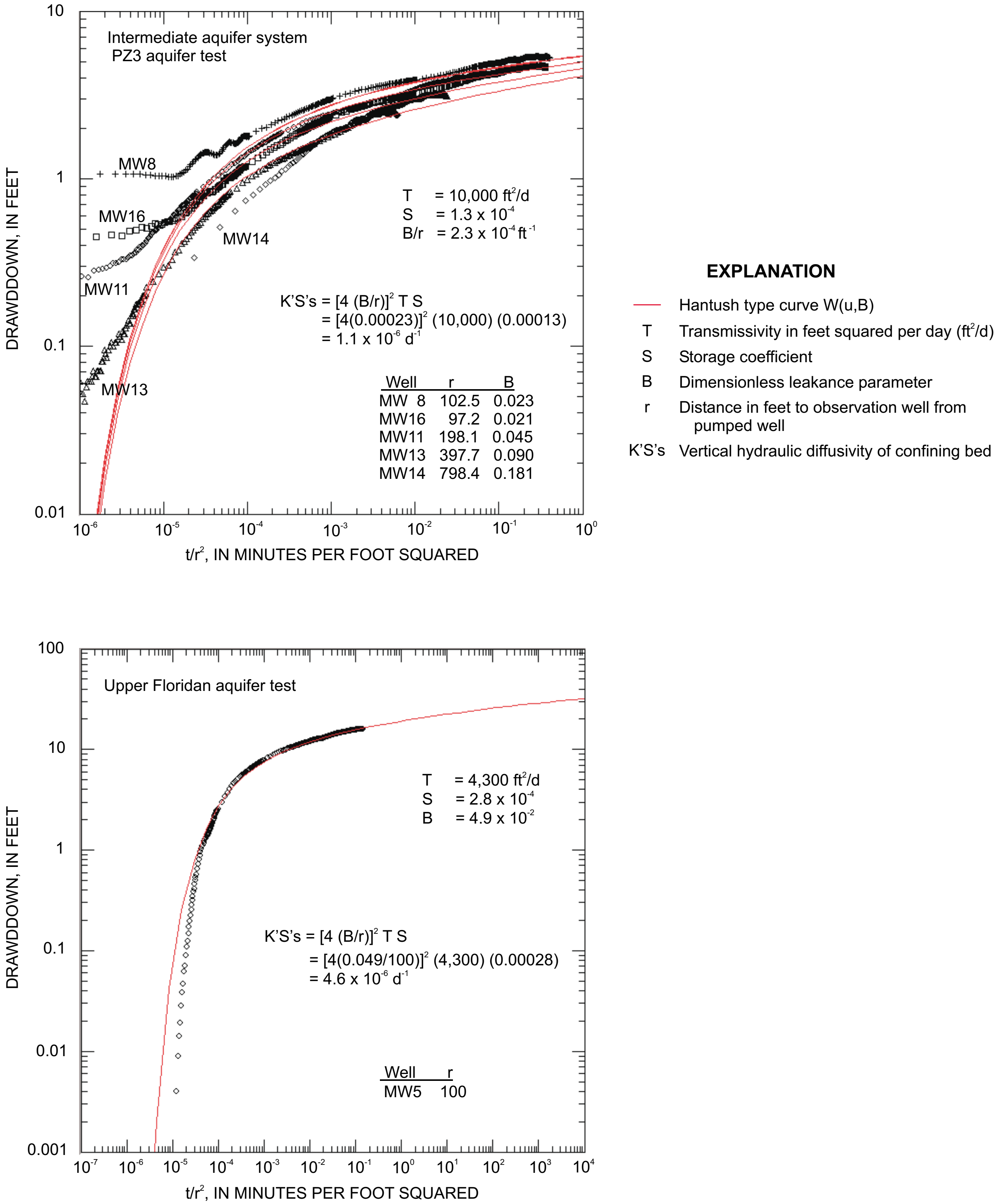
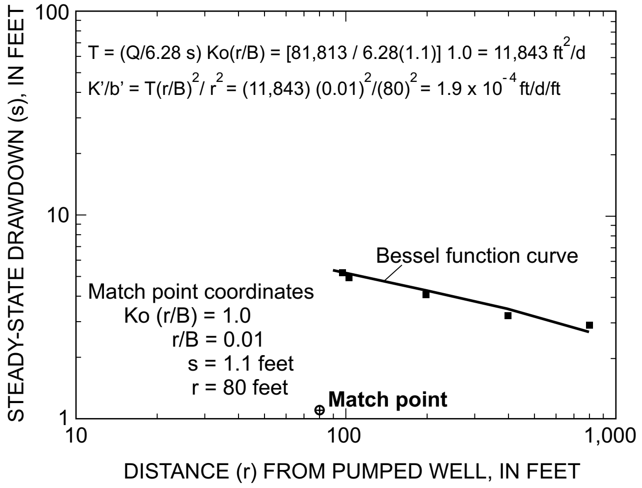


Figure 15. Analysis of data from the Lower Arcadia zone (PZ3) and Upper Floridan aquifer tests at the ROMP 9.5 site using the Hantush (1960) method.



EXPLANATION

Ko (r/B)	Modified Bessel function of the second kind and of zero order
K'/b'	Leakance coefficient of confining bed
T	Transmissivity in feet squared per day
Q	Pumpage in cubic feet per day

Figure 16. Analysis of data from the Lower Arcadia zone (PZ3) aquifer test at the ROMP 9.5 site using the Jacob (1946) method.

Neuman and Witherspoon (1972) Ratio Method

Neuman and Witherspoon (1972) developed a technique for determining the hydraulic diffusivity (K'/S'_s) of the confining unit by analyzing the hydraulic response measured in a confining unit to that in the aquifer at the same time and at the same radial distance from the pumped well. A ratio of the drawdowns in the confining unit to the pumped aquifer (s'/s) is plotted on logarithmic paper in relation to time (t) since pumping started (fig 17). The appropriate ratio method t_D type curve (fig.18) to which the ratio data are matched is determined, as shown in the figures, by using the estimates of aquifer transmissivity and storage coefficient. Results of the test analysis are shown in figure 17 and table 5.

Numerical Analysis of Aquifer Tests

Numerical simulation of the aquifer test data provided an alternative method for determining hydraulic properties of the intermediate aquifer system and the Upper Floridan aquifer. The USGS model, MODFLOW (McDonald and Harbaugh, 1988), was used in a radial mode to simulate the water-level changes in observation wells. MODFLOW uses a block-centered finite-difference approach to solve partial differential equations governing ground-water flow. Parameter estimation was facilitated by a parameter-estimation program (Halford, 1992). The parameter-estimation procedure uses a minimization of the sum of squared residuals (SS) between observed and simulated heads; the procedure is based on a modified Gauss-Newton method (Gill and others, 1981). The SS is defined as:

$$SS(x) = \sum_{k=1}^{n} [(h_{ks} - h_{km})]^2, \qquad (1)$$

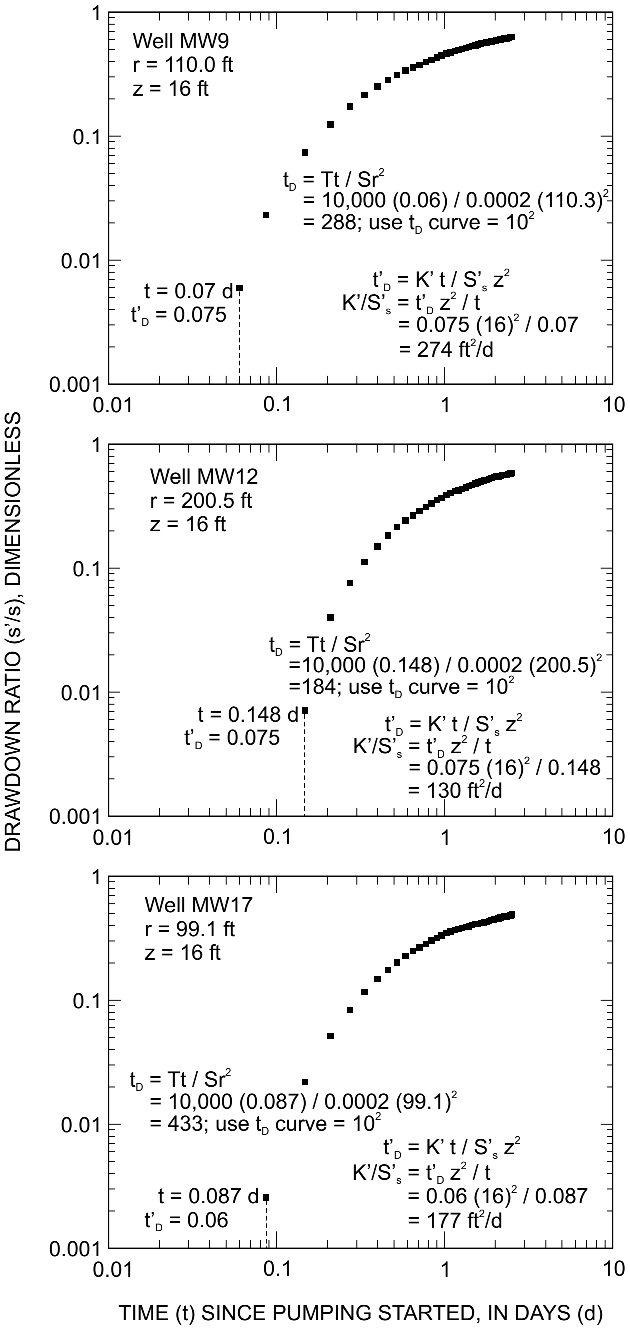
where

h_{ks} is the k^{th} simulated water level, in feet;
h_{km} is the k^{th} measured water level, in feet; and
n is the number of water-level comparisons.

Although the SS serves as the objective function (measure of model fit), the root-mean-square error (RMSE) is reported because it is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set. RMSE is related to the SS by

$$RMSE = (SS/n)^{0.5}, \qquad (2)$$

The hydrogeologic system underlying the ROMP 9.5 site is conceptualized as a multi-layered system containing discrete water producing zones separated by leaky confining units. Hydraulic properties of the hydrogeologic units at the ROMP 9.5 site were estimated from drawdown data by using the numerical model to match simulated water-level changes to measured water-level changes in observation wells, above, below, and within the pumped zones. Data from the two aquifer tests, the 2.77-day test of the Lower Arcadia zone (PZ3), and the 1-day test of the Upper Floridan aquifer were combined into one simulation routine to increase overall confidence in the optimization results. The system was allowed to recover 97 days after cessation of the initial 2.77-day pumping scenario to eliminate residual drawdown effects from the initial test. Hydraulic properties of the surficial aquifer system, the uppermost confining unit in the intermediate aquifer system, and the Upper Arcadia zone (PZ2) were specified and not estimated. These specified hydraulic property values were obtained from aquifer test results conducted at other sites. The model, however, was found to be insensitive to these parameters.



EXPLANATION

r	Distance to observation well from pumped well
Z	Distance from bottom of confining bed piezometer to top of aquifer
T	Transmissivity of aquifer
S	Storage coefficient of aquifer
t_D	Dimensionless time factor for aquifer (Tt / Sr^2)
t'_D	Dimensionless time factor for confining unit ($K't / S'_s z^2$)
K'/S'	Vertical hydraulic diffusivity of confining bed
s	Drawdown in aquifer
s'	Drawdown in confining bed
K'	Vertical hydraulic conductivity of confining beds
S'	Storage coefficient of confining beds

Figure 17. Analysis of data from the Lower Arcadia zone (PZ3) aquifer test at the ROMP 9.5 site using the Neuman-Witherspoon (1972) method.

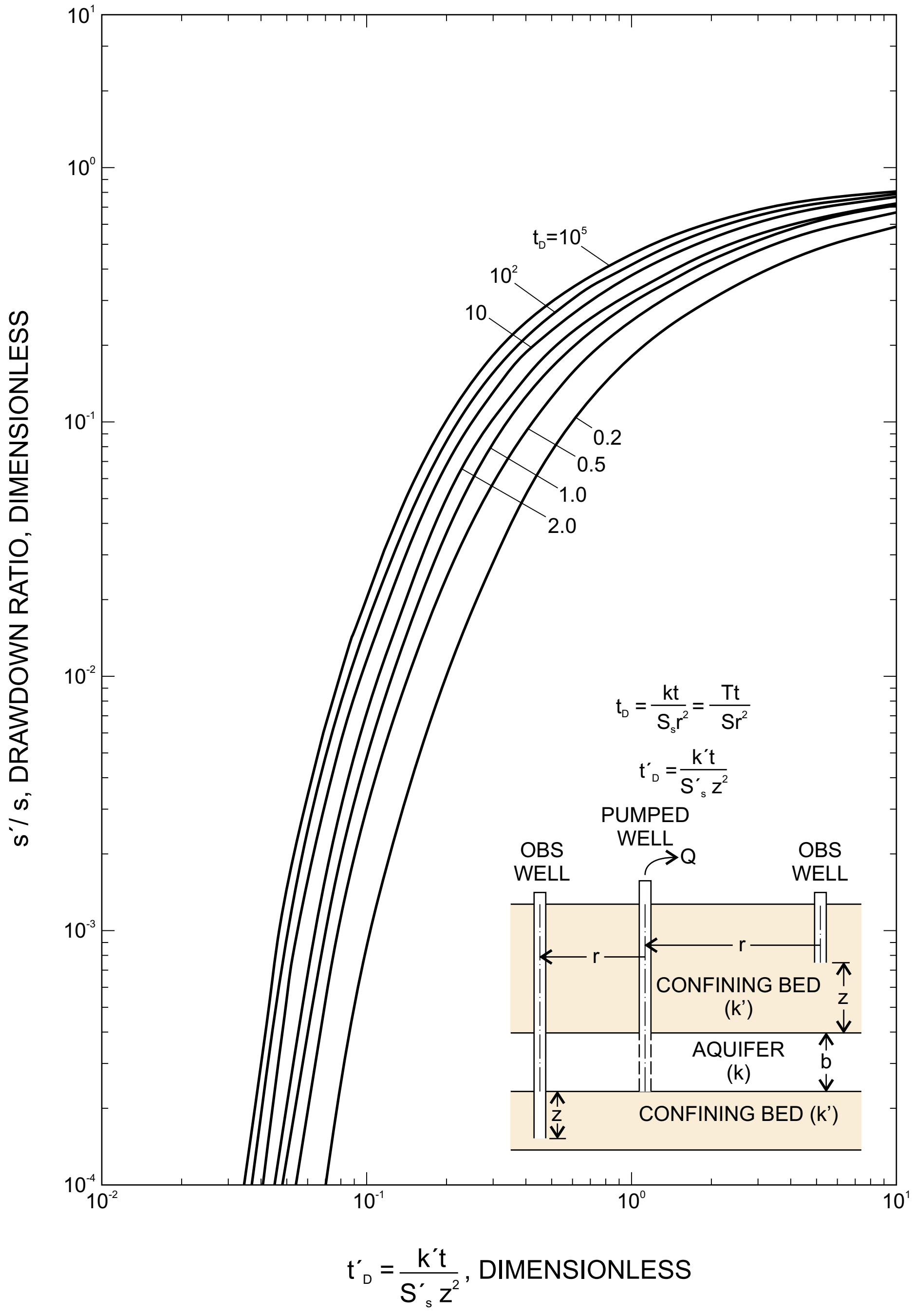


Figure 18. Type curves of s′/s versus t'_d (from Neuman and Witherspoon, 1972).

The numerical model was constructed using a radial-model grid with seven layers to represent the hydrogeologic framework underlying ROMP 9.5 (fig. 19). The model consisted of 28 variable-width rows in the vertical direction and 85 variable-width columns in the radial direction. The model dimensions represent 500,000 ft horizontally and 800 ft vertically. Figure 19 shows only the model grid for the first 1,000 ft from the pumping wells. The top, bottom, outer radial edge, and the cased interval above the simulated production wells were assigned no-flow boundaries. The radial grid spacing is accomplished beginning with a 0.5-ft wide ring at the production well, with successive rings being 1.187 times wider than the previous ring.

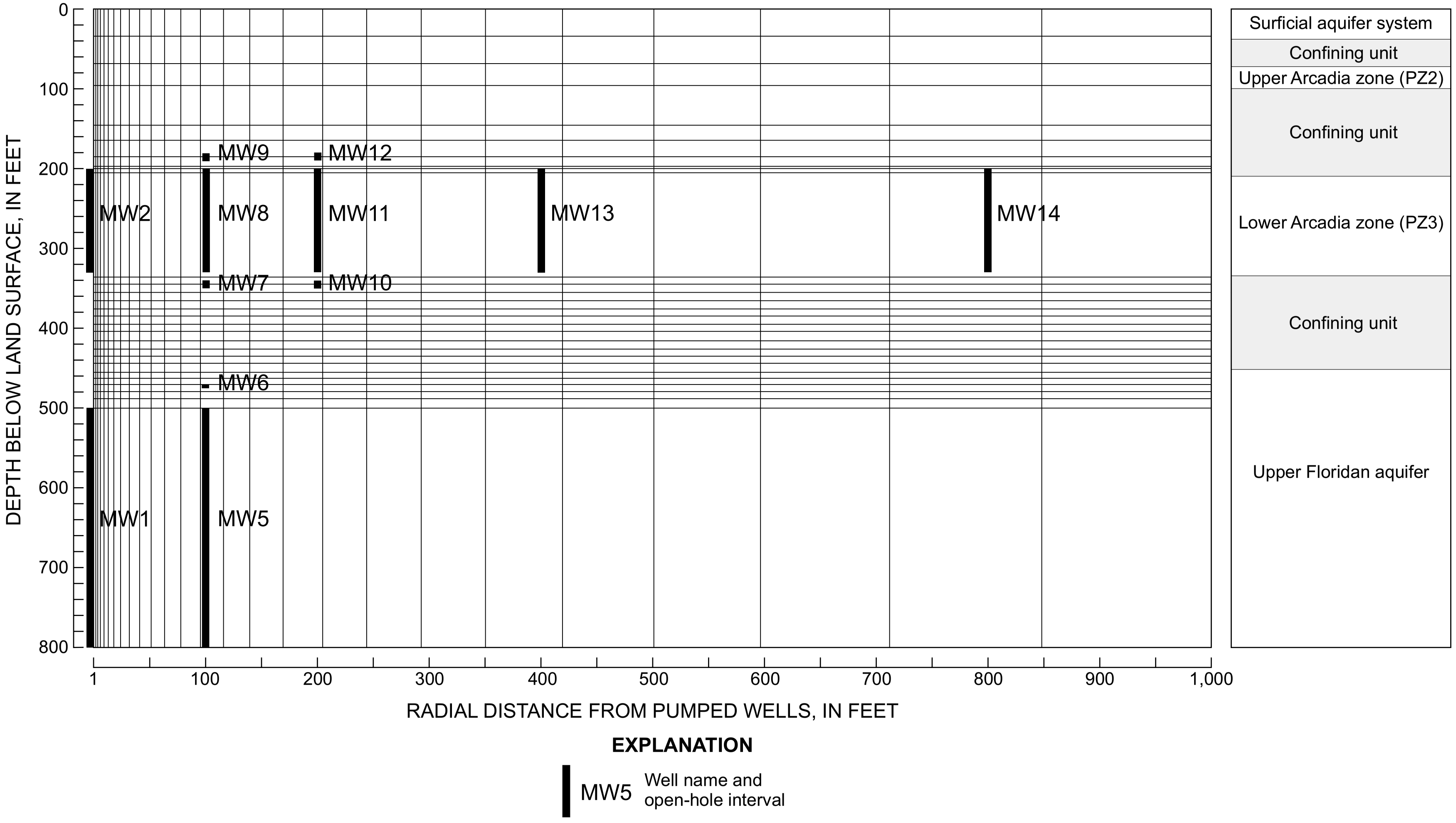


Figure 19. Radial-model grid used for the simulation of hydraulic properties of the aquifer systems at the ROMP 9.5 site (wells MW15, MW16, and MW17 are not shown, but are open to the same intervals as wells MW10, MW11, and MW12).

The measured and simulated (optimized) drawdown curves for PZ3 and the Upper Floridan aquifer tests are shown in figures 20 and 21. Overall, simulated water-level changes compare favorably with measured changes; however, model-simulated changes do not parallel the observed hydrographs during the late phases of the tests. As indicated previously, the measured water levels were influenced by additional stresses near the test area. Additionally, some degree of horizontal anisotropy exists in PZ3 as evidenced by the variation in measured and simulated drawdown curves for wells MW8 and MW16 (fig. 21). The RMSE for the simulation was 0.30 ft. Results of the numerical analysis are presented in table 6.

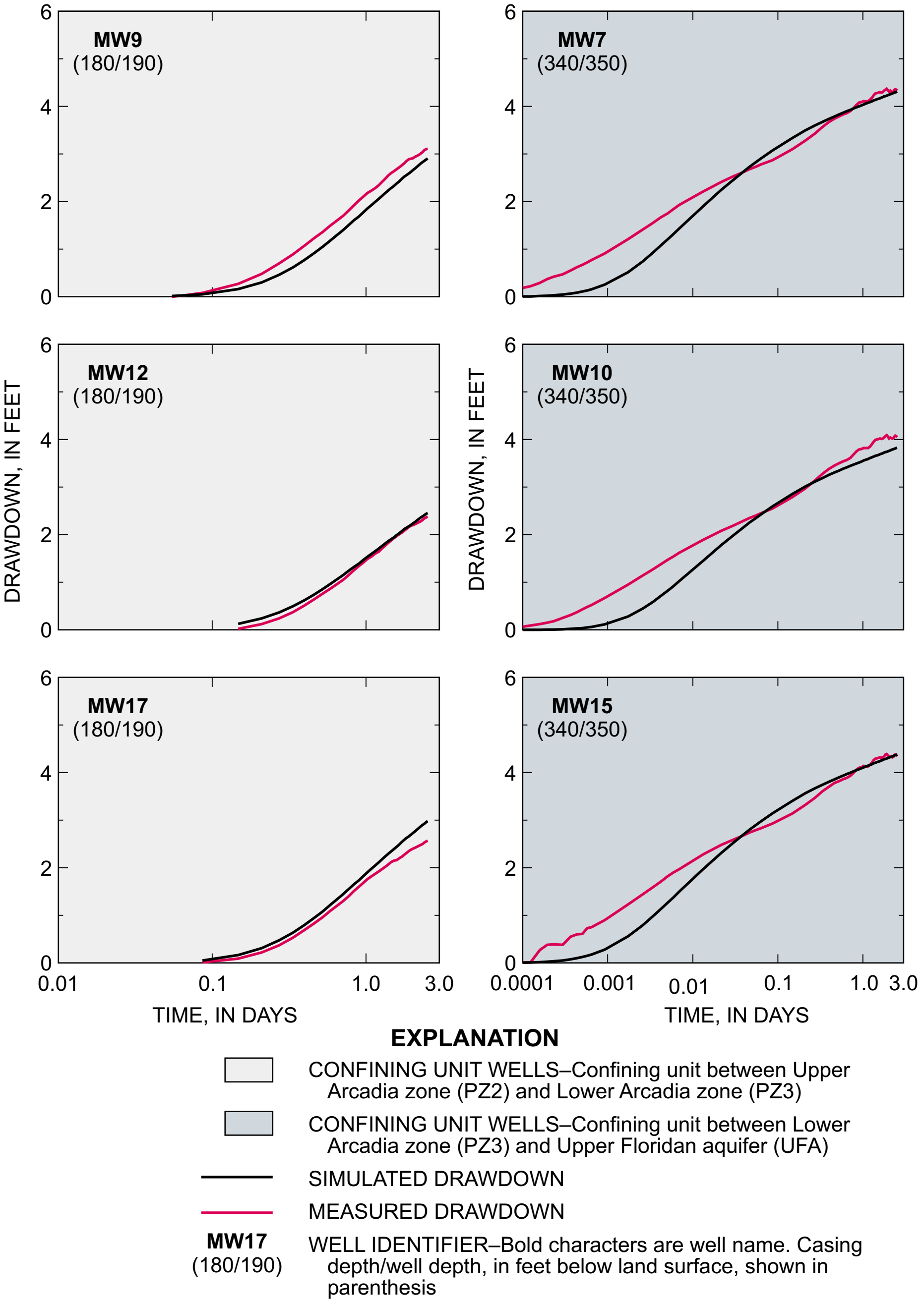


Figure 20. Simulated and measured drawdown in selected confining unit wells at the ROMP 9.5 site.

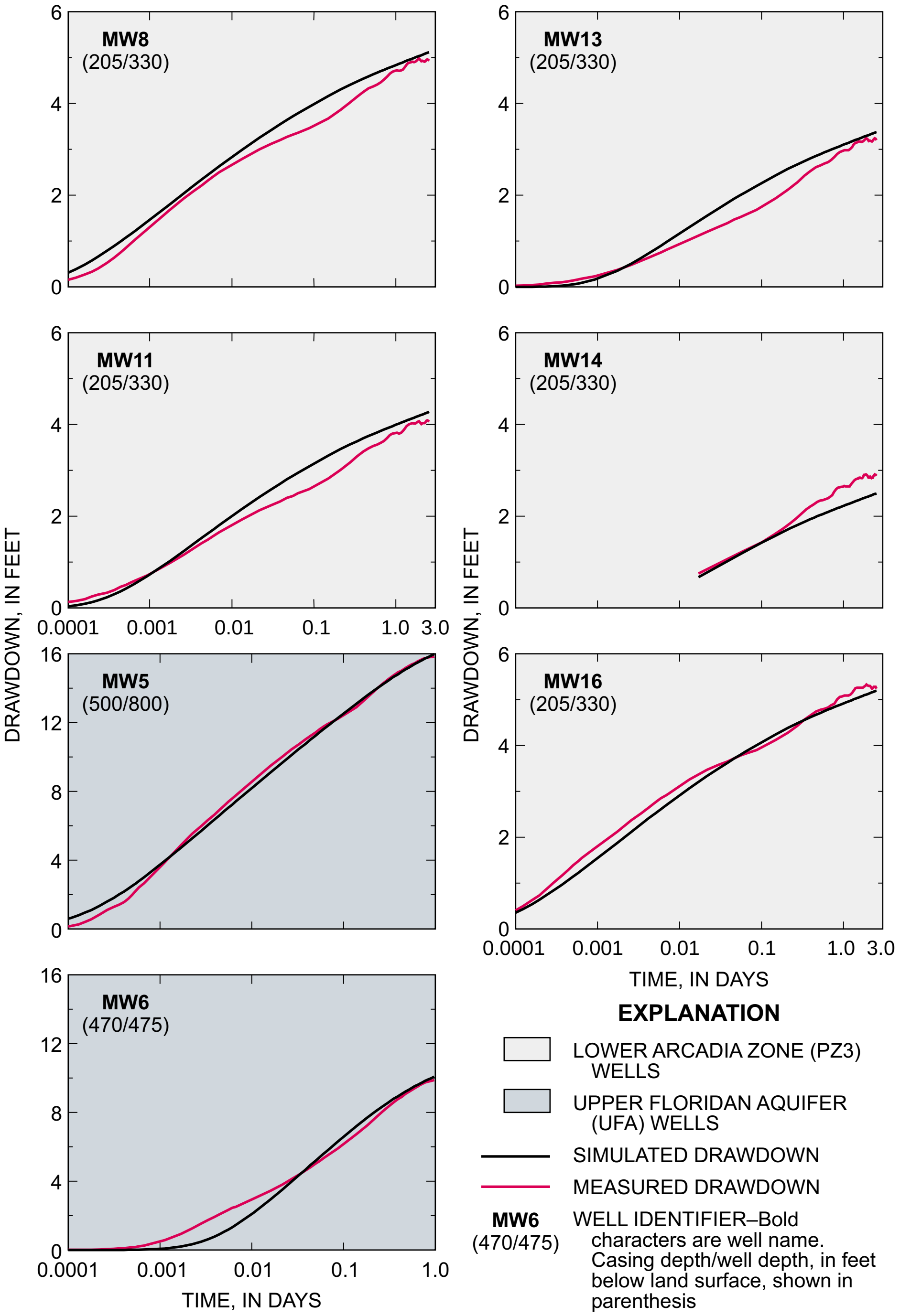


Figure 21. Simulated and measured drawdown in selected Lower Arcadia zone (PZ3) and Upper Floridan aquifer wells at the ROMP 9.5 site.

Table 6. Summary of aquifer test results for the ROMP 9.5 site using numerical analysis

[PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; CU, confining unit; b, thickness of unit; K_h, horizontal hydraulic conductivity; T, transmissivity; S, storage coefficient; S_s', specific storage; K_v, vertical hydraulic conductivity; L, leakance; ft, feet; ft/d, feet per day; ft^2/d, feet squared per day ;--, not determined]

Hydrogeologic unit	b (ft)	K_h (ft/d)	T (ft^2/d)	S	S_s' (1/ft)	K_v (ft/d)	L (ft/d/ft)
PZ3	124	80.2	9,945	2.0×10^{-4}	1.6×10^{-6}	5.09	--
UFA	346	17.9	6,193	2.8×10^{-4}	8.0×10^{-7}	0.38	--
CU between PZ2 and PZ3	111	0.5	56	3.0×10^{-3}	2.7×10^{-5}	0.01	9.0×10^{-5}
CU between PZ3 and UFA	124	1.2	149	1.1×10^{-4}	9.0×10^{-7}	0.04	3.2×10^{-4}

Limitations of Aquifer Test Analysis

Analysis of aquifer test data at the ROMP 9.5 site is difficult because the aquifer system is layered and has non-uniform permeability distribution. In addition, characterizing hydraulic properties is more difficult in heterogeneous, fractured rock than in homogenous, granular rock. At small scales, on the order of inches to feet, contrasts in horizontal hydraulic conductivity could result from the presence or absence of fractures. At larger scales, on the order of tens to hundreds of feet, contrasts in horizontal hydraulic conductivity values could arise from differences between zones of numerous, open, well-connected fractures rather than sparse, tight, poorly connected fractures in which wells may be completed. Consequently, hydraulic properties determined with quantitative analytical methods at a particular location in the aquifer may not be representative of properties at an adjacent location (P.A. Hsieh, USGS, written commun.,1992).

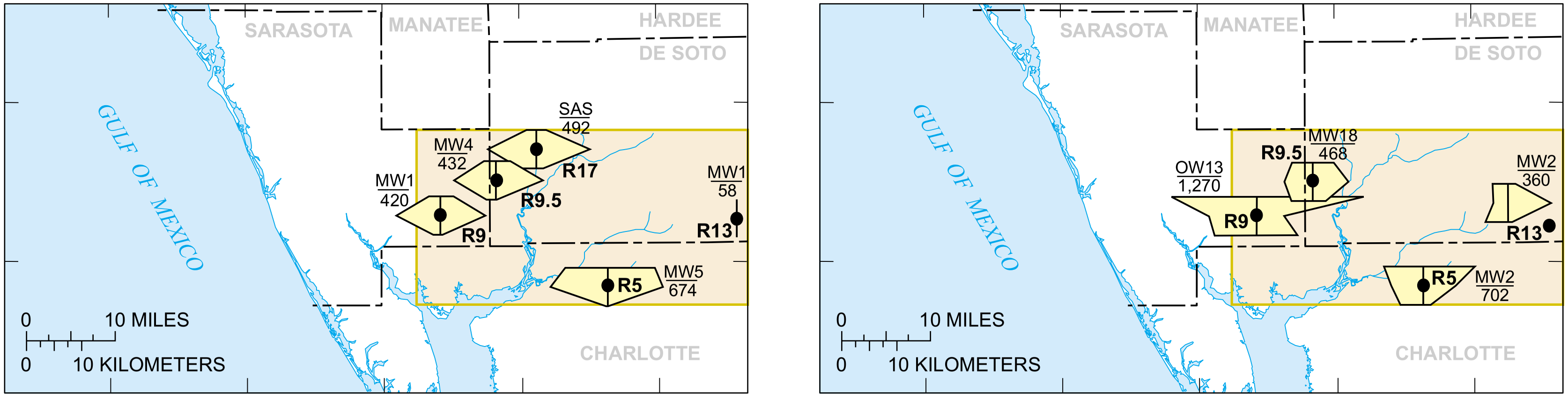
The hydraulic properties determined from numerical analysis of the ROMP 9.5 aquifer test data are considered more realistic for the heterogeneous and complex ground-water flow system at the ROMP 9.5 site in contrast to analytical methods that have inherent limitations. In contrast to analytical methods, numerical analysis is not constrained by multiple phases of discharge and recovery, length of testing, assumptions concerning storage within a confining unit, or the number of layers in the hydrogeologic system.

GEOCHEMISTRY OF AQUIFER SYSTEMS

Water-quality samples from discrete producing zones of the intermediate aquifer system at five of the ROMP sites (5, 9, 9.5, 13, and 17; fig. 1) were collected and analyzed for major ions and selected isotopes. Water from the surficial aquifer system and Upper Floridan aquifer also was collected at each site to understand the chemical and isotopic character of water potentially entering the system from above or below. The main objectives of the geochemical analysis were: (1) to evaluate mixing from underlying or overlying aquifers, (2) to better understand chemical reactions that influence ground-water composition, and (3) to estimate the age of the ground water. Isotopes of hydrogen, oxygen, and carbon were used to understand the sources and age of ground water. Geochemical modeling was used to evaluate mixing between aquifers and to quantify geochemical reactions.

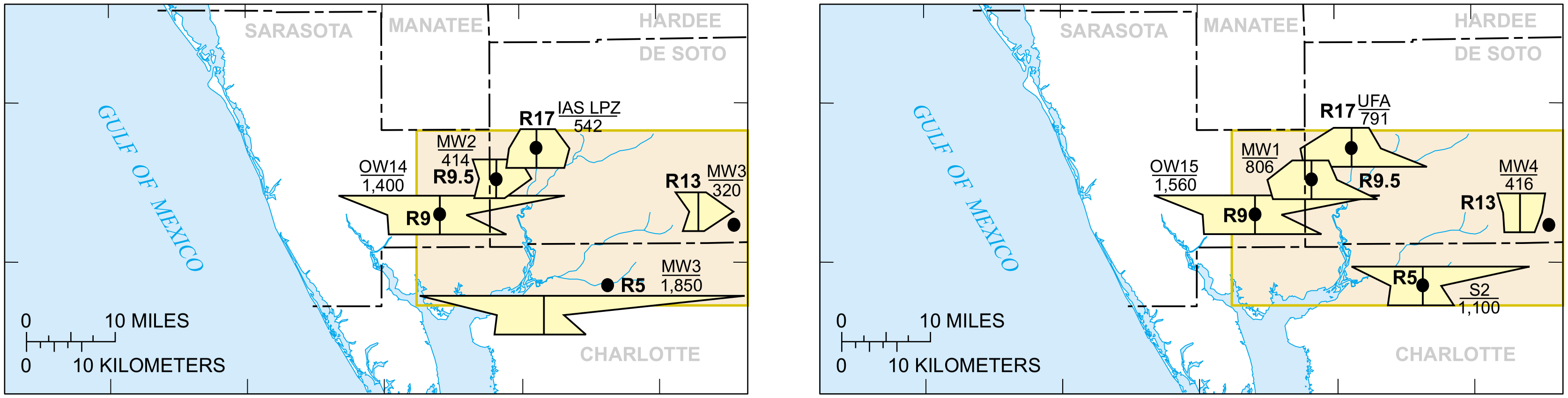
Chemical Composition of Ground Water

Water from the surficial aquifer system was a calcium bicarbonate type, except at the ROMP 13 site, which was a sodium bicarbonate type water (fig. 22a). Generally, surficial aquifer system water was more dilute than water from the intermediate aquifer system at all of the sites. Water from the ROMP 13 site was the most dilute, and thus, appears as a straight line in figure 22a. At each ROMP site, chloride, sulfate, magnesium, potassium, and strontium concentrations were lower in the surficial aquifer system than in the intermediate aquifer system (table 7). Alkalinity was higher in the surficial aquifer system than in the intermediate aquifer system at all sites except at the ROMP 13 site. The high calcium and bicarbonate concentrations are probably from dissolution of calcium carbonate in the surficial deposits, enhanced by high partial pressure of carbon dioxide (PCO_2) levels from the soil zone. Lower magnesium concentrations are due to the lack of dolomite in the surficial deposits.



(a) Surficial aquifer system

(b) Upper Arcadia zone (PZ2)



Base from SWFWMD digital data, 1:250,000, 1992
Albers Equal-Area Conic projection
Standard Parallels and central meridian

(c) Lower Arcadia zone (PZ3)

(d) Upper Floridan aquifer

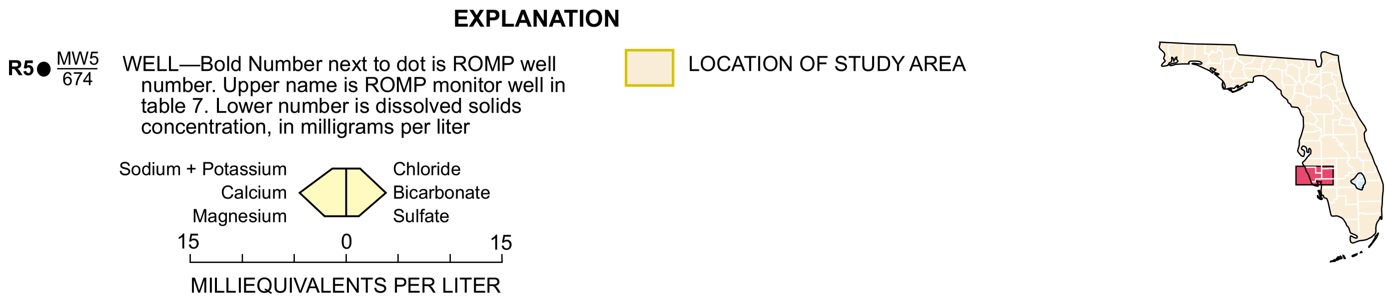


Figure 22. Dissolved-solids concentrations and Stiff diagrams showing chemical composition of water from wells at the ROMP 5, 9, 9.5, 13, and 17 sites that tap the (a) surficial aquifer system, (b) Upper Arcadia zone (PZ2), (c) Lower Arcadia zone (PZ3), and (d) Upper Floridan aquifer.

Water from the intermediate aquifer system had a wide range in chemical composition, but generally fit into two categories. At the sites furthest inland (ROMP 9.5, 13, and 17), water from PZ2 and/or PZ3 was a mixed ion or mixed cation-bicarbonate type (fig. 22b and 22c). Sites closer to the coast (ROMP 9 and 5) had a sodium-chloride or mixed cation-chloride type water. Water within the same permeable zone of the intermediate aquifer system did not have a distinct chemical composition throughout the study area. For the Upper Arcadia zone (PZ2), lowest chloride and sulfate concentrations were at the ROMP 13 site, and highest chloride and sulfate concentrations were at the ROMP 9 site (table 7). Similarly, lowest chloride and sulfate concentrations for PZ3 were at the ROMP 13 site. The highest chloride concentration in PZ3 was at the ROMP 5 site, and the highest sulfate concentration was at the ROMP 9 site (table 7). Water from both PZ2 and PZ3 at the ROMP 9 site and from PZ3 at the ROMP 5 site had chloride concentrations greater than 250 mg/L (secondary drinking water standard; Florida Department of Environmental Protection, 1994). Water from PZ3 at the ROMP 9 site was the only intermediate aquifer system site with a sulfate concentration greater than the secondary drinking water standard of 250 mg/L.

At four of the sites (ROMP 5, 9, 9.5, and 13), wells completed in both PZ2 and PZ3 were sampled. Very few consistent trends were apparent in comparing the composition of water between permeable zones at all sites. Chloride concentrations were about 300 percent higher in PZ3 at the ROMP 5 site than they were in PZ2 (800 mg/L in PZ3 and 210 mg/L in PZ2), but at the other three sites, chloride concentrations were less than 10 percent higher in PZ3 than in PZ2. Sulfate concentrations were higher in PZ3 compared to PZ2 at three sites (ROMP 5, 9, and 13), but at the ROMP 9.5 site, sulfate was lower in concentration in PZ3 compared to PZ2 (43 mg/L in PZ3 and 73 mg/L in PZ2). At the ROMP 9 and 13 sites, the chemical character of water in both permeable zones was similar (fig. 22), which may indicate leakage between these zones.

The chemical composition of water from the Upper Floridan aquifer was variable at the five sites (fig. 22d, table 7). None of the Upper Floridan aquifer waters had a dominant cation (no cation greater than

Table 7. Chemical and isotopic data for water collected from wells at the ROMP 5, 9, 9.5, 13, and 17 sites during 1996 and 1997

[^{0}C, degrees Celsius; mS/cm, microsiemens per centimeter at 25^{0}C; mg/L, milligrams per liter; mg/L, micrograms per liter; δD, delta deuterium; permil, parts per thousand; pc/L, picocuries per liter; δ^{13}C, delta carbon-13; ^{14}C, carbon-14; DIC, dissolved inorganic carbon; PMC, Percent Modern Carbon (normalized); δ^{18}O, delta oxygen-18; ROMP, Regional Observation and Monitor-Well Program; MW, monitor well; OW, observation well; SAS, surficial aquifer system; IAS, intermediate aquifer system; LPZ, lower permeable zone; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; SWNN, Suwannee; <, less than; --, no data]

Well name	Station identification number	Depth of casing/total depth below land surface (feet)	Principal hydrogeologic unit	Sample collection date	Temperature (^{0}C)	Specific conductance (µS/cm)	pH (standard units)	Alkalinity (mg/L as $CaCO_3$)
ROMP 5 MW5	265644081483305	5/85	SAS	9-25-96	26.2	1,160	7.03	314
ROMP 5 MW2	265644081483304	130/230	PZ2	9-24-96	26.6	1,140	7.15	187
ROMP 5 MW3	265644081483303	450/600	PZ3	9-24-96	30.6	3,040	7.66	105
ROMP 5 MW4	265643081483301	720/970	UFA	9-25-96	28.5	1,870	7.85	105
ROMP 9 MW1	270432082085707	7/27	SAS	8-26-96	26.2	675	7.08	256
ROMP 9 OW13	270432082085704	122/165	PZ2	8-27-96	26.8	2,070	7.51	153
ROMP 9 OW14	270432082085703	190/320	PZ3	8-27-96	24.6	2,260	7.51	147
ROMP 9 OW15	270432082085702	545/860	UFA	8-26-96	27.1	2,450	7.18	148
ROMP 9.5 MW4	270737082025104	2/8	SAS	8-20-97	25.8	703	6.83	266
ROMP 9.5 MW18	270737082025001	61/77	PZ2	8-20-97	28.1	800	7.73	209
ROMP 9.5 MW2	270737082025102	205/331	PZ3	8-19-97	27.1	749	7.69	202
ROMP 9.5 MW1	270737082025101	505/801	UFA	8-19-97	26.4	1,140	7.55	148
ROMP 13 MW1	270418081365805	7/22	SAS	9-26-96	26.9	74	5.53	17
ROMP 13 MW2	270418081365804	282/417	PZ2	9-26-96	26.4	587	7.61	246
ROMP 13 MW3	270418081365803	510/592	PZ3	9-26-96	26.8	544	8.05	200
ROMP 13 MW4	270418081365802	671/786	UFA	9-27-96	26.0	716	8.24	123
ROMP 17 SAS	271026081583605	8/18	SAS	8-28-96	25.3	751	7.04	304
ROMP 17 IAS LPZ	271026081583604	200/240	PZ3	10-2-96	25.7	853	7.63	185
ROMP 17 UFA	271026081583603	395/470	UFA	8-28-96	26.3	973	7.40	225
[1]ROMP 17 SWNN	271026081583602	620/670	UFA	5-27-92	27.7	1,148	7.17	157

[1] Data from Sacks and Tihansky (1996).

Table 7. Chemical and isotopic data for water collected from wells at the ROMP 5, 9, 9.5, 13, and 17 sites during 1996 and 1997 (Continued)

[0C, degrees Celsius; mS/cm, microsiemens per centimeter at 250C; mg/L, milligrams per liter; mg/L, micrograms per liter; dD, delta deuterium; permil, parts per thousand; pc/L, picocurries per liter; d13C, delta carbon-13; 14C, carbon-14; DIC, dissolved inorganic carbon; PMC, Percent Modern Carbon (normalized); d18O, delta oxygen-18; ROMP, Regional Observation and Monitor-Well Program; MW, monitor well; OW, observation well; SAS, surficial aquifer system; IAS, intermediate aquifer system; LPZ, lower permeable zone; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; SWNN, Suwannee; <, less than; --, no data]

Well name	Principal hydro-geologic unit	Hardness (mg/L as CaO_3)	Dis-solved solids (mg/L)	Calcium, dissolved (mg/L as Ca)	Mag-nesium, dissolved (mg/L as Mg)	Sodium, dissloved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate dissolved (mg/L as SO_4)	Sulfide, dis-solved (mg/L as S)	[1]Excess sulfate (mg/L as SO_4)
ROMP 5 MW5	SAS	330	674	130	2	110	0.9	190	2	--	-26
ROMP 5 MW2	PZ2	310	702	72	31	100	3	210	43	--	12
ROMP 5 MW3	PZ3	600	1,850	110	70	320	12	800	220	--	105
ROMP 5 MW4	UFA	410	1,100	73	48	180	9.3	430	170	--	108
ROMP 9 MW1	SAS	290	420	100	10	29	1.1	53	12	--	3
ROMP 9 OW13	PZ2	530	1,270	110	59	220	7.7	430	220	--	158
ROMP 9 OW14	PZ3	570	1,400	110	67	250	9	460	280	--	213
ROMP 9 OW15	UFA	620	1,560	120	71	260	8.2	500	360	--	288
ROMP 9.5 MW4	SAS	290	432	95	13	30	1.5	58	5	<0.01	-5
ROMP 9.5 MW18	PZ2	280	468	64	29	52	2.6	86	73	1.3	59
ROMP 9.5 MW2	PZ3	230	414	40	31	61	2.6	93	43	2.4	28
ROMP 9.5 MW1	UFA	490	806	104	53	47	4.4	69	359	1.5	348
ROMP 13 MW1	SAS	15	58	4	1	8	0.5	7	2	--	0
ROMP 13 MW2	PZ2	220	360	33	31	36	6.8	31	24	--	18
ROMP 13 MW3	PZ3	150	320	20	21	56	4.6	32	33	--	27
ROMP 13 MW4	UFA	200	416	39	22	58	3	100	78	--	62
ROMP 17 SAS	SAS	370	492	110	22	25	0.9	40	38	--	31
ROMP 17 IAS LPZ	PZ3	340	542	63	42	40	3.9	74	150	--	138
ROMP 17 UFA	UFA	370	628	64	48	65	4.9	110	120	--	103
ROMP 17 SWNN	UFA	--	791	110	58	38	4.9	64	380	2.3	370

[1]Negative value indicates SO_4 is depleted in sample, relative to conservative mixing.

50 percent of the total in milliequivalent per liter (meq/L)). The dominant anion was chloride at the ROMP 5 and 9 sites. Sulfate was the dominant anion at the ROMP 9.5 and 17 sites, and anions were mixed at the ROMP 13 site. Similar to the Lower Arcadia zone (PZ3) of the intermediate aquifer system, chloride concentrations were greater than 250 mg/L for the sites closest to the coast (ROMP 5 and 9). Sulfate concentrations were greater than 250 mg/L at the ROMP 9, 9.5, and 17 sites. At some sites, chloride concentrations were higher in the Upper Floridan aquifer than in PZ3 (ROMP 9 and ROMP 13), but at other sites chloride concentrations were lower in the Upper Floridan aquifer compared to PZ3 (ROMP 5, 9.5, and 17 sites) (table 7). The chemical character of water between PZ3 and the Upper Floridan aquifer was very similar at some sites (ROMP 5 and 9), but at other sites, the waters were distinctly different (ROMP 9.5) (figs. 22c and 22d). Similarity in the chemical composition of waters from both aquifers may indicate a good hydraulic connection between aquifers.

Sources of elevated sulfate concentrations in the Upper Floridan aquifer are from dissolution of gypsum in deep parts of the Upper Floridan aquifer and from mixing with saline water (Sacks and Tihansky, 1996). Sulfate from gypsum dissolution can be distinguished from that of seawater mixing by computing the amount of excess sulfate relative to conservative mixing. Calculations were made assuming mixing between a dilute upgradient water (surficial aquifer system water from the ROMP 13 site) and modern seawater (Hem, 1985). The fraction of seawater (x) was computed using chloride as the conservative tracer:

$$x = (Cl_{gw} - Cl_{ug})/(Cl_{sw} - Cl_{ug}), \qquad (3)$$

where Cl is the chloride concentration of the sampled ground water (gw), the upgradient ground water (ug), and the seawater (sw). An expected sulfate concentration was computed based on conservative mixing of the two end-member waters. The difference between the sulfate concentration (SO_4) in the sampled ground

Table 7. Chemical and isotopic data for water collected from wells at the ROMP 5, 9, 9.5, 13, and 17 sites during 1996 and 1997 (Continued)

[^{0}C, degrees Celsius; mS/cm, microsiemens per centimeter at 25^{0}C; mg/L, milligrams per liter; mg/L, micrograms per liter; δD, delta deuterium; permil, parts per thousand; pc/L, picocurries per liter; δ^{13}C, delta carbon-13; ^{14}C, carbon-14; DIC, dissolved inorganic carbon; PMC, Percent Modern Carbon (normalized); δ^{18}O, delta oxygen-18; ROMP, Regional Observation and Monitor-Well Program; MW, monitor well; OW, observation well; SAS, surficial aquifer system; IAS, intermediate aquifer system; LPZ, lower permeable zone; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; SWNN, Suwannee; <, less than; --, no data]

Well name	Principal hydro-geologic unit	Strontium, dissolved (µg/L as Sr)	NO_2+NO_3 dissolved (mg/L as N)	Phos-phorus, dissolved (mg/L as P)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	δD (per mil)	Tritium (TU)	δ^{13}C of DIC (per mil)	^{14}C of DIC (as PMC)	δ^{18}O (per mil)
ROMP 5 MW5	SAS	580	<0.02	5.3	0.1	11	-7.8	10	-10	62.4	-1.86
ROMP 5 MW2	PZ2	1,900	<0.02	7.6	1.2	55	-1.5	<0.3	-7.8	2.03	-1.51
ROMP 5 MW3	PZ3	29,310	<0.02	<0.02	0.8	17	-3.3	<0.3	-5.4	2.67	-1.54
ROMP 5 MW4	UFA	26,000	<0.02	<0.02	0.9	18	-3.4	<0.3	-5.75	5.23	-1.55
ROMP 9 MW1	SAS	600	<0.02	<0.02	0.2	12	-12.1	9.9	-17.2	83.4	-2.48
ROMP 9 OW13	PZ2	14,000	<0.02	<0.02	1.2	17	-4.0	<0.3	-9.8	1.83	-1.41
ROMP 9 OW14	PZ3	20,000	<0.02	<0.02	1.4	18	-3.7	<0.3	-4.4	0.89	-1.27
ROMP 9 OW15	UFA	25,000	<0.02	<0.02	1.6	22	-4.4	<0.3	-3.2	1.8	-1.25
ROMP 9.5 MW4	SAS	310	<0.02	0.16	0.6	17	-2.8	10.56	-11.4	45.58	-0.91
ROMP 9.5 MW18	PZ2	1,700	<0.02	0.08	0.6	22	-3.5	--	-9.68	10.93	-1.51
ROMP 9.5 MW2	PZ3	5,100	<0.02	0.06	0.1	20	-4.5	--	-5.39	2.24	-1.76
ROMP 9.5 MW1	UFA	11,380	<0.02	0.06	2.0	27	-7.6	--	-4.6	0.83	-1.89
ROMP 13 MW1	SAS	30	<0.02	0.74	0.2	7	-13.8	11	-17	112	-2.95
ROMP 13 MW2	PZ2	8,300	<0.02	<0.02	2.1	47	-6.8	<0.3	-4.7	0.41	-1.89
ROMP 13 MW3	PZ3	8,600	<0.02	<0.02	1.8	24	-5.5	<0.3	-6.6	0.55	-1.67
ROMP 13 MW4	UFA	13,000	<0.02	<0.02	0.4	16	-1.6	<0.3	-5.76	0.98	-1.18
ROMP 17 SAS	SAS	590	<0.02	0.63	1.0	25	-12.9	11	-13.1	70.3	-2.60
ROMP 17 IAS LPZ	PZ3	9,300	<0.02	<0.02	2.1	25	-6.5	<0.3	-6.4	1.37	-2.08
ROMP 17 UFA	UFA	10,000	<0.02	<0.02	1.8	23	-6.7	<0.3	-6	0.84	-2.00
ROMP 17 SWNN	UFA	16,000	<.002	--	2.0	24	-8.0	--	-5.8	--	-2.05

water and the expected concentration, is the “excess sulfate” concentration (SO_{4ex}):

$$SO_{4ex} = SO_{4gw} - [SO_{4sw}\ x + SO_{4ug}\ (1-x)]. \qquad (4)$$

At each ROMP site, water from the Upper Floridan aquifer had higher excess sulfate concentrations than water from the intermediate aquifer system and surficial aquifer system (table 7). The excess sulfate concentration is because gypsum, the mineral source of sulfate, occurs in rocks in the Upper Floridan aquifer. Excess sulfate concentration was lowest in the Upper Floridan aquifer at the ROMP 13 site, probably because heads in the Upper Floridan decrease with depth at this site, which limits upward movement of sulfate-rich water that dissolved gypsum deeper in the aquifer. In contrast, excess sulfate concentrations were highest at the ROMP 9, 9.5, and 17 sites (greater than 250 mg/L), and these sites are in an area where upward flow in the Upper Floridan aquifer is enhanced by discharging conditions near the Peace River.

Vertical Profiles of Chloride and Sulfate

Profiles of sulfate and chloride concentrations in the intermediate aquifer system and the upper part of the Upper Floridan aquifer are illustrated in figure 23. Differences in trends in sulfate and chloride profiles are indicators of differences in mixing of recharge water, saline water, and sulfate-rich water from the Upper Floridan aquifer. Differences in the profiles illustrate the complexity of delineating water sources in the intermediate aquifer system. Chloride and sulfate concentrations during drilling typically correspond to concentrations in the monitor wells finished to the same zones. The only major discrepancy was that sulfate concentrations were much lower during drilling in the intermediate aquifer system at the ROMP 17 site than when the wells were sampled. This site was drilled about 5 years earlier than the other sites, and perhaps sampling methods during drilling were problematic. Alternatively, water quality may have degraded over time, resulting in higher sulfate concentrations in the intermediate aquifer system.

Profiles at the ROMP 13, 9.5, and 17 sites are characterized by relatively low concentrations of

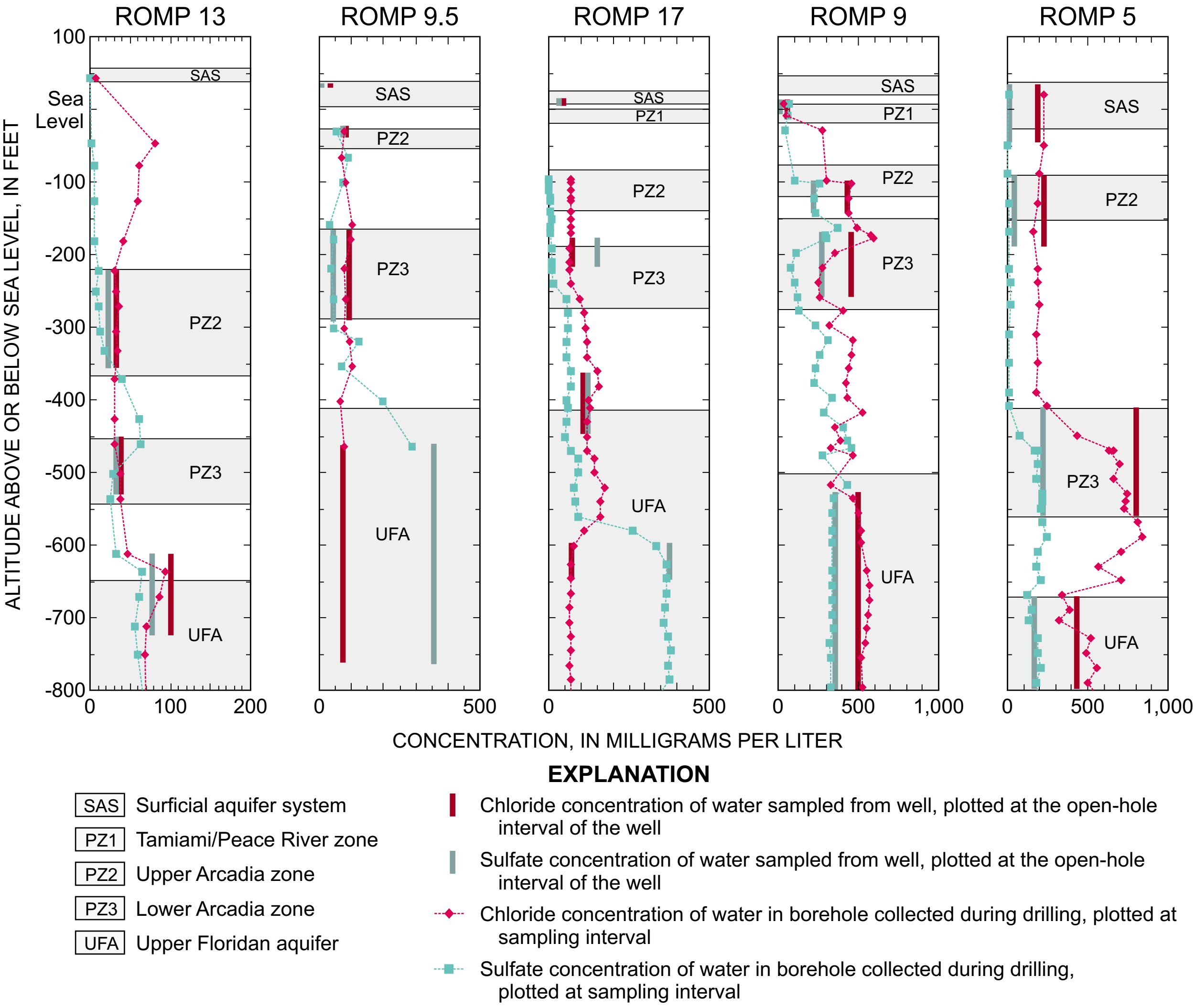


Figure 23. Concentrations of chloride and sulfate in samples collected during drilling of the exploratory boreholes and during sampling of wells at the ROMP 13, 9.5, 17, 9, and 5 sites.

chloride. At the ROMP 13 site, sulfate and chloride concentrations are generally less that 100 mg/L in both the intermediate aquifer system and upper part of the Upper Floridan aquifer (fig. 23). Chloride concentrations in the intermediate aquifer system were generally about 30 mg/L, except for higher concentrations in the upper confining unit (between about 60 and 80 mg/L). Chloride concentrations in the Upper Floridan aquifer were slightly higher (typically between 50 and 100 mg/L) than in the intermediate aquifer system. Sulfate concentrations were lowest in the Upper Arcadia zone (PZ2) and increased slightly in the Lower Arcadia zone (PZ3), as well as in the Upper Floridan aquifer. Excess sulfate concentrations were low in both PZ2 and PZ3 (table 7).

At the ROMP 9.5 site, chloride concentrations were relatively low and uniform throughout the intermediate aquifer system (PZ2 and PZ3) and upper part of the Upper Floridan aquifer (below or about 100 mg/L), but sulfate had a wider range in concentration (fig. 23). Sulfate concentrations were about twice as high in PZ2 and the middle confining unit (about 70 mg/L) than in PZ3 (about 40 mg/L); sulfate concentrations increased in the lower confining unit and were the highest in the Upper Floridan aquifer (about seven times higher than in PZ3). Similarly, excess sulfate concentrations were much higher in the Upper Floridan aquifer than in PZ3 (table 7), suggesting less of a hydraulic connection between these hydrogeologic units.

Although chloride concentrations were relatively low at the ROMP 17 site, concentrations were somewhat elevated in the lower confining unit of the intermediate aquifer system and in the upper part of the Upper Floridan aquifer (about 130 mg/L). Deeper than about 600 ft below sea level, chloride concentrations in the Upper Floridan aquifer decreased substantially (to about 70 mg/L), and sulfate concentrations increased to greater than 350 mg/L (fig. 23). Excess sulfate concentrations in PZ3 at the ROMP 17 site were higher than in PZ3 at the ROMP 9.5 site (table 7) which may indicate a greater hydraulic connection between the Upper Floridan aquifer and PZ3 at the ROMP 17 site compared to the ROMP 9.5 site.

In contrast, chloride concentrations were much higher in the profiles at the ROMP 9 and 5 sites than at the other three sites (fig. 23). At the ROMP 9 site, chloride concentrations were almost always greater than 250 mg/L in the intermediate aquifer system and Upper Floridan aquifer. In the intermediate aquifer system, sulfate and chloride concentrations generally increased and decreased the same, with both concentrations decreasing slightly in the middle intervals of PZ3. In the Upper Floridan aquifer, chloride and sulfate concentrations were fairly uniform to 800 ft below sea level. Excess sulfate concentrations were highest in the Upper Floridan aquifer, but also were elevated in PZ2 and PZ3 (table 7), indicating that a hydraulic connection exists between the Upper Floridan aquifer and both permeable zones of the intermediate aquifer system at the ROMP 9 site.

At the ROMP 5 site, chloride concentrations were greater than 150 mg/L throughout the profile, but were substantially higher in PZ3 (greater than 600 mg/L) than in PZ2 and the surficial aquifer system (about 200 mg/L). In the upper part of the Upper Floridan aquifer, chloride concentrations decreased to about half that in PZ3. Sulfate concentrations were low in PZ2 and the middle confining unit (less than 20 mg/L), but were consistently higher by about an order of magnitude (about 200 mg/L) in PZ3, the lower confining unit, and the Upper Floridan aquifer (fig. 23). This increase in sulfate concentration with depth is related to seawater mixing. Excess sulfate concentrations in PZ3 and the Upper Floridan aquifer were nearly the same (105 and 108 mg/L, respectively, table 7); however, excess sulfate concentration in PZ2 was much lower, indicating that PZ2 may be more isolated hydraulically from PZ3 than PZ3 is to the Upper Floridan aquifer. The isolation of PZ2 from PZ3 is consistent with the estimated hydraulic connection from aquifer tests, which indicated little hydraulic connection between PZ2 and PZ3. Excess sulfate is lower throughout the ROMP 5 profile than in the ROMP 9 profile (table 7), which illustrates the importance of seawater mixing on sulfate concentrations at the ROMP 5 site compared to the ROMP 9 site.

Saturation State of Ground Water

Information on the saturation state of water with respect to mineral phases can help identify probable reactions considered for geochemical modeling, which is discussed later in the report. Saturation indexes were computed using WATEQF (integrated as part of geochemical mass-balance model NETPATH; Plummer and others, 1994) and WATEQ4F (Ball and Nordstrom, 1991). The saturation index (SI) is a measure of the departure from equilibrium of the water with respect to mineral phases. An SI value of zero, with an associated range of uncertainty, indicates the water is in equilibrium or saturated with respect to the mineral phase, a value less than zero indicates undersaturation (mineral dissolution is possible), and a value greater than zero indicates supersaturation (mineral precipitation is possible).

Ground water in the intermediate aquifer system and Upper Floridan aquifer is near saturation or supersaturated with respect to calcite (saturation index (SI) between -0.17 and 0.5; table 8). Saturation for calcite is assumed to be between -0.15 and 0.15, based on uncertainties in chemical analyses and pH determinations. Most waters from the surficial aquifer system were close to saturation with respect to calcite (SI between -0.16 and 0.20), except for water from the ROMP 13 site, which was highly undersaturated (SI of -3.80).

For dolomite, there is an uncertainty in the exact value of the equilibrium reaction constant (K_r), and so the SI for both "crystalline” dolomite ($K_r = -17.09$) and “disordered” dolomite ($K_r = -16.54$) are reported here (Nordstrom and others, 1990). Previous investigators concluded that disordered dolomite is the form dissolving in the Upper Floridan aquifer (Hsu, 1963; Hanshaw and others, 1971; Plummer, 1977). Waters from the intermediate aquifer system and Upper Floridan aquifer were typically supersaturated with respect to crystalline dolomite (SI range between -0.34 to 1.11; table 8; saturation for dolomite is assumed to be between -0.30 and 0.30). However, most waters from the intermediate aquifer system and Upper Floridan aquifer were near saturation or undersaturated with respect to disordered dolomite (SI range between -0.88 and 0.57). Water from the surficial aquifer system was undersaturated for both crystalline and disordered dolomite (table 8).

Table 8. Saturation state of ground water at the ROMP 5, 9, 9.5, 13, and 17 sites with respect to mineral phases and calculated partial pressure of carbon dioxide

[PCO_2, partial pressure of carbon dioxide; SAS, surficial aquifer system; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer]

Well name	Principal hydrogeologic unit	Saturation index					Log PCO_2
		Calcite	Crystalline dolomite1[1]	Disordered dolomite [2]	Gypsum	Celestite	
ROMP 5 MW5	SAS	0.20	-1.00	-1.55	-3.05	-3.68	-1.48
ROMP 5 MW2	PZ2	-0.17	-0.34	-0.88	-2.05	-1.90	-1.83
ROMP 5 MW3	PZ3	0.22	0.64	0.10	-1.38	-0.23	-2.59
ROMP 5 S2	UFA	0.26	0.72	0.17	-1.55	-0.28	-2.78
ROMP 9 MW1	SAS	0.10	-0.44	-0.99	-2.37	-2.90	-1.60
ROMP 9 OW13	PZ2	0.22	0.53	-0.02	-1.33	-0.49	-2.28
ROMP 9 OW14	PZ3	0.15	0.42	-0.12	-1.24	-0.26	-2.32
ROMP 9 OW15	UFA	-0.13	-0.12	-0.66	-1.12	-0.09	-1.97
ROMP 9.5 MW4	SAS	-0.16	-0.82	-1.36	-2.80	-3.57	-1.33
ROMP 9.5 MW18	PZ2	0.46	0.96	0.42	-1.84	-1.69	-2.34
ROMP 9.5 MW2	PZ3	0.21	0.68	0.13	-2.24	-1.42	-2.32
ROMP 9.5 MW1	UFA	0.22	0.49	-0.05	-1.08	-0.33	-2.33
ROMP 13 MW1	SAS	-3.80	-7.86	-8.40	-4.12	-4.56	-1.17
ROMP 13 MW2	PZ2	0.14	0.62	0.08	-2.55	-1.43	-2.15
ROMP 13 MW3	PZ3	0.28	0.96	0.41	-2.59	-1.24	-2.68
ROMP 13 MW4	UFA	0.50	1.11	0.57	-1.98	-0.73	-3.10
ROMP 17 SAS	SAS	0.14	-0.07	-0.61	-1.90	-2.46	-1.50
ROMP 17 IAS LPZ	PZ3	0.24	0.65	0.11	-1.57	-0.69	-2.31
ROMP 17 UFA	UFA	0.11	0.45	-0.09	-1.68	-0.77	-1.99
[3] ROMP 17 SWNN	UFA	0.10	-0.11	-0.65	-1.05	-0.17	-1.92

[1] Equilibrium reaction constant (Kr) = -17.09.

[2] Kr = -16.53.

[3] Data from Sacks and Tihansky (1996).

All waters were undersaturated with respect to gypsum, celestite, and amorphous silica, and all waters were supersaturated with respect to quartz and sepiolite. The saturation state of water with respect to most clay minerals could not be assessed because water samples were not analyzed for aluminum. Waters from the intermediate aquifer system and Upper Floridan aquifer in the general study area, reported in Sacks and Tihansky (1996), were supersaturated with respect to calcium montmorillinite, illite, and kaolinite. The SI of clay minerals, however, reflects much uncertainty because of variability in stoichiometry and uncertainty in thermodynamic properties of aluminous clays (Fritz, 1985).

Isotopic Composition of Ground Water

Water samples were analyzed for isotopes of the water molecule (tritium, deuterium, and oxygen-18) and dissolved inorganic carbon (carbon-13 and carbon-14). The radioactive isotopes tritium and carbon-14 were used to estimate the age of the water, whereas the stable isotopes of water (deuterium and oxygen-18) and inorganic carbon (carbon-13) provided insights into the source of water, mixing between waters, and the chemical evolution of the water.

Stable Isotopes

Values of δD and $\delta^{18}O$ typically are plotted on a diagram showing δD versus $\delta^{18}O$, and are related to a global meteoric water line (GMWL), representing rainfall from around the world (Craig, 1961). The stable isotope composition of waters relative to the GMWL can indicate important information on ground-water recharge patterns, waters that have undergone evaporation, recharge during different climatic conditions, and mixing of ground water and surface water. Waters sampled from the surficial aquifer system for this study were isotopically heavy compared to the composition of modern rainwater and were offset from the GMWL (fig. 24). Most surficial aquifer system waters were isotopically lighter than waters from the intermediate aquifer system (PZ2 and PZ3) and from the Upper Floridan aquifer at the same site; however, water from the surficial aquifer system at the ROMP 9.5 site was isotopically heavier than water from the other aquifers. Surficial aquifer system water at the ROMP 9.5 site also was offset from the GMWL, indicating that the water had undergone evaporation prior to recharging the surficial aquifer system. Much of the study area is low lying and evaporation of standing water at the surface prior to recharge probably resulted in the enrichment of δD and $\delta^{18}O$ at the ROMP 9.5 site. Waters from the surficial aquifer system plot along a line described by the expression $\delta D = 5.7\ \delta^{18}O + 2.4$ ($r^2 = 0.99$), and most likely represent a mixture of meteoric water with an isotopically light composition and ground water that has been recharged by water that has undergone evaporation with an enriched isotopic composition.

The stable isotope composition of waters from the Lower Arcadia zone (PZ3) is quite similar to that for the Upper Floridan aquifer at the ROMP 17, 9, and 5 sites, suggesting that water moved upward from the Upper Floridan aquifer into PZ3. In contrast, the different isotope compositions for waters from PZ2, PZ3, and the Upper Floridan aquifer at the ROMP 9.5 site indicate complex mixing of waters from overlying and underlying aquifer systems. Trend lines connecting isotopically enriched waters from the intermediate aquifer system ($\delta D = 5.0\ \delta^{18}O + 3.8$; $r^2 = 0.56$) and Upper Floridan aquifer ($\delta D = 6.5\ \delta^{18}O + 5.3$; $r^2 = 0.82$) also indicate mixing between waters with distinct isotopic compositions; the poorer relation for the intermediate aquifer system suggests that the mixing of water in the intermediate aquifer system is more complex than a mixing model between two end members. However, the enriched $\delta^{18}O$ and δD composition of ground water from the intermediate aquifer system and Upper Floridan aquifer may be the result of recharge that occurred under climatic conditions that differed from present conditions. Plummer and others (1993) found stable isotope enrichment in the confined part of the Upper Floridan aquifer in southern Georgia in waters that were recharged during the last glacial maximum. Some enrichment in the stable isotope composition of waters from the intermediate aquifer system and Upper Floridan aquifer may result from mixing of enriched paleowaters with somewhat depleted younger meteoric water.

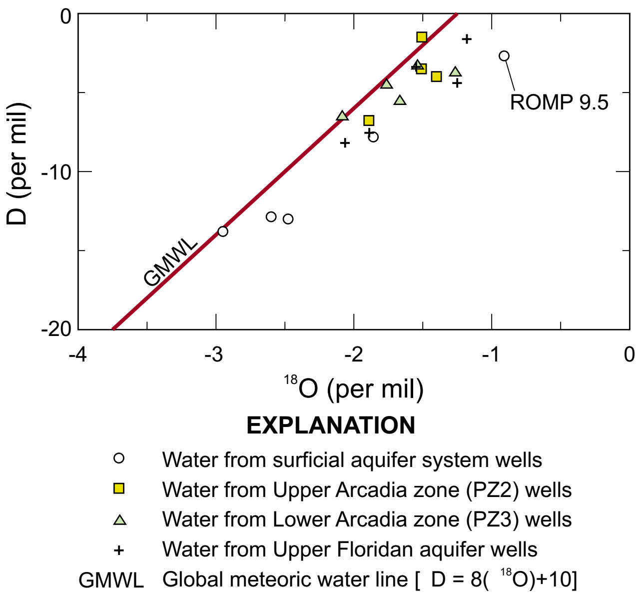


Figure 24. Relation between delta deuterium (δD) and delta oxygen-18 ($\delta^{18}O$) values in water from wells at the ROMP 5, 9, 9.5, 13, and 17 sites that are completed in the surficial aquifer system, intermediate aquifer system, and Upper Floridan aquifer.

Water from the three aquifer systems had isotopically distinct carbon-13 signatures of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) (table 7). For example, $\delta^{13}C_{DIC}$ values were isotopically lighter, or more depleted in carbon-13, in the surficial aquifer system (-10.0 to -17.2 per mil) compared to the intermediate aquifer system and Upper Floridan aquifer. In addition, $\delta^{13}C_{DIC}$ values for water from PZ2 were lighter (-9.8 to -4.7 per mil) than for water from PZ3 (-6.6 to -4.4 per mil). Water from the Upper Floridan aquifer typically had the heaviest $\delta^{13}C_{DIC}$ values (-6.0 to -3.2 per mil). Sacks and Tihansky (1996) also noted that water in the intermediate aquifer system typically had lighter $\delta^{13}C_{DIC}$ values than water in the Upper Floridan aquifer. The difference in $\delta^{13}C_{DIC}$ is related to the evolution of inorganic carbon in the aquifer systems. Water from the surficial aquifer system was most recently in contact during recharge with soil-zone CO_2, which is isotopically light (usually between -20 and -25 per mil; Deines and others, 1974). This recharging water dissolved different amounts of calcite in the shallow surficial aquifer system, resulting in high bicarbonate concentrations (greater than 250 mg/L as $CaCO_3$) in most surficial aquifer system waters and a wide range of $\delta^{13}C_{DIC}$ values reflecting different carbon sources. Waters in deeper aquifer systems evolve to a heavier $\delta^{13}C_{DIC}$ composition because they are isolated from soil-zone CO_2 and because the dissolution of isotopically heavy dolomite results in an enrichment of $\delta^{13}C_{DIC}$. Dolomite dissolution is illustrated by higher concentrations of magnesium and waters closer to saturation with respect to dolomite in the deeper aquifers compared to the surficial aquifer system.

An inverse relation exists between $\delta^{13}C_{DIC}$ and ^{14}C values in ground water from the surficial aquifer system and PZ2 of the intermediate aquifer system (fig. 25). This relation is further evidence of the evolution of inorganic carbon from recharge waters (with higher ^{14}C activity and lighter $\delta^{13}C_{DIC}$ values from soil gas) toward deeper ground water (with lower ^{14}C activity and heavier $\delta^{13}C_{DIC}$ values from dissolution of calcite and dolomite in the aquifer). A similar relation between $\delta^{13}C_{DIC}$ and ^{14}C was observed for ground water in South Carolina (Landmeyer and Stone, 1995). Differences in the $\delta^{13}C$ composition of the originating organic matter result in different $\delta^{13}C_{DIC}$ signatures in incoming CO_2 and organic carbon in ground water (McMahon and others, 1990).

Age of Ground Waters

Tritium is useful for age dating relatively young ground water (less than 50 years old) because of its short half life (12.4 years), whereas ^{14}C can be used for estimating ages of older ground water (500-40,000 years old) because of its longer half life (5,730 years). All waters sampled from the surficial aquifer system had tritium present at concentrations ranging between about 10 and 11 TU, indicating that the water is “young” and was probably recharged between 30 and 40 years ago (based on tritium concentrations measured in rainfall in Ocala, Florida between 1961 and 1991, adjusted for radioactive decay; fig. 26). Present-day rainfall in Florida has a much lower tritium concentration (about 5 TU) than rainfall between the late 1950's and early 1960's, even after considering radioactive decay of rainfall from the 1960's. Tritium was not detected in waters from the intermediate aquifer system and Upper Floridan aquifer, indicating that these waters are “old” (greater than 50 years old, based on the detection limit of 0.3 TU and considering radioactive decay). Thus, it appears that little, if any, present-day recharge is moving from the surficial aquifer system into the intermediate aquifer system in the study area. This apparent lack of recharge is supported by upward head differences between the intermediate aquifer system and the surficial aquifer system in much of the study area, inhibiting recharge from the surficial aquifer system to the intermediate aquifer system.

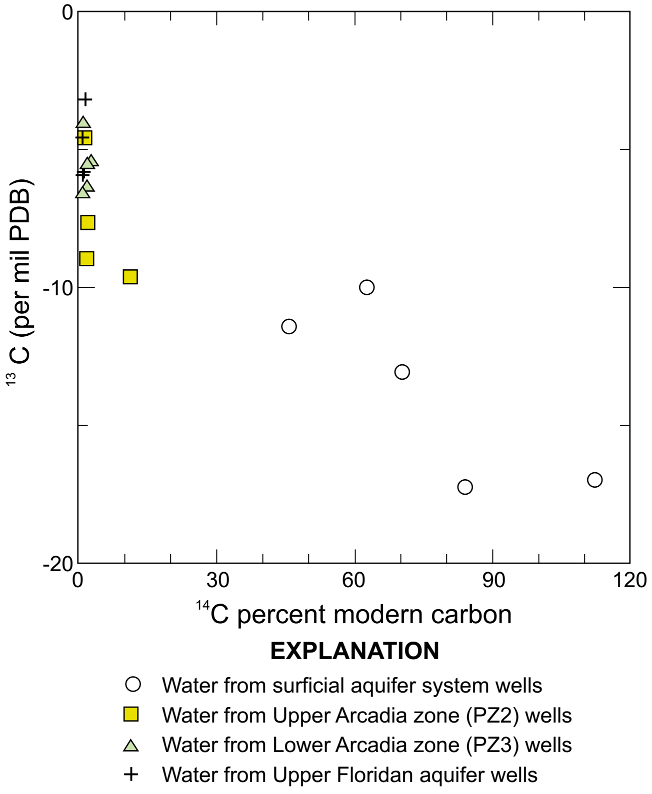


Figure 25. Relation between delta carbon-13 (d13C) and carbon-14 (14C) values in water from wells at the ROMP 5, 9, 9.5, 13, and 17 sites that are completed in the surficial aquifer system, intermediate aquifer system, and Upper Floridan aquifer.

Age was estimated for waters from the intermediate aquifer system and from the Upper Floridan aquifer using ^{14}C, and was corrected for reactions with inorganic carbon (table 9). Uncertainties in computed ages are due to analytical precision of ^{14}C, the ^{14}C adjustment models, and input parameters to the models. Most waters had ^{14}C values less than 10 PMC, with an analytical uncertainty of 1 PMC. As the measured ^{14}C concentration decreases, the uncertainty in the age increases. For example, water with a ^{14}C value of 5 PMC can have an age uncertainty of plus or minus 2,000 years, whereas a water with ^{14}C value of less than 0.6 PMC can have an uncertainty range of plus or minus 10,000 years. Values assumed for input parameters to the correction models also can contribute uncertainty to the computed age. For example, changing the ^{13}C value for soil CO_2 from -25 to -20 per mil resulted in computed ages that were about 2,000 years older than those in table 9.

Several trends are apparent in the computed ages of the water, after considering uncertainties in the ages. All intermediate aquifer system and Upper Floridan aquifer waters are probably greater than about 10,000 years old, and many are greater than 20,000 years old (table 9). Thus, both aquifer systems may have been recharged under different hydraulic conditions than currently observed.

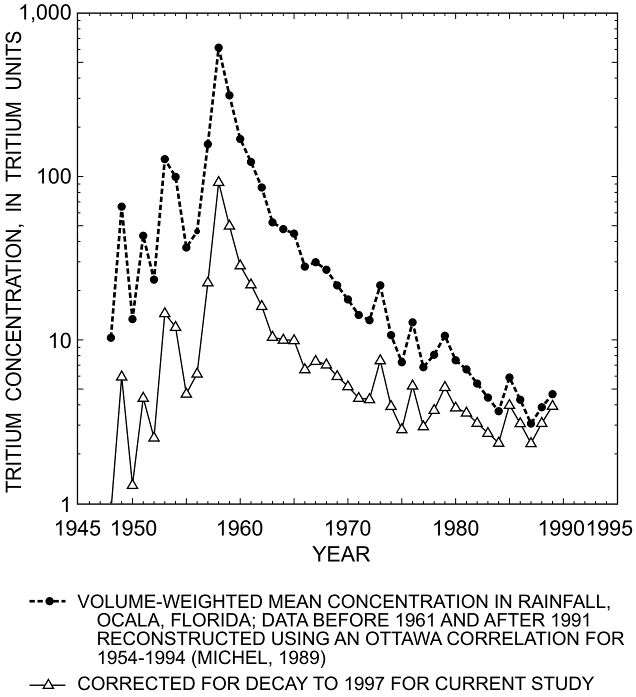


Figure 26. Tritium concentration in rainfall in Ocala, Florida.

At the ROMP 9.5 site, water in the Upper Arcadia zone (PZ2) is younger than water in the Lower Arcadia zone (PZ3), considering the uncertainty ranges (table 9). This younger age may indicate the influence of recharge from the surficial aquifer system in PZ2. Water in PZ3 may be on a longer flow path moving laterally from an upgradient recharge area, or may be a mixture of younger water from PZ2 and older water in the Upper Floridan aquifer (table 9). Water in the Upper Floridan aquifer at the ROMP 9.5 site probably evolved over long flow paths from recharge areas to the north and east (Hanshaw and others, 1965; Plummer and others, 1983; Sacks and Tihansky, 1996). At the ROMP 13 and 17 sites, similar ages were computed for water in both the intermediate aquifer system and the Upper Floridan aquifer (table 9).

In contrast, waters at the ROMP 5 and 9 sites decrease in age between the intermediate aquifer system and Upper Floridan aquifer (table 9). Water in the Upper Floridan aquifer at these sites is about 10,000 years younger than water sampled from the Upper Floridan aquifer at the other sites. These waters also had about four times higher chloride concentrations than the other Upper Floridan aquifer waters. The younger apparent age at these sites is contradictory to the predevelopment flow direction in the Upper Floridan aquifer, which originates to the north and east of the study area (Ryder, 1982; Plummer and others, 1983). Because the ROMP 5 and 9 sites are downgradient of the other ROMP sites6, the Upper Floridan aquifer water would be expected to be older than water at the other ROMP sites. The hypothesis was tested that the saline end member for these waters is young, and mixing with the older Upper Floridan aquifer water results in a younger apparent age of water in these Upper Floridan aquifer wells. Assuming linear mixing between modern seawater (as the most extreme end member) and upgradient water (ROMP 9.5), a mixture of 40-percent seawater and 60-percent upgradient Upper Floridan aquifer water would account for the younger water at the ROMP 9 site. Such a mixture, however, would have a chloride concentration of about 7,600 mg/L, which is more than an order of magnitude greater than the observed chloride concentration at the ROMP 9 site (500 mg/L). If the age of the seawater is

Table 9. Adjusted carbon-14 age of ground water at the ROMP 5, 9, 9.5, 13, and 17 sites from the intermediate aquifer system and the Upper Floridan aquifer

[MW, monitoring well; SUW, Suwannee; OW, observation well; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; IAS, intermediate aquifer system; LPZ, lower permeable zone; CU(PZ3:UFA), confining unit between PZ3 and UFA; UFA, Upper Floridan aquifer]

Well name	Principal hydrogeologic unit	Adjusted age [1] (years)	Range in ages due to analytical uncertainty[2] (years)
ROMP 5 MW2	PZ2	22,000	19,000-28,000
ROMP 5 MW3	PZ3	17,000	14,000-21,000
ROMP 5 SUW2	UFA	12,000	10,000-14,000
ROMP 9 OW13	PZ2	25,000	22,000-32,000
ROMP 9 OW14	PZ3	24,000	18,000-31,000
ROMP 9 OW15	UFA	15,000	11,000-22,000
ROMP 9.5 MW18	PZ2	10,000	9,000-11,000
ROMP 9.5 MW2	PZ3	18,000	15,000-23,000
ROMP 9.5 MW1	UFA	25,000	18,000-33,000
ROMP 13 MW2	PZ2	31,000	21,000-43,000
ROMP 13 MW3	PZ3	32,000	23,000-46,000
ROMP 13 MW4	UFA	26,000	20,000-32,000
ROMP 17 IAS LPZ	PZ3	24,000	19,000-35,000
ROMP 17 UFA	UFA	27,000	21,000-35,000

[1] Adjusted using Fontes and Garnier (1979) correction model, which assumes carbon-14 activity of carbonate minerals and soil CO_2 to be equal to 0 and 100 percent modern carbon, respectively, and delta carbon-13 of carbonate minerals and soil CO_2 to be equal to 0 and -25 per mil, respectively; age values rounded to nearest 1,000 years.

[2] For carbon-14 values greater than 10 percent modern carbon, analytical uncertainty is 2 percent modern carbon; for carbon-14 values less than 10 percent modern carbon, analytical uncertainty is 1 percent modern carbon; for carbon-14 values less than 1 percent modern carbon, analytical uncertainty is assumed to be 0.5 percent modern carbon.

older, then even higher chloride concentrations would be computed for the ROMP 9 site. Therefore, the younger age in the Upper Floridan aquifer at the ROMP 5 and 9 sites is not strictly a mixture between younger seawater and upgradient ground water, and may indicate mixing with another, perhaps shallower, freshwater end member.

Mineralogical and Isotopic Composition of Aquifer System Material

The mineralogy and isotopic composition of rocks that compose the aquifer system were evaluated to assist in interpreting the chemical and isotopic composition of the ground water. These mineralogic and isotopic composition data also were used as input parameters to the geochemical model described in the following section. Mineralogy was defined by x-ray diffraction for eight intervals of the core from the ROMP 9.5 site (table 10) and from the literature. The intermediate aquifer system is a heterogeneous unit, with calcite, dolomite, and quartz being the most abundant minerals. The exact stoichiometry of calcite and dolomite in the intermediate aquifer system is unknown. Clay minerals in the aquifer system include

Table 10. Mineralogy, carbon content, and isotopic composition of organic and inorganic carbon from selected samples of the core at the ROMP 9.5 site, De Soto County, Florida

[Identifications, by x-ray diffraction, are ranked from highest to lowest intensity of the principle peak for each mineral; <1µm, less than one micrometer; per mil, parts per thousand; $\delta^{13}C$, delta carbon-13; ROMP, Regional Observation and Monitor-Well Program; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; ?, uncertain identification; --, no data; NA, not applicable]

Sample depth below land surface (feet)	Hydrogeologic unit	Bulk contents	Ultrafine clays (<1µm)	Organic carbon (traditional method) (percent) [1]	Organic carbon (persulfate method) (percent) [2]	Mean persulfate (percent)	Organic $\delta^{13}C$ (per mil)	Inorganic $\delta^{13}C$ (per mil)
68	PZ2	Quartz, dolomite, calcite, and total clay	Palygorskite smectite, kaolinite (trace), and illite (trace ?)	1.5	2.16 1.14	1.65	-20.56	-0.24
188	confining unit between PZ2 and PZ3	Dolomite, quartz, total clay, and calcite	Palygorskite, smectite, sepiolite, and kaolinite	2.1	1.99 1.74	1.86	-20.46	--
239	PZ3	Calcite, dolomite, quartz, and total clay	Palygorskite, smectite, sepiolite, and kaolinite	1.5	0.099 2.22	1.64	-22.38	--
280	PZ3	Quartz, calcite, potassium feldspar, dolomite, plagioclase (trace ?), and total clay (?)	Smectite, sepiolite, palygorskite, and kaolinite	1.4	2.01 1.02 1.09	1.37	-21.11	-0.16
320	PZ3	Calcite, quartz, potassium feldspar, plagioclase (?), total clay (?), and dolomite (trace ?)	Smectite, plagioclase, sepiolite (?), and kaolinite (trace)	1.3	0.11 0.05 0.42	0.19	-25.16	--
340	confining unit between PZ3 and UFA	Calcite, quartz, plagioclase, dolomite (trace ?), and potassium feldspar	Smectite, chain-structure clays (?), and kaolinite (trace ?)	1.7	0.12 0.30	0.21	-22.11	--
480	UFA	Calcite, quartz (trace), and total clay (trace)	Smectite, chain-structure clays (?), and kaolinite (?)	2.2	0.29 0.10 0.10	0.16	-21.29	--
520	UFA	Calcite, quartz, cristobalite (?), and total clay	Palygorskite, smectite (trace) and kaolinite (trace)	2.1	0.09 0.10 0.87	0.35	-23.44	--
Standard reference material [3]	NA	NA	NA	2.0	1.90 1.85	0.19	--	--

[1] Total organic carbon content determined by a combustion method (Wershaw and others, 1987); inorganic carbon content determined by a gasometric method (Wershaw and others, 1987); organic carbon content determined by subtracting inorganic carbon from organic carbon.

[2] Organic carbon content determined by a modified persulfate-oxidation method (Sandstrom and others, 1986).

[3] Analyzed using methods by Wershaw and others, (1987), and Sandstrom and others, (1986).

illite, smectite, sepiolite, palygorskite, and kaolinite; other minor minerals include phosphatic minerals (apatite [$Ca_5(PO_4)_3(F,Cl,OH)$], fluorapatite, and francolite [$(Ca,Na)_5(PO_4,CO_3)_3(F,OH)$]), pyrite ($FeS_2$), and celestite ($SrSO_4$) (Scott, 1988; McCartan, Duerr, and Hawkins, 1992; McCartan, Plummer, and others, 1992; Florida Geological Survey, written commun., 1993; Kauffman, 1994; McCartan and others, 1995). Gypsum has not been found in the intermediate aquifer system.

The organic carbon content of the rock material in the intermediate aquifer system and Upper Floridan aquifer was determined from eight intervals of the core collected at the ROMP 9.5 site. The organic carbon content was relatively uniform, ranging from 1.3 to 2.2 percent of the bulk material. In the intermediate aquifer system, the lowest amounts of organic carbon were in the permeable zones, with slightly higher amounts of organic carbon found in the confining units. The persulfate method provided similar results for samples from the upper zones of the core; however, results for samples from deeper zones were an order of magnitude lower than results using the traditional method, indicating incomplete recovery of organic carbon. It is probable that organic carbon in deeper zones is more resistant to oxidation than carbon in shallower zones.

Selected intervals of the ROMP 9.5 core were analyzed for $\delta^{13}C$ of the organic and inorganic carbon of the rock material (table 10). Values of $\delta^{13}C$ of the organic carbon ranged from -20.46 to -25.16 per mil, with an average value of -22.1 per mil (table 10). These values are similar to those for organic carbon from a carbonate aquifer in South Carolina (McMahon and others, 1990). In the upper part of the intermediate aquifer system, $\delta^{13}C$ of organic carbon was isotopically heavier than in the deeper part of the intermediate aquifer system and in the upper part of the Upper Floridan aquifer. For inorganic carbon, the two samples had $\delta^{13}C$ values near 0 per mil, indicating little change from seawater composition. Minerals were not distinguished in the analysis, but were observed to be both calcite and dolomite in the rock core. Other values of $\delta^{13}C$ of calcite in the intermediate aquifer system range from -7.1 to 1.9 per mil (Sacks and Tihansky, 1996). Values of $\delta^{13}C$ in the Floridan aquifer system range from -6.4 to 3.1 per mil for calcite and from -7.5 to 3.1 per mil for dolomite (Hanshaw and Back 1972; Sprinkle, 1989; Cander, 1991; Sacks and Tihansky, 1996).

Geochemical Evolution of Ground Water Along Flow Paths

For ground-water resources in the intermediate aquifer system to be adequately protected from water-quality degradation for future use, it is important to understand how water moves laterally within permeable zones and vertically between overlying and underlying permeable zones and aquifer systems. The geochemical model NETPATH was used (1) to evaluate the lateral continuity of flow within permeable zones, (2) to determine the extent of mixing between overlying and underlying aquifer systems, and (3) to understand important geochemical reactions occurring within the aquifer.

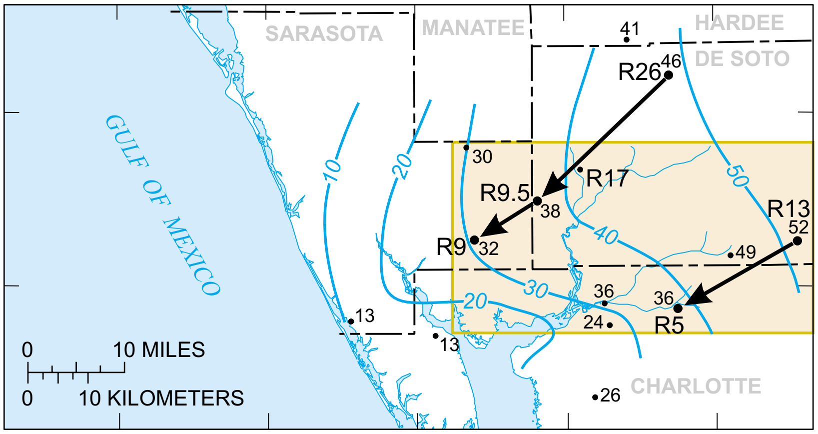
Defining Flow Paths

Potentiometric-surface maps of the Upper Arcadia zone (PZ2) and the Lower Arcadia zone (PZ3) were used to establish preliminary flow paths (fig. 27). These paths assume that water in PZ2 and PZ3 moves laterally within the permeable zone between sites. Modifications were made to flow paths if no valid models were found. In PZ2, flow is from east-northeast to the west-southwest; in PZ3, flow is generally from east-southeast to west-northwest. Flow paths were modeled from upgradient to downgradient sites, but are inherently limited by well distribution. The flow paths were used to understand the chemical evolution of water in PZ2 at the ROMP 9.5, 9, and 5 sites (fig. 27a), and in PZ3 at the ROMP 17, 9.5, and 9 sites (fig. 27b).

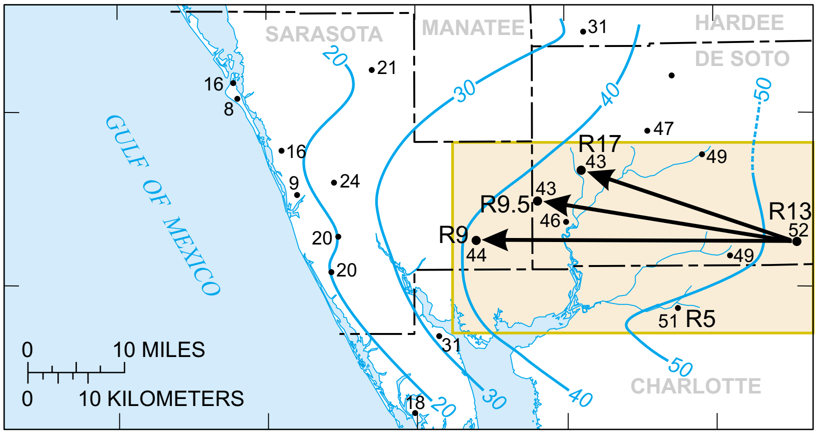
Besides lateral flow paths within a permeable zone, vertical mixing also was considered. Mixing directions were based on measured head differences between permeable zones and aquifer systems. Thus, reactions and mixing were typically computed between several initial wells and a final well along the flow path.

Description of Geochemical Model and Assumptions

The geochemical model NETPATH (Plummer and others, 1994) computes a series of chemical reactions between initial and final waters, given a set of constraints (elements, isotopes, or electron balance) and phases (including mineral dissolution or precipitation, ion exchange, or gas exchange). The model also can compute the isotopic composition of the final water, provided that the isotopic composition of the initial water(s), and dissolving phases and fractionation factors of precipitating phases are defined. Although computed models cannot be validated, they can be



(a) Upper Arcadia zone (PZ2)



(b) Lower Arcadia zone (PZ3)

EXPLANATION

▭	STUDY AREA
—20---	POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximate. Contour interval is 10 feet. Datum is sea level
←	PRESUMED FLOW PATH USED IN NETPATH MODELING
•37	OBSERVATION WELL—Number is altitude of water level in feet above sea level, September 1998
•R5	ROMP WELL AND NUMBER ALONG PATH

Base from SWFWMD digital data, 1:250,000, 1992
Albers Equal-Area Conic projection
Standard Parallels and , central meridian

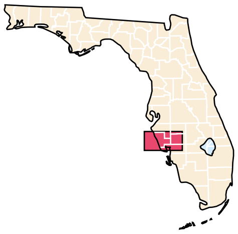


Figure 27. Ground-water flow paths simulated in the intermediate aquifer system, (a) Upper Arcadia zone (PZ2) and (b) Lower Arcadia zone (PZ3), using the geochemical model NETPATH.

rejected when they violate thermodynamic principles (for example, dissolution of a mineral from a supersaturated water) or when large discrepancies occur between the observed and computed isotopic composition of the final water. Models were constrained by calcium, magnesium, carbon, sulfur, electron balance (redox state), sodium, and in most cases, chloride. Mixing ratios were typically computed from chloride concentrations. Electron balance considerations were required to model redox reactions, such as oxidation of organic matter.

Reaction phases that were considered include stoichiometric calcite and dolomite, organic matter (represented as CH_2O in the models), CO_2 gas, gypsum, pyrite (FeS_2), and cation exchange (Ca for Na and Mg for Na). Because of wide uncertainties in the stoichiometry and saturation state of clay minerals, it is difficult to assess the validity of clay mineral precipitation or dissolution models. Thus, the simplification was made that modeled cation exchange reactions also represent clay mineral dissolution and precipitation that involve the mass transfer of calcium, magnesium, and sodium. Most waters were saturated or supersaturated with respect to calcite, and so only calcite precipitation was considered. Dissolution was considered if initial or final waters were undersaturated with respect to disordered dolomite (the prevalent form in the Upper Floridan aquifer in the study area); dolomite precipitation was not considered to be a realistic geochemical process in this freshwater aquifer. Gypsum has not been identified in the intermediate aquifer system, and the depositional environment during the Miocene was not conducive to the formation of permanent evaporite minerals. Minor amounts of gypsum dissolution, however, were sometimes considered to balance sulfate. All waters from the intermediate aquifer system had a sulfide odor, indicating sulfate-reducing conditions; at the ROMP 9.5 site, sulfide concentrations were greater than 1 mg/L (table 7). Pyrite precipitation was considered as a phase because of reducing conditions (where pyrite oxidation cannot occur). Iron concentrations typically are low, but measurable (5-500 μg/L) in the intermediate aquifer system (Southwest Florida Water Management District, 1991; Sacks and Tihansky, 1996), although iron was not analyzed in this study. The choice of carbon phases (CO_2 gas and CH_2O) were selected on the basis of geochemical modeling of the Upper Floridan aquifer (Plummer, 1977; Plummer and others, 1983); CH_2O was only allowed to oxidize representing microbial degradation of organic matter.

Sometimes several models were computed for a given flow path. Mixing ratios were usually similar, with models typically differing by the amount of mass transfer of CO_2 and CH_2O, and carbonate mineral and cation exchange reactions. Models with calculated $\delta^{13}C$ values similar to observed values were considered more realistic than those with large discrepancies. Models without gypsum dissolution were favored over those containing gypsum dissolution, particularly when mixing could be an explanation for an increase in sulfate. Many models contained CO_2 outgassing. The exact mechanism of carbon exchange (CO_2 ingassing, fermentation, microbial respiration), however, is not well understood and is beyond the scope of the present study. Minor charge imbalances also can influence the mass transfer of neutral compounds like CH_2O or CO_2 (Plummer and others, 1994, p. 15).

Upper Arcadia Zone (PZ2)

Water in the Upper Arcadia zone (PZ2) at the ROMP 9.5 site was modeled along a presumed flow path from an upgradient well in northern De Soto County, which is outside the immediate study area (ROMP 26; data from Sacks and Tihansky, 1996) (fig. 27a). The assumption was made that this water is chemically similar to upgradient water in the study area. Mixing with water from the Lower Arcadia zone (PZ3) was considered because heads were greater in PZ3 than in PZ2 along most of this path (figs. 8, 9, 10, and 27). Major ions increase in concentration along this path. A model with plausible reactions and similar computed and observed $\delta^{13}C$ values had 12 percent of the water flowing laterally in PZ2 (initial 1 well, table 11) and 88 percent of the water moving upward from PZ3 (initial 2 well, table 11). In that model, dominant reactions (greater than 0.20 millimoles per liter (mmol/L)) were CH_2O oxidation, CO_2 outgassing, pyrite precipitation, and cation exchange (also a surrogate for clay mineral reactions); no carbonate mineral reactions were computed. This model indicates that lateral flow from the upgradient part of the aquifer is minor compared to upward flow from PZ3 in the evolution of water in PZ2 at the ROMP 9.5 site.

Water in PZ2 at the ROMP 9 site was modeled on a flow path originating at the ROMP 9.5 site (fig. 27a). Mixing with water from PZ3 was considered because heads are higher in PZ3 than in PZ2. All major ions increase along this path, except for bicarbonate, which decreases slightly. Although a lateral head difference exists from the ROMP 9.5 site to the ROMP 9 site, model results indicate that limited lateral flow occurs in PZ2 between these two sites (less than 10 percent), and the source of most of the water in PZ2

Table 11. NETPATH geochemical modeling results along selected flow paths within the intermediate aquifer system

[Units in millimoles per liter (mmol/L) unless otherwise noted; positive mass transfer indicates dissolution or ingassing; negative mass transfer indicates precipitation or outgassing; CH_2O, represents organic matter; CO_2, carbon dioxide; Ca, calcium; Na, sodium; Mg, magnesium; $\delta^{13}C$, delta carbon-13; calc, calculated; obs, observed; Cl, chloride concentration; mg/L, milligrams per liter; R, ROMP; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; Swnn, Suwannee; --, not in model or less than 0.01 mmol/L; n/a, not applicable; for precipitating phases, $\delta^{13}C$ or $\delta^{34}S$ computed by model based on Rayleigh calculations and fractionation factors defined at the final water (X=1.0)]

Initial 1 (fraction) well	Initial 2 (fraction) well	Initial 3 (fraction) well	Final well	Calcite	Dolo-mite	CH_2O	CO_2	Pyrite	Ca/Na exchange	Mg/Na exchange	$\delta^{13}C$ calc (per mil)[1]	$\delta^{13}C$ obs (per mil)	Calc age (years)[2]	Cl calc (mg/L)	Cl obs (mg/L)
(0.12) R26 PZ2	(0.88) R17 PZ3		R9.5 PZ2	--	--	0.98	-0.41	-0.36	--	0.42	-9.5	-9.7	n/a	66	64
(0.08) R9.5 PZ2	(0.92) R9 PZ3	n/a	R9 PZ2	-0.42	--	0.68	-0.22	-0.23	-0.51	0.20	-8.0	-9.8	17,000	n/a	n/a
(0.07) R9 SAS	(0.93) R9 PZ3	n/a	R9 PZ2	-0.44	--	0.63	-0.27	-0.21	-0.45	0.16	-8.6	-9.8	20,000	n/a	n/a
(0.44) R13 PZ2	(0.32) R13 SAS	(0.24) R5 PZ3	R5 PZ2	0.36	--	0.36	-0.73	-0.11	0.09	--	-6.2	-7.8	19,000	n/a	n/a
(0.33) R13 PZ3	(0.44) R17 UFA[3]	(0.23) R17 Swnn	R17 PZ3	-0.26	--	--	-0.20	--	-0.33	-0.02	-6.0	-6.4	n/a	n/a	n/a
(0.86) R13 PZ3	(0.14) R9 PZ3	n/a	R9.5 PZ3	-0.46	0.14	0.42	--	-0.11	-0.49	--	-7.6	-5.4	18,000	n/a	n/a
(0.09) R13 PZ3	(0.91) R9 UFA	n/a	R9 PZ3	-0.21	0.17	0.81	-1.22	-0.27	--	0.16	-4.9	-4.4	19,000	n/a	n/a

[1] $\delta^{13}C$ or inorganic carbon, assuming the following $\delta^{13}C$ values for dissolving phases: dolomite = 0 per mil; CH_2O = -22 per mil; CO_2 = -25 per mil.

[2] Using carbon-14, adjusted using Fontes and Garnier (1979) correction model, assuming carbon-14 activity of carbonate minerals and soil CO_2 are 0 and 100 percent modern carbon, respectively, and $\delta^{13}C$ of carbonate minerals and soil CO_2 are 0 and -25 per mil, respectively; age values rounded to nearest 1,000 years.

[3] Well open to the deepest part of the intermediate aquifer system and the shallowest part of the Upper Floridan aquifer (fig. 5).

at the ROMP 9 site is upward flow from PZ3 (table 11). An alternate scenario for evolution of water at the ROMP 9 site had no lateral flow occurring within PZ2 and a minor fraction (7 percent) of localized recharge from the surficial aquifer system mixing with deeper water from PZ3 (table 11). Surficial aquifer system water is not recharging the intermediate aquifer system under current hydraulic conditions, but this recharge scenario does indicate that water in PZ2 at the ROMP 9 site could have evolved in a very localized system, isolated from upgradient PZ2 waters. Dominant reactions computed for either scenario include calcite precipitation, CH_2O oxidation, CO_2 outgassing, and pyrite precipitation.

The last flow path modeled in PZ2 was from the ROMP 13 site to the ROMP 5 site (fig 27a). Along this path, recharge from the surficial aquifer system at the ROMP 13 site was considered because this site is in a recharge setting (fig. 9). Upward flow from PZ3 at the ROMP 5 site also was considered because the head in PZ3 is substantially greater than the head in PZ2 at this site (figs. 9 and 10). Most major ions increase along this path, except for bicarbonate, which decreases slightly, and magnesium, which remains the same. A plausible model for this flow path had 44 percent of water moving laterally, 32 percent recharging from the surficial aquifer system, and 24 percent moving upward from PZ3 (table 11). This path has less upward flow than the other flow paths modeled in PZ2, which is consistent with a low leakance value expected between PZ2 and PZ3 at the ROMP 5 site. Dominant chemical reactions along this path are calcite dissolution (water from surficial aquifer system at ROMP 13 is undersaturated with calcite), CH_2O oxidation, and CO_2 outgassing.

Lower Arcadia Zone (PZ3)

Two upgradient sites were tested as the initial water for lateral flow in the Lower Arcadia zone (PZ3): the ROMP 13 and ROMP 5 sites. Water from PZ3 at the ROMP 5 site had the highest chloride concentration of all waters sampled, and models were not realistic with large decreases in chloride along the path (for example, substantial amounts of recharge would need to occur from the surficial aquifer system, which is contrary to head differences). Thus, water from the ROMP 13 site was considered to be the upgradient end member for lateral flow in PZ3.

The first PZ3 flow path modeled was from the ROMP 13 site to the ROMP 17 site (fig. 27b). Mixing with water from the Upper Floridan aquifer was considered because heads are greater in the Upper Floridan aquifer than in PZ3 at the ROMP 17 site (figs. 9 and 10). Most major ions increase in concentration in PZ3 between the ROMP 13 and ROMP 17 sites; sodium and bicarbonate concentrations decrease slightly. The composition of water in PZ3 at the ROMP 17 site can be modeled by mixing 33 percent of water moving laterally from PZ3 at the ROMP 13 site with 67 percent moving upward from the deepest part of the intermediate aquifer system and the Upper Floridan aquifer (fig. 5). At the ROMP 17 site, these NETPATH modeling results indicate that mixing with water from the Upper Floridan aquifer is important in the evolution of water in PZ3. Dominant reactions for this path were calcite precipitation and cation exchange (table 11).

The next path modeled in PZ3 was between the ROMP 13 and ROMP 9.5 sites (fig. 27b). Mixing with water from the Upper Floridan aquifer was considered for this path because heads are greater in the Upper Floridan aquifer than in PZ3. Major ions increase or are similar in concentration along this path. No plausible models were computed for this flow path from the ROMP 13 site to the ROMP 9.5 site when mixing from the Upper Floridan aquifer was considered. Computed $\delta^{13}C$ values were not close to observed values, and some models computed gypsum precipitation, which is not likely because waters are undersaturated with respect to gypsum. A model with improved $\delta^{13}C$ values was computed when considering mixing with another lateral source of water from PZ3 (ROMP 9), with no mixing from the Upper Floridan aquifer. This model has 86 percent of the water coming from PZ3 at the ROMP 13 site and 14 percent from PZ3 at the ROMP 9 site (table 11). Major reactions include calcite precipitation, CH_2O oxidation, and cation exchange. Although the low sulfate concentration in PZ3 at the ROMP 9.5 site seems anomalous, it indicates that this zone is isolated chemically from the Upper Floridan aquifer, which has a higher sulfate concentration (fig. 23). This NETPATH modeling conclusion is contrary to aquifer test results and computed values of leakance, which suggest that a hydraulic connection exists between PZ3 and the Upper Floridan aquifer at the ROMP 9.5 site. Reasons for this apparent contradiction are unresolved and warrant further investigation. It is possible that computed leakance from the aquifer test could have been overestimated. Alternatively, low ground-water withdrawals from PZ3 could have resulted in water in PZ3 that is chemically isolated from the Upper Floridan aquifer. If withdrawals increase, leakage from the Upper Floridan aquifer may result in degraded water quality in PZ3 (particularly increased sulfate concentrations).

The last flow path modeled in PZ3 was between the ROMP 13 and ROMP 9 sites (fig. 27b). Mixing with water from the Upper Floridan aquifer was again considered because heads are greater in the Upper Floridan aquifer than in PZ3 at the ROMP 13 site (but not presently at the ROMP 9 site). At present, the small downward head difference observed at the ROMP 9 site between PZ3 and the Upper Floridan aquifer can not be explained. The chemical evolution of water in the intermediate aquifer system and the Upper Floridan aquifer at the ROMP 9 site presumably predates ground-water pumpage in the area (for example, carbon-14 modeled ages were greater than 10,000 years old; table 9). All major ions increase in concentration along this path from the ROMP 13 to ROMP 9 sites, except for bicarbonate, which decreases in concentration. A plausible model for this path had 9 percent of water moving laterally mixing with 91 percent moving upward from the Upper Floridan aquifer. This model indicates that the evolution of water in PZ3 at the ROMP 9 site is dominated by water from the Upper Floridan aquifer, and lateral flow is essentially insignificant. Dominant reactions along this path include calcite precipitation, CH_2O oxidation, CO_2 outgassing, and pyrite precipitation.

Importance of Geochemical Modeling in Assessing Ground-Water Flow

Several important findings about flow patterns in the intermediate aquifer system have been corroborated by combining geochemical modeling with hydraulic head data. Geochemical modeling results suggest that vertical flow from underlying aquifers is important in the evolution of water in the intermediate aquifer system. Flow patterns derived only from potentiometric-surface maps may be misleading because the maps are based on an assumption of a homogenous, isotropic system where lateral flow is the dominant ground-water flow component. When vertical flow is incorporated with lateral flow paths, however, a more realistic assessment of ground-water flow patterns is possible. The study area is primarily an area of discharge from the Upper Floridan aquifer to the intermediate aquifer system, and upward head differences dominate (fig. 9). The potential for downward flow between permeable zones and recharge from the surficial aquifer system probably occurs in the intermediate aquifer system to the north and in the eastern part of the study area (ROMP 13, fig. 9). The downward head difference from the surficial aquifer system to PZ2 at the ROMP 5 site is anomalous and cannot be explained at this time.

Results from NETPATH geochemical modeling suggest that recent flow patterns delineated strictly on the basis of potentiometric-surface maps do not accurately represent predevelopment ground-water flow paths in PZ3. For example, water from the ROMP 5 site does not appear to influence the chemical composition of water to the northeast, along presumed flow paths. Present-day flow paths in PZ3 probably have been modified by ground-water withdrawals, particularly in the Upper Floridan aquifer to the north and west of the study area. The chemical composition of intermediate aquifer system waters sampled during this study most likely reflect predevelopment conditions.

Besides mixing, two dominant reactions that control the composition of water in the intermediate aquifer system are oxidation of organic matter (most likely microbially mediated; McMahon and others, 1990) and cation exchange (and other clay-mineral reactions). Calcite precipitation also was consistently modeled, but mass transfer of dolomite was minimal.

Although geochemical modeling indicates areas where upward flow strongly influences the chemical evolution of ground water in the intermediate aquifer system, it does not provide information on the mechanism, location, and timing of this upward flow. For example, it is likely that upward flow has occurred as slow diffuse flow through confining units, although preferential flow through fractures or paleokarst features may locally reduce confinement. In addition, areas where large amounts of upward flow are modeled may actually indicate that the permeable zone is not continuous, thereby limiting lateral flow. An alternative mechanism for mixing deeper ground water into shallower zones is flow through wells open to both the Upper Floridan aquifer and intermediate aquifer system (Metz and Brendle, 1996). The location of mixing along a flow path also is not known, and models are inherently limited by availability and distribution of wells.

SUMMARY

The hydrogeologic framework and the geochemical processes controlling ground-water composition in parts of Charlotte, De Soto, and Sarasota Counties, Florida, were evaluated. Particular emphasis was given to the analysis of hydrogeologic and geochemical data for the intermediate aquifer system.

The geologic framework that forms the aquifer systems in the study area consists of undifferentiated surficial deposits, the heterogeneous marine deposits comprising the Hawthorn Group, and the persistent carbonates comprising the Suwannee Limestone, Ocala Limestone, and Avon Park Formation. The stratigraphic and hydraulic units forming the hydrogeologic framework were delineated using lithologic and geophysical logs, water levels, water quality, and hydraulic characteristics from five existing Regional Observation and Monitor-Well Program (ROMP) sites and one new ROMP test site constructed in De Soto County during this study.

The regional ground-water system underlying the study area consists of a sequence of aquifers and confining units, each containing discrete zones of varying permeabilities. The principal hydrogeologic units that underlie the study area are the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. Aquifer heterogeneity results in vertical and areal variability in hydraulic and water-quality properties.

The surficial aquifer system is the uppermost aquifer and consists of relatively thin, unconsolidated sand, shell, and limestone and is unconfined. The thickness of the surficial aquifer system ranges from 19 ft at the ROMP 13 site to 69 ft at the ROMP 5 site. Hydraulic properties are variable because of the large range of horizontal hydraulic conductivity for the lithologic units that make up the aquifer. Transmissivity and horizontal hydraulic conductivity range from 752 to 32,900 ft^2/d and from 33 to1,490 ft/d, respectively.

The intermediate aquifer system is a confined system, having as many as three permeable zones. It is composed of clastic sediments interbedded with carbonate rocks. Interbedded clay and finer grained clastics separate the permeable zones. On a regional scale, the heterogeneous distribution of carbonate and siliciclastic sediments makes delineation of water-producing zones within the intermediate aquifer system difficult to characterize, both in quality and quantity. The hydraulic properties of these zones vary depending on (1) the original texture of the sediments and (2) post-depositional processes such as dolomitization, recrystallization, fracturing, and dissolution. Based on interpretation from test-hole data, two apparent water-producing zones were delineated at the ROMP 5 and 9.5 sites and three were delineated at the ROMP 9, 12, 13, and 17 sites.

The uppermost permeable zone of the intermediate aquifer system is designated as the Tamiami/Peace River zone (PZ1), which is the thinnest and least productive zone. The thickness of the Tamiami/Peace River zone (where it exists) ranges from 24 ft (ROMP 9) to 49 ft (ROMP 12). The reported values for transmissivity, horizontal hydraulic conductivity, and specific capacity were 47 and 5,420 ft^2/d; 2 and 102 ft/d; and 2 and 160 gal/min/ft for the ROMP 9 and 12 sites, respectively.

The second permeable zone of the intermediate aquifer system is designated as the Upper Arcadia zone (PZ2). Productivity in this zone is moderate but higher than the overlying permeable zone. The thickness of the Upper Arcadia zone ranges from 53 ft (ROMP 9) to 131 ft (ROMP 12). The Upper Arcadia zone is separated from the Tamiami/Peace River zone by a clay bed within the Peace River Formation. The clay bed is thinner in the northern study area than in the southern study area. The clay ranges in thickness from about 20 to about 60 ft. Hydraulic properties of PZ2 were estimated from aquifer tests conducted at four of the ROMP sites in the study area. The reported ranges for transmissivity, horizontal hydraulic conductivity, and specific capacity were 258 to 24,633 ft^2/d; 2 to 14 ft/d; and 1 to 47 gal/min/ft, respectively.

The third and lowermost permeable zone of the intermediate aquifer system is designated as the Lower Arcadia zone (PZ3), and is typically the most productive zone. The thickness of PZ3 ranges from 57 ft (ROMP 13) to 234 ft (ROMP 12). The hydraulic properties of PZ3 are more variable than overlying zones and are probably related to the degree of solution development within the limestone and dolomite beds. Hydraulic properties of PZ3 were estimated from aquifer tests conducted at five of the ROMP sites. The reported ranges for transmissivity, horizontal hydraulic conductivity, and specific capacity were 766 to 44,900 ft^2/d; 10 to 201 ft/d; and 3 to 49 gal/min/ft, respectively.

The Upper Floridan aquifer is the lowermost aquifer included in this study, and consists of a thick, stratified sequence of limestone and dolomite. The Upper Floridan aquifer is the most productive aquifer in the study area; however, use of the aquifer is generally restricted because of poor water quality. Generally, permeability of the Upper Floridan aquifer is very high in parts of the Avon Park Formation, somewhat lower in the Suwannee Limestone, and lowest in the Ocala Limestone. Hydraulic properties have been estimated from aquifer tests conducted at five of the ROMP sites in the study area. Aquifer test data are presented for wells that only penetrated the Suwannee Limestone. The reported values for transmissivity, horizontal hydraulic conductivity, and specific capacity were 2,350 to 7,640 ft^2/d; 10 to 41 ft/d; and 3 to 24 ga/min/ft, respectively. The relatively low hydraulic properties reported for the Suwannee Limestone indicate that a substantial water-production zone was not tested in the Upper Floridan aquifer.

Confining units separating permeable zones and aquifers in the study area consist of clays and low permeable carbonates. Variation in hydraulic properties of the confining units vary according to lithology and thickness. Confining units separating the aquifer systems have leakance coefficients estimated to range from 2.3×10^{-5} to 5.6×10^{-3} (ft/d/ft). Strata composing the confining unit separating the Upper Floridan aquifer from the intermediate aquifer system is substantially more permeable than the overlying confining units.

Heads within the hydrogeologic units generally increase with aquifer depth except in the eastern part of the study area. Five of the six ROMP sites are located in discharge areas where the flow potential is upward. At the ROMP 5 site, an anomalous mixed head difference exists and a downward head was observed between the surficial aquifer system and PZ2.

This study used hydrogeologic and geochemical information to evaluate the hydraulic connection between permeable zones within the intermediate aquifer system and between overlying and underlying aquifer systems. Knowledge of these connections will ultimately help to protect ground-water quality in the intermediate aquifer system. Hydraulic connection between the hydrogeologic units is variable in the study area. The degree of hydraulic connection probably depends on the presence and thickness of clay beds within the confining units; however, many facies changes within the confining units result in local hydraulic connection with overlying and underlying aquifers. Generally, a hydraulic connection exists between the Upper Floridan aquifer and PZ3. Relatively small head differences (up to 5 ft) exist and water levels in wells finished in either aquifer respond to pumping from above or below. Little hydraulic connection exists between PZ3 and PZ2. Moderate head differences (up to 12 ft) exist and hydraulic separation is evidenced by little or no water-level response when one or the other zone is pumped. Little hydraulic connection also exists between the surficial aquifer system and either PZ1 or PZ2. Relatively larger head differences are observed (up to 8 ft) and aquifer testing on the zones shows no response when one or the other is pumped.

Water in the surficial aquifer system was chemically more dilute than water in underlying aquifers and generally was a calcium bicarbonate type. Water in the intermediate aquifer system had a wide range in chemical composition, but generally fit into two categories. At the more inland sites, water was a mixed ion or mixed cation-bicarbonate type. Sites closer to the coast had a sodium-chloride or mixed cation-chloride type water. Water within the same permeable zone of the intermediate aquifer system did not have a distinct chemical composition throughout the study area. Water from the Upper Floridan aquifer also was variable in the study area and did not have a dominant cation. The chemical character of water between PZ3 and the Upper Floridan aquifer was quite similar at some sites (ROMP 5 and ROMP 9), but was distinctly different at other sites (ROMP 9.5). Water from the Upper Floridan aquifer had higher excess sulfate concentrations (equation 5) than water from overlying aquifers.

Most water from the surficial aquifer system had lighter δD and $\delta^{18}O$ values than waters from the intermediate aquifer system or the Upper Floridan aquifer. Water from the surficial aquifer system most likely represents a mixture of meteoric water having an isotopically light composition and ground water that has been recharged by water that has undergone evaporation and may be the result of an enriched isotopic composition. Waters from the intermediate aquifer system and the Upper Floridan aquifer may be the result of recharge that occurred under different climatic conditions than those under present conditions. Waters from the three aquifer systems have isotopically distinct $\delta^{13}C$ signatures of dissolved inorganic carbon, which is related to the evolution of inorganic carbon (soil CO_2 and reactions with carbonate minerals).

Based on data for ^{14}C of dissolved inorganic carbon, all intermediate aquifer system and Upper Floridan aquifer waters are probably greater than 10,000 years old, and many waters are greater than

20,000 years old. Thus, both aquifer systems may have been recharged under different hydraulic conditions than currently observed.

Several important findings about flow patterns in the intermediate aquifer system have been supported by combining geochemical modeling with hydraulic head data. Vertical flow from underlying aquifers is important in the evolution of water in the intermediate aquifer system. Flow patterns derived only from potentiometric-surface maps may be misleading because the maps presume lateral flow paths. Recent flow patterns delineated strictly by potentiometric-surface maps also do not represent predevelopment ground-water flow paths. The chemical composition of intermediate aquifer system waters most likely reflects predevelopment conditions. Besides vertical mixing, two dominant processes that control the composition of water in the intermediate aquifer system are oxidation of organic matter and cation exchange. Areas where geochemical models indicate large amounts of upward flow may actually indicate discontinuity of the permeable zone, thereby limiting lateral flow.

REFERENCES

Baldini, S.M., 1998, ROMP 13, Tippen Bay monitor well site, De Soto County, Florida, Phase Two, exploratory drilling and monitor well construction: Brooksville, Southwest Florida Water Management District, 16 p.

Baldini, S.M., 1999, ROMP 13, Tippen Bay monitor well site, De Soto County, Florida, Phase Three, aquifer performance testing: Brooksville, Southwest Florida Water Management District, 13 p.

Ball, J.W., and Nordstrom, D.K., 1991, User’s manual for WATEQ4F, with revised thermodynamic data base and test cases for calculating speciation of major, trace, and redox elements in natural water: U.S. Geological Survey Open-File Report 91-183, 189 p.

Barr, G.L., 1996, Hydrogeology of the surficial and intermediate aquifer systems in Sarasota and adjacent counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 96-4063, 81 p.

Barrie, A., and Prosser, S.J., 1996, Automated analysis of light-element stable isotope ratio mass spectrometry, *in* Bouton, T.W., and Yamasaki, S-i., eds., Mass Spectrometry of Soils: New York, Marcel Dekker, p. 1-46.

Berndt, M.P., and Katz, B.G., 1992, Hydrochemistry of the surficial and intermediate aquifer systems in Florida: U.S. Geological Survey Water-Resources Investigations Report 91-4186, 24 p.

Beukens, R.P., 1992, Radiocarbon accelerator mass spectrometry: Background, precision, and accuracy, *in* R.E., Taylor, A., Long, and R.S., Kra, eds., Radiocarbon after Four Decades, New York, Springer-Verlag, p. 230-239.

Brindley, G.W., and Brown, G., eds., 1980, Crystal structures of clay minerals and their x-ray diffraction: London, Mineralogical Society Monograph no. 5, 495 p.

Broska, J.C., and Knochenmus, L.A., 1996, Assessment of the hydrogeology and water quality in a near-shore well field, Sarasota, Florida: U.S. Geological Survey Water-Resources Investigations Report 96-4036, 64 p.

Cander, H.S., 1991, Dolomitization and water-rock interaction in the middle Eocene Avon Park Formation, Floridan aquifer: Austin, University of Texas, Ph.D. dissertation, 172 p.

Clark, W.E., 1964, Possibility of salt-water leakage from proposed intracoastal waterway near Venice, Florida well field, Florida Geological Survey Report of Investigations 38, 33 p.

Clayton, J.M., 1999, ROMP 12, Prairie Creek, Final report-Drilling and testing program, Southern District Water-Resources Assessment Project, De Soto County, Florida: Brooksville, Southwest Florida Water Management District.

Coplen, T.B., 1994, Reporting of stable hydrogen, carbon, and oxygen isotopic abundances. Pure and Applied Chemistry, v. 66, p. 273-276.

Coplen, T.B., Wildman, J.D., and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibration technique for hydrogen isotope ratio analysis: Analytical Chemistry, v. 63, p. 910-912.

Craig, H., 1961, Standard for reporting concentrations of deuterium and oxygen-18 in natural waters: Science, v. 133, p. 1833-1834.

Decker, J.L., 1988, Executive summary, ROMP 17, Horse Creek, De Soto County, Florida: Brooksville, Southwest Florida Water Management District, 15 p.

Deines, P., Langmuir, D., and Harmon, R.S., 1974, Stable carbon isotope ratios and the existence of a gas phase in the evolution of carbonate ground waters, Geochimica et Cosmochimica Acta, v. 38, 1147-1164.

Duerr, A.D., and Enos, G.M., 1991, Hydrogeology of the intermediate aquifer system and Upper Floridan aquifer, Hardee and De Soto Counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4104, 46 p.

Duerr, A.D., Hunn, J.M., Lewelling, B.R., and Trommer, J.T., 1988, Geohydrology and 1985 water withdrawals of the aquifer systems in southwest Florida, with emphasis on the intermediate aquifer system: U.S. Geological Survey Water-Resources Investigations Report 87-4259, 115 p.

Duerr, A.D., and Wolansky, R.M., 1986, Hydrogeology of the surficial and intermediate aquifers of central Sarasota County, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4068, 48 p.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, 174 p.

Florida Department of Environmental Protection, 1994, Primary and secondary drinking water standards, *in* Florida Administrative Code, Chapters 62-520 and 62-550, Tallahassee, Fla.

Fontes, J.-Ch., and Garnier, J.M., 1979, Determination of the initial ^{14}C activity of the total dissolved carbon: A review of existing models and a new approach: Water Resources Research, v. 15, no. 2: p. 399-413.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood, N.J., Prentice-Hall, 604 p.

Fritz, B., 1985, Multicomponent solid solutions for clay minerals and computer modeling of weathering processes, *in* Drever, J.I., ed., The chemistry of weathering: NATO ASI Serial C., v. 149, p. 19-34.

Gates, T.M., 1997a, ROMP 5, Cecil Webb monitor well site, Charlotte County, Florida, Core drilling and testing: Brooksville, Southwest Florida Water Management District, v. 1, 14 p.

Gates, T.M., 1997b, ROMP 5, Cecil Webb monitor well site, Charlotte County, Florida, Monitor well construction and aquifer performance testing: Brooksville, Southwest Florida Water Management District, v. 3 and 4, 11 p.

Gates, T.M., 1998a, ROMP 9.5, Intermediate aquifer system monitor well site, De Soto County, Florida, Core drilling and testing: Brooksville, Southwest Florida Water Management District, 11 p.

Gates, T.M., 1998b, ROMP 25, Monitor well site, Hardee County, Florida, Phase one, Core drilling and testing: Brooksville, Southwest Florida Water Management District, 31 p.

Gilboy, A.E., 1985, Hydrogeology of the Southwest Florida Water Management District: Brooksville, Southwest Florida Water Management District, 18 p.

Gill, T.E., Murray, W., and Wright, M.H., 1981, Practical optimization: Orlando, Fla., Academic Press, Inc., 401 p.

Gonfiantini, R., 1981, The d-notation and the mass-spectrometric measurement techniques, *in* J.R., Gat, and R., Gonfiantini, eds., Stable isotope hydrology: Deuterium and oxygen-18 in the water cycle: Vienna, Austria, International Atomic Energy Agency, chap. 4, p. 35-84.

Hach Company, 1989, Water analysis handbook: Loveland, Colorado, 689 p.

Halford, K.J., 1992, Incorporating reservoir characteristics for automatic history matching: Baton Rouge, Louisiana State University, Ph.D. dissertation, 150 p.

Hanshaw, B.B., and Back, William, 1972, On the origin of dolomites in the Tertiary aquifer of Florida, *in* Puri, H.S., ed., Proceedings of the Seventh Forum on Geology of Industrial Minerals: Tallahassee, Florida Bureau of Geology Special Publication no. 17, p. 139-153.

Hanshaw, B.B., Back, William, and Deike, R.G., 1971, A geochemical hypothesis for dolomitization by ground water: Economic Geology, v. 66, p. 710-724.

Hanshaw, B.B., Back, William, and Rubin, Meyer, 1965, Carbonate equilibria and radiocarbon distribution related to groundwater flow in the Floridan limestone aquifer, U.S.A.: International Association of Scientific Hydrology, Symposium of Dubrovnik, p. 601-614.

Hantush, M.S., 1960, Modification of the theory of leaky aquifers: Journal of Geophysical Research, v. 65, no. 11, p. 3713-3725.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 264 p.

Hobbie, A.E., 1993, Chemical variation in groundwater composition with depth through a lithologically heterogeneous carbonate aquifer system: Charlottesville, University of Virginia, M.S. Thesis, 170 p.

Hsu, K.J., 1963, Solubility of dolomite and composition of Florida ground waters: Journal of Hydrology, v. 1, p. 288-310.

Hutchinson, C.B., 1992, Assessment of hydrogeologic conditions with emphasis on water quality and wastewater injection, southwest Sarasota and Charlotte Counties, Florida: U.S. Geological Survey Water-Supply Paper 2371, 74 p.

HydroSOLVE, Inc., 1996, AQTESOLV for Windows: Reston, Va., 84 p.

Jacob, C.E., 1946, Radial flow in a leaky artesian aquifer; American Geophysical Union Transactions, v. 27, p. 198-205.

Joyner, B.F., and Sutcliffe, H., Jr., 1976, Water resources of Myakka River basin area, southwest Florida: U.S. Geological Survey Water-Resources Investigations Report 76-58, 87 p.

Kauffman, S.J., 1994, The geochemical effects of confining units on the groundwater evolution of a lithologically heterogeneous carbonate aquifer: Charlottesville, University of Virginia, M.S., Thesis, 113 p.

Kauffman, S.J., Herman, J.S., and Jones, B.F., 1998, Lithological and hydrological influences on groundwater composition in a heterogeneous carbonate-clay aquifer system: Geological Society of America Bulletin, v. 110, no. 9, p. 1163-1173.

Knochenmus, L.A., and Bowman, Geronia (Moe), 1998, Transmissivity and water quality of water-producing zones in the intermediate aquifer system, Sarasota County, Florida: U.S. Geological Survey Water-Resources Investigations Report 98-4091, 27 p.

Kruseman, G.P., and de Ridder, N.A., 1991, Analysis and evaluation of pumping test data: Publication 47: Wageningen, The Netherlands, International Institute for Land Reclamation and Improvement, 307 p.

Landmeyer, J.E., and Stone, P.A., 1995, Radiocarbon and d^{13}C values related to ground-water recharge and mixing: Ground Water, v. 33, no. 2, p. 227-234.

Lewelling, B.R., 1988, Potentiometric surface of the intermediate aquifer system, west-central Florida, September 1987: U.S. Geological Survey Open-File Report 88-303, 1 sheet.

McCartan, Lucy, Duerr, A.D., and R.M., Hawkins, 1992, Magnesium-rich clay minerals in Tertiary carbonate rocks of southwestern Florida, *in* Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey Workshop on the Geology and Geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 121-128.

McCartan, Lucy, Plummer, L.N., Hosterman, J.W., Busenburg, E., Dwornik, E.J., Duerr, A.D., Miller, R.L., and Kiesler, J.L., 1992, Celestine ($SrSO_4$) in Hardee and De Soto Counties, Florida, *in* Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey Workshop on the Geology and Geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 129-138.

McCartan, Lucy, Weedman, S.D., Wingard, G.L., and Edwards, L.E., 1995, Age and diagenesis of the Upper Floridan aquifer and the intermediate aquifer system in southwestern Florida: U.S. Geological Survey Bulletin 2122, 26 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

McMahon, P.B., Williams, D.F., and Morris, J.T., 1990, Production and carbon isotopic composition of bacterial CO_2 in deep Coastal-Plain sediments of South Carolina: Ground Water, v. 28, p. 693-702.

Metz, P.A., and Brendle, D.L., 1996, Potential for water-quality degradation of interconnected aquifers in west-central Florida: U.S. Geological Survey Water-Resources Investigations Report 96-4030, 54 p.

Michel, R.M., 1989, Tritium deposition in the continental United States 1953-1983, U.S. Geological Survey Water Resources Investigation 89-4072, 46 p.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama, and South Carolina. U.S. Geological Survey Professional Paper 1403-B, 91 p.

Miller, J.A., 1997, Hydrogeology of Florida, *in* Randazzo, A.F., and Jones, D.S., eds., The Geology of Florida: Gainesville, University Press of Florida, chap 6, p. 69-88.

Missimer, T.M., 1992, Stratigraphic relationships of sediment facies within the Tamiami Formation of southwestern Florida: Proposed intraformational correlations, *in* Scott, T.M., and Allmon, W.D., eds., Plio-Pleistocene stratigraphy and paleontology of southern Florida: Tallahassee, Florida Geological Survey Special Publication no. 25, p. 63-92.

Moore, D.M., and Reynolds, R.C., Jr., 1989, X-ray diffraction and the identification and analysis of clay minerals: New York, Oxford University Press, 333 p.

Neuman, S.P., and Witherspoon, P.A., 1972, Field determination of the hydraulic properties of leaky multiple aquifer systems: Water Resources Research, v. 8, no. 5, p. 1284-1298.

Nordstrom, D.K., Plummer, L.N., Langmuir, D., Busenberg, Eurybiades., May, H.M., Jones, B.F., and Parkhurst, D.L., 1990, Revised chemical equilibrium data for major water-mineral reactions and their limitation, *in* Melchior, D.C., and Basset, R.L., eds., Chemical modeling of aqueous systems II: American Chemical Society Symposium Series 416, p. 398-413.

Peterman, D.C.H., 1997, ROMP 13, Tippen Bay monitor well site, De Soto County, Florida, v. 1, Core drilling and testing: Brooksville, Southwest Florida Water Management District, 13 p.

Plummer, L.N., 1977, Defining reactions and mass transfer in part of the Floridan aquifer: Water Resources Research, v. 13, no. 5, p. 801-812.

Plummer, L.N., Michel, R.L., Thurman, E.M., and Glynn, P.D., 1993, Environmental tracers for age-dating young ground water, *in* Alley, W.A., ed., Regional Ground-Water Quality, New York, Van Nostrand Reinhold, p. 255-294.

Plummer, L.N., Parkhurst, D.L., and Thorstenson, D.C., 1983, Development of reaction models for ground water systems: Geochimica et Cosmochimica Acta, v. 47, p. 665-686.

Plummer, N.L., Prestemon, E.C., and Parkhurst, D.L., 1994, An interactive code (NETPATH) for modeling *net* geochemical reactions along a flow path, Version 2: U.S. Geological Survey Water-Resources Investigations Report 94-4169, 130 p.

Randazzo, A.F., 1997, The sedimentary platform of Florida: Mesozoic to Cenozoic, *in* Randazzo, A.F., and Jones, D.S., eds., The Geology of Florida: Gainesville, University Press of Florida, chap 4, p. 39-56.

Ryder, P.D., 1982, Digital model of predevelopment flow in the Tertiary limestone (Floridan) aquifer system in west-central Florida: U.S. Geological Survey Water-Resources Investigations 81-54, 61 p.

Ryder, P.D., 1985, Hydrology of the Floridan Aquifer System in west-central Florida: U.S. Geological Survey Professional Paper 1403-F, 63 p.

Sacks, L.A., and Tihansky, A.B., 1996, Geochemical and isotopic composition of ground water, with emphasis on sources of sulfate, in the Upper Floridan aquifer and intermediate aquifer system in southwest Florida: U.S. Geological Survey Water-Resources Investigations Report 96-4146, 67 p.

Scott, T.M., 1988, The lithostratigraphy of the Hawthorn Group (Miocene) of Florida: Tallahassee, Florida Geological Survey Bulletin no. 59, 148 p.

Scott, T.M., 1997, Miocene to Holocene history of Florida, *in* Randazzo, A.F., and Jones, D.S., eds., The Geology of Florida: Gainesville, University Press of Florida, chap 5, p. 57-67.

Skougstad, M.W., Fishman, M.J., Friedman, L.C., Erdmann, D.E., and Duncan, S.S., editors, 1979, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 626 p.

Southeastern Geological Society, 1986, Hydrogeological units of Florida: Tallahassee, Florida Bureau of Geology Special Publication 28, 9 p.

Southwest Florida Water Management District, 1991, Ground-water quality of the Southwest Florida Water Management District, southern region, section 2: Ambient Ground-Water Quality Monitoring Program: Brooksville, Fla., 275 p.

Southwest Florida Water Management District, 1994, Aquifer characteristics within the Southwest Florida Water Management District: Brooksville, Fla., 111 p.

Sprinkle, C.L., 1989, Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-I, 105 p.

Stuiver, M., and Polach, H.A., 1977, Reporting of ^{14}C data: Radiocarbon, v. 19, p. 355-363.

Sutcliffe, H., Jr., 1975, Appraisal of the water resources Charlotte County, Florida: Tallahassee, Florida Geological Survey Report of Investigations 78, 53 p.

Sutcliffe, H., Jr., and Thompson, T.H., 1983, Occurrence and use of ground water in the Venice-Englewood area, Sarasota and Charlotte Counties, Florida: U.S. Geological Survey Open-File Report 82-700, 59 p.

Thompson, D.L., 1997, ROMP 9, North Port monitor well site, Sarasota County, Florida, Drilling and testing report: Brooksville, Southwest Florida Water Management District, 27 p.

Torres, A.E., Broska, J.C., and Corral, M.A., 1999, Potentiometric surface of the Upper Floridan aquifer, west-central Florida, September 1998: U.S. Geological Survey Open-File Report 99-225, 1 sheet.

Vacher, H.L., Jones, G.W., and Stebnisky, R.J., 1992, Heterogeneity of the surficial aquifer system in west central Florida: Tallahassee, Florida Geological Survey Special Publication No. 36, p. 93-99.

Vail, P.R., and Mitchum, R.M., Jr, 1979, Global Cycles of relative changes of sea level from seismic stratigraphy, in Watkins, J.S., Montadert, L., and Dickerson, P.W., eds., Geological and geophysical investigations of continental margins: American Association of Petroleum Geologists Mem. 29, p. 469-472

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level. American Association of Petroleum Geologists Memoir no. 26, p. 49-212.

White, W.A., 1970, The geomorphology of the Florida peninsular: Tallahassee, Florida Bureau of Geology Bulletin 51, 164 p.

Wigley, T.M.L., and Muller, A.B., 1981, Fractionation corrections in radiocarbon dating: Radiocarbon, v. 23, p. 173-190.

Wilson, W.E., 1977, Ground water resources of DeSoto and Hardee Counties, Florida: Tallahassee, Florida Bureau of Geology, Report of Investigation 83, 102 p.

Wolansky, R.M., 1983, Hydrogeology of the Sarasota-Port Charlotte area, Florida: U.S. Geological Survey Water-Resources Investigations Report 82-4089, 48 p.

Wolansky, R.M., and Corral, M.A., 1985, Aquifer tests in west-central Florida, 1952-76: U.S. Geological Survey Water Resources Investigations Report 84-4044, 127 p.

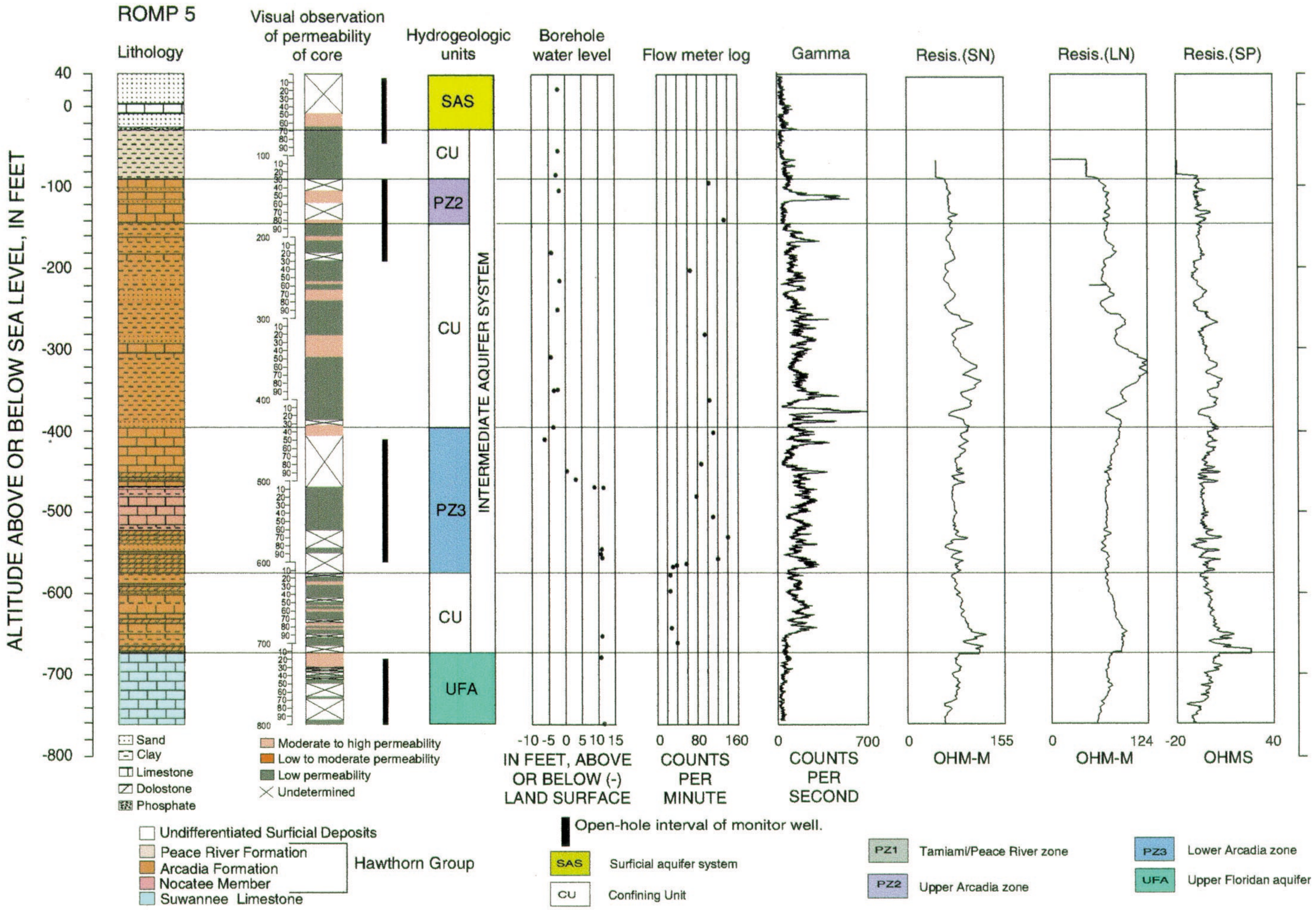
Wood, W.W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water-Resources Investigations, book 1, chap. D2, 24 p.

APPENDICES

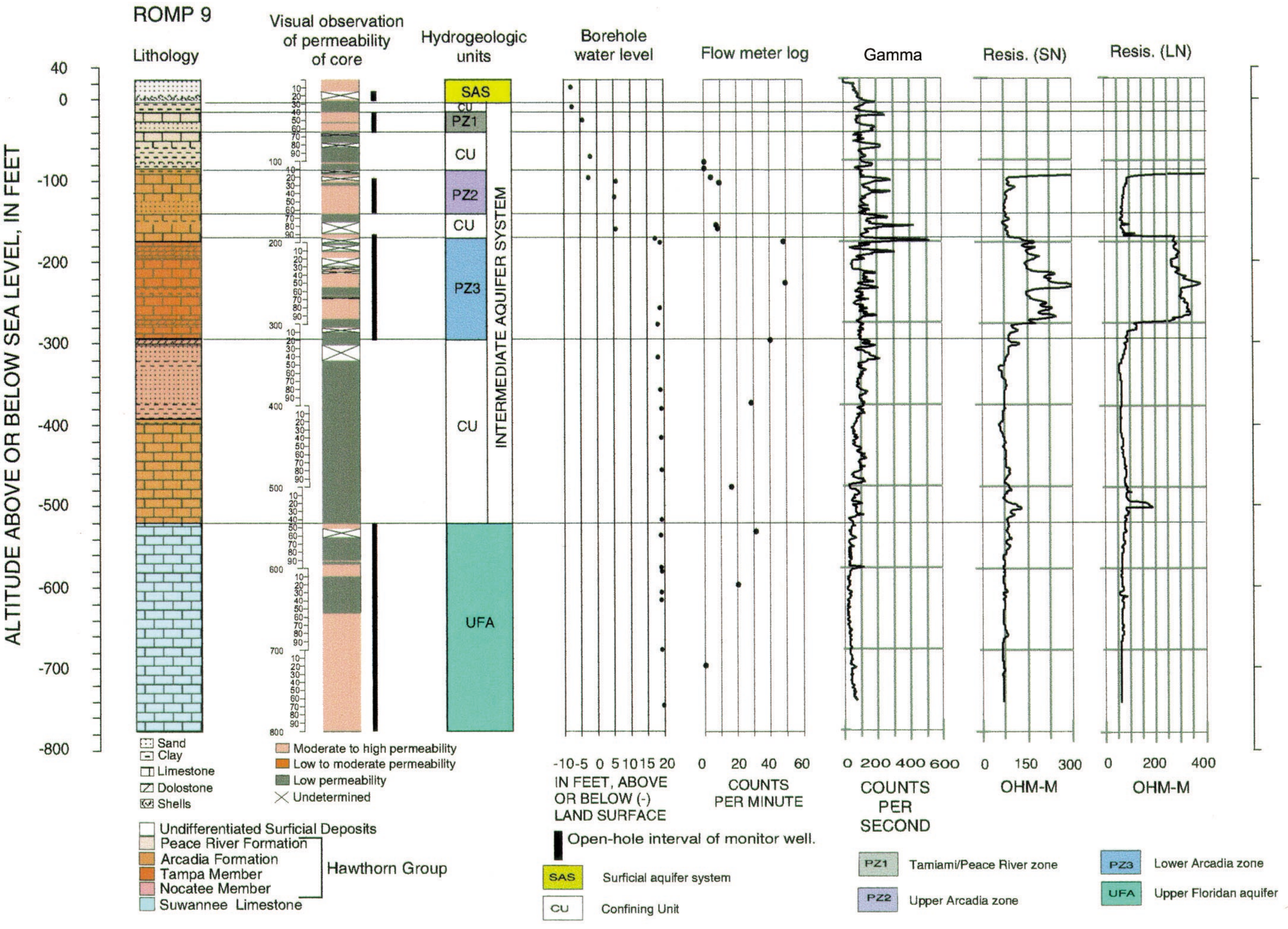
Appendix A. Depth of geologic formations determined by the Florida Geological Survey (FGS) at the ROMP 5, 9, 9.5, 12, 13, and 17 sites

[ft, feet; lsd, land surface datum; msl, mean sea level; na, not available]

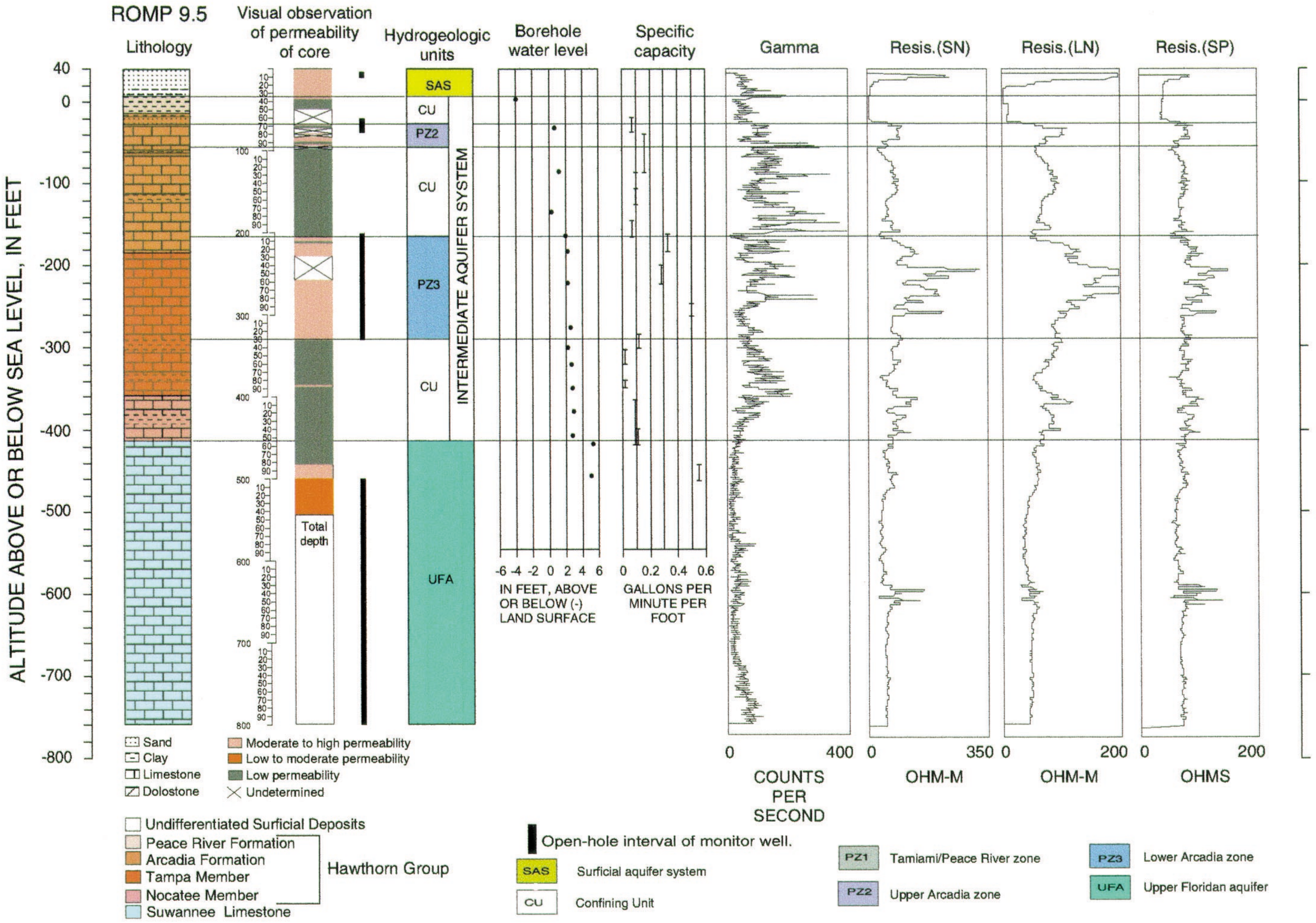
Site	Well identification number	Land surface datum[1]	Lithologic unit	Thickness in ft	Top below lsd in ft	Bottom below lsd in ft	Top above or below msl in ft	Bottom above or below msl in ft
ROMP 5	W-16913	40	Undifferentiated Surficial Deposits	69	0	69	40	-29
			Peace River Formation	59	69	128	-29	-88
			Undifferentiated Arcadia Formation (upper unit)	380	128	508	-88	-468
			Nocatee Member	53	508	561	-468	-521
			Undifferentiated Arcadia Formation (lower unit)	150	561	711	-521	-671
			Suwannee Limestone	278	711	989	-671	-949
			Ocala Limestone	281	989	1,270	-949	-1230
			Avon Park Formation	na	1,270	na	-1230	na
ROMP 9	W-17056	25	Undifferentiated Surficial Deposits	28	0	28	25	-3
			Peace River Formation	81	28	109	-3	-84
			Undifferentiated Arcadia Formation (upper unit)	89	109	198	-84	-173
			Tampa Member	119	198	317	-173	-292
			Nocatee Member	100	317	417	-292	-392
			Undifferentiated Arcadia Formation (lower unit)	128	417	545	-392	-520
			Suwannee Limestone	320	545	865	-520	-840
			Ocala Limestone	284	865	1,149	-840	-1124
			Avon Park Formation	na	1,149	na	-1124	na
ROMP9.5	W-17597	38	Undifferentiated Surficial Deposits	34	0	34	38	4
			Peace River Formation	19	34	53	4	-15
			Undifferentiated Arcadia Formation (upper unit)	171	53	224	-15	-186
			Tampa Member	174	224	398	-186	-360
			Nocatee Member	56	398	454	-360	-416
ROMP 12	W-16578	41	Undifferentiated Surficial Deposits	40	0	40	41	1
			Peace River Formation	136	40	176	1	-135
			Undifferentiated Arcadia Formation (upper unit)	230	176	406	-135	-365
			Nocatee Member	196	406	602	-365	-561
			Undifferentiated Arcadia Formation (lower unit)	117	602	719	-561	-678
			Suwannee Limestone	186	719	905	-678	-864
			Ocala Limestone	227	905	1,132	-864	-1,091
			Avon Park Formation	958	1,132	2,090	-1091	-2,049
ROMP 13	W-17396	60	Undifferentiated Surficial Deposits	19	0	19	60	41
			Peace River Formation	188	19	207	41	-147
			Undifferentiated Arcadia Formation (upper unit)	322	207	529	-147	-469
			Nocatee Member	136	529	665	-469	-605
			Undifferentiated Arcadia Formation (lower unit)	34	665	699	-605	-639
			Suwannee Limestone	78	699	777	-639	-717
			Ocala Limestone	284	777	1,061	-717	-1001
			Avon Park Formation	na	1,061	na	-1001	na
ROMP 17	W-15303	22	Undifferentiated Surficial Deposits	26	0	26	22	-4
			Peace River Formation	53	26	79	-4	-57
			Undifferentiated Arcadia Formation (upper unit)	100	79	179	-57	-157
			Tampa Member	113	179	292	-157	-270
			Nocatee Member	147	292	439	-270	-417
			Suwannee Limestone	401	439	840	-417	-818
			Ocala Limestone	275	840	1,115	-818	-1093
			Avon Park Formation	na	1,115	na	-1093	na



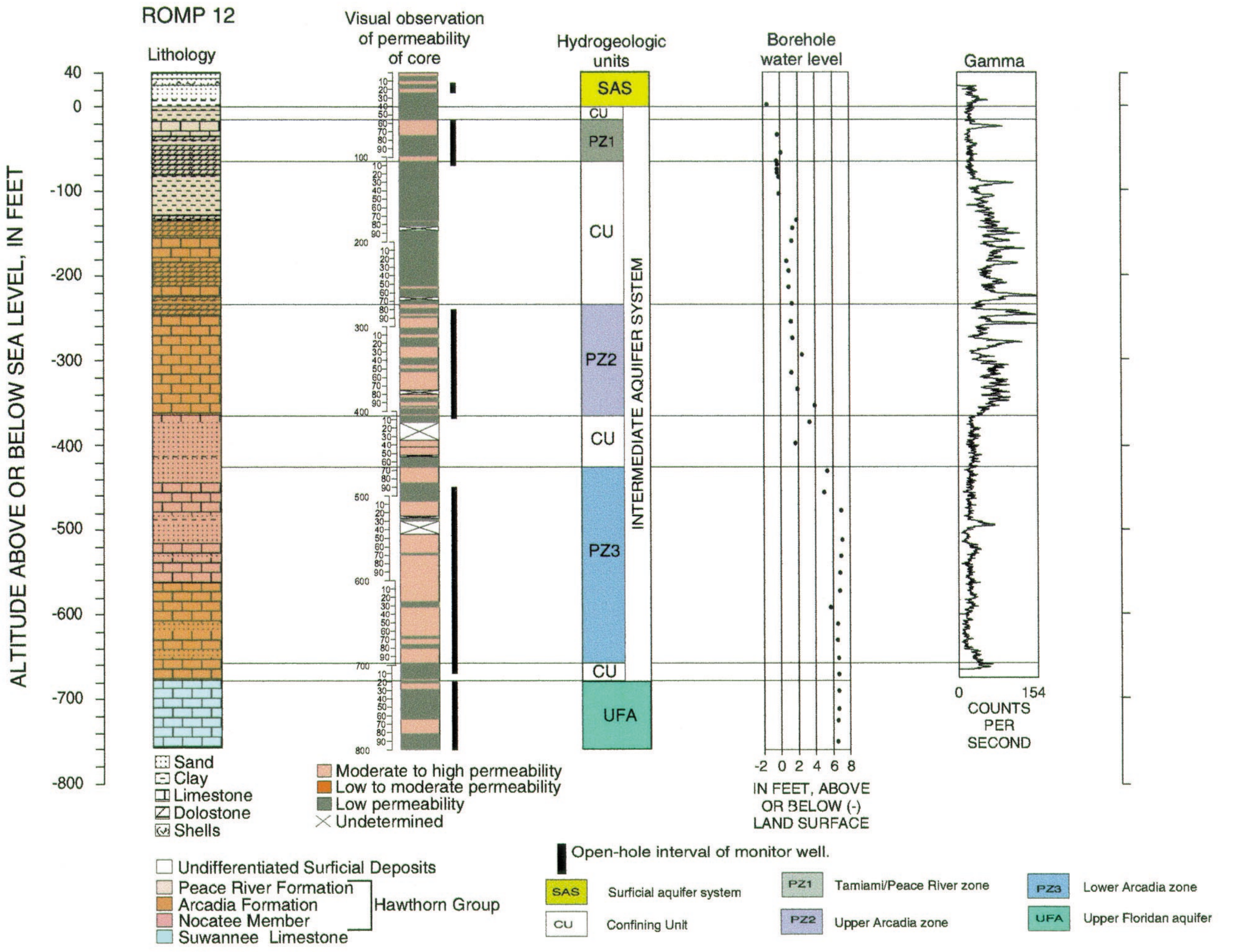
Appendix B. Hydrogeologic, lithostratigraphic, and borehole geophysical data collected at the ROMP 5, 9, 9.5, 12, 13, and 17 sites.



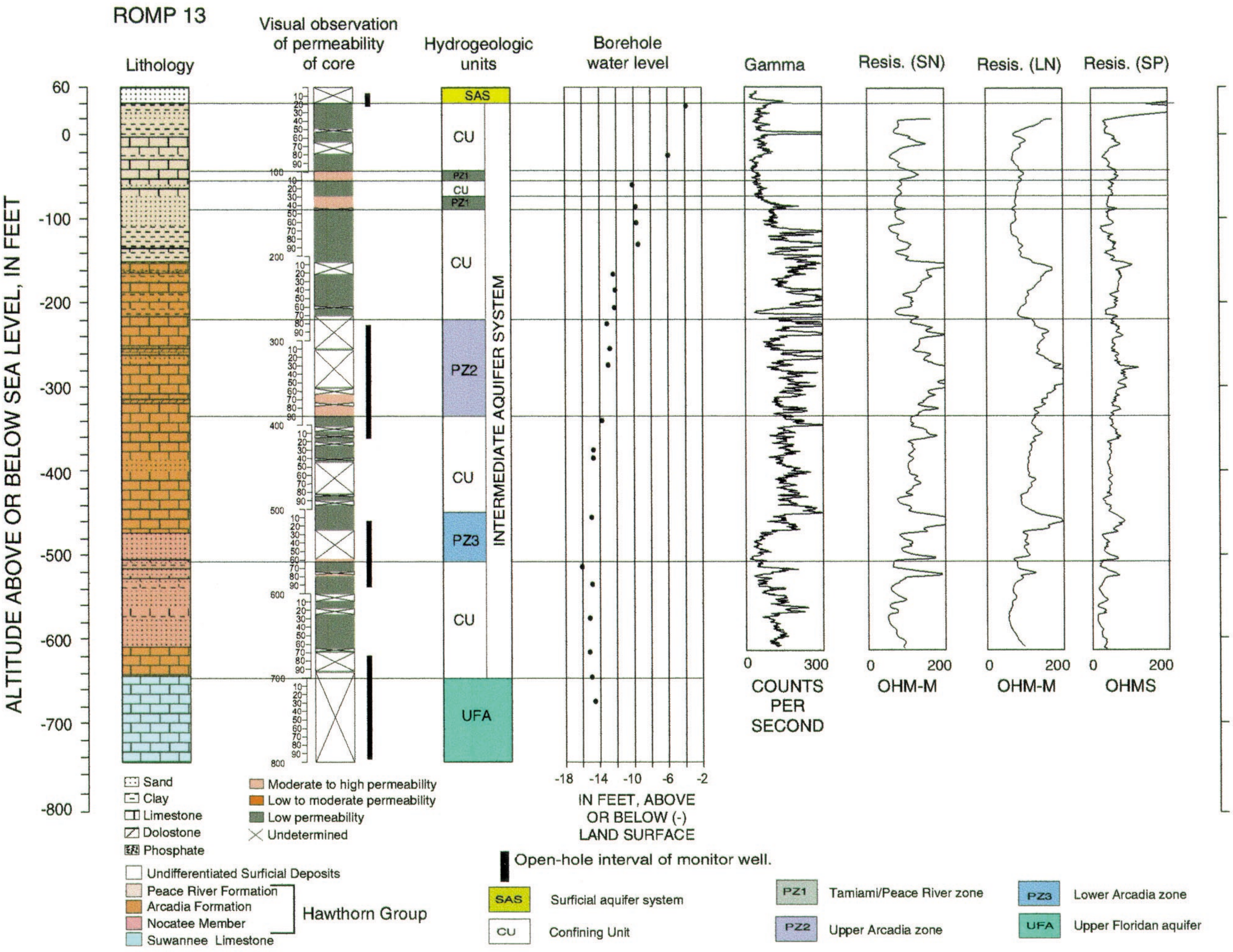
Appendix B. Hydrogeologic, lithostratigraphic, and borehole geophysical data collected at the ROMP 5, 9, 9.5, 12, 13, and 17 sites.--Continued



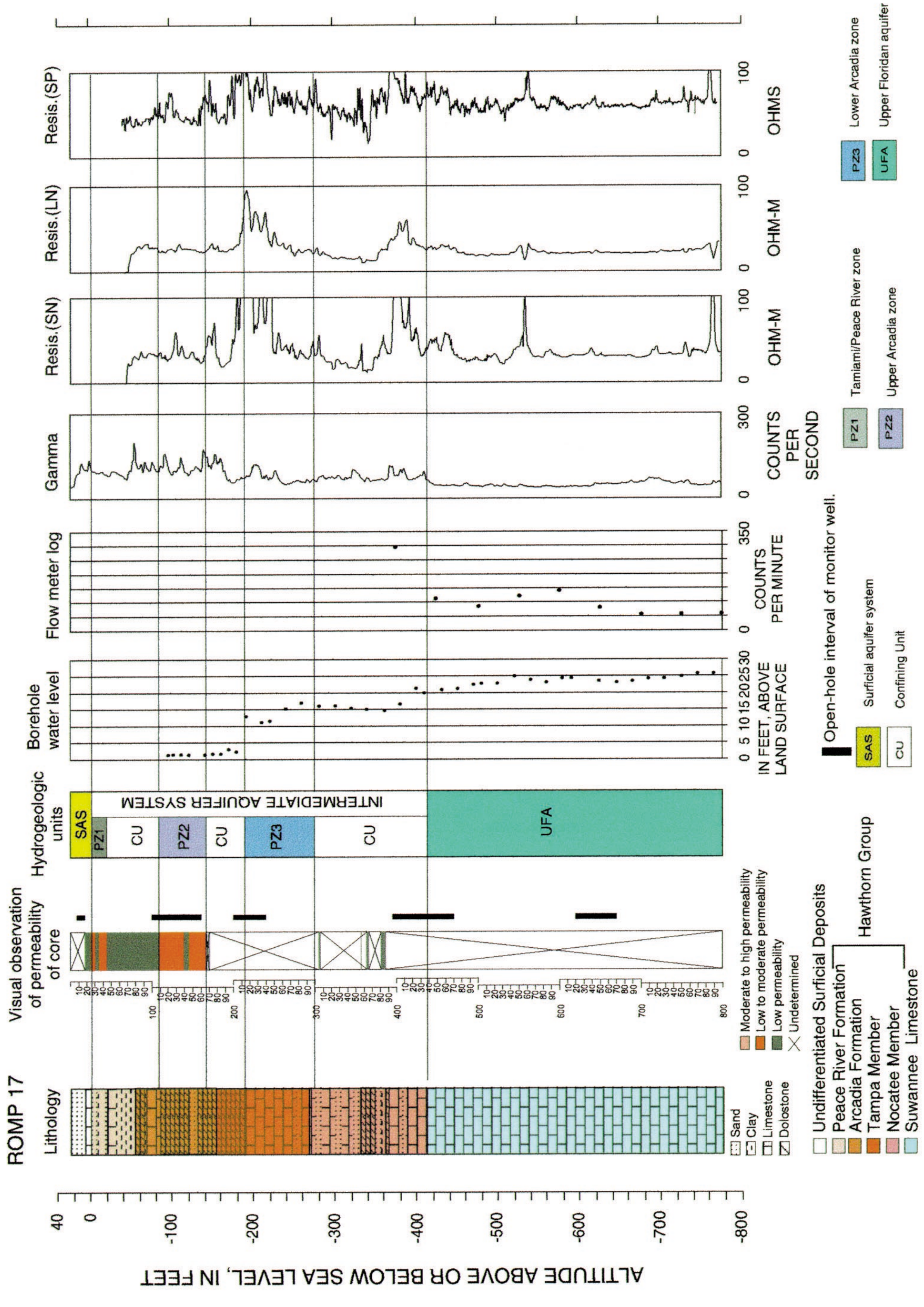
Appendix B. Hydrogeologic, lithostratigraphic, and borehole geophysical data collected at the ROMP 5, 9, 9.5, 12, 13, and 17 sites.--Continued



Appendix B. Hydrogeologic, lithostratigraphic, and borehole geophysical data collected at the ROMP 5, 9, 9.5, 12, 13, and 17 sites.--Continued



Appendix B. Hydrogeologic, lithostratigraphic, and borehole geophysical data collected at the ROMP 5, 9, 9.5, 12, 13, and 17 sites.--Continued



Appendix B. Hydrogeologic, lithostratigraphic, and borehole geophysical data collected at the ROMP 5, 9, 9.5, 12, 13, and 17 sites.--Continued

Appendix C. Classification criteria used to describe the hydrogeologic units at the ROMP 5, 9, 9.5, 12, 13, and 17 sites

[SAS, surficial aquifer system; CU, confining unit of the intermediate aquifer system; PZ1, permeable zone 1 in the Tamiami/Peace River Formation; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; BH, borehole data; GP, geophysical data; WQ, water-quality data]

Site	Hydrogeo-logic unit	Depth below land surface, in feet	Depth above (+) or below (-) sea level, in feet	Criteria
ROMP 5	SAS	0-69	+40-29	Lithology: unconsolidated quartz sand and shell beds with porosity ranging from 15-50 percent; possibly high permeability from 49-64 ft bls (app. B); GP: gamma peak at about 64 ft
	CU	69-128	-29-88	Lithology: persistent low permeability clay and phosphatic sediments
	PZ2	128-184	-88-144	Lithology: visual observation of permeable sediments from 144 to 159 ft; BH: water-level rise below 128 ft; GP: higher formation resistivity from about 128 to 190 ft
	CU	184-433	-144-393	Lithology: persistent low permeability sediments, although some permeable sediments are contained within; BH: decrease in flow below 180 ft
	PZ3	433-613	-393-573	BH: water-level rise below 450 ft; end of production on flow log; WQ: rise in specific conductance, chloride, and sulfate below 450 ft (fig. 23)
	CU	613-711	-573-671	Lithology: persistent low permeability sediments, although some permeable sediments are contained within
	UFA	711	-671	Lithology: top of Suwannee Limestone picked at 711 ft; GP: gamma radiation decreases significantly below 711 ft; WQ: increase in chloride concentration below 740 ft
ROMP 9	SAS	0-28	+25-3	Lithology: unconsolidated, high permeability quartz sand and shell beds; GP: gamma peak at 28 ft bls (app. B)
	CU	28-40	-3-15	Lithology: persistent low permeability clay and chert sediments
	PZ1	40-64	-15-39	Unnamed permeable zone within the Peace River Formation, probably discontinuous; Lithology: bottom of chert bed; top of high permeability limestone and sand sediments; BH: water-level rise below 40 ft; WQ: field specific conductance, chloride, and sulfate different than in underlying PZ2 (fig. 23)
	CU	64-112	-39-87	Lithology: top of persistent low permeability sediments, although some permeable sediments are contained within
	PZ2	112-165	-87-140	Lithology: high permeability limestone and sand sediments; BH: water-level rise below 119 ft; increase in flow below 120 ft; GP: gamma kick at bottom; WQ: increase in field conductance, chloride, and sulfate at 124 ft
	CU	165-195	-140-170	Lithology: persistent low permeability carbonate and increase clay content; BH: no significant change in water level or flow; GP: low formation resistivity between 165 and 195 ft; gamma kick at bottom
	PZ3	195-320	-170-295	Lithology: interbedded high and low permeability sediments; BH: rise in water level below 195 ft; GP: high resistivity between 195 and 320 ft; significant rise in flow below 195 ft (may be related to change in borehole diameter)
	CU	320-545	-295-520	Lithology: persistent low permeability sediments; BH: no significant change in water level; GP: low formation resistivity between 320 and 545 ft
	UFA	545	-520	Lithology: top of Suwannee Limestone picked at 545 ft; interbedded high and low permeability sediments below 545 ft; BH: rise in flow between 500 and 555 ft ; GP: gamma radiation decreases below 545 ft

Appendix C. Classification criteria used to describe the hydrogeologic units at the ROMP 5, 9, 9.5, 12, 13, and 17 sites (Continued)

[SAS, surficial aquifer system; CU, confining unit of the intermediate aquifer system; PZ1, permeable zone 1 in the Tamiami/Peace River Formation; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; BH, borehole data; GP, geophysical data; WQ, water-quality data]

Site	Hydrogeo-logic unit	Depth below land surface, in feet	Depth above (+) or below (-) sea level, in feet	Criteria
ROMP 9.5	SAS	0-34	+38+4	Lithology: unconsolidated quartz sand with porosity ranging from 20 to 30 percent;
	CU	34-68	+4-32	Lithology: low permeability clay and low porosity carbonate sediments; BH: low specific capacity; GP: gamma peak at 37 ft (app. B); low formation resistivity from 37 to 68 ft
	PZ2	68-95	-32-59	Lithology: interbedded high and low permeability sediments; BH: rise in water level below 74 ft; higher specific capacity than overlying interval; GP: high formation resistivity between 68 and 95 ft
	CU	95-206	-59-170	Lithology: persistent low permeability sediments; BH: decline in water level; low specific capacity; GP: low formation resistivity
	PZ3	206-330	-170-294	Lithology: interbedded high and low permeability sediments; BH: rise in water level; higher specific capacity than overlying CU; GP: high formation resistivity between 206 and 330 ft;
	CU	330-454	-294-418	Lithology: persistent low permeability sediments; BH: no significant change in water level; lower specific capacity than overlying PZ3; GP: low formation resistivity WQ: increase in chloride and sulfate concentration at top (fig. 23)
	UFA	454	-418	Lithology: top of Suwannee Limestone picked at 454 ft; interbedded high and low permeability sediments below 454 ft; BH: rise in water level below 458 ft; high specific capacity in 493 to 513 ft interval; GP: gamma radiation decreases significantly below 454 ft; rise in borehole water temperature and fluid conductance, and decline in fluid resistivity below 475 ft; WQ: rise in field specific conductance, hardness, dissolved solids, magnesium, sulfate, and strontium in the 500 to 800 ft interval.
ROMP 12	SAS	0-40	+41+1	Lithology: unconsolidated, high to low permeability quartz sand, shell, limestone, and phosphate beds (app. B)
	CU	40-57	+1-16	Lithology: persistent low permeability sediments
	PZ1	57-106	-16-65	Unnamed permeable zone within the Peace River Formation, probably discontinuous; Lithology: interbedded high and low permeability sediments; BH: rise in water level at about 70 ft.
	CU	106-275	-65-266	Lithology: persistent low permeability sediments; GP: gamma radiation increases below 125 ft
	PZ2	275-406	-266-397	Lithology: interbedded high and low permeability sediments; GP: gamma radiation decreases at about 275 ft
	CU	406-465	-397-456	Lithology: persistent low permeability sediments; BH: decline in water level at 410 ft; GP: gamma radiation decreases at about 405 ft
	PZ3	465-699	-456-690	Lithology: interbedded high and low permeability sediments; BH: rise in water level at about 470 ft
	CU	699-719	-690-710	Lithology: persistent low permeability sediments; GP: gamma radiation increases at about 699 ft
	UFA	719	-710	Lithology: top of Suwannee Limestone picked at 719 ft; interbedded high and low permeability sediments below 719 ft; GP: small decrease in gamma radiation at 719 ft

Appendix C. Classification criteria used to describe the hydrogeologic units at the ROMP 5, 9, 9.5, 12, 13, and 17 sites (Continued)

[SAS, surficial aquifer system; CU, confining unit of the intermediate aquifer system; PZ1, permeable zone 1 in the Tamiami/Peace River Formation; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; BH, borehole data; GP, geophysical data; WQ, water-quality data]

Site	Hydrogeo-logic unit	Depth below land surface, in feet	Depth above (+) or below (-) sea level, in feet	Criteria
ROMP 13	SAS	0-19	+62+43	Lithology: unconsolidated quartz sand with porosity ranging between 25 and 35 percent; relatively permeable beds (ROMP 13 Tech. Pub., 1998, Phase 2, fig 7); GP: gamma peak at 19 ft (app. B)
	CU	19-99	+43-37	Lithology: relatively impermeable beds (ROMP 13 Tech. Pub., 1998, Phase 2, fig. 7); WQ: increase in chloride at about 26 ft (fig. 23)
	PZ1	99-111	-37-40	Unnamed permeable zone within the Peace River Formation, probably discontinuous; Lithology: interbedded high and low permeability sediments; GP: increase in formation resistivity below 99 ft
	CU	111-129	-40-58	Lithology: persistent low permeability sediments; GP: decrease in formation resistivity between 111 and 129 ft
	PZ1	129-144	-58-73	Unnamed permeable zone within the Peace River Formation, probably discontinuous; Lithology: interbedded high and low permeability sediments
	CU	144-275	-73-204	Lithology: persistent low permeability sediments; GP: gamma radiation increases at about 144 ft
	PZ2	275-390	-204-319	Lithology: relatively permeable beds (ROMP 13 Tech. Pub., 1998, Phase 2, fig. 7); BH: decline in water level below 260 ft; GP: high formation resistivity between 275 and 390 ft
	CU	390-505	-319-443	Lithology: relatively impermeable beds (ROMP 13 Tech. Pub., 1998, Phase 2, fig. 7); BH: decline in water level below 420 ft; GP: low formation resistivity; WQ: increase in sulfate at about 420 ft
	PZ3	505-562	-443-500	Lithology: relatively permeable beds (ROMP 13 Tech. Pub., 1998, Phase 2, fig. 7); GP: high formation resistivity; WQ: slightly higher chloride and sulfate concentration than in PZ2
	CU	562-699	-500-637	Lithology: relatively impermeable beds (ROMP 13 Tech. Pub., 1998, Phase 2, fig. 7); GP: low formation resistivity; WQ: increase in chloride and sulfate concentration at about 680 ft
	UFA	699	-637	Lithology: top of Suwannee Limestone picked at 699 ft; interbedded high and low permeability sediments below 699 ft; GP: gamma radiation decreases significantly below 699 ft

Appendix C. Classification criteria used to describe the hydrogeologic units at the ROMP 5, 9, 9.5, 12, 13, and 17 sites (Continued)

[SAS, surficial aquifer system; CU, confining unit of the intermediate aquifer system; PZ1, permeable zone 1 in the Tamiami/Peace River Formation; PZ2, permeable zone 2 in the Upper Arcadia Formation; PZ3, permeable zone 3 in the Lower Arcadia Formation; UFA, Upper Floridan aquifer; BH, borehole data; GP, geophysical data; WQ, water-quality data]

Site	Hydrogeo-logic unit	Depth below land surface, in feet	Depth above (+) or below (-) sea level, in feet	Criteria
ROMP 17	SAS	0-26	+23-3	Lithology: unconsolidated quartz sand with porosity ranging between 10 and 30 percent; low porosity and low permeability limestone (Tamiami Fm.) from 18 to 26 ft, not an economical water-bearing unit (Decker, 1988, SWFWMD)
	PZ1	26-45	-3-22	Unnamed permeable zone within the Peace River Formation (app.B), probably discontinuous; Lithology: water-bearing beds from 26 to 31 and 35 to 45 ft (Decker, 1988, SWFWMD)
	CU	45-109	-22-86	Lithology: low permeability clay and carbonate sediments (Decker, 1988, SWFWMD)
	PZ2	109-167	-86-141	Lithology: major water-bearing interval 109-167 ft described by Decker (1988);bottom of interval overlies clayey dolostone; GP: high formation resistivity units within the interval
	CU	167-214	-141-191	Lithology: Dolostone with 10-20 percent clay from 167-179 ft; GP: increase in gamma radiation at about 167 ft; low formation resistivity
	PZ3	214-299	-191-276	Lithology: described by Decker (1988) as a major water-bearing interval; previous pick of bottom by Duerr (1986); this is the base of the Tampa LS; BH: rise in water level below 204 ft; GP: high formation resistivity between 205 and 250 ft; WQ: increase in chloride and sulfate concentration at about 275 ft (fig. 23)
	CU	299-439	-276-416	Lithology: interval from 363 to 390 ft appears to have confining properties (Decker, 1988); previous pick by Duerr (1986, and 1991 work notes); BH: decline in water level below 335 ft; GP: low formation resistivity in interval from 335 to 390 ft
	UFA	439	-416	Lithology: top of Suwannee Limestone picked at 439 ft (app. B); interbedded high and low permeability sediments below 390 ft; BH: rise in water level below 384 ft; GP: gamma radiation decreases significantly below 439 ft; high formation resistivity below 390 ft; WQ: changes in chloride and sulfate concentrations at about 600ft (fig. 23)