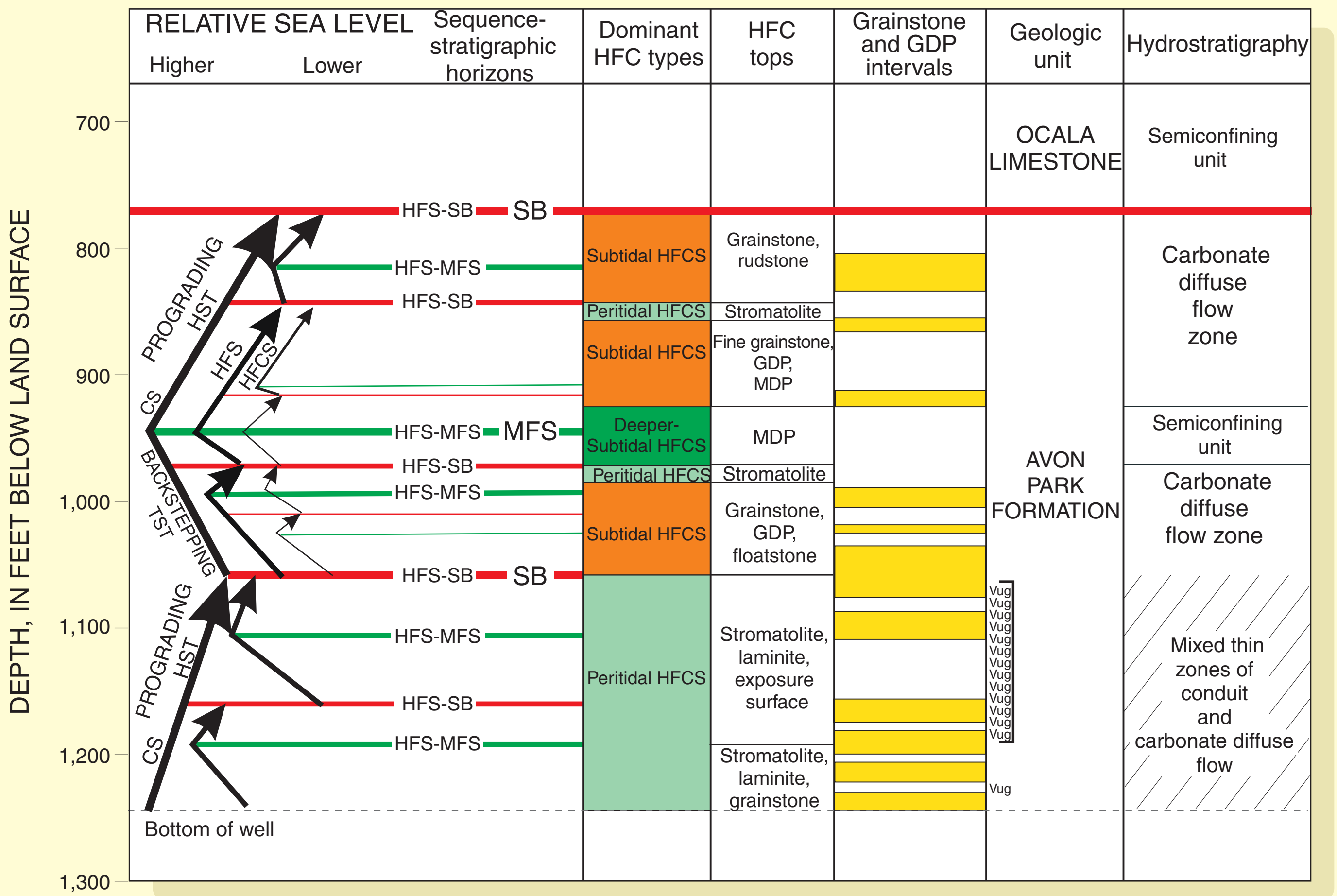
Sequence-Stratigraphic Analysis of the Regional Observation Monitoring Program (ROMP) 29A Test Corehole and its Relation to Carbonate Porosity and Regional Transmissivity in the Floridan Aquifer System, Highlands County, Florida



U.S. Geological Survey
Open-File Report 03-201

Prepared as part of the
Comprehensive Everglades Restoration Program

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By William C. Ward[1], Kevin J. Cunningham[2], Robert A. Renken[2], Michael A. Wacker[2] and Janine I. Carlson[3]

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Tallahassee, Florida
2003

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CONVERSION FACTORS, ACRONYMS, AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day

ACRONYMS

ASR	Aquifer storage and recovery
CERP	Comprehensive Everglades Restoration Plan
HFC	High-frequency cycle
HFCS	High-frequency cycle set
HFS	High-frequency sequence
PVC	Polyvinyl chloride
ROMP	Regional Observation and Monitoring Program
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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ABSTRACT

An analysis was made to describe and interpret the lithology of a part of the Upper Floridan aquifer penetrated by the Regional Observation Monitoring Program (ROMP) 29A test corehole in Highlands County, Florida. This information was integrated into a one-dimensional hydrostratigraphic model that delineates candidate flow zones and confining units in the context of sequence stratigraphy. Results from this test corehole will serve as a starting point to build a robust three-dimensional sequence-stratigraphic framework of the Floridan aquifer system.

The ROMP 29A test corehole penetrated the Avon Park Formation, Ocala Limestone, Suwannee Limestone, and Hawthorn Group of middle Eocene to Pliocene age. The part of the Avon Park Formation penetrated in the ROMP 29A test corehole contains two composite depositional sequences. A transgressive systems tract and a highstand systems tract were interpreted for the upper composite sequence; however, only a highstand systems tract was interpreted for the lower composite sequence of the deeper Avon Park stratigraphic section. The composite depositional sequences are composed of at least five high-frequency depositional sequences. These sequences contain high-frequency cycle sets that are an amalgamation of vertically stacked high-frequency cycles. Three types of high-frequency cycles have been identified in the Avon Park Formation: peritidal, shallow subtidal, and deeper subtidal high-frequency cycles.

The vertical distribution of carbonate-rock diffuse flow zones within the Avon Park Formation is heterogeneous. Porous vuggy intervals are less than 10 feet, and most are much thinner. The volumetric arrangement of the diffuse flow zones shows that most occur in the highstand systems tract of the lower composite sequence of the Avon Park Formation

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as compared to the upper composite sequence, which contains both a backstepping transgressive systems tract and a prograding highstand systems tract. Although the porous and permeable layers are not thick, some intervals may exhibit lateral continuity because of their deposition on a broad low-relief ramp. A thick interval of thin vuggy zones and open faults forms thin conduit flow zones mixed with relatively thicker carbonate-rock diffuse flow zones between a depth of 1,070 and 1,244 feet below land surface (bottom of the test corehole). This interval is the most transmissive part of the Avon Park Formation penetrated in the ROMP 29A test corehole and is included in the highstand systems tract of the lower composite sequence.

The Ocala Limestone is considered to be a semiconfining unit and contains three depositional sequences penetrated by the ROMP 29A test corehole. Deposited within deeper subtidal depositional cycles, no zones of enhanced porosity and permeability are expected in the Ocala Limestone. A thin erosional remnant of the shallow marine Suwannee Limestone overlies the Ocala Limestone, and permeability seems to be comparatively low because moldic porosity is poorly connected.

Rocks that comprise the lower Hawthorn Group, Suwannee Limestone, and Ocala Limestone form a permeable upper zone of the Upper Floridan aquifer, and rocks of the lower Ocala Limestone and Avon Park Formation form a permeable lower zone of the Upper Floridan aquifer. On the basis of a preliminary analysis of transmissivity estimates for wells located north of Lake Okeechobee, spatial relations among groups of relatively high and low transmissivity values within the upper zone are evident. Upper zone transmissivity is generally less than 10,000 feet squared per day in areas located south of a line that extends through Charlotte, Sarasota, DeSoto, Highlands, Polk, Osceola, Okeechobee, and St. Lucie Counties. Transmissivity patterns within the lower zone of the Avon Park Formation cannot be regionally assessed because insufficient data over a wide areal extent have not been compiled.

INTRODUCTION

Implementation of carbonate sequence stratigraphy can have a dramatic impact on development of an accurate stratigraphic interpretation that can be integrated into a conceptual carbonate-aquifer hydrogeologic model (Loizeaux, 1995). Carbonate sequence-stratigraphic methods offer the best correlation strategy that can reduce the risk of miscorrelating critical carbonate aquifer flow zones and confining units, as Kerans and Tinker (1997) have discussed its application to the petroleum industry. A regional sequence-stratigraphic framework has not been developed previously for all the Tertiary marine carbonates included in the Floridan aquifer system throughout southern Florida, but has for part of the carbonate rocks of the Floridan aquifer system in west-central Florida ((Hammes, 1992; Loizeaux, 1995; Budd, 2001). Carbonate rocks of the Upper Floridan aquifer have been targeted as injection zones for aquifer storage and recovery (ASR) projects as part of the Comprehensive Everglades Restoration Plan (CERP). As a result, it is critical that their sequence stratigraphy be developed to reduce the risk of failure of CERP-ASR projects.

In 2002, the U.S. Geological Survey (USGS) initiated a study, which is part of the CERP and authorized by the U.S. Army Corps of Engineers, to describe and interpret the lithology of part of the Upper Floridan aquifer in a single continuous corehole and integrate this information into a

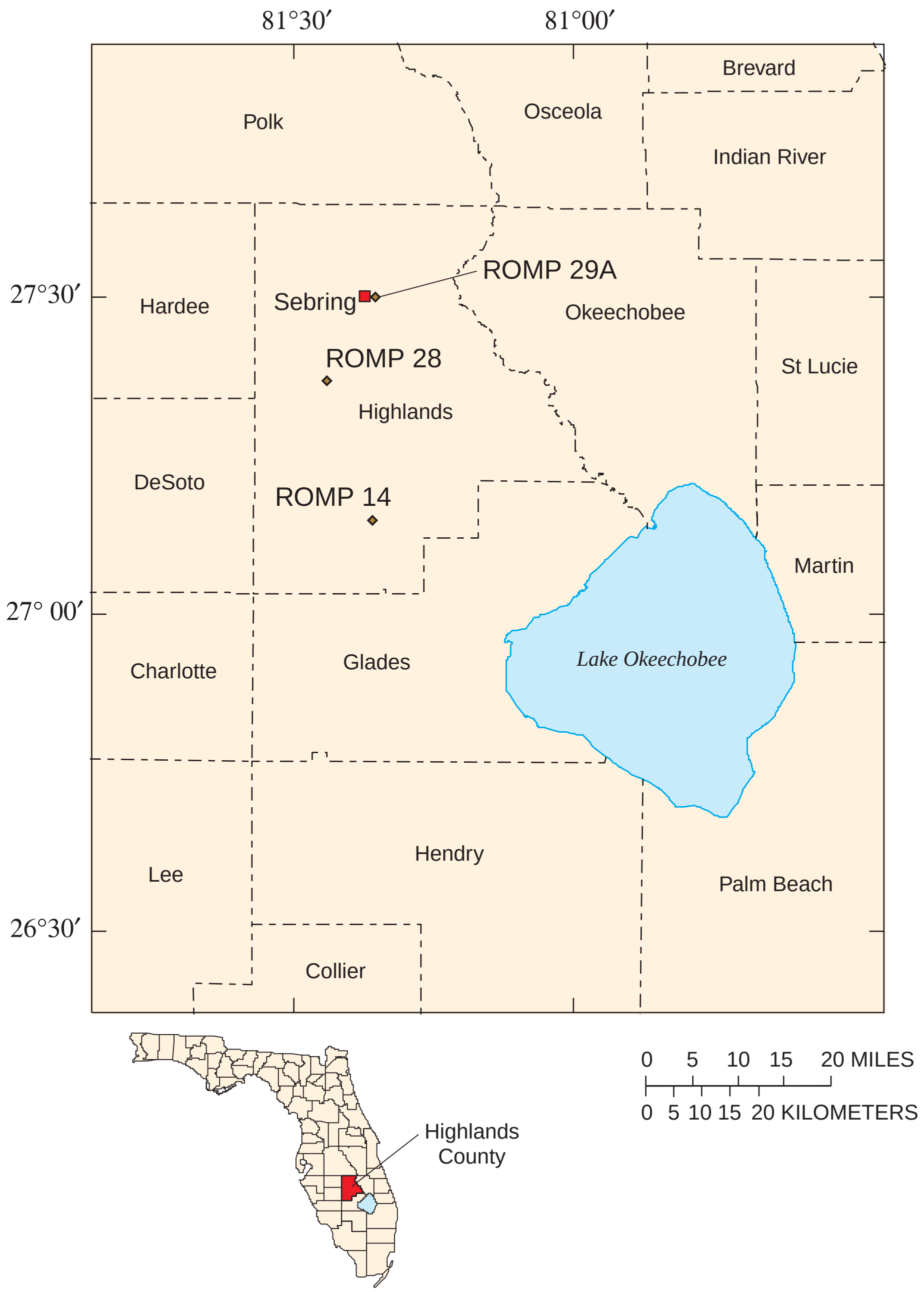


Figure 1. Location of ROMP test coreholes in Highlands County, Florida, included in this study. (ROMP is Regional Observation and Monitoring Program.)

one-dimensional hydrostratigraphic model to delineate candidate flow zones and confining units in the context of sequence stratigraphy. The Regional Observation Monitoring Program (ROMP) 29A test corehole was used for the evaluation. This test corehole site is located near Sebring in northern Highlands County, south-central Florida (fig. 1). The analysis of existing core samples from the ROMP 29A test corehole represents an early phase task authorized by the CERP Regional ASR Project Management Team. The effort provides insight into the thickness and stratigraphic distribution of zones of transmissivity within the Upper Floridan aquifer.

Purpose and Scope

The purpose of this report is to describe and interpret the lithology of part of the Upper Floridan aquifer penetrated by the ROMP 29A test corehole in Highlands County, Florida, and to integrate this information into a hydrogeologic model that delineates potential carbonate flow zones and confining units in the context of a sequence-stratigraphic framework. The report provides a detailed description of the uppermost 475 ft of the Avon Park Formation of middle Eocene age, Ocala Limestone of late Eocene age, and Suwannee Limestone of late Eocene and Oligocene ages. Attention is given to the stratigraphic distribution and thickness of porous and permeable zones and their relation to a sequence-stratigraphic framework established from this core. Lithologic descriptions are based on examination of 834 ft of slabbed core and 59 petrographic thin sections, and include petrologic and microfaunal analyses to determine the mineralogy, geologic age, and paleoenvironments of deposition. Percent vuggy porosity is estimated by a new method for the quantification of vuggy porosity using digital borehole images (Cunningham and others, 2003, in press). Geophysical log and aquifer-test data collected in Highlands County and elsewhere are compared to assess relations between geology, hydrogeology, and transmissivity.

Acknowledgments

Numerous individuals and governmental agencies provided technical contributions and other assistance. Richard Lee of the Southwest Florida Water Management District coordinated access to the ROMP 29A core, geophysical logs, and well site. Bruce Ward of Earthworks, Inc., provided technical assistance. Core samples were slabbed and prepared by Jared Lutz of the Earth Sciences Department, Florida International University. Dominicke Merle helped with report preparation.

SITE SELECTION AND METHODS OF EVALUATION

Three continuously cored test sites, having sufficient length and recovery in the stratigraphic interval of interest in the Lake Okeechobee area, were considered for evaluation of sequence stratigraphy; namely, the ROMP 14, ROMP 28, and ROMP 29A test coreholes (fig. 1). Because of its close proximity to the ROMP 29A test corehole, the ROMP 28 test corehole was used to test stratigraphic continuity between test coreholes; the ROMP 14 test corehole was not used. More than 2,500 ft of cored rock samples from the three test coreholes were obtained from the Florida Geological Survey Core Repository in Tallahassee, Fla., and from the Southwest Florida Water Management District (SWFWMD) in Brooksville, Fla. The unslabbed core samples from these test coreholes were evaluated, and the ROMP 29A test corehole was determined to be best suited for this analysis because of superior definition of the unconformity at the top of the Avon Park Formation and the percentage and quality of core recovered. A cursory comparison of the three test coreholes was conducted to assess continuity and correlation of selected rock units between coreholes.

The SWFWMD drilled the ROMP 29A test corehole as a temporary exploratory test corehole to provide geologic and hydrologic information needed to establish three nearby permanent monitoring wells in the surficial and intermediate aquifer systems and in the Upper Floridan aquifer. During the drilling process, continuous core samples were collected in combination with other geologic, borehole geophysical, and hydrologic data. The corehole was drilled to a depth of 1,244 ft below land surface.

Drilling and Geophysical Data Collection

The SWFWMD constructed the ROMP 29A test corehole in four stages. Initially, a 21-in.-diameter borehole was drilled to 40 ft below land surface and completed with a 16-in. inner diameter schedule 40 polyvinyl chloride (PVC) casing that was grouted with 5-percent bentonite cement.

A $14\frac{3}{4}$-in.-diameter borehole was then drilled from 40 to 250 ft below land surface. This borehole was lined with a 10-in. inner diameter schedule 40 PVC casing from land surface to a depth of 250 ft and was grouted with 5-percent bentonite cement. A $9\frac{7}{8}$-in.-diameter borehole was drilled to 494 ft and lined from land surface with a 6-in. inner diameter schedule 40 PVC casing, also grouted with 5-percent bentonite cement. Finally, a temporary 4-in. inner diameter casing was installed from land surface to 496 ft, and the borehole was then cored to a depth of 1,244 ft and $1\frac{7}{8}$-in.-diameter cores were retrieved. Core recovery was at 70 percent.

While the ROMP 29A test corehole was filled with clear freshwater, digital borehole image logs were run using the Mount Sopris OBI-40 Optical Televiewer. This instrument is designed for clear freshwater borehole environments to monitor, process, and record optical images of borehole walls in digital format for geological and geotechnical analysis. Quantification of vuggy porosity in borehole images of limestone and dolomite carbonate aquifers is a three-step process using Baker Atlas RECALL software (Cunningham and others, 2003, in press). This process includes measurement of the proportion of vugs in images of slabbed whole-core samples, identification of potential vuggy porosity in borehole images, and calibration of the core-sample values to the results from borehole-images. In the method, the color digital borehole image is converted to gray scale, and then a nonstatic gray scale threshold is applied to count valid elements and make an estimate of vuggy porosity (Cunningham and others, 2003, in press).

For purposes of this investigation and due to time and funding constraints, digital borehole images were not calibrated with whole-core samples. Threshold values similar to those identified in core-calibrated Pleistocene carbonates of southern Florida (Cunningham and others, 2003, in press) were used to calculate vuggy porosity in the ROMP 29A test corehole. Accordingly, the synthetic porosity log provides only an estimate of vuggy porosity. However, the synthetic vuggy porosity log can be used to compare changes in porosity within the entire open-hole, optically logged interval. A limitation of the method is that porosity can be overcounted over intervals where the rock is very dark colored, but contains no visible porosity. Additionally, porosity can be undercounted over intervals where the rock is very light colored, but contains significant visible porosity. A comprehensive explanation of the method is provided by Cunningham and others (2003, in press).

The ROMP 29A test corehole was cored continuously from land surface to 1,244 ft using a 5-ft long wireline core barrel that allows recovery of a $1\frac{7}{8}$-in.-diameter, 5-ft-long (or shorter) core. Core samples ($1\frac{7}{8}$-in. diameter) were retrieved, measured, described, and placed in cardboard boxes for preservation and storage at the SWFWMD office in Brooksville, Fla. Each core box contains about 10 ft of core. Core recovery ranged from poor to excellent, with an overall recovery of about 70 percent. Detailed lithologic logs of the slabbed core are presented and include descriptions of lithology, color, texture, porosity, exposure surfaces, depositional features, bedding thickness, and fossils and assignment of formational units, sequence boundaries, and maximum flooding surfaces to the rock core (app. I). The core was photographed, and the photographs were converted to digital images by the USGS. Digital photographs of cores (in core boxes) are presented in appendix II.

Caliper, natural gamma, and resistivity logs were collected and provided by the SWFWMD. A digital optical borehole image of the open borehole below 735 ft was collected by the USGS using a Mount Sopris ALT OBI-40 Optical Televiewer. Geophysical and image logs at scales of 1:360 and 1:60 are provided in appendixes III and IV, respectively. The X-ray diffraction of six samples also was made to aid in the determination of mineralogy.

Quantification of Carbonate Vuggy Porosity from Digital Borehole Images

Vuggy porosity is visible “pore space that is within grains or crystals or that is significantly larger than the grains or crystals; that is, pore space that is not interparticle” (Lucia, 1995). Intraparticle pores, particle molds, fenestrals, channels, and caverns as defined by Choquette and Pray (1970) are included in this definition, as is interparticle porosity that is visible to the naked eye. Identification of vugs and fractures by geophysical logging is normally accomplished, in the absence of image logs, by combining and interpreting several logs, including: sonic, dipmeter, laterolog, induction, density, spontaneous potential, caliper, and natural gamma-ray spectrometry (Crary and others, 1987). Identification of vugs and fractures using these logs is challenging and interpretive in the absence of a borehole-wall image.

Visual interpretation of digital borehole images can improve delineation of zones of preferential flow and is the most reliable and practical method of identifying vuggy porosity in the limestone of the Floridan aquifer system. Electronic images of borehole walls are used to quantify vuggy porosity (Hickey, 1993; Newberry and others, 1996; Hurley and others, 1998, 1999) in petroleum reservoirs and fracture porosity in aquifers (Williams and Johnson, 2000). The technique also has been used successfully to quantify digital borehole images of the carbonate Pleistocene Biscayne aquifer (Cunningham and others, 2003, in press).

SEQUENCE-STRATIGRAPHIC ANALYSIS

The ROMP 29A test corehole penetrates poorly consolidated to consolidated siliciclastics and carbonate rocks. The sediments and rocks range in age from middle Eocene to Pliocene and include, in ascending order, carbonate rocks of the Avon Park Formation, Ocala Limestone, and Suwannee Limestone, and siliciclastics of the Hawthorn Group (fig. 2). Core descriptions are limited to these formations. The Hawthorn Group is generally included as part of the intermediate confining unit, which overlies the Floridan aquifer system (fig. 2). However, a description of the Hawthorn Group from 412 to 461 ft below land surface is provided in the detailed lithologic logs (app. I).

The shallow marine limestones and dolomites of the Avon Park Formation were deposited mostly on the inner part of a broad, flat-lying carbonate ramp that sloped gently toward the Gulf of Mexico during the Eocene. The fine-grained carbonates of the Ocala Limestone of central Florida were deposited on the middle to outer-ramp setting at water depths generally below storm wavebase. The Suwannee Limestone represents a return to shallow marine conditions in central Florida during the early Oligocene. The Hawthorn Group is composed of shallow marine to nonmarine coastal and deltaic sandstone and mudstone, which prograded out over the older carbonate platform during the late Oligocene to Pliocene.

Avon Park Formation

Twelve lithofacies were identified for the Avon Park Formation (table 1). The vertical distribution of lithofacies is highly cyclic; consequently, considerable vertical heterogeneity of porosity and permeability exists within the Avon Park Formation. Few thick intervals are present in any one lithofacies as shown in appendix I.

Depositional Sequences and Sequence Stratigraphy

The vertical distribution of lithofacies within the Avon Park Formation inner ramp shows that its depositional setting in south-central Florida changed repeatedly over brief periods at the location of the ROMP 29A test corehole. Short-term, low-amplitude changes in relative sea level are recorded by a multitude of high-frequency depositional cycles. These high-frequency cycles (HFC’s) are the fundamental depositional units that characterize the Avon Park Formation (fig. 3).

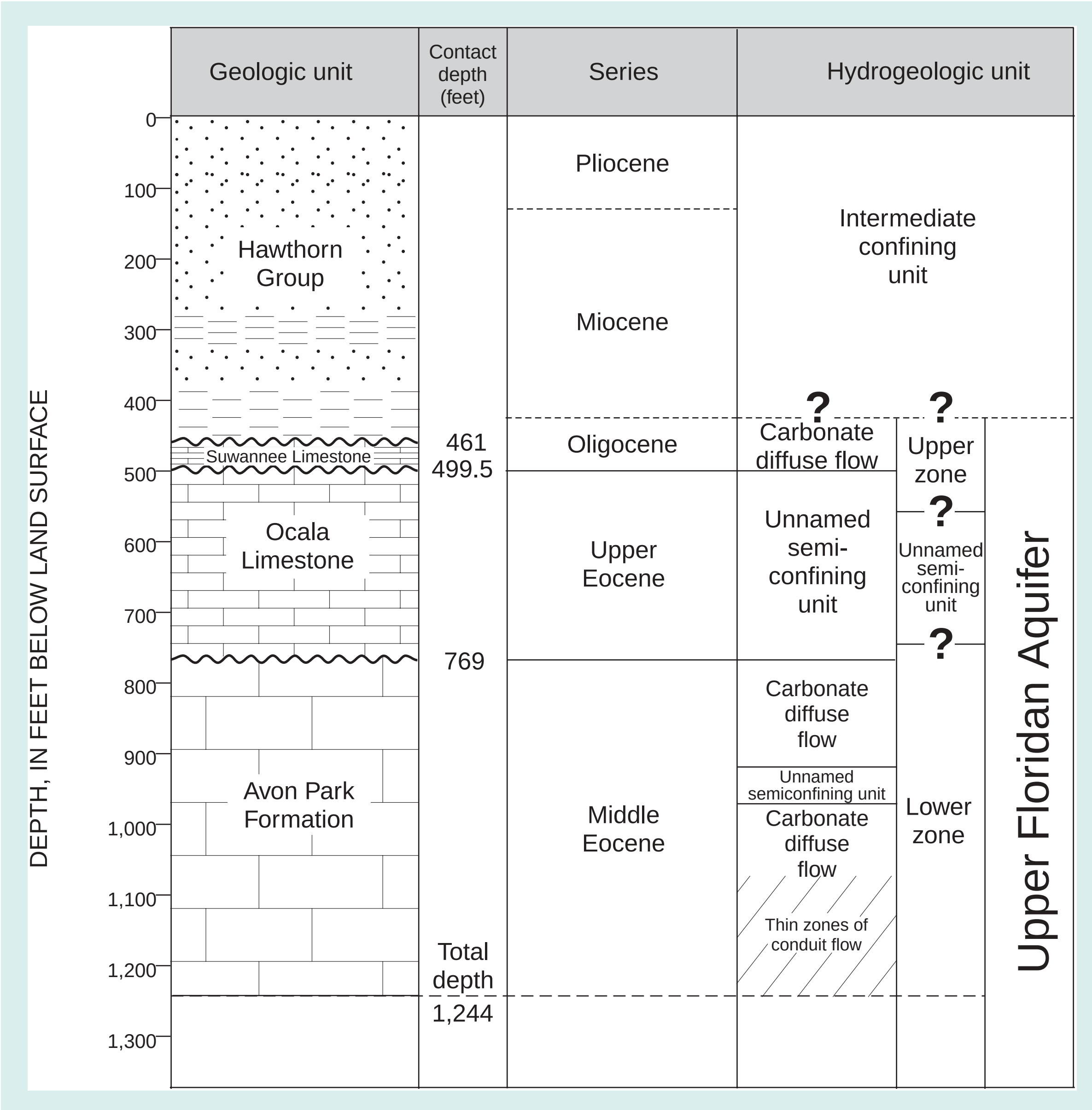


Figure 2. Hydrogeologic section of the Upper Floridan aquifer penetrated by the ROMP 29A test corehole in Highlands County, Florida. (ROMP is Regional Observation Monitoring Program.)

The HFC's of the Avon Park Formation can be grouped into high-frequency cycle sets (HFCS) reflecting fluctuations of relative sea level on a lower order time scale. These HFCS's have been further grouped into high-frequency sequences (HFS's) as shown in figure 3. The nomenclature that is commonly applied to the various orders of depositional cyclicity in carbonate rocks is presented in table 2.

The lithofacies contained in the HFC's record three principal depositional settings during accumulation of the carbonate rocks comprising the Avon Park Formation: (1) peritidal; (2) open-shelf, shallow subtidal; and (3) open-shelf, deeper subtidal. A descriptive summary of three common types of HFC's associated with these three general depositional settings is provided in table 3. The successive shifting of these depositional settings through time

Table 1. Avon Park Formation lithofacies

Lithofacies	Composition	Interpretation
Benthic-foram wackestone/mud-dominated packstone	Carbonate-muddy limestone dominated by benthic foraminifers, most commonly miliolds. Other common constituents: *Dictyoconus*, *Fabularia*, ostracodes, mollusks, pellets and peloids. Generally low and highly variable porosity: moldic, vuggy, microcrystalline, and intraskeletal.	Low-energy inner shelf. Shallow subtidal to intertidal.
Benthic foram grain-dominated packstone/grainstone	Grainy limestone dominated by benthic foraminifers, most commonly miliolids. Other common constituents: *Dictyoconus*, *Fabularia*, ostracodes, mollusks, and intraclasts. Generally good porosity (10-25 percent estimated in thin section): intergranular, intraskeletal, moldic, and vuggy.	High-energy inner shelf. Shallow subtidal to intertidal.
Skeletal wackestone/mud-dominated packstone	Carbonate-muddy limestone with echinoids, mollusks, and mixtures of benthic and planktic foraminifers. Generally low and highly variable porosity: moldic, vuggy, microcrystalline, and intraskeletal.	Low-energy open shelf. Shallow subtidal.
Skeletal grain-dominated packstone/grainstone	Grainy limestone with benthic foraminifers, echinoids, mollusks, peloids, and intraclasts. Generally good porosity (10-25 percent estimated in thin section): intergranular, intraskeletal, moldic, and vuggy.	High-energy open shelf. Shallow subtidal.
Skeletal floatstone/rudstone	Coarse-grained equivalent of skeletal wackestone/mud-dominated packstone and grain-dominated packstone/grainstone rich in gravel-size mollusks and/or echinoids. Variable porosity (low in echinoid-rich layers): intergranular, intraskeletal, moldic (especially in mollusk-rich layers), and vuggy.	Shallow subtidal.
Planktic foram wackestone/mud-dominated packstone	Carbonate-muddy limestone with abundant planktic foraminifers, ostracodes, echinoids, and pellets. Porosity low: microcrystalline, moldic, vuggy, and intraskeletal.	Open shelf. Deeper subtidal.

Table 1. Avon Park Formation lithofacies (Continued)

Lithofacies	Composition	Interpretation
Stromatolite	Wavy laminated carbonate mudstone, fine packstone, or fine grainstone with thin irregular organic-rich laminae. Constituents: pellets, ostracodes, and benthic foraminifers. Porosity highly variable, up to estimated 20 percent in grainy laminae: moldic, fenestral, vuggy, intergranular, and minor fracture.	Restricted inner shelf. Intertidal to supratidal.
Laminite	Laminated carbonate mudstone and/or wackestone. Poorly fossiliferous. Ostracodes, benthic foraminifers, and pellets. Generally very low porosity: fenestral, fracture, and moldic.	Restricted inner shelf. Low-energy tidal flats.
Intraclastic floatstone/rudstone	*In situ* carbonate conglomerate composed of gravel-size fragments of limestone and dolomite. Porosity highly variable depending on amount of matrix: intergranular, fracture, and moldic.	High-energy event.
Rip-up clast breccia	Intraclast floatstone/rudstone composed of mostly angular fragments of laminite, stromatolite, or other carbonate rock types.	Mostly shallow inner shelf. Occasional surges of wave energy. Peritidal and shallow subtidal.
Collapse breccia	Intraclast floatstone/rudstone composed of rounded to angular fragments of various limestone rock types. Some with cave cements.	Zones of post-depositional collapse breccia, mostly associated with large vugs or caves. Others associated with dissolution of evaporites in tidal flats.
Caliche	Carbonate mudstone with clotty microstructure, circumgranular cracking, and fitted clasts. Poorly to nonfossiliferous. Very low porosity: fracture and vuggy. Commonly hard and dense.	Subaerial exposure.

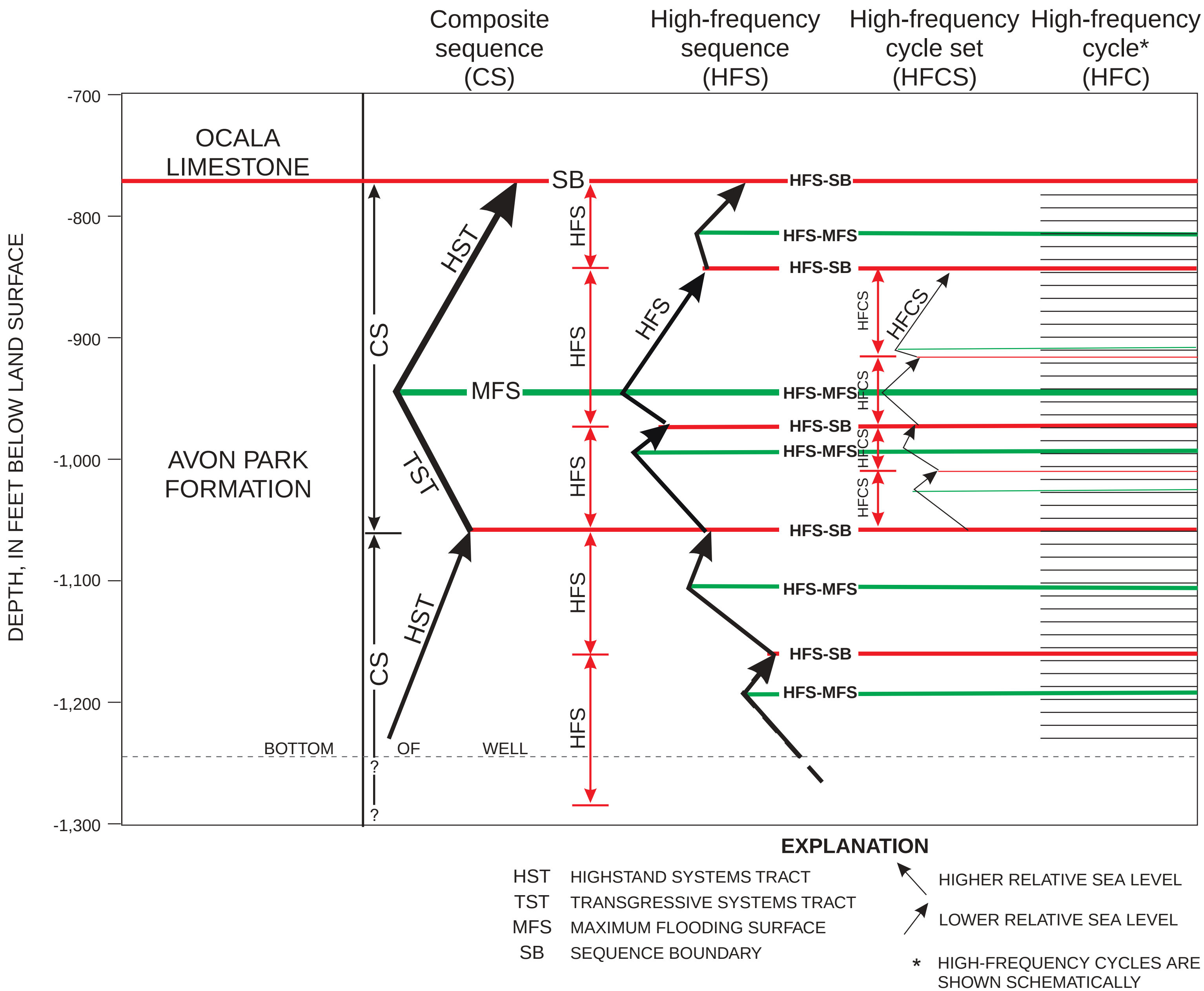


Figure 3. Hierarchy of depositional cycles within the Avon Park Formation.

Table 2. Nomenclature of stratigraphic cycle hierarchies and order of cyclicity

[Modified from Kerans and Tinker, 1997. <, less than the value; >, greater than the value]

Tectono-eustatic/ eustatic cycle order	Sequence-stratigraphic unit	Duration (million years)	Relative sea-level amplitude (meters)	Relative sea-level rise/fall rate (centimeters per 1,000 years)
First		>100		<1
Second	Supersequence	10 - 100	50 - 100	1 -3
Third	Composite sequence/ Depositional sequence	1 - 10	50 - 100	1 - 10
Fourth	High-frequency sequence/ High-frequency cycle set	0.1 - 1	1 - 150	40 - 500
Fifth	High-frequency cycle	0.01 - 0.1	1 - 150	60 - 700

Table 3. High-frequency cycle types of the Avon Park Formation

High-frequency cycle type	General depositional setting	Description
Peritidal	Peritidal; very shallow subtidal, intertidal, and supratidal.	Less than 1 foot to a few feet thick (15 feet maximum). Mostly fining upward sequences. Mostly benthic foram wackestone/mud-dominated packstone or benthic foram grain-dominated packstone/grainstone at the base to stromatolite or laminite at the top. A few cycles capped by exposure surfaces (caliche and/or microkarst).
Shallow subtidal	Open-shelf, shallow subtidal.	From 1 to 10 feet thick. Mostly coarsening upward. From skeletal wackestone/mudstone-dominated packstone or skeletal grain-dominated packstone at the base to grain-dominated packstone or grainstone at the top. Some crossbedding at the top. Some burrowing in the lower part.
Deeper subtidal	Open-shelf, deeper subtidal; generally below wavebase.	From 10 to 20 feet thick (definition of these high-frequency cycles is locally difficult). From planktic-foram wackestone at the base to mud-dominated packstone at the top. Well-preserved laminations in some places. Other zones highly burrowed.

was closely related to relative sea-level changes recorded by the HFC's. The overall large-scale vertical changes in lithology of the Avon Park Formation are evidence of lower orders of relative sea-level changes, reflected in the HFS's and two composite sequences (fig. 3 and table 2). The hierarchical scheme of sequence stratigraphy made from the ROMP 29A test corehole is considered tentative (fig. 3). The stratigraphic sections for several other wells in southern Florida would need to be evaluated to determine which cycles and sequences defined herein are regionally significant. Excellent correlation between many lithologic units in the Avon Park Formation in the ROMP 29A test corehole and the slightly downdip ROMP 28 test corehole suggests that the proposed intermediate-order cycles may have regional significance.

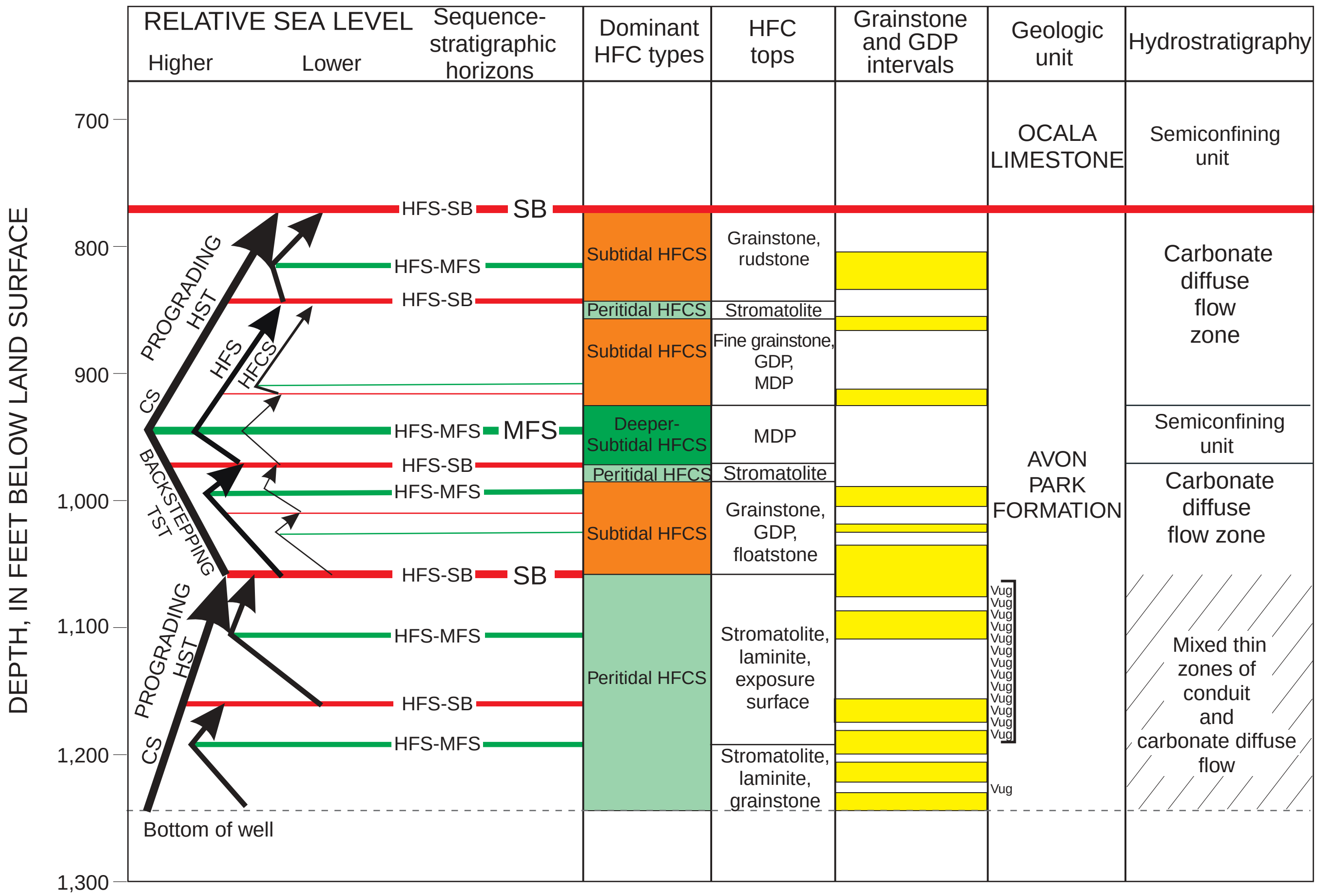
Relation of Porosity to Sequence Stratigraphy

Most zones with high vuggy porosity calculated from digital borehole image logs (app. I) are located in the lower composite sequence (fig. 4). This relative abundance in vuggy porosity corresponds to a thick carbonate section dominated by peritidal HFC's that collectively compose the interpreted highstand and progradational part of the lower composite sequence of the Avon Park Formation. These peritidal HFC's have the most abundant amount of grainstones and grain-dominated packstones. Visual examination of core samples and thin sections suggests these grainy lithofacies have relatively high intergranular porosity and relatively high matrix permeability. Thus, the carbonate rocks of the lower composite sequence are a heterogeneous interlayering of thin conduit flow and carbonate rock diffuse flow zones, and thus, the lower composite sequence also contains the greatest volume of conduit and carbonate diffuse flow zones (fig. 4). The common occurrence of grainstone and relatively high porosity is more typical of highstand systems tracts than transgressive systems tracts using the modeled carbonate sequence stratigraphy of Lucia (1999) and the Permian carbonate ramp model of the San Andres Formation, Guadalupe Mountains, Texas and New Mexico as analogue examples (Kerans and others, 1994).

Although calculated zones of high vuggy porosity (app. I) are uncommon in the upper composite sequence of the Avon Park Formation (fig. 4), grainstone and grain-dominated packstone lithofacies with a relatively high matrix porosity and permeability is common. These zones are thin, however, showing the influence of depositional bedding on porosity development. Thus, the upper composite sequence is dominated by carbonate rock with diffuse flow, but does contain a semi-confining unit near the middle that corresponds to deeper subtidal HFC's and the shift from a back-stepping transgressive to a prograding highstand systems tract (fig. 4). The highstand systems tract of the upper composite sequence seems to represent a slightly deeper position on the platform, and consequently, less vuggy porosity and carbonate diffuse flow zones. The slightly deeper condition is suggested by the predominance of subtidal HFC's in the upper composite sequence relative to peritidal HFC's dominating the lower composite sequence.

The maximum-flooding surface of the upper composite sequence (that is, the record of the maximum relative sea-level transgression during Avon Park Formation deposition) is within an interval of deeper subtidal, planktic-foraminiferal wackestone. This fine-grained unit possibly could form a regional confining unit that separates porous zones in the upper Avon Park Formation from those in the middle and lower Avon Park Formation (fig. 4) and may be part of the middle confining unit of Miller (1986).

A 115-ft thick-interval (1,070-1,185 ft below land surface) of the lower composite sequence of the ROMP 29A test corehole has numerous large vugs (fig. 4 and app. I). This vuggy interval is within the middle and upper part of the thick unit of peritidal HFC's (fig. 4). The peritidal HFC's contain some evidence of tidal flat or supratidal flat evaporites, such as thin solution breccias, fractures, and molds of gypsum crystals. Thin evaporite layers probably dissolved during an early burial phase and provided porous and permeable zones of enhanced ground-water flow, thus promoting postburial dissolution and creating the vuggy interval.



EXPLANATION

(yellow box)	GRAINSTONE OR GDP	HFS	HIGH-FREQUENCY SEQUENCE
HST	HIGHSTAND SYSTEMS TRACT	HFC	HIGH-FREQUENCY CYCLE
TST	TRANSGRESSIVE SYSTEMS TRACT	HFCS	HIGH FREQUENCY CYCLE SETS
MFS	MAXIMUM FLOODING SURFACE	GDP	GRAIN-DOMINATED PACKSTONE
SB	SEQUENCE BOUNDARY	MDP	MUD-DOMINATED PACKSTONE
CS	COMPOSITE SEQUENCE		

Figure 4. Relation of proposed sequence-stratigraphic framework to vertical distribution of major packages of high-frequency cycles and to intervals of grainstone/grain-dominated packstone and hydrostratigraphy. (Most carbonate diffuse flow is associated with the grainstone and GDP intervals.)

A 162-ft-thick interval between 1,082 and 1,244 ft below land surface contains several small-scale faults with mineralized striations or slickenlines on both surfaces. The mineralized slickenlines are composed of a darker material than the host rock and are easily identified on the digital borehole image. The fault-plane dip is oblique to the sense of motion on the slickenlines; however, the latter does not have visible steps or other kinematic features that indicate whether the dominant motion is normal or reverse. Measurable dips of fault planes range from 33 to 60 degrees, and there is no pattern to the dip direction. The faults formed in the wackestones and packstones, but not in any of the dolomitized layers. Occurrence of fault structures is possibly related to dissolution of evaporites. These faults along with the fractured dolomites found near the base of the core, large dissolution cavities, and vugs in the interval from 1,070 to 1,185 ft indicate enhanced permeability below 1,070 ft.

Porosity and Diagenesis

The ROMP 29A test corehole penetrated the upper 18 ft of a pervasively dolomitized zone of the lower Avon Park Formation between 1,226 and 1,244 ft below land surface (app. I). This vuggy and fractured section probably has relatively high porosity and permeability. The overlying part of the Avon Park Formation, however, has only scattered thin zones of finer crystalline dolomite with relatively low porosity and permeability. Most of the Avon Park Formation core shows little alteration of the depositional fabric by postburial diagenesis. In this area of the carbonate ramp, sediments of the Avon Park Formation apparently were buried without being subjected to a substantial influx of freshwater. Intergranular and moldic porosity of 30 to 40 percent is still preserved in many grainstones and grain-dominated packstones. Additionally, matrix porosity is equally high in mud-dominated packstone and wackestone. Even intraskeletal porosity in many foraminifers is preserved. However, matrix permeability is high only in the grainy limestones (Budd, 2001).

Secondary porosity is not as important to fluid flow as is the preserved intergranular porosity, except in the coarse dolomitized intervals, vuggy zones, and open fractures. Minor fossil moldic porosity is present in the generally foraminifer-rich limestones of the Avon Park Formation, but only a few thin mollusk-rich layers have extensive moldic porosity. In echinoid-rich grainstones, intergranular porosity is occluded by coarse syntaxial cement.

The 115-ft-thick zone of large vugs (1,070 and 1,185 ft below land surface) in the lower part of the cored interval of the Avon Park Formation (fig. 4) shows evidence of a late stage invasion of dolomitizing ground-water brines. A narrow and dense zone around many vugs was dolomitized, and large fibrous crystals of strontianite and anhydrite grew in the vugs. It seems that this late stage diagenesis created a dense poorly permeable zone around many of the vugs. If so, this would decrease the volume of fluid flow from vug to vug through time.

Ocala Limestone

The 270-ft-thick Ocala Limestone section penetrated by the ROMP 29A test corehole (app. I) is composed of poorly consolidated carbonate mud-rich limestone of late Eocene age. In south-central Florida, the Ocala Limestone probably was deposited in a mid- to outer-ramp depositional environment, generally below normal wavebase. Wave- or current-winnowed grainy limestones, therefore, are minor in the Ocala Limestone in this corehole. Even so, cyclic vertical heterogeneity in lithology is characteristic (app. I).

The two principal lithofacies are: (1) large, benthic-foraminiferal (*Nummulites* and/or *Lepidocyclina)* wackestone with a soft micrite matrix; and (2) poorly indurated, large, benthic-foraminiferal, mud-dominated packstone. Additionally, there are some intervals of floatstone and mud- or grain-dominated rudstone composed of abundant *Lepidocyclina* foraminifers. Another less common lithofacies is mixed skeletal wackestone with few or no large foraminifers. Other fossils in these lithofacies include planktic foraminifers, small benthic foraminifers, thin-shelled bivalves, echinoids, bryozoans, ostracodes, and planktic crinoids.

Depositional Sequences and Sequence Stratigraphy

The Ocala Limestone of this region is composed of deeper subtidal depositional cycles containing at least two orders of frequency. Loizeaux (1995) and Budd (2001) traced three lower-frequency depositional sequences within the Ocala Limestone across west-central Florida east to the ROMP 28 test corehole in Highlands County. Loizeaux (1995) designated these major coarsening- and shallowing-upward depositional units as likely third-order sequences.

Using the nearby ROMP 28 test corehole for comparison, three depositional sequences also can be defined in the Ocala Limestone of the Romp 29A test corehole:

1. The lower depositional sequence overlying the unconformity at the top of the Avon Park Formation consists principally of 91 ft of large, benthic-foraminiferal wackestone between 679 and 770 ft. Most of the lower 55 ft is well laminated with alternating layers of light gray and darker gray *Nummulites* wackestone. Mostly above 715 ft, the higher frequency units consist of nonbedded (presumably highly bioturbated) *Lepidocyclina-Nummulites* wackestone that coarsens upward to *Lepidocyclina-Nummulites* mud-dominated packstone. The top 8 ft of the Ocala Limestone consists of large *Lepidocyclina* floatstone and rudstone.
2. The middle sequence consists of 93 ft (between 586 and 679 ft below land surface) of limestone with at least seven higher frequency units. Each higher frequency unit generally consists of 93 ft of *Lepidocyclina* wackestone with a thin cap of *Lepidocyclina* mud-dominated packstone. The upper sequence boundary is based on a color change observed in the core (app. I) and its correlation to the regional sequence boundaries of Loizeaux (1995).
3. The upper sequence is composed of 86.5 ft (between 499.5 and 586 ft below land surface) of mostly mixed-skeletal wackestone, with minor mud-dominated packstone, and a 2-ft-thick layer of *Lepidocyclina* floatstone at 541.5 ft. This sequence consists of at least three higher frequency units. The upper boundary of the sequence is a regional unconformity at the top of the Ocala Limestone.

Within each “third-order” sequence, Loizeaux (1995) tentatively defined two to three higher order, coarsening-upward, depositional cycles. Typically, the high-frequency depositional cycles are 15- to 50-ft thick and consist of large, foraminiferal wackestone overlain by large foram mud-dominated packstone. Using the criteria of Loizeaux (1995), the lower sequence of the Ocala Limestone in the ROMP 29A test corehole tentatively can be divided into six higher frequency units, the middle sequence into seven, and the upper sequence into three units. The significance of textural changes in a middle to outer-ramp, large, foraminiferal buildup is problematic.

Relation of Porosity and Permeability to Sequence Stratigraphy

The Ocala Limestone near the ROMP 29A test corehole is composed entirely of carbonate mud-rich rocks. Much of the original high matrix porosity, however, is preserved. Porosity of the lime mud-rich rocks of the Ocala Limestone typically ranges from 30 to 40 percent (Loizeaux, 1995). By contrast, matrix permeability and vertical hydraulic conductivity are low in the mud-dominated lithofacies of the Ocala Limestone in west-central Florida (Loizeaux, 1995; Budd, 2001).

For this area of deeper subtidal depositional cycles, zones of enhanced porosity and permeability would seem unlikely in the Ocala Limestone, regardless of location in the depositional systems tracts. The Ocala Limestone is considered to be a semiconfining unit in the ROMP 29A test corehole (fig. 2). Loizeaux (1995) recognized part of the Ocala Limestone as a relatively impermeable barrier in west-central Florida.

Suwannee Limestone

In the area where the ROMP 29A test corehole was drilled, only a thin erosional remnant of shallow marine Suwannee Limestone overlies the unconformity at the top of the Ocala Limestone. In the ROMP 29A test corehole, three higher frequency units are recognized (app. I). The two lower units consist of the basal unit of the Suwannee Limestone, which is a 21.5-ft-thick interval of white, slightly silty, mollusk floatstone and lime mud-dominated rudstone (app. I). Molds of whole bivalves and gastropods are abundant, and echinoid fragments are common. Moldic porosity is high, but permeability probably is low because the molds do not seem to be well connected.

The upper higher frequency unit (app. I) is a 17-ft-thick interval that coarsens upward from silty and sandy skeletal mud-dominated packstone to silty and sandy skeletal grain-dominated packstone to silty and sandy miliolid-echinoid grainstone. Molds of gastropods and bivalves are common at the top of this depositional cycle. The intergranular porosity of the grainstone estimated in this thin section is only 10 to 15 percent because much of the pore space is occluded by syntaxial echinoid overgrowths.

Irregular vertical cavities at the top of this thin remnant of the Suwannee Limestone are infiltrated by silt of the Hawthorn Group. These features, probably microkarst, were produced during subaerial exposure, which followed extensive erosion of the Suwannee Limestone and preceded deposition of the shallow marine silt and sand of the basal Hawthorn Group.

REGIONAL DISTRIBUTION OF TRANSMISSIVITY IN THE NORTHERN LAKE OKEECHOBEE AREA

Optimum transmissivities for successful ASR injection and recovery in southern Florida are reported to range from a lower limit of 5,000 to 7,000 ft^2/d to an upper limit of 30,000 to 50,000 ft^2/d (Reese, 2002, p. 40; T.M. Missimer, Missimer-CDM, Inc., oral commun., 2001). Therefore, maps showing the spatial distribution of transmissivity within likely water-bearing storage zones are useful tools that could be used to guide CERP regional ASR well siting activities. A number of different elements are reported to influence the distribution of transmissivity in the Floridan aquifer system (Miller, 1986). Properties that influence the regional distribution of transmissivity in the Floridan aquifer system include the original lithologic character of the carbonate rock, carbonate depositional patterns, subsequent diagenesis including dolomitization, widening of fractures and joints by dissolution, and other types of karstification.

Estimates of transmissivity for the Upper Floridan aquifer (table 4) were derived by analyzing aquifer-test data published in the literature (Shaw and Trost, 1984; Southwest Florida Water Management District, 2000). Transmissivities derived by Shaw and Trost (1984) were estimated using the Theis analytical equation; transmissivity estimates obtained from the Southwest Florida Water Management District (2000) were derived using various analytical methods including those of Theis (1935), Cooper and Jacob (1946), and Jacob (1946) for confined aquifers. Analytical methods by Hantush and Jacob (1955) and by Walton (1962) were used for semiconfined, leaky, hydrologic conditions. Time constraints were provided for only a preliminary analysis of regional transmissivity patterns within the Upper Floridan aquifer. Additional data extending over a wider area could improve the understanding of regional transmissivity patterns.

Table 4. Data for selected wells

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
Charlotte County										
Cecil Webb Romp 5	265645	0814828	12	720	970	Suwannee	720-970	APT	Hantush	2,616
North Port Deep Injection Well	270043	0821442		1,100	2,000	Avon Park	1,100-2,000	Packer		150,348
North Port Deep Injection Well	270043	0821442		1,100	3,200	Avon Park	1,100-3,200	Packer		255,940
North Port Deep Injection Well	270043	0821442		560	1,100	Suwannee	560-1,100	Packer		8,978
North Port Deep Injection Well	270043	0821442		560	1,600	Suwannee/Ocala/ Avon Park	560-1,600	Packer		72,226
Collier County										
CO-2080	260249	0814145	12	360	1,608	Avon Park	1,345-1,606	Packer		5,762
CO-2080	260249	0814145	12	360	1,608	Hawthorn	465-530	Packer		26,800
CO-2080	260249	0814145	12	360	1,608	Lower Hawthorn	680-760	Packer		14,740
CO-2080	260249	0814145	12	360	1,608	Ocala	1,180-1,220	Packer		62,980
CO-2080	260249	0814145	12	360	1,608	Suwannee	930-1,020	Packer		6,700
CO-2081	260952	0814107	12	318	1,616	Lower Hawthorn	630-720	Packer		1,340
CO-2081	260952	0814107	12	318	1,616	Lower Suwannee/ Ocala	1,250-1,616	Packer		13,400
CO-2081	260952	0814107	12	318	1,616	Suwannee	945-1,000	Packer		4,020

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
DeSoto County										
Amax	271439	0820253	24	280	1,550	Ocala/Avon Park		APT		160,800
DeSoto Land & Cattle	270413	0814009	12		1,600	Suwannee/Ocala/ Avon Park		APT		
Fort Ogden Test Site 15	270417	0815901	20	160	1,090	Suwannee/Ocala		APT		13,400
Horse Creek ROMP 17	271028	0815835	6 (395-1,430)	1,430	1,430	Suwannee	670-780	APT	Theis	
Long Island Marsh ROMP 15	271233	0813922	10	576	880	Suwannee/Ocala				3,618
North Grove PW-1	270501	0813520	12	650	1,544	Suwannee/Ocala/ Avon Park		APT		112,158
Peace River Well 0414-5847	270402	0815956		124	1,072	Avon Park		APT		10,988
Prairie Creek ROMP 12	270228	0814432	22 (710-1,100)	1,100	1,133	Suwannee	725-909	APT	Hantush	
ROMP 9.5	270737	0820250	12 (505-800)	800	801	Avon Park	505-801	APT	Hantush	
Sunpure Groves Well 101	270314	0813413	10	638	1,547					301,500
Sunpure Groves Well 201	270502	0813410	8	688	1,154					132,660

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmissivity, (feet squared per day)
Tippen Bay ROMP 13	270419	0813658	6	674	786	Suwannee	671-786	APT	Hantush	2,358
Tropical River Groves	271628	0813714	12	175	1,340	Suwannee/Ocala		APT		268,000
Wilson	271405	0814532				Floridan		APT		844,200
Hardee County										
CF Industries	273446	0815851				Avon Park	1,500-1,702	APT		188
CF Industries (101)	273446	0815851	20	514	1,175	Avon Park	950-1,175	APT		268,000
Estech	273818	0820149	14	950	1,320	Ocala/Avon Park		APT		103,180
Farmland Industries FIF-1	272841	0815403	18	472	1,400	Ocala/Avon Park	1,000-1,400	APT	Hantush-Jacob	70,752
Lily ROMP 25	272159	0820025	12 (960-1,785)	1,785	1,911	Avon Park	970-1,785	APT	Hantush	
Lily ROMP 25	272159	0820025	12 (300-676)	676	1,911	Suwannee	305-675	APT	Hantush	
Mississippi Chemical	273024	0820145	10	700	1,100	Ocala/Avon Park	750-1,100	APT		134,000
USSAC-S Rockland Mine	273817	0815201	24	400	1,050	Ocala	700-1,050	APT		9,353,200

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
Highlands County										
Consolidated Tomoca	271252	0812030	10	682	1,682	Suwannee/Ocala/ Avon Park		APT		
FPC Avon Park	273446	0812925	12	425	1,492	Ocala/Avon Park		APT		69,680
Hicoria ROMP 14 (Well no. 1)	270915	0812130	10	1,003	1,670	Avon Park		APT		7,598
Hicoria ROMP 14 (Well no. 2)	270915	0812130	8	650	730	Suwannee		APT		6,579
HIF-1	271335	0810520	6	450	640	Lower Hawthorn/ Suwannee	450-640	Single well	Theis	3,082
HIF-39	272158	0810827	10	370	1,332	Suwannee/Ocala/ Avon Park	370-1,332	Single well	Theis	14,740[a]
HIF-39	272158	0810827	10	370	1,332	Suwannee/Ocala/ Avon Park	370-1,332	Single well	Theis	22,110[a]
HIF-41	272655	0812132	16	420	1,205	Suwannee/Ocala/ Avon Park	420-1,205	Single well	Theis	5,494[a]
Sebring	273028	0812630	8	520	1,400	Ocala/Avon Park		APT		26,800
Tropical River Grove Test Site	271623	0812528	12	397	1,317	Suwannee/Ocala/ Avon Park		APT		
W-2859	273040	0812800	14	464	1,400	Suwannee/Ocala/ Avon Park	464-1,400	Single well	Theis	8,308

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
Lee County										
LM-1527	262624	0820639	4	750	770	Suwannee	760-775*	APT	Jacob	13,132
LM-1527	262624	0820639	4	750	770	Suwannee	760-775*	APT	Hantush-Jacob	10,586
LM-1527	262624	0820639	4	750	770	Suwannee	760-775*	APT	Walton	10,988
LM-1622	264003	0820859	16	365	963	Lower Hawthorn		APT	Walton	8,040
LM-1914	263100	0815444	6	0	0	Lower Hawthorn		APT		12,328
LM-1980	262242	0814918	8	350	660	Lower Hawthorn		APT	Hantush-Jacob	
LM-1980	262242	0814918	8	350	660	Lower Hawthorn		APT	Semi Log-Recovery	8,040
LM-1980	262242	0814918	8	350	660	Lower Hawthorn		APT	Theis-Recovery	8,978
LM-1980	262242	0814918	8	350	660	Lower Hawthorn		APT	Theis	7,772
LM-2041	262243	0814921	4	350	620	Lower Hawthorn		APT	Hantush-Jacob	7,772
LM-2213	263738	0820200	10	360	863	Lower Hawthorn		APT		7,236
LM-2213	263738	0820200	10	360	863	Suwannee		APT		6,700
LM-2221	263740	0820115	4	360	863	Lower Hawthorn/ Suwannee		APT		13,936

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
LM-2417	263532	0820020	12	450	707	Lower Hawthorn		APT		
LM-2418	263532	0820007	12	440	700	Lower Hawthorn		APT		
LM-2419	263533	0815948	12	495	722	Lower Hawthorn		APT		
LM-2420	263533	0815918	12	490	710	Lower Hawthorn		APT		
LM-2421	263533	0815904	12	508	720	Lower Hawthorn		APT		
LM-2422	263533	0815849	12	510	720	Lower Hawthorn		APT		
LM-2423	263533	0815835	12	515	642	Lower Hawthorn		APT		
LM-2424	263720	0820049	12	599	764	Lower Hawthorn		APT		
LM-2425	263720	0820028	12	599	742	Lower Hawthorn		APT		2,412
LM-2426	263720	0820015	12	590	765	Lower Hawthorn		APT		8,509
LM-2427	263720	0820002	12	520	702	Lower Hawthorn		APT		
LM-2428	263722	0815947	12	558	782	Lower Hawthorn		APT		
LM-2464	262707	0820732	4	665	905	Lower Hawthorn		APT		2,278
LM-2464	262707	0820732	4	665	905	Suwannee		APT		4,406
LM-3249	264147	0820119	12	500	735	Lower Hawthorn		APT		6,566
LM-3273	264128	0815631	12	0	800	Lower Hawthorn		APT		3,216
LM-3508	264124	0815631	6	785	1,100	Suwannee		APT		9,112

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmissivity, (feet squared per day)
LM-3513	262838	0820943	16	616	682	Lower Hawthorn		APT		1,822
LM-944	262753	0820910	10	440	608	Lower Hawthorn		APT	Hantush-Jacob	2,090
LM-944	262753	0820910	10	440	608	Lower Hawthorn		APT	Jacob	2,358
LM-987	262625	0820641	12	660	774	Lower Hawthorn		APT		4,020
LM-987	262625	0820641	12	660	774	Suwannee		APT		5,896
LM-988	262624	0820639	4	660	775	Lower Hawthorn		APT	Jacob	10,988
LM-988	262624	0820639	4	660	775	Lower Hawthorn		APT	Jacob	11,792
LM-988	262624	0820639	4	660	775	Lower Hawthorn	660-715	APT	Hantush-Jacob	11,122
LM-988	262624	0820639	4	660	775	Lower Hawthorn	660-715	APT	Walton	10,988
Manatee County										
4-Corner Mines Well CB-8	272324	0821140		522	1,200	Suwannee/Ocala/Avon Park		APT		261,300
Beker	273030	0820845	12	750	1,225	Ocala/Avon Park		APT		61,640
Bradenton WWTD Injection Well	272800	0824102	24	1,067	1,659	Avon Park		APT		281,400
Elsberry Farms Test Site 5	272616	0821742	12	250	1,250	Suwannee/Ocala/Avon Park		APT		45,560

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
FP&L-Willow	273815	0821930	12	346	1,568	Suwannee/Ocala/ Avon Park		APT		116,580
Hecht Ranch	273726	0822533		200	900	Suwannee/Ocala		APT	Jacob	134,000
L-3 Farms	273531	0821833		503	1,264	Suwannee/Ocala		APT		91,522
Long Creek Farm	272414	0820546	8	632	1,405	Avon Park		APT		74,638
Myakka City Pacific Tomato	272233	0821044	16	600	1,500	Suwannee/Ocala/ Avon Park		APT		134,000
Oneco ROMP TR 7-2	272615	0823301	12	358	700	Suwannee	358-700	APT	Cooper-Jacob	18,224
Rubonia ROMP TR 8-1	273459	0823246	8	462	1,260	Suwannee/Ocala/ Avon Park		APT		2,948
Rutland Ranch Test Site 4	273018	0822036		200	1,050	Suwannee/Ocala		APT		44,488
Waterbury-Kibler ROMP 33	272728	0821526	12	404	750	Suwannee		APT	Jacob	3,954
Okeechobee County										
OKF-13	273043	0804400	10	600		Ocala/Avon Park	600-1,200	Single well	Theis	74,504[a]
OKF-15	271934	0805913	8	375	1,600	Lower Hawthorn/ Suwannee	375-1,600	Single well	Theis	4,288[a]
OKF-18	272726	0810039	8	255	1,015	Lower Hawthorn /Suwannee	225-1,015	Single well	Theis	3,618[a]

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
OKF-26	271830	0804935	12	625	825	Suwannee/Ocala	625-825	Single well	Theis	858[a]
OKF-27	271830	0804935	12	477	725	Suwannee/Ocala	477-725	Single well	Theis	670[a]
OKF-34	273217	0810126	10	276	1,143	Lower Hawthorn/ Suwannee	276-1,143	Single well	Theis	6,834[a]
OKF-54	273740	0805512	12	260	973	Lower Hawthorn/ Suwannee	260-973	Single well	Theis	415,400[a]
Orange County										
A	283343	0812227				No data		Multiple well	Theis	670,000
B	282531	0810957	4	226	300	Lower Hawthorn Suwannee	226-300	Multiple well	Theis	59,630
C	282352	0813132	12	237	910	Suwannee/Ocala	237-910	Multiple well	Theis	79,060
D	283100	0812200	12	88	350	Suwannee/Ocala	88-350	Single well	Theis	60,970
ORF-43	282622	0811828	12	211	500	Suwannee/Ocala	211-500	Single well	Theis	32,562
Osceola County										
OSF-10	281937	0812501	16	278	458	Suwannee/Ocala	278-458	Single well	Theis	141,102[a]
OSF-11	280905	0812701	6	134	398	Suwannee/Ocala	134-398	Single well	Theis	8,174
OSF-11	280905	0812701	6	134	398	Suwannee/Ocala	134-398	Single well	Theis	4,154

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
OSF-2	281802	0813516	10	85		Suwannee/Ocala/ Avon Park	85-365	Single well	Theis	124,754
OSF-25	281955	0813707	6	99	300	Suwannee/Ocala	99-300	Single well	Theis	27,068[a]
OSF-26	281159	0811428	10	322	622	Suwannee/Ocala	322-622	Single well	Theis	51,188
OSF-27	282051	0811332	6	373	463	Suwannee/Ocala	373-463	Single well	Theis	7,772
OSF-31	281719	0811340	8	239	474	Suwannee/Ocala	239-474	Single well	Theis	24,254
OSF-42	274307	0805824	6	218	767	Suwannee/Ocala	218-767	Single well	Theis	11,256
OSF-44	281456	0811717	8	481	614	Suwannee/Ocala	481-614	Single well	Theis	37,386
OSF-54	275634	0811027	10	249	869	Lower Hawthorn/ Suwannee/Ocala	249-869	Single well	Theis	77,452[a]
OSF-55	280533	0810410	13	354	891	Suwannee/Ocala	354-891	Single well	Theis	60,032[a]
OSF-9	281937	0812459	16	283	1,195	Suwannee/Ocala	283-1,195	Single well	Theis	55,476
Polk County										
POF-2	281511	0813931	6	358	447	Suwannee/Ocala	358-447	Single well	Theis	4,958
POF-4	280229	0813252	8	146	453	Lower Hawthorn/ Suwannee/Ocala	146-453	Single well	Theis	66,330
POF-7	275805	0813219	3					Single well	Theis	2,010

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
Sarasota County										
Atlantic Utilities Test Well	271825	0822821		1,480	1,902	Avon Park		APT		4,958
Englewood IW-1	265712	0822057		1,040	1,600	Ocala/Avon Park		APT		48,106
Englewood IW-1	265712	0822057		1,040	1,800	Ocala/Avon Park		APT		80,132
Geronimo ROMP TR 5-7	270921	0822342	6	510	700	Suwannee		APT		13,333
Knight Trail Pk. Exp. Well	270929	0822436		1,599	1,915	Avon Park		APT		300,696
Murdock N.W. ROMP 18	271135	0820748	10	57	1,100	Suwannee/Ocala	670-890	APT		16,080
Northport ROMP 9 (MW-5)	270434	0820856	12	545	860	Suwannee	545-860	APT	Theis, Jacob, Hantush	7,276
Osprey ROMP 20	271138	0822845	6	500	1,480	Avon park	1,220-1,405	APT		21
Osprey ROMP 20	271138	0822845	12	500	840	Suwannee		APT		20,502
Osprey ROMP 20	271137	0822845	6	500	1,480	Avon Park	1,220-1,305	APT		21
Osprey ROMP 20	271137	0822845	6	500	1,480	Avon Park	1,300-1,405	APT		7

Table 4. Data for selected wells (Continued)

[Data modified from Shaw and Trost (1984), SWFWMD (2000), Michael Beach, SFWMD, written commun., 2002; and Emily Hopkins, SFWMD, written commun. 2002. APT, aquifer performance test. Absence of numerical values means data were not included in this report]

Well name	Latitude	Longitude	Diameter (inches)	Casing depth (feet)	Total well depth (feet)	Formation	Zone tested	Type of test	Anaytical method	Transmis-sivity, (feet squared per day)
Osprey ROMP 20	271137	0822845	6	500	1,480	Avon Park	1,430-1,480	APT		113
Plantation DITW	270414	0822138		1,102	1,605	Ocala/Avon Park		APT		67,161
Utopia Romp 22	271813	0822013	12	940	1,685	Avon Park	1,200-1,660	APT	Jacob	201,000
Utopia ROMP 22	271813	0822013	6	409	635	Suwannee	400-635	APT	Cooper-Jacob/ Jacob-Hantush	9,648
Venice Gardens DIW	270415	0822332		1,388	1,705	Avon Park		APT		24,120

[a]Estimated.

*Discrepancy noted between casing depth and zone tested. To be updated following receipt of corrected values from source of data.

The thicknesses of open-hole aquifer-test intervals varied from as little as 1 ft to as much as 2,250 ft (fig. 5). For example, most transmissivity estimates are based on open-hole intervals that range between 101 and 1,000 ft thick (fig. 5). However, the large open-hole thickness present in most wells prohibits hydraulic evaluation or direct comparison of discrete flow zones within the stratigraphic section.

For purposes of this analysis, the Upper Floridan aquifer is divided into upper and lower zones (fig. 2). The upper zone is considered to represent open-hole well conditions contained within the lower part of Hawthorn Group, Suwannee Limestone, and Ocala Limestone. The lower zone includes open-hole well intervals in the Ocala Limestone and Avon Park Formation. This arbitrary division into upper and lower zones is based partly on comparison of major hydrogeologic units identified in the ROMP 29A test corehole and a cursory examination of the nearby ROMP 28 test corehole, suggesting subregional flow zone continuity. An important assumption in the following discussion is that flow zones identified in ROMP 29A are relatively continuous and are representative of subsurface conditions in a wide area that extends northwest, north, and northeast of Lake Okeechobee.

Contour maps showing the configuration and extent of different geologic and hydrogeologic units were used to assign aquifer-test data to specific geologic or hydrogeologic units (Miller, 1986). Based on the assignment of each well's open-hole interval, the estimated transmissivity was mapped for the upper and lower zones (figs. 6 and 7, respectively). Some wells were not included in this analysis because they could not be clearly separated into upper and lower zones of the Upper Floridan aquifer.

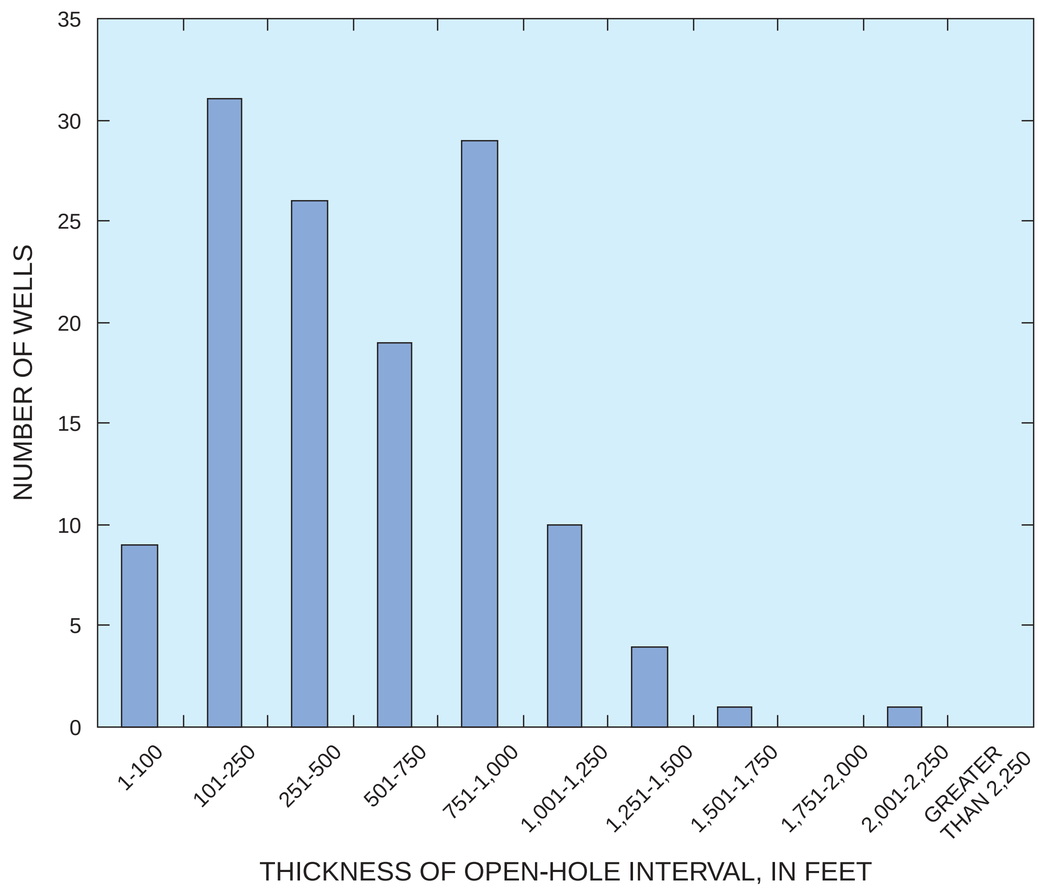


Figure 5. Distribution of the thickness of open-hole interval.

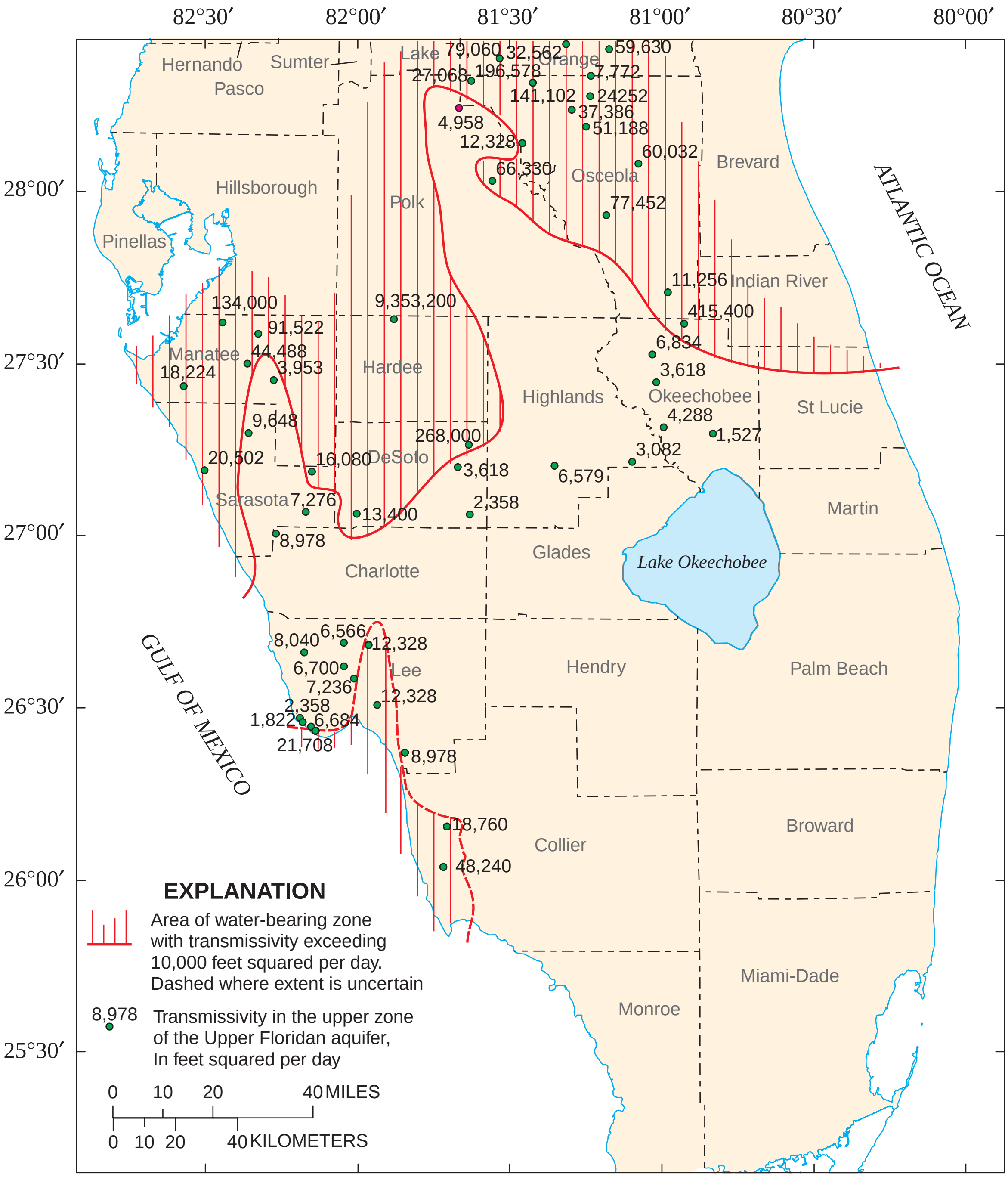


Figure 6. Regional distribution of transmissivity in the upper zone of the Upper Floridan aquifer.

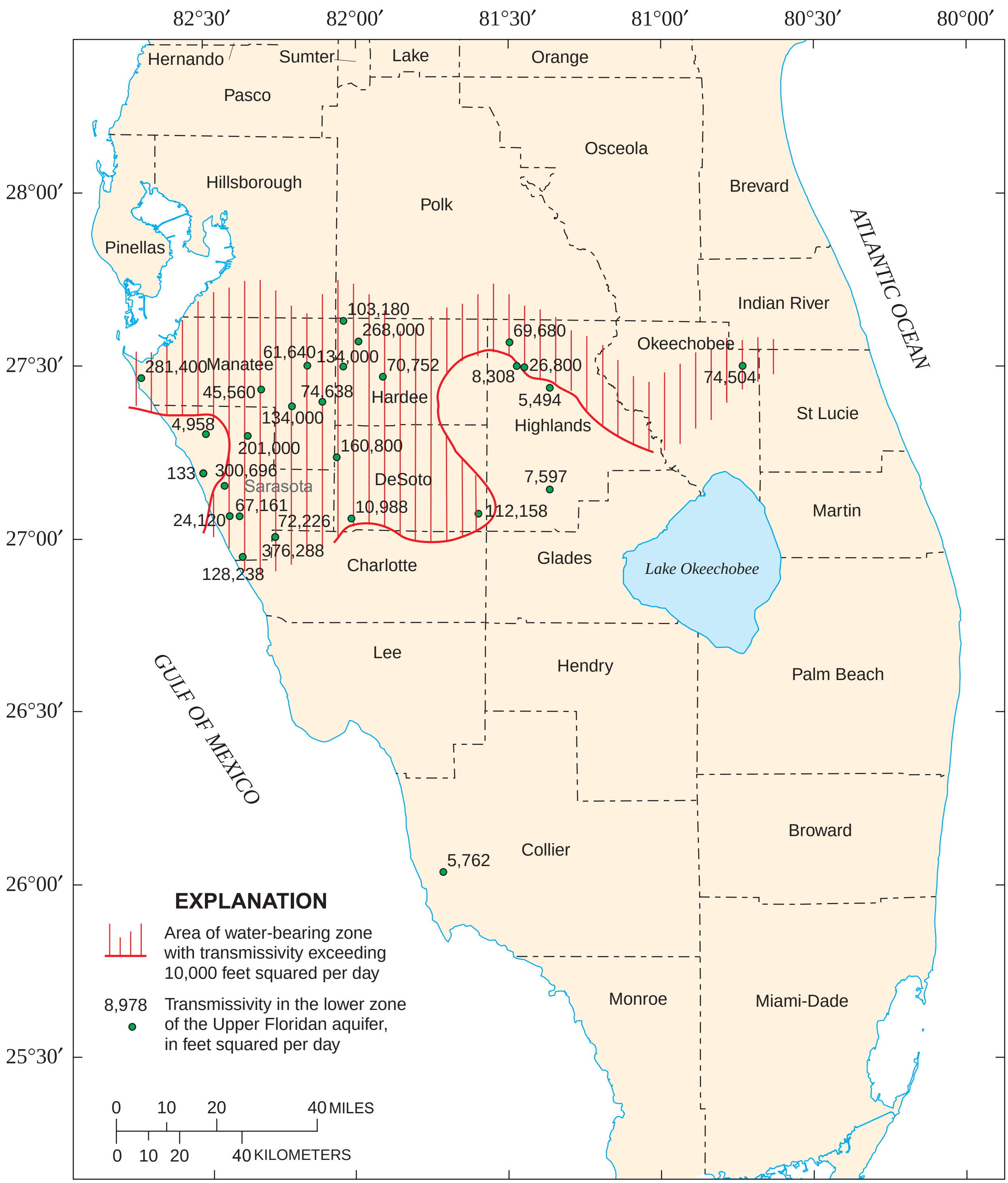


Figure 7. Regional distribution of transmissivity in the lower zone of the Upper Floridan aquifer.

An arbitrary boundary of 10,000 ft^2/d was used to separate transmissivities in open-hole intervals that differ by at least one order of magnitude. An "order of magnitude" transmissivity boundary has been shown to be well suited to map regional transmissivity patterns within the Floridan aquifer system (Bush and Johnston, 1988).

Regional transmissivity of the upper zone appears to be less than 10,000 ft^2/d in areas nearest to Lake Okeechobee. Transmissivity of the upper zone is less than 10,000 ft^2/d in most wells located in Charlotte, Highlands, Lee, Okeechobee, and Sarasota Counties. Transmissivity of the upper zone increases in areas north and northwest of Lake Okeechobee and in parts of coastal Lee and Collier Counties. Transmissivity is greater than 10,000 ft^2/d in most wells open to the upper zone in Osceola, Hardee, Manatee, and Collier, Lake, and Orange Counties (fig. 6).

Hydraulic data for the lower zone of the Upper Floridan aquifer are more limited, both in terms of available "Avon Park" control points (table 3 and 4) and a more limited spatial distribution (fig. 7). Accordingly, it is more difficult to access regional transmissivity patterns. Transmissivity of the lower zone exceeds 10,000 ft^2/d in most wells located in Manatee, Hardee, DeSoto, and Sarasota Counties. The transmissivity of the lower zone in one well in Okeechobee County and in one well located in Charlotte County exceeds 10,000 ft^2/d. Transmissivity of the lower zone is less than 10,000 ft^2/d in most wells drilled in Highlands County.

SUMMARY AND CONCLUSIONS

This report describes the lithology for part of the Upper Floridan aquifer penetrated by the ROMP 29A test corehole in Highlands County, Fla. A conceptual hydrogeologic model of flow zones and confining units in the Upper Floridan aquifer is delineated in the context of a sequence-stratigraphic framework. The sequence-stratigraphic framework developed for the ROMP 29A test corehole serves as a comparative guide to the correlation of a regional carbonate sequence-stratigraphic framework of the Floridan aquifer system.

The ROMP 29A test corehole penetrated several geologic units ranging in age from middle Eocene to Pliocene including the Avon Park Formation, Ocala Limestone, Suwannee Limestone, and the Hawthorn Group. The portion of the Avon Park Formation penetrated in the ROMP 29A test corehole comprises two composite depositional sequences. A transgressive systems tract and a highstand systems tract were interpreted for the upper composite sequence, but because of depth limitations, only a highstand systems tract was interpreted for the lower composite sequence. The composite depositional sequences are composed of at least five high-frequency depositional sequences. The high-frequency depositional sequences contain high-frequency cycle sets that are an amalgamation of vertically stacked high-frequency cycles. Three types of high-frequency cycles have been identified in the Avon Park Formation: peritidal, shallow subtidal, and deeper subtidal high-frequency cycles.

The vertical distribution of carbonate-rock diffuse flow zones within the Avon Park Formation is heterogeneous. Porous vuggy intervals are all less than 10 ft thick and most are much thinner. The volumetric arrangement of the zones of diffuse flow shows that most occur in the highstand systems tract of the lower composite sequence of the Avon Park Formation as compared to the upper composite sequence, which contains both a backstepping transgressive systems tract and a prograding highstand systems tract. The diffuse flow zones are characterized by grainstone and grain-dominated packstone lithologies. Although the porous and permeable layers are not thick, some intervals may exhibit extensive lateral continuity because they were deposited on a flat-lying, low-relief ramp. A thick interval of thin vuggy zones and open faults forms thin conduit flow zones mixed with relatively thicker carbonate-rock diffuse flow zones between a depth of 1,070 and 1,244 ft below land surface (corresponding to the total depth of the test corehole). This interval is the most transmissive part of the Avon Park Formation penetrated in the ROMP 29A test corehole and is included in the highstand systems tract of the lower composite sequence.

Three lower order depositional sequences are defined in the Ocala Limestone cored in the ROMP 29A test corehole. The Ocala Limestone is mostly composed of deeper subtidal depositional cycles. The formation is considered a semiconfining unit because zones of secondary porosity and permeability are not common. A thin erosional remnant of shallow marine Suwannee Limestone overlies the Ocala Limestone. Permeability of the Suwannee Limestone seems to be low because its pore system is characterized by poorly connected moldic porosity.

Geophysical log and aquifer test data collected in Highlands County and elsewhere were compared to assess regional relations between geology, hydrogeology, and transmissivity. Unfortunately, most aquifer tests have been conducted in wells having open-hole intervals that range from 250 to 1,200 ft thick, making comparison of discrete flow zones and assessment of their regional continuity difficult. However, regional transmissivity patterns could be evaluated by assigning open-hole intervals to generalized rock-stratigraphic units and hydrogeologic units. On the basis of a preliminary analysis of aquifer-test data, there appears to be a spatial relation among wells that penetrate water-bearing rocks having relatively high and low transmissivities. The transmissivity in an upper zone that is composed of rocks within the lower Hawthorn Group, Suwannee Limestone, and upper part of the Ocala Formation is generally less than 10,000 ft^2/d in areas south of a line that extends through northern St. Lucie, Okeechobee, Osceola, Polk, Highlands, DeSoto, Sarasota, and Charlotte Counties. Limited data have been compiled for a lower zone water-bearing unit that includes the lower part of the Ocala Formation and the Avon Park Formation; accordingly, transmissivity patterns cannot yet be regionally assessed.

Implementing carbonate sequence stratigraphy in this study enabled the development of an accurate stratigraphic interpretation, which can be integrated into a conceptual model of the subsurface carbonate aquifer. As a result, it is concluded that using carbonate sequence stratigraphy can reduce the risk of miscorrelation of key ground-water flow zones and confining units.

REFERENCES CITED

Budd, D.A., 2001, Permeability loss with depth in the Cenozoic carbonate platforms of west-central Florida: American Association of Petroleum Geologists Bulletin, v. 85, p. 1253-2172.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida, and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p.

Choquette, P.W., and Pray, L.C., 1970, Geological nomenclature and classification of porosity in sedimentary carbonates: American Association of Petroleum Geologists Bulletin, v. 54, p. 207-250.

Cooper, H.H., Jr., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: American Geophysical Union Transactions, v. 27, no. 4, p. 526-534.

Crary, Steven, Dennis, Robert, Denoo, Stanley, and others, 1987, Fracture detection with logs: The Technical Review 35, p. 22-34.

Cunningham, K.J., Carlson, J.I., and Hurley, N.F., 2003 (in press), New method for quantification of vuggy porosity from digital optical borehole images as applied to the karstic Pleistocene limestone of the Biscayne aquifer, southeastern Florida: Journal of Applied Geophysics.

Hammes, Ursula, 1992, Sedimentation patterns, sequence stratigraphy, cyclicity, and diagenesis of early Oligocene carbonate ramp deposits, Suwannee Formation: Ph.D. Dissertation, University of Colorado, Boulder, 344 p.

Hantush, M.S., and Jacob, C.E., 1955, Nonsteady radial flow in an infinite leaky aquifer: American Geophysical Union Transactions, v. 36, no. 1, p. 95-100.

Hickey, J.J., 1993, Characterizing secondary porosity of carbonate rocks using borehole video data [abstract]: Geological Society of America, Abstracts with Programs, 25, Southeastern Section, p. 23.

Hurley, N.F., Pantoja, David, and Zimmerman, R.A., 1999, Flow unit determination in a vuggy dolomite reservoir, Dagger Draw Field, New Mexico: SPWLA 40th Annual Logging Symposium, May 30-June 3, Oslo, Norway, p. 1-14.

Hurley, N.F., Zimmerman, R.A., and Pantoja, David, 1998, Quantification of vuggy porosity in a dolomite reservoir from borehole images and core, Dagger Draw Field, New Mexico: Annual Technical Conference and Exhibition, New Orleans, Louisiana, Society of Petroleum Engineers Paper 49323, p. 789-802.

Jacob, C.E., 1946, Drawdown test to determine effective radius of artesian well: American Society of Civil Engineers Proceedings, v. 72, p. 629-646.

Kerans, C., Lucia, F.J., and Senger, R.K., 1994, Integrated characterization of carbonate ramp reservoirs using outcrop analogs: American Association of Petroleum Geologists Bulletin, v. 78, p. 181-216.

Kerans, Charles, and Tinker, S.W., 1997, Sequence stratigraphy and characterization of carbonate reservoirs: SEPM Short Course Notes, no. 40, 130 p.

Loizeaux, N.T., 1995, Lithologic and hydrogeologic framework for a carbonate aquifer: Evidence for facies controlled hydraulic conductivity in the Ocala Limestone, west-central Florida: University of Colorado, Unpublished Master's Thesis, 298 p.

Lucia, F.J., 1995. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization: American Association Petroleum Geologists Bulletin, v. 79, p. 1275-1300.

Lucia, F.J., 1999, Carbonate reservoir characterization: New York, Springer, 226 p.

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

Newberry, B.M, Grace, L.M., and Stief, D.D., 1996, Analysis of carbonate dual porosity systems from borehole electrical images: Midland, Texas, Permian Basin Oil and Gas Recovery Conference, Society of Petroleum Engineers (SPE) Paper 35158, p. 123-125.

Reese, R.S., 2002, Inventory and review of aquifer storage and recovery in southern Florida: U.S. Geological Survey Water-Resources Investigations Report 02-4036, 56 p.

Shaw, J.E., and Trost, S.M., 1984, Hydrogeology of the Kissimmee Planning area: West Palm Beach, South Florida Water Management District Technical Publication 84-1, 235 p.

Southwest Florida Water Management District, 2000, Aquifer characteristics within the Southwest Florida Water Management District: Brooksville, Southwest Florida Water Management District, Technical Services Department Report 99-1, 122 p.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transactions, v. 16, p. 519-524.

Walton, W.C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Bulletin, v. 49, 81 p.

Williams, J.H., and Johnson, C.D., 2000, Borehole-wall imaging with acoustic and optical televiewers for fractured-bedrock aquifer investigations: Proceedings of the 7th Minerals and Geotechnology Logging Symposium, Golden, Colorado, October 24-26, 2000, p. 43-53.