Synthesis of the Hydrogeologic Framework of the Floridan Aquifer System and Delineation of a Major Avon Park Permeable Zone in Central and Southern Florida

By Ronald S. Reese[1] and Emily Richardson[2]

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Prepared in cooperation with the
South Florida Water Management District

Scientific Investigations Report 2007-5207

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

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

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Suggested citation:

Reese, R.S., and Richardson, Emily, 2008, Synthesis of the Hydrogeologic Framework of the Floridan Aquifer System and Delineation of a Major Avon Park Permeable Zone in Central and Southern Florida: U.S. Geological Survey Scientific Investigations Report 2007-5207, 60 p., 4 pls., plus apps. (on CD).

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Conversion Factors, Datums, and Acronyms,

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Temperature	
Fahrenheit (°F)	°C = (°F - 32)/1.8	Celsius (°C)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929); horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 1983).

Altitude, as used in this report, refers to distance above or below the vertical datum.

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

API	American Petroleum Institute
ASR	Aquifer Storage and Recovery
BOG	Branch of Oil and Gas
CERP	Comprehensive Everglades Restoration Plan
FAS	Floridan Aquifer System
FGS	Florida Geological Survey
GLAUC	Glauconite
GWSI	Ground-Water Site Inventory
MAP	Middle Avon Park
RASA	Regional Aquifer System Analysis
SFWMD	South Florida Water Management District
SJRWMD	St. Johns River Water Management District
SP	Spontaneous borehole potential
SWFWMD	Southwest Florida Water Management District

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Abstract

The carbonate Floridan aquifer system of central and southern Florida (south of a latitude of about 29 degrees north) is an invaluable resource with a complex framework that has previously been mapped and managed primarily in a subregional context according to geopolitical boundaries. As interest and use of the Floridan aquifer system in this area increase, a consistent regional hydrogeologic framework is needed for effective management across these boundaries.

This study synthesizes previous studies on the Floridan aquifer system and introduces a new regional hydrogeologic conceptual framework, linking physical relations between central and southern Florida and between the west and east coastal areas. The differences in hydrogeologic nomenclature and interpretation across the study area from previous studies were identified and resolved. The Floridan aquifer system consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer. This study introduces and delineates a new major, regional productive zone or subaquifer, referred to as the Avon Park permeable zone. This zone is contained within the middle confining unit and synthesizes an extensive zone that has been referred to differently in different parts of the study area in previous studies. The name of this zone derives from the description of this zone as the "Avon Park highly permeable zone" in west-central Florida in a previous study. Additionally, this zone has been identified previously in southeastern Florida as the "middle Floridan aquifer."

An approximately correlative or approximate time-stratigraphic framework was developed and was used to provide guidance in the identification and determination of aquifers, subaquifers, and confining units within the Floridan aquifer system and to determine their structural relations. Two stratigraphic marker horizons within the Floridan aquifer system and a marker unit near the top of the aquifer system were delineated or mapped. The marker horizons are correlative points in the stratigraphic section rather than a unit with upper and lower boundaries. The two marker horizons and the marker unit originated from previous studies, wherein they were based on lithology and correlation of geophysical log signatures observed in boreholes. The depths of these marker horizons and the marker unit were extended throughout the study area by correlation of natural gamma-ray logs between wells. The Floridan aquifer system includes, in ascending order, the upper part of the Cedar Keys Formation, Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone, and in some areas the lower part of the Hawthorn Group. The first marker horizon is in the lower part of the aquifer system near the top of the Oldsmar Formation and is associated with the top of distinctive glauconitic limestone beds that are present in some regions; the second marker horizon is near the middle of the aquifer system in the middle part of the Avon Park Formation. The marker unit lies at the top of a basal unit in the Hawthorn Group and provides a stratigraphic constraint for the top of the Floridan aquifer system. The marker horizons do not have distinguishing lithologic characteristics or a characteristic gamma-ray log pattern in all areas but are still thought to be valid because of correlation of the entire section and correlation of all sufficiently deep wells with gamma-ray logs.

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The Avon Park permeable zone is contained entirely within the Avon Park Formation; its position within the section is either near the middle Avon Park marker horizon or within a thick part of the section that extends several hundred feet above the marker horizon. This subaquifer is present over most of the study area and characteristically consists of thick units of dolostone and interbedded limestone, and limestone in its upper part. Permeability is primarily associated with fracturing. This subaquifer is well developed in west-central Florida, parts of east-central Florida, and the northern part of southeastern Florida.

The Avon Park permeable zone has been identified in previous studies as the: (1) upper part of the Lower Floridan aquifer in the northern part of southeastern Florida and in a central peninsular area; or (2) lower part of the Upper Floridan aquifer in west-central Florida, the northern part of east-central Florida, and the southern part of southeastern Florida. This zone is interpreted to be the lower zone B of the Upper Floridan aquifer as defined in a previous study of east-central Florida, and the Upper Floridan aquifer of this study is equivalent to upper zone A of the Upper Floridan aquifer in the same previous study. The Upper Floridan aquifer as defined in this study in west-central Florida includes only the Suwannee Limestone, and in some areas the upper part of the Ocala Limestone.

Occurrence of permeable dolostone shallower in the section can greatly affect the upper boundary of the Avon Park permeable zone, and this occurrence appears to be highly localized in some areas causing large variations in the top of the zone from one to several hundred feet over relatively short distances (6 miles or less). Additionally, there can be considerable uncertainty regarding hydraulic connectivity in the Avon Park permeable zone between wells in some areas, where correlative stratigraphic relations suggest that the subaquifer is developed in different parts of the section with vertical offset of one to several hundred feet.

Transmissivity of the Avon Park permeable zone is generally an order of magnitude higher than transmissivity in the Upper Floridan aquifer, and ranges from less than 100,000 to more than 1 million square feet per day. A large area in southern Florida, where limestone is the predominant lithology in the zone, tends to coincide with an area where transmissivity is less than 100,000 square feet per day. Development of dolomite as a major component in the zone to the north of this area appears to be related to structure as indicated by the altitude of the middle Avon Park marker horizon.

The uppermost permeable zone of the Lower Floridan aquifer is contained within the lower part of the Avon Park Formation. This zone is defined as the shallowest major permeable zone that occurs below the middle Avon Park marker horizon. This deeper zone is similar to the Avon Park permeable zone and occurs primarily in fractured dolomite units. The "Boulder Zone" in the lower part of the Lower Floridan aquifer is a thick (as much as 700 feet), highly transmissive zone characterized by fractured to cavernous dolomite, and is used for the disposal of treated wastewater in southern Florida. The top of the Boulder Zone was found to generally occur at a similar stratigraphic position in the Oldsmar Formation, one to several hundred feet below the lower marker horizon that is associated with glauconitic limestone.

The hydraulic connectivity of the aquifers and permeable zones mapped in this study, particularly those below the Upper Floridan aquifer, remains uncertain in some areas. The degree of confinement provided by confining units mapped between these permeable zones in some areas is also uncertain. Additional data and studies are needed to confirm connectivity, including collection of hydraulic head, hydrogeochemical, and water temperature data and their three-dimensional mapping and interpretation.

Introduction

Utilization and exploitation of the Floridan aquifer system of central and southern Florida (fig. 1) has increased greatly since the early 1990s. Prior to the development of new treatment and storage technologies, use for public supply was limited to specific areas of potable water quality. Major uses now include withdrawal for reverse-osmosis treatment and blending operations, aquifer storage and recovery (ASR), and disposal of treated wastewater. A comprehensive understanding of the hydrogeology of the system necessary for its effective management has remained elusive owing to a need to integrate new information acquired during the last 20 years and geologic, hydrogeologic, and hydraulic uncertainties.

Many Floridan aquifer system ASR facilities have been constructed since 1992, and many future ASR projects are planned; in southern Florida (fig. 1) alone, ASR or ASR test wells have been drilled or constructed at 30 sites, mostly in coastal areas. ASR has been proposed as a cost-effective water-supply and storage alternative as part of the Comprehensive Everglades Restoration Plan (CERP) on an unprecedented scale to meet the needs of agricultural, municipal and recreational users and the Everglades ecosystem (U.S. Army Corps of Engineers and South Florida Water Management District, 1999). Under CERP, the construction of more than 300 ASR wells is proposed in southern Florida, each with an assumed capacity of 5 Mgal/d during recharge (injection) or recovery. Currently, wells have been drilled at five sites as part of CERP; ASR cycle tests are planned at four of these sites using large diameter (24 in.) ASR injection wells that have been constructed.

Reverse-osmosis methods are used to desalinate brackish ground water withdrawn from the Floridan aquifer system in southern Florida; less commonly, withdrawn water is blended with freshwater from the surficial aquifer system. Despite this treatment requirement, public-supply withdrawal from the aquifer system has been increasing rapidly in recent years in southeastern Florida (fig. 1) with the construction of new well fields (Reese, 2004). Water-level and water-quality conflicts could arise between use of the aquifer system for both ASR and public or agricultural supply withdrawals.

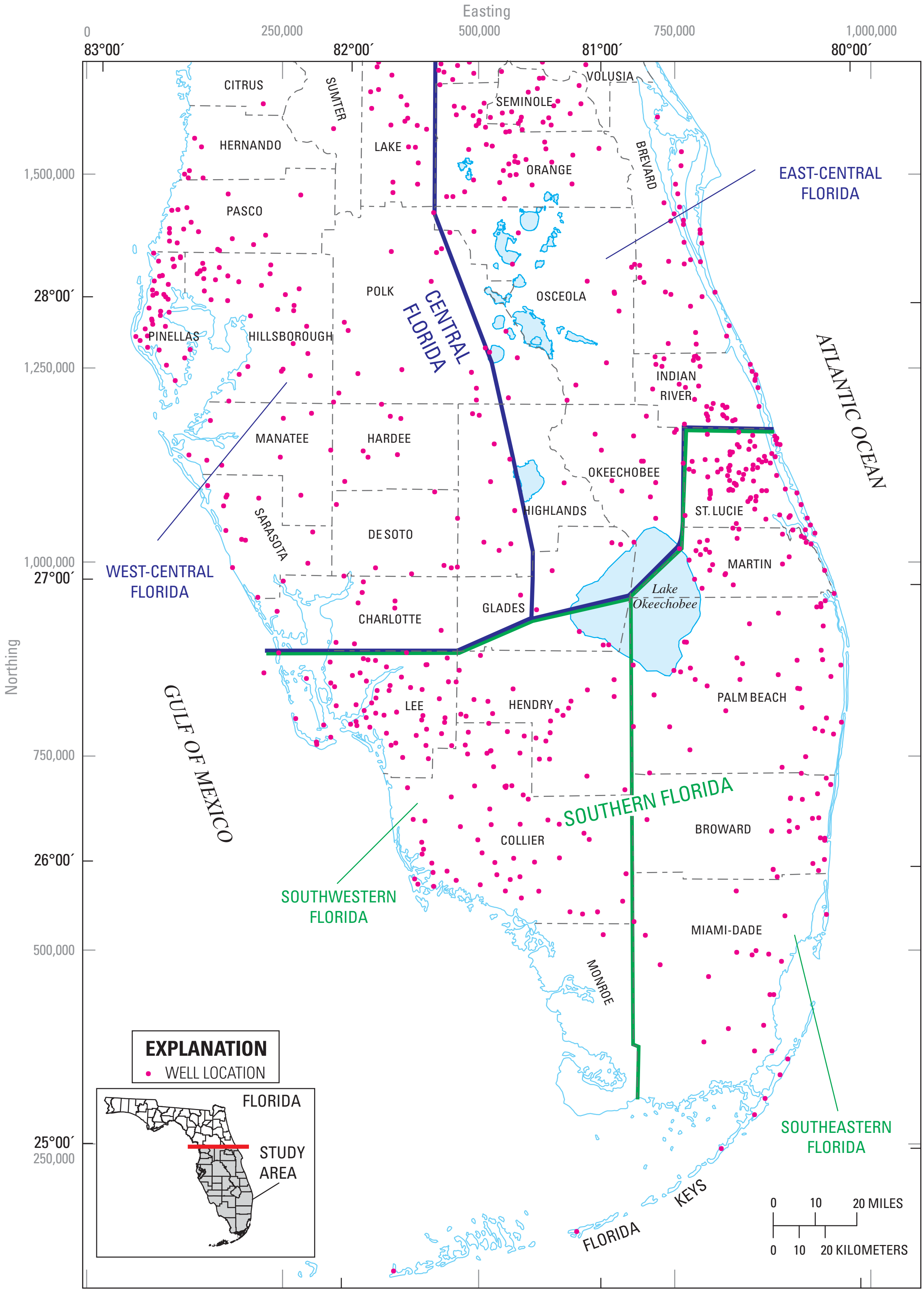


Figure 1. Study area, regions within the study area, and all wells used in the study in central and southern Florida.

Nonpotable water zones of the Floridan aquifer system below the saltwater-freshwater interface have been used extensively for storage of treated wastewater. The Florida Department of Environmental Protection (2003) reported there were 91 Class I injection facilities with 122 active wells located within the study area (fig. 1) with an average daily flow rate in 2002 of about 358 Mgal/d. Most facilities are concentrated in the densely populated coastal areas of southern and west-central Florida. Treated wastewater is injected primarily into a highly transmissive zone of fractured and cavernous dolostone in the Oldsmar Formation, referred to as the "Boulder Zone." In west-central Florida, however, wastewater injection is commonly within the shallower, highly transmissive Avon Park Formation (Maliva and Walker, 1998). The degree and continuity of confinement between injection zones and overlying or updip potable sections of the Floridan aquifer system have been a matter of considerable interest to resource managers and regulators.

Although 20 years have passed since Miller (1986) conducted a comprehensive regional overview of the Floridan aquifer system, correlative hydrogeologic relations between central and southern Florida remain poorly understood. The study by Miller (1986) was regional in nature, covering almost the entire extent of the aquifer system (all of Florida and parts of Georgia, Alabama, and South Carolina). Since the 1980s, numerous hydrogeologic test wells have been drilled to collect data deep within the Floridan aquifer system to better understand its hydrogeology. Most of the data available for the Miller (1986) study, however, were either from oil test wells or wastewater injection wells. The oil test wells were drilled much deeper than the Floridan aquifer system and, therefore, were not designed for data collection in this system. The wastewater injection wells were limited to coastal areas, and focused primarily on the lower part of the system. The relative lack of integration of new data and local studies, coupled with the increased uses of the aquifer system highlight the need for an updated regional synthesis of the Floridan aquifer system in central and southern Florida.

To address this need for an updated regional synthesis, the U.S. Geological Survey (USGS), in cooperation with the South Florida Water Management District (SFWMD), initiated a study in 2003 under CERP as part of the regional ASR program and the USGS Greater Everglades Priority Ecosystems Science Initiative. The purposes of this study were fourfold: (1) identify correlative uncertainties and interpretive differences in the hydrogeologic nomenclature and existing Floridan aquifer system framework in central and southern Florida, (2) tentatively resolve these uncertainties and differences and update the existing hydrogeologic framework, (3) identify areas where data are sparse and guide in the placement of new CERP program test wells and the collection of additional data, and (4) map hydrogeologic unit surfaces and hydrologic properties for use in regional numerical flow models of the Floridan aquifer system. A "final hydrogeologic framework" was planned under the CERP regional ASR program and is in progress.

Purpose and Scope

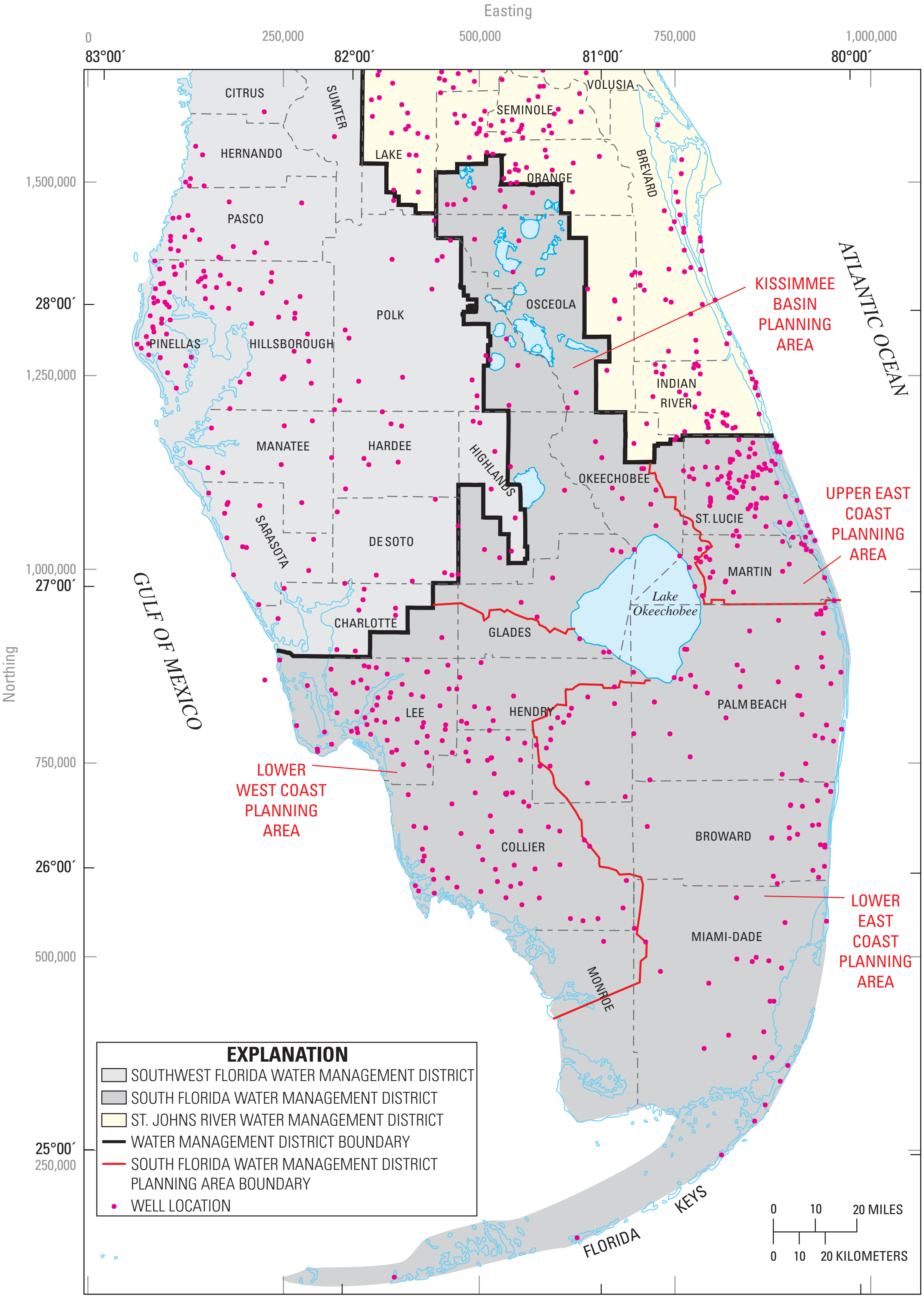
The purposes of this report are to: (1) document the resolution of regional differences in hydrogeologic nomenclature and framework interpretation of the Floridan aquifer system between central and southern Florida and between west and east coastal areas; (2) establish a consistent hydrogeologic framework interpretation thoroughout central and southern Florida; and (3) develop hydrogeologic surface and thickness maps of units within the upper part of the Floridan aquifer system, thereby allowing for better comparisons of existing ASR sites and their performance and improved selection of future ASR sites.

To accomplish this regional synthesis, a number of maps and cross sections were constructed to illustrate regional features and delineate aquifer and permeable zone boundaries and characteristics. An approximately correlative or approximate time-stratigraphic framework was developed and is shown by four regional stratigraphic sections and two structure maps. Eight regional hydrogeologic sections are presented showing the distribution of hydrogeologic units across the study area. The boundaries of aquifers or subaquifers within the Floridan aquifer system are delineated, and maps of the upper and lower surfaces and thickness of three of these major hydrogeologic units are presented. A subaquifer, as defined in this study, is a major productive zone usually containing multiple flow zones that may or may not be contained within a formally defined aquifer.

Description of Study Area

The study area includes central and southern Florida, including the Florida Keys, south of a latitude of about 28 degrees 50 seconds north. Central Florida is divided into west-central Florida (commonly known as southwestern Florida) and east-central Florida, and southern Florida is divided into southwestern and southeastern Florida (fig. 1). For convenience, the boundaries between these four regions in some cases follow the boundaries between counties, however, their selection was primarily determined based on other factors. These divisions are based, in part, on jurisdictional boundaries of the State water-management districts (fig. 2). These districts are the SFWMD (southern Florida and a large central part of east-central Florida), Southwest Florida Water Management District (SWFWMD, west-central Florida), and St. Johns River Water Management District (SJRWMD, east-central Florida). The SFWMD has been subdivided into the four planning areas (fig. 2), one which includes the central part of east-central Florida (Kissimmee Basin Planning Area).

The north to south boundaries between the four regions approximately follow boundaries between physiographic units of peninsular Florida (fig. 3). The boundary between west-central and east-central Florida approximately follows the east side of Lake Wales Ridge, which divides plains and uplands, and the boundary between southwestern and southeastern Florida approximately follows the boundary between the Immokalee Rise and Big Cypress Spur units to the west and the Everglades unit to the east.



Base from South Florida Water Management District State Planar Coordinates
Datum NAD 83

Figure 2. Water management districts, South Florida Water Management District planning areas, and all wells used in the study area.

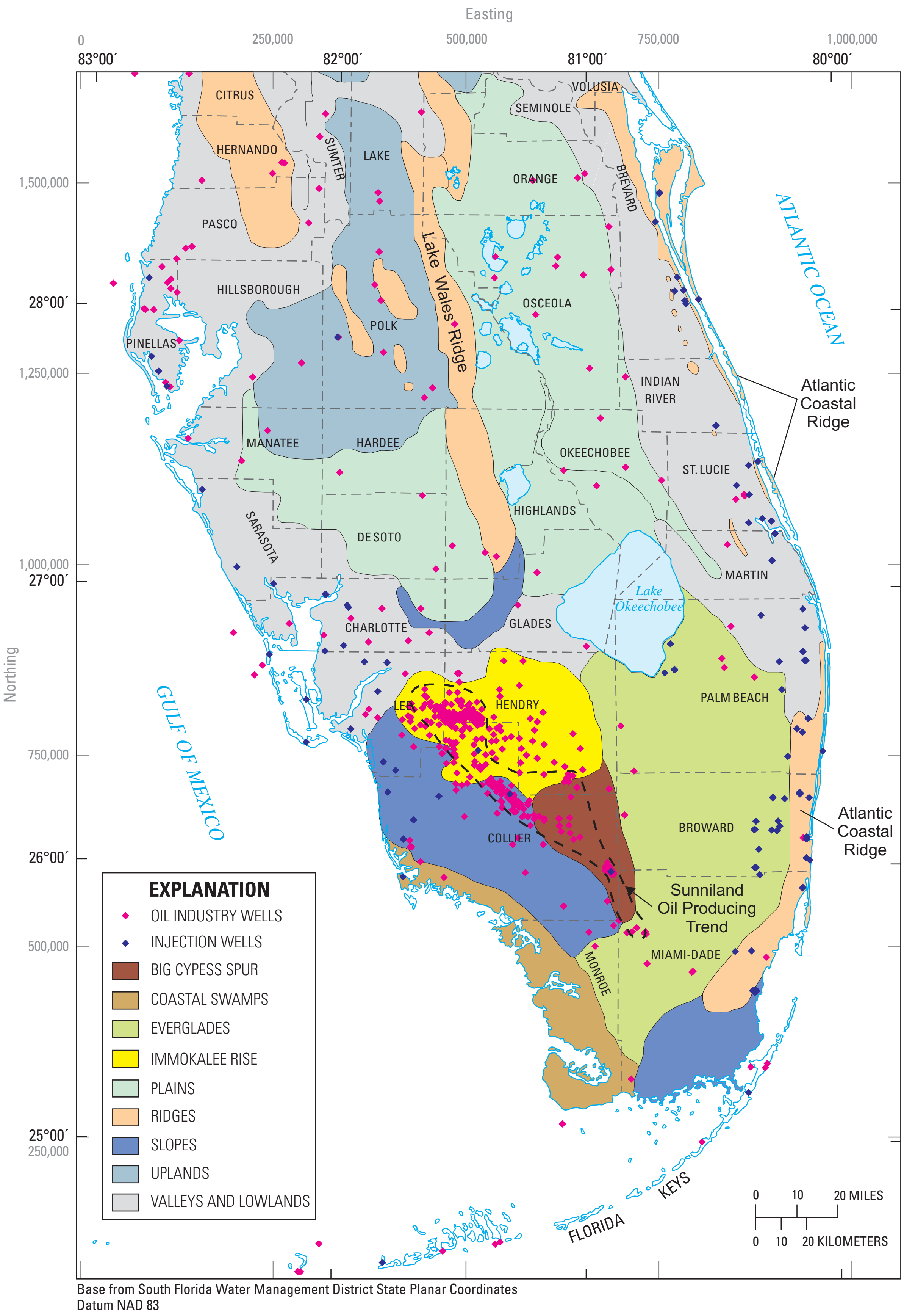


Figure 3. Physiographic units and oil industry and deep wastewater injection wells in the study area. Physiographic units modified from White (1970, pl. 1).

Previous Studies

The most recent comprehensive investigation of the hydrogeology of the Floridan aquifer system was conducted in the 1980s as part of the USGS Regional Aquifer System Analysis (RASA) program (USGS Professional Paper 1403 series reports). The hydrogeologic framework of the Floridan aquifer system was described by Miller (1986) over its full extent, including all of Florida and parts of Georgia, Alabama, and South Carolina. The ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system were described for the same region by Bush and Johnston (1988). Meyer (1989) analyzed the hydrogeology and ground-water movement in southern Florida. Hydrologic conditions within the Floridan aquifer system were quantitatively assessed in east-central Florida by Tibbals (1990) and in west-central Florida by Ryder (1985). Non-RASA local (State water-management district or planning area boundaries, or county boundaries) studies that include hydrogeologic mapping of the Floridan aquifer system were also completed during the 1980s. These investigations include those of Indian River County (Schiner and others, 1988), the Kissimmee Basin Planning Area (Shaw and Trost, 1984), all west-central Florida (Wolansky and others, 1980), and Pinellas County (Hickey, 1982).

More recent hydrogeologic studies of the Floridan aquifer system have been conducted in parts of the study area. Studies of the hydrogeology and distribution of salinity within the Floridan aquifer system have recently been conducted in southern Florida including Miami-Dade and Broward Counties in southeastern Florida (Reese, 1994); Lee, Collier, and Hendry Counties in southwestern Florida (Reese, 2000); Palm Beach County in southeastern Florida (Reese and Memberg, 2000); and Martin and St. Lucie Counties in southeastern Florida (Reese, 2004). Simulation of the Floridan aquifer system in the Upper East Coast Planning Area of southeastern Florida also included some hydrogeologic mapping (Lukasiewicz, 1992). Hydrogeologic mapping of west-central Florida has been conducted by the Florida Geological Survey (Arthur and others, 2007, in review); additionally, parts of Sarasota and Charlotte Counties in west-central Florida were mapped by Hutchinson (1992). A study of Okeechobee County in east-central Florida included some mapping (Bradner, 1994). The hydrogeology of the Lower Floridan aquifer in the northern part of east-central Florida (Lake, Orange, Seminole, most of northern Polk, Osceola, and Brevard Counties) was mapped by O'Reilly and others (2002), and a detailed hydrogeologic study of an active pumping well field was conducted in west-central Florida (Tihansky, 2005).

Many studies have focused on the stratigraphy of the Floridan aquifer system and overlying rocks. Chen (1965) studied the lithology and stratigraphy of Paleocene and Eocene strata in Florida and made paleogeographic interpretations. Other pertinent stratigraphic studies include those encompassing an area east and northeast of Lake Okeechobee (Mooney, 1980), Collier County in southwestern Florida (Peacock, 1983), the Hawthorn Group in all of the study area (Scott, 1988), and one of a corehole in Indian River County in east-central Florida (Weedman and others, 1995). Duncan and others (1994a, b) assessed the Lower Floridan aquifer in Brevard, St. Lucie, Martin, and Palm Beach Counties and identified and mapped two stratigraphic marker horizons within the Floridan aquifer system. Regional stratigraphic analysis of the Cretaceous to Oligocene-aged section in the Florida peninsula was conducted by Winston (1993; 1995).

An inventory and review of existing ASR wells utilizing the Floridan aquifer system of southern Florida was conducted by Reese (2002). A more complete comparative analysis of Floridan aquifer system ASR wells located in southern Florida that included ASR site performance and hydrogeologic framework definition was performed by Reese and Alvarez-Zarikian (2007).

Methods of Evaluation

This study involved several methods of evaluation. These methods include: (1) review of previous studies, (2) identification of differences in hydrogeologic nomenclature and interpretation, (3) collection and assimilation of available data, (4) development of a correlative or time-stratigraphic framework, and (5) development of a preliminary hydrogeologic framework with consistent nomenclature based on the stratigraphic framework and construction of maps and sections showing major aquifers, subaquifers, and confining units.

Inventory of Well Data

A total of 708 wells were inventoried and used in this study; they were drilled and constructed for various purposes and are irregularly distributed in the study area (figs. 1 and 2). Both location and type of available data are related to the original purpose for the well. Their purposes include hydrogeologic investigation, oil exploration, deep wastewater injection, ASR, and water supply. The wells with the most extensive data sets are hydrogeologic test wells constructed by State or Federal government agencies. Even though wastewater injection and oil test wells penetrate the deepest part of the Floridan aquifer system, the data associated with them are generally limited. Data collected in test wells drilled by State water-management districts normally include lithologic descriptions from cuttings or cores; complete geophysical log suites including borehole fluid logs; water-quality and water-level data; and hydrologic data from aquifer performance and packer tests. Injection wells tend to be clustered along the coasts in the major population centers (fig. 3), and the oil test wells are clustered along the Sunniland oil-producing trend in southwestern Florida (fig. 3). ASR wells also tend to be located along the coast, and well data from all 30 of the ASR test sites or facilities in southern Florida (Reese and Alvarez-Zarikian, 2007) are included in this study.

Data for all wells used in this study are presented in table A1 in the appendix, and their locations are shown in figure 1 and figure A1 in the appendix; figure A1 also shows the

station name in addition to the location. Table A1 includes the location of each well along with its associated identifiers. The SFWMD station name is the primary identifier used for each well; other identifiers include the USGS local name, USGS 15-digit site identifier, SJRWMD identifier, SWFWMD identifier, Florida Geological Survey (FGS) W number identifier, FGS Gas Section (formerly Branch of Oil and Gas) BOG number, and alternate names as applicable. Table A1 gives the location of wells in latitude/longitude and state planar coordinates; wells plotted in figure 1 and all other maps in this report were plotted using the state planar coordinates and Viewlog™ software.

Wells used in this study are given by type in table A1 and shown by type in figure A1. Types of wells identified are State water-management district and Federal hydrogeologic test wells (at least 71 wells including 4 SFWMD test wells drilled for hydrogeologic data collection at potential ASR sites), ASR system wells (26 wells), deep wastewater injection system wells (68 wells), and wells drilled for oil exploration and production (87 wells). Only the State water-management district test wells that could be readily identified are indicated; owner information on some older wells was not available. Most other wells not identified are non-State or Federal water-supply test or production wells.

Data for all wells used in this investigation are archived in the DBHYDRO database, developed and operated by the SFWMD. These data are available to the public at *http://glades.sfwmd.gov/pls/dbhydro_pro_plsql/show_dbkey_info.main_page*. Data can be retrieved from this site using the station name or any associated identifier listed in table A1 (app. 1), except the "other name or identifier" in the last column. Well-construction data for most of the wells used in southern Florida also are stored in the USGS Ground Water Site Inventory (GWSI) database. All wells having a 15-digit USGS site identifier in table A1 are stored in a GWSI database.

Depth in a well, as used in this report, refers to feet below the measuring point. In most cases, the measuring point and the land surface coincide; however, in some instances the measuring point lies slightly above land surface. The land-surface altitude, in feet above NGVD of 1929, of a station is referred to as "landmsl" in DBHYDRO and in table A1. If measurement of a point in a well is referenced herein to NGVD 1929, then the phrase "altitude, in feet above or below NGVD 1929" or simply "feet below (or above) NGVD 1929" is used.

Development of an Approximate Time-Stratigraphic Framework

An approximate time-stratigraphic framework was developed in this study primarily using geophysical log correlation between wells, beginning with stratigraphic marker units or lithologic changes established in certain wells or areas. A stratigraphic marker unit near the top of the Floridan aquifer system and two stratigraphic marker horizons within the middle and lower parts of the Floridan aquifer system were delineated and mapped to provide stratigraphic guidance in the identification and delineation of aquifers, subaquifers, and confining units. The marker unit has a finite thickness, whereas the marker horizons are points of correlation on natural gamma-ray logs. The two marker horizons originated from work by Duncan and others (1994a, b) in studies of east coast Lower Floridan aquifer injection wells located in Brevard, St. Lucie, Martin, and Palm Beach Counties; they were mapped by Duncan and others (1994a, b) using changes in lithology and natural gamma-ray logs for the purpose of establishing correlative relations. Starting with wells where they were determined by Duncan and others (1994a,b), the depths of these same two marker horizons were extended throughout the study area primarily using correlation of natural gamma-ray curves between wells. The marker unit near the top of the Floridan aquifer system in southern Florida (Reese, 2000, 2004; Reese and Memberg, 2000) was extended beyond where it was previously mapped.

Gamma-ray logging tools respond to naturally occurring radioactive emissions in the formation and record patterns that can be consistent between wells. The sources of these gamma emissions are radioactive potassium and radioactive elements of the thorium and uranium series (Schlumberger, 1972). Minerals that can produce higher natural gamma emissions in the Tertiary sedimentary section of Florida are phosphate, dolomite, and glauconite.

Correlation between wells using gamma-ray logs identifies points that follow or approximate bedding planes in the stratigraphic section that are assumed to be continuous between wells. In this approach, which can be subjective, gamma-ray curve patterns are recognized as repeating in each well; these patterns can show considerable variation in the amplitudes or thicknesses of individual deflections or characters and still be recognized. A missing or additional section in a well resulting from erosion, faulting, or localized depositional buildup, however, can commonly be recognized. Individual gamma-ray log peaks and their associated lithologic unit, such as a highly phosphatic limestone bed, do not necessarily represent timelines and may or may not be continuous, but correlation of the section as a whole, including all peaks and characteristics, can provide an approximate time-stratigraphic framework. A correlation, however, can also follow a regional disconformity, with the age of the sediments above or below this surface transgressing time laterally because of erosion or shifting patterns of deposition above the surface. Gamma-ray log peak(s) can occur in association with such a surface or a surface of subaerial exposure due to concentration of radioactive minerals (Krupa, 1999).

Correlation of gamma-ray logs of wells in this investigation was carried out at a vertical scale of 1 in. = 125 ft using working copies plotted through Viewlog™ software. The entire section from surface to total depth was correlated between wells in order to best establish the depths of stratigraphic marker horizons. Correlation within the

carbonate rocks of the Floridan aquifer system, which tend to have low natural radioactivity, was aided by plotting curves using an expanded scale, such as 0 to 100 API (American Petroleum Institute) standard units, instead of a more standard scale of 0 to 200 API units, to enhance gamma-ray curve variations.

The reliability of correlation of the marker horizons by gamma-ray logs in this study was improved by correlating all the deep wells with gamma-ray logs, not just wells on cross sections. Additionally, wells were correlated in loops, first regionally then locally, to check for correlation error of closure in returning to the original well. If an error greater than 20 to 30 ft was found, the correlations for the wells in a loop were reviewed and corrections were made. Once a regional loop was satisfactorily correlated, thereby establishing the correlations in a new region, then smaller loops were conducted in the new region.

Although the correlation marker horizons used in this study are originally tied to lithologic characteristics or changes in some wells along the east coast of Florida (Duncan and others, 1994a,b), they should not be considered to be marker beds or units. In many wells and areas, distinguishing lithologic characteristics cannot be found or are not present. In some cases, however, the absence of lithologic characteristics may be due to the quality of lithologic samples collected or the available lithologic description. The reliability of the these marker horizons could be substantially improved if a more detailed geologic investigation using a network of continuously cored wells were conducted. Marker beds or units or important stratigraphic boundaries, such as depositional sequence boundaries, may be found in such a study that could be related to the marker horizons.

Determination of Hydrogeologic Unit Boundaries

Hydrogeologic unit boundaries were determined in this study primarily using geophysical logs and lithologic descriptions. Where available, the results of hydraulic tests such as aquifer and packer tests were also reviewed. Additionally, in one area a formation boundary was used for the top of a confining unit because of the nature of the formation in the area and the unavailability of adequate other data. Assistance in the identification of units and determination of their boundaries between the major divisions of the study area (figs. 1 and 2) was provided by the construction of hydrogeologic sections (discussed in the following section) and the approximate time-stratigraphic framework, including the marker horizons and the marker unit previously described. More specific criteria used for the determination of certain aquifer boundaries are discussed in later sections of this report. Hydrogeologic unit boundaries determined in previous studies were reviewed for consistency in their methods of determination with those used in this study, and utilized wherever possible.

For the purpose of determining hydrogeologic boundaries in each well, geophysical logs and, when available, lithologic data were plotted together at a uniform scale (1 in. = 125 ft) using Viewlog™ software. Borehole geophysical logs were grouped by type into four columns that include: (1) natural formation gamma ray, spontaneous potential (SP), and caliper curves, (2) formation resistivity curves, (3) formation porosity curves, and (4) borehole flow and fluid properties logs including fluid resistivity, temperature, and flowmeter. Lithologic data were plotted in a fifth column using graphic symbols.

The boundaries for aquifers or permeable water-bearing zones in the Floridan aquifer system are best defined using a full suite of geophysical logs, hydraulic tests such as aquifer and packer tests, lithologic descriptions, drilling characteristics, and zone specific water-quality and hydraulic head data. Having extensive data available for a site can allow for the determination of whether permeable zones are hydraulically separate (individual aquifers or subaquifers) or hydraulically connected (permeable zones within a single aquifer or subaquifer). The availability of all of this information at a single site was limited primarily to test wells constructed by State water-management districts. The vertical distribution of hydraulic head in a test well was used to assist in determining boundaries in some water-management district well construction reports, and after review, these boundaries were usually accepted in this study. Generally, however, determination of the hydrogeologic boundaries through hydraulic head and hydrogeochemical data could not be done in this study, because these data were not available in most wells.

Flow zones that define a permeable zone are marked by abrupt and commonly large changes in borehole flow or fluid properties and are determined primarily using borehole fluid logs, including the flowmeter, fluid resistivity, and temperature logs, but other geophysical logs such as the caliper, formation resistivity, and porosity logs can provide supporting data. Borehole fluid logs were not collected in many wells, or were obtained only under static hydrologic conditions limiting their utility. Also, if flowmeter logging was conducted over a thick open-hole interval with multiple flow zones, one or several highly permeable zones can mask the effects of other zones that may be present. Hydraulic test data in the zone(s) of interest also were commonly not collected. In the absence of these data, however, an approximate determination of aquifer or permeable zone boundaries was made using lithologic descriptions and standard geophysical logs including formation resistivity and porosity, gamma-ray, caliper, and SP.

Some previous studies have used a large increase in salinity with depth to define a hydrogeologic boundary in the Floridan aquifer system, but this criterion was not used in this study. The top of the Lower Floridan aquifer was defined based on an increase in ground-water salinity from freshwater to brackish water in Okeechobee County (Bradner, 1994) and from brackish to saline water (seawater-like salinity) in southern Florida (Meyer, 1989).

Most of the hydrogeologic data used to determine hydrogeologic unit boundaries in this study were archived in the SFWMD DBHYDRO database; the data include geophysical logs, packer and aquifer performance tests, lithologic descriptions, and formation contact depths. The most complete coverage of these data is in the SFWMD area (fig. 2), but data on many of the wells used in the other water-management district areas were also archived in this database. Most of the lithologic descriptions in DBHYDRO were done by FGS and came from their database. Other data and lithologic descriptions used that are not in DBHYDRO were available from well construction reports done by consulting firms and government agencies other than FGS, including the USGS and the State water-management districts. Hydrogeologic unit boundary depths determined during this study or obtained from other investigations were also archived in DBHYDRO. All hydrogeologic boundary depths used in this study are shown in table A2 (app. 1).

Hydrogeologic Sections

The regional synthesis and development of a new hydrogeologic conceptualization of the Floridan aquifer system in the study area was in large part based on eight hydrogeologic sections created for this study. The primary purpose of these sections was to assist in delineating aquifers, subaquifers, and confining units between the major divisions of the study area (figs. 1 and 2). Working copies of the sections were constructed at a vertical scale of 1 in. = 125 ft with geophysical logs and lithologic columns plotted for each well using Viewlog™ software (fig. 4). Geophysical logs were grouped by function as previously described. Aquifer and formation boundaries and marker horizons were delineated.

Key wells were used to constrain interpretations across each section. Selected wells on each section were sufficiently deep to intersect the primary zones of interest and have high quality geophysical logs and ancillary data (such as water-quality or water-level data). The ancillary data could be used to help identify an aquifer or determine whether a permeable zone was a unique aquifer or a flow zone within a larger aquifer. Priority was given to State water-management district test wells, but wastewater injection and oil test wells were also used. Five sections were extended west to east across the peninsula as tie lines, and three sections were extended north to south, one along each coast and one along the center of the peninsula (fig. 4).

Stratigraphic and Hydrogeologic Maps

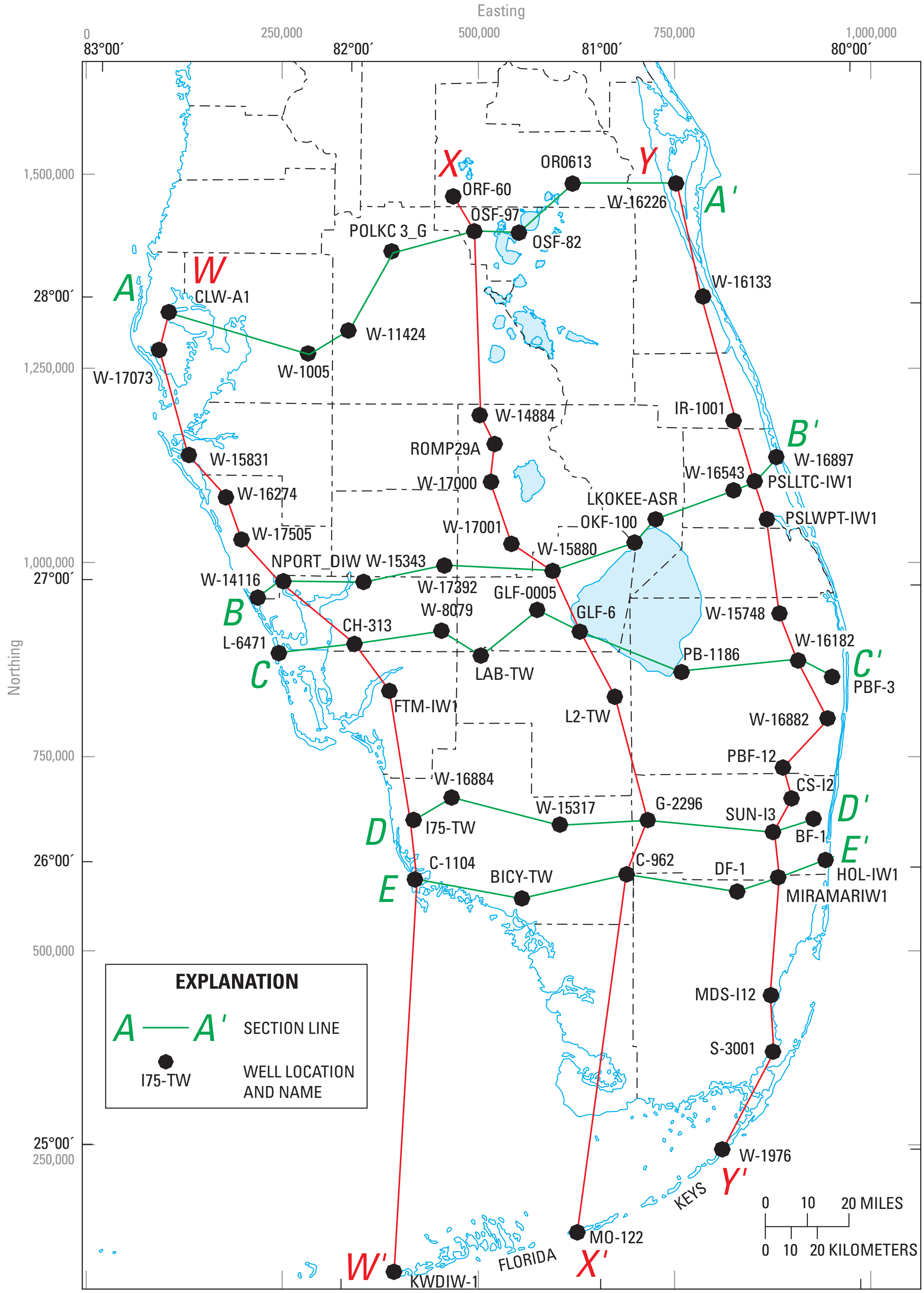
Maps of the two stratigraphic marker horizon surfaces and the top surface and thickness of hydrogeologic units, including aquifers, subaquifers, and one confining unit, were constructed in this study. The mapping was completed in three steps: (1) determination of the stratigraphic marker horizon and hydrogeologic unit boundary depths in wells used in the study, (2) generation of surface maps by fitting the well data to a statistical model, and (3) review and revision of these surfaces and generation of thickness maps.

Generation of Surfaces by Fitting Data to a Statistical Model

Stratigraphic marker horizon and hydrogeologic unit surface maps were produced using ordinary kriging techniques available with Viewlog™ software. There are a number of methods available for interpolating spatial data; however, kriging was chosen for its flexibility. Unlike other common interpolation techniques, such as the nearest neighbor or inverse distance weighted methods, kriging allows the user to build a model specific to the data being studied and to work with the model to minimize the error variance.

A semivariogram model and associated parameters, which are range, sill, and nugget, were selected based on the best visual and statistical fit for each surface data set. The range in a semivariogram is the distance between well locations beyond which the semivariance no longer increases (semivariogram curve reaches a plateau), and the sill is this maximum semivariance value. The nugget is a “relaxation factor” that determines how closely the model must adhere to the observed data points. The smaller the nugget, the more closely the model must adhere to observations. Some aspects of this model were the same for all of the surfaces. Due to the regional southerly dip of strata and units comprising the Floridan aquifer system into the southern Florida basin, a linear trend had to be removed from all data prior to selecting the semivariogram model. All of the detrended surface data sets fit best to an exponential form of the model. In addition, a nugget of zero was used for all surfaces to force the surface produced by the model to pass through the actual data points.

Kriging gives stronger weight to pairs of points that are closer together. For this reason, semivariogram models that best fit those points were selected for this study. Achieving a well-fitting semivariogram model using this approach commonly required specifying a relatively small range (less than 50,000 ft, or about 10 mi). This presented a problem in the deeper units of the Floridan aquifer system, because there are relatively few control points within 10 mi of each other, and those that exist are clustered in certain areas. One consequence of this strict adherence to geostatistical principle is that it requires the semivariogram to be tuned to where the fewest data points are available. Another consequence is that large portions of the generated surface are outside the range of any control point, and the uncertainty in these areas is large.



Base from South Florida Water Management District State Planar Coordinates
Datum NAD 83

Figure 4. Location of hydrogeologic sections and wells used on the sections.

Review and Revision of Surfaces and Generation of Thickness Maps

Generating the stratigraphic marker horizon and hydrogeologic unit surfaces was an iterative process. After the first round of kriging, the surfaces and control point values were plotted. Data points that were anomalous because of a value inconsistent with those in nearby wells were reviewed, and any that were determined or evaluated in this study were reevaluated to establish their reliability. One of the following steps then was taken:

- Anomalous points were reviewed for how well they met the criteria used in this project for boundary depth determination. Upon this additional review, points found not to meet project criteria or based on a weak data set (for example, a control point based solely on poor quality geophysical logs without supporting borehole fluid logs, lithologic descriptions, or hydraulic tests) were removed from the interpolation or retained with the uncertainty indicated manually by dashing contour lines.

- Anomalous points with strong supporting data were assumed to be reliable and were retained.

- In rare cases, data points met project criteria with relatively strong supporting data at the local well scale, but were removed from the interpolation because of the undue influence they exerted at a larger scale. An example of this is the top for the Lower Floridan aquifer in well MO-122, located at the southernmost end of section *X-X′* in the Florida Keys (fig. 4). The geophysical logs and stratigraphic framework developed in this study support the identification of a permeable zone in this well from a depth of 2,088 to 2,122 ft below land surface as the uppermost permeable zone of the Lower Floridan aquifer (LF1). The problem is that this data point is the middle well of only three wells in the Keys deep enough to intercept the LF1, and the presence of LF1 was not indicated in the other two. In addition, a deepening trend was observed in the LF1 from Lake Okeechobee southward on the mainland, and the top of the LF1 at MO-122 deviated strongly from that trend, being almost 500 ft higher in the section than the closest mainland data point for LF1. Therefore, although the value at MO-122 met project criteria for LF1, the point was not included in the interpolation because there was insufficient evidence that the observed permeable zone in the well was the one mapped on the mainland.

After modifications were made to the input data set based on this review, the integrity of the kriging model was checked and the surface was regenerated. Once satisfactory upper and lower surfaces for a hydrogeologic unit were completed, they were used to generate the unit thickness map by subtraction.

The final step in the generation of surface and unit thickness maps was manual modification, which is typically required in order to produce a map that conforms well to professional judgment, and provides the viewer with sufficient information to interpret the map correctly. Computer automated kriging routines generally require the study area to be subdivided into a uniform grid and, consequently if large changes occur over short distances (within a single grid cell), the program cannot accurately account for all of the control points. The programs also tend to have difficulty dealing with poorly distributed data sets. This becomes problematic when dealing with large areal data gaps or zone pinchouts. Thus, in addition to reviewing individual anomalous data points, the surfaces as a whole were reviewed for consistency. Contours lines on maps were moved to account for all data points, and the positions of zone pinchouts, if present, were interpreted and drawn in manually. Finally, contour lines were smoothed and, where necessary, dashed to indicate less confidence in their position because of large areal data gaps or values that were less certain.

Results of Surface Generation

Data from this regional study were compiled in an effort to provide statistically valid maps that can be refined as more data become available. Four aquifers or subaquifers in the Floridan aquifer system were mapped, but the number of data points for each decreases markedly with depth (table 1). The best-fit semivariogram model parameters shown in table 2 were used to generate the surfaces representing the top and base of all the hydrogeologic units and the two stratigraphic correlation marker horizons determined in this study. The “goodness of fit” values in table 2 represent a least-squares fit of the data to the selected model. Table 2 indicates that small numbers of data pairs coupled with small range values for some surfaces produced large uncertainties in the estimated surfaces. It is necessary, therefore, to consider these uncertainties when utilizing the surfaces generated.

While the data resolution decreases with depth, it also becomes poorly distributed in horizontal space. This is because much of the deeper data were obtained from injection and oil test wells. The injection well data points tend to be clustered along the coasts in major population centers, and the oil well points tend to cluster along the Sunniland oil-producing trend in southwestern Florida (fig. 3). In these circumstances, extra input was sometimes required to guide the automated interpolation routine for fitting data to a statistical model that generates a surface to a satisfactory result.

Modeled semivariograms for the top and base of the Upper Floridan aquifer are presented in figure 5 to illustrate the fitting procedure and point out process limitations. These two surfaces demonstrate the range of suitability for the selected model, from good to poor (fig. 5a and b, respectively). Statistically, both models appear to fit the data well, but that is the extent of the similarity. The model for the top of the Upper Floridan aquifer is substantially more robust.

Table 1. Summary of hydrogeologic data used to estimate surfaces of hydrogeologic units.

[Altitude is in feet above or below NGVD 1929. Aquifers: UF, Upper Floridan aquifer; APPZ, Avon Park permeable zone; LF1, upper permeable zone of the Lower Floridan aquifer; BZ, Boulder Zone. Stratigraphic marker: MAP, middle Avon Park; GLAUC, glauconite]

Aquifer or stratigraphic correlation marker	Surface	Number of data points	Minimum altitude	Maximum altitude	Median altitude	Mean altitude	Standard deviation in altitude
UF	Top	683	-1,165	48	-448	-440	334
UF	Base	177	-1,514	-112	-781	-779	413
APPZ	Top	109	-1,898	-194	-1,370	-1,233	468
APPZ	Base	104	-2,038	-354	-1,635	-1,445	453
LF1	Top	162	-2,644	-537	-1,889	-1,741	534
LF1	Base	87	-2,755	-1,108	-2,160	-2,103	409
BZ	Top	64	-3,402	-1,615	-2,894	-2,804	328
MAP	Marker horizon	104	-2,123	-575	-1,703	-1,528	437
GLAUC	Marker horizon	59	-2,797	-1,355	-2,510	-2,287	486

Table 2. Best-fit semivariogram model parameters used to estimate surfaces of hydrogeologic units.

[Aquifers: UF, Upper Floridan aquifer; APPZ, Avon Park permeable zone; LF1, upper permeable zone of the Lower Floridan aquifer; BZ, Boulder Zone. Stratigraphic correlation marker horizon: MAP, middle Avon Park; GLAUC, glauconite. Total goodness of fit represents the overall fit of the model to the detrended data; Trend goodness of fit is the percentage of the fit accounted for by the linear trend]

Aquifer or stratigraphic correlation marker	Surface	Number of pairs of points	Maximum distance between pairs of points (feet)	Number of intervals	Range (feet)	Sill (feet)	Goodness of fit (percent)	
							Total	Trend
UF	Top	26,253	175,000	23	70,000	8,100	99.7	66.8
UF	Base	619	100,000	19	43,000	14,650	97.0	33.1
APPZ	Top	582	160,000	16	32,580	23,400	97.7	25.9
APPZ	Base	540	170,000	15	53,000	45,000	99.7	8.0
LF1	Top	2,374	225,000	32	80,000	29,000	96.9	47.7
LF1	Base	719	225,000	20	40,000	31,500	98.3	30.0
BZ	Top	299	165,000	12	50,000	30,000	97.1	11.2
MAP	Marker horizon	557	170,000	14	41,000	9,400	99.2	46.4
GLAUC	Marker horizon	246	200,000	8	76,791	13,056	99.1	48.2

The base of the Upper Floridan aquifer model exhibits a wide spread in the data pairs around the model line, whereas the data pairs for the top are clustered tightly around the model line. This variability is reflected in the distribution of calculated standard error of estimate for these two surfaces (fig. 6). For the top of the Upper Floridan aquifer model, the standard error of estimate is less than 75 ft over most of the peninsula, and less than 50 ft over much of southern Florida. The base of the Upper Floridan aquifer model, in contrast, exhibits a much larger range of error, with a standard error of less than 50 ft only in the immediate vicinity of a control point, and an error of 100 to 150 ft over most of the peninsula. This is due, in part, to the poorer fit of the semivariogram model, but primarily it is due to the relatively small number of control points. The surface for the top of the Upper Floridan aquifer was generated from more than 26,000 data pairs, whereas the one for the base was generated from only about 600 data pairs. Even if the base of the Upper Floridan aquifer data pairs coincided with the semivariogram model line, the standard error would still be high because the distance between most of the available data pairs is outside of the model range value shown in table 2.

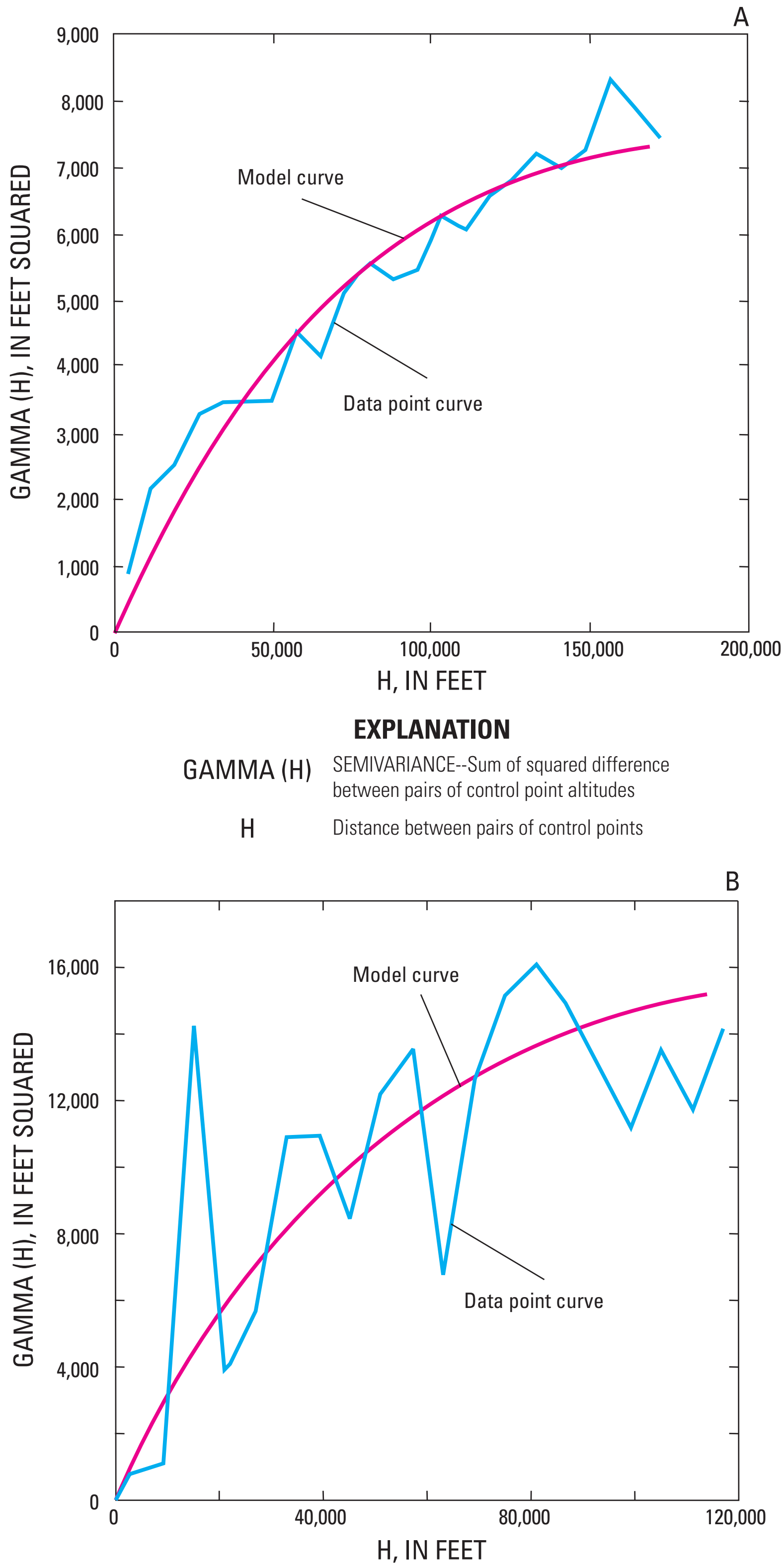


Figure 5. Semivariogram models for the (A) top of the Upper Floridan aquifer, and (B) base of the Upper Floridan aquifer.

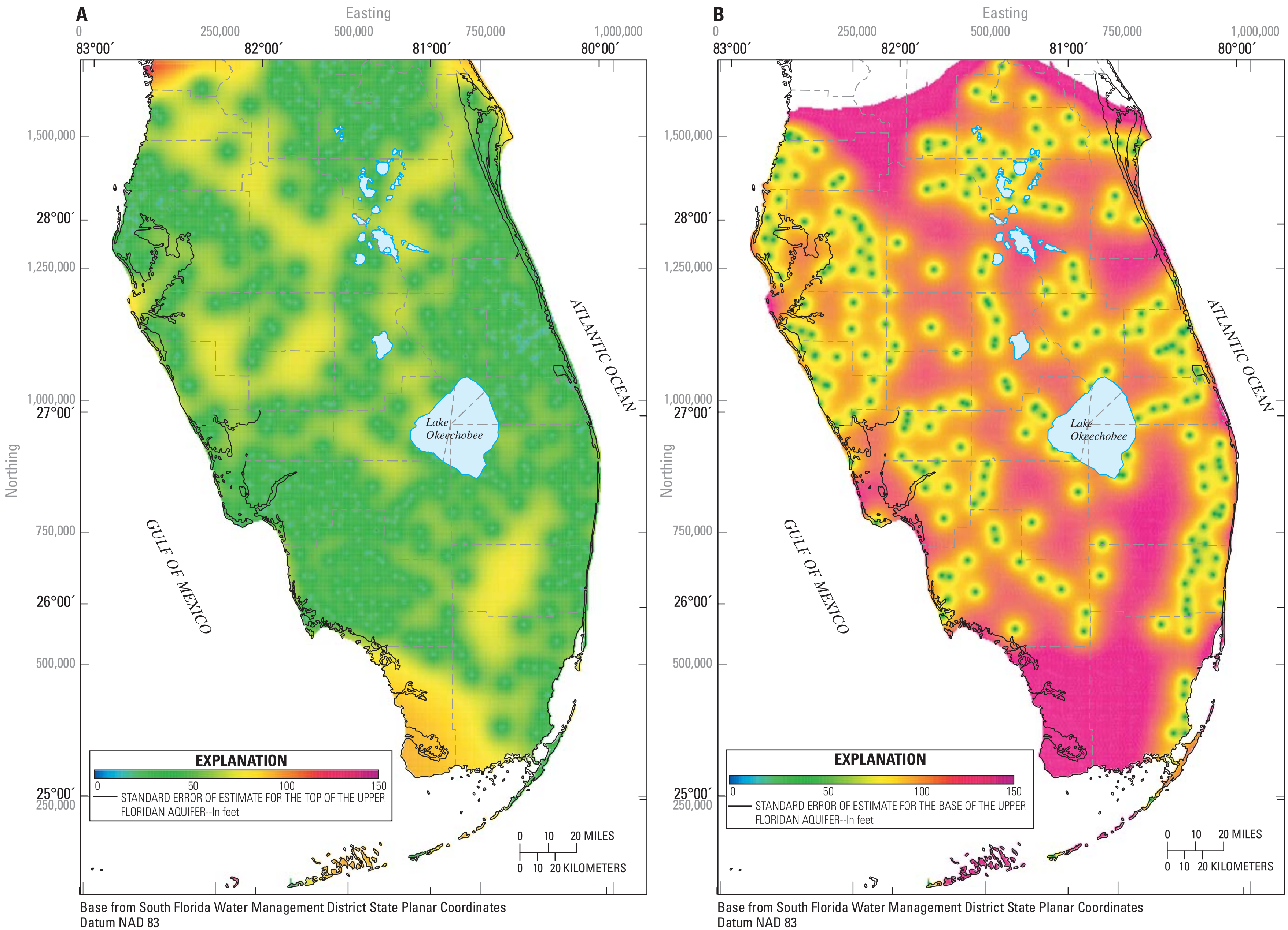


Figure 6. Standard error of estimate for the (A) top and (B) base of the Upper Floridan aquifer.

Almost four times more data are available for the top of Upper Floridan aquifer than for the base, and even fewer data points are available for the top of the Avon Park permeable zone (table 1). In some cases, this is because wells did not penetrate the full thickness of the aquifer; in others, it is because the base of the zone was not of interest. Additionally, as previously described, much of the data used to define the base of the Upper Floridan aquifer and units below this aquifer are poorly distributed aerially. In these circumstances, an automated interpolation routine sometimes requires extra input to guide it to a satisfactory result. Figure 7 illustrates this with a simple example, showing a cross section through five wells. The top of an aquifer or permeable zone, which could be the Upper Floridan aquifer or the Avon Park permeable zone, is an interpolated surface based on all of the wells on the section and other nearby wells off the section line. The base of the aquifer was determined only at wells 1 and 5. With only those two points as input, the automated interpolation routine will produce a base of the aquifer surface similar to the dashed line in figure 7. Given that the top of the aquifer was identified in wells 2 and 3, it is unreasonable to assign the aquifer zero thickness at those points as indicated by the interpolated basal surface. In order to prevent this type of problem, it was necessary to add infill data points to the interpolation in some places to guide the software to a more reasonable surface for the base of the aquifer. These points were stored separately from the actual data points and were not used in formulating the kriging model.

Geologic Framework

The geologic framework that contains the Floridan aquifer system in central and southern Florida is a thick sequence of predominantly carbonate rocks. In ascending order, formations included in the aquifer system are the upper part of the Cedar Keys Formation of Paleocene age, Oldsmar Formation of early Eocene age, Avon Park Formation of middle Eocene age, Ocala Limestone of late Eocene age, and Suwannee Limestone of Oligocene age (Miller, 1986). The Hawthorn Group, which ranges in age from at least as old as late Oligocene to at least as young as the Miocene (Wingard and others, 1994), overlies the Suwannee Limestone and contains the older Arcadia Formation and the younger Peace River Formation (Scott, 1988). A basal part of the Hawthorn Group is also generally accepted as being included in the Floridan aquifer system, at least in southwestern Florida (fig. 8).

The geologic characteristics of these formations and units, including their lithology and post-depositional changes that relate to aquifer hydraulic properties, and an approximate time-stratigraphic framework for the Floridan aquifer system developed in this study are described in the subsequent section. The time-stratigraphic framework includes the presentation of four stratigraphic sections and two maps showing the altitude of two stratigraphic marker horizons.

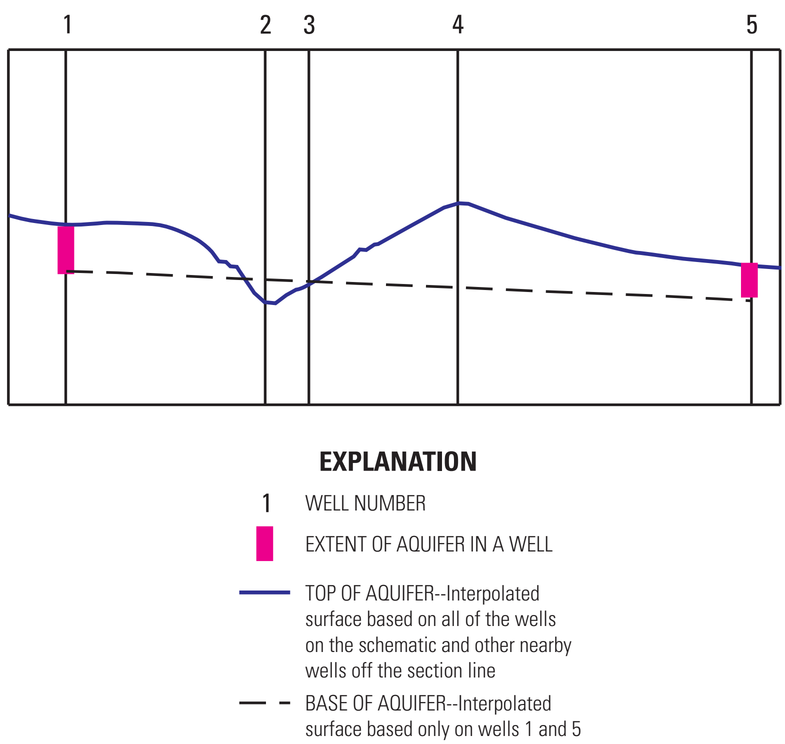


Figure 7. Schematic section showing problems associated with automatic interpolation routines in areas with large data gaps where the base of an aquifer has fewer data points than the top.

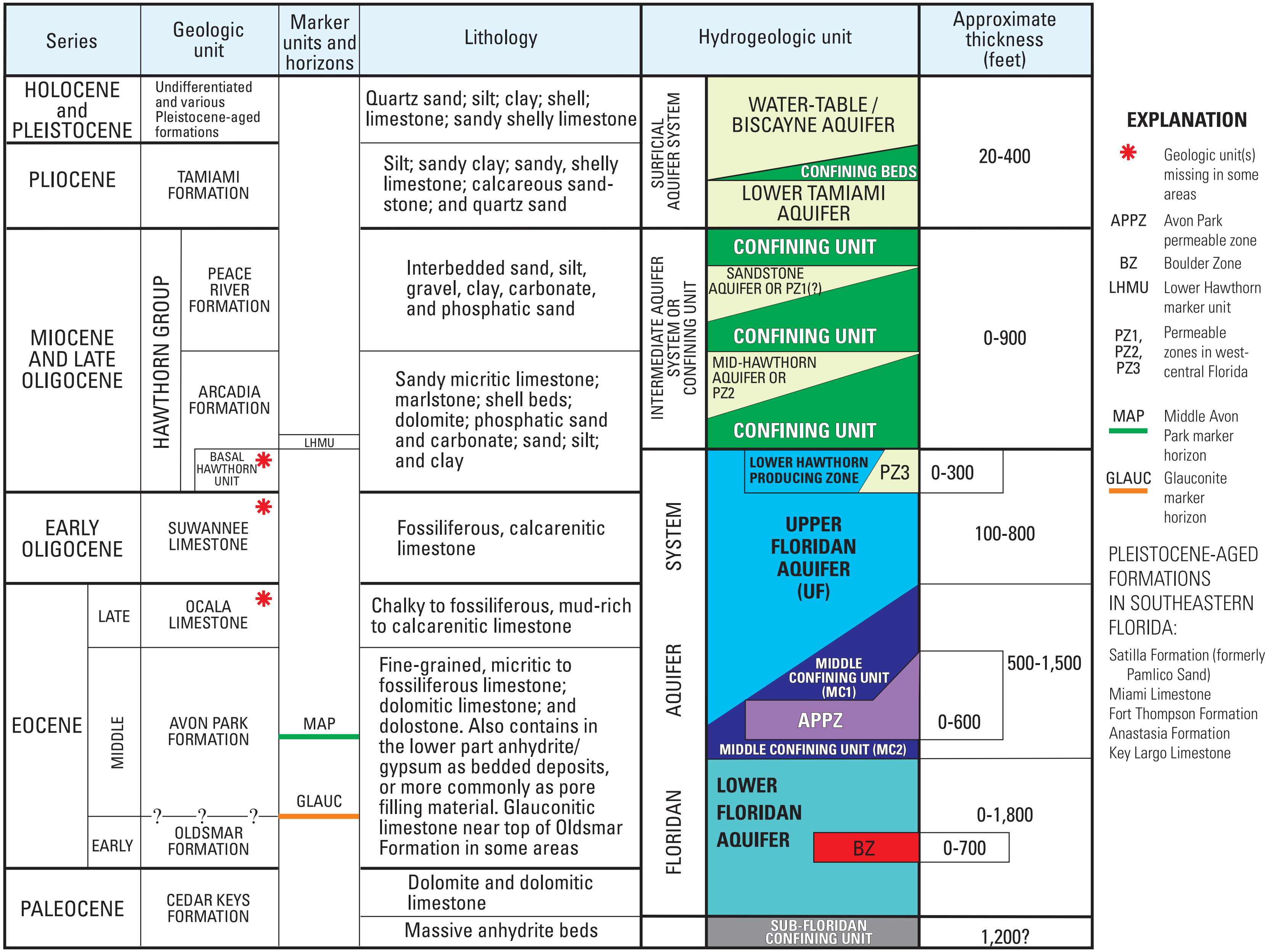


Figure 8. Chart showing relation of hydrogeologic units as defined in this study to geologic units and their lithology.

Geologic Units and Lithology

Dolomite, dolomitic limestone, and anhydrite constitute the Cedar Keys Formation. The anhydrite is present as thick massive beds in the lower part of the formation, and the top of these beds mark the base of the Floridan aquifer system.

The Oldsmar Formation primarily consists of a sequence of white to gray, micritic limestone and interbedded tan to light-brown dolomite, and ranges from about 500 to 1,500 ft thick in the study area (Miller, 1986, pl. 5). Anhydrite and gypsum are common lithologic components of the Oldsmar Formation in west-central Florida. The top of the Oldsmar Formation in east-central Florida is marked by glauconitic limestone (Duncan and others, 1994a), whereas in southern Florida, it has been placed at the top of the uppermost thick dolostone unit (Meyer, 1989). According to Winston (1993), the top of the Oldsmar Formation in southern Florida is not identifiable or distinguishable on the basis of lithologic and faunal criteria. The "Boulder Zone" forms part of the Oldsmar Formation, and characteristically contains massively bedded to cavernous or fractured dolostone (fig. 8).

The Avon Park Formation consists principally of micritic to fossiliferous limestone, dolomitic limestone, and dolostone or dolomite (fig. 8). Fine- to medium-grained calcarenite that is moderately to well sorted is intermittently present. Dolomite ranges from light brown to orangish brown to dark brown or even black and from sucrosic to dense. The top of the Avon Park Formation is marked in some places by light-brown, finely crystalline to fossiliferous dolomitic limestone or dolomite thinly interbedded with limestone. The cone-shaped *Dictyoconus* sp. is the foraminifera characteristic of the Avon Park Formation (Duncan and others, 1994a). Thick intervals containing mostly dolomite, but in some places interbedded with limestone, are commonly present in the middle to lower part of the Avon Park Formation in southern Florida. High permeability due to fracturing is common, particularly in dolomite units. Gypsum and anhydrite also occur in the lower part of this formation in southwestern Florida, either as bedded deposits or more commonly as intergranular or pore filling material in the carbonate rocks. The thickness of the formation ranges from less than 900 to greater than 1,600 ft in the study area (Miller, 1986, pl. 7).

The Ocala Limestone consists of micritic or chalky limestone, calcarenitic limestone, and coquinoid limestone. The limestone is characterized by abundant large benthic foraminifera, such as *Operculinoides* sp., *Camerina* sp., and *Lepidocyclina* sp. (Peacock, 1983). These characteristic foraminifera, where present, have been used by various workers to distinguish the Ocala Limestone from the overlying Suwannee Limestone and the underlying Avon Park Formation. The Ocala Limestone has been mapped as being absent in the southern part of southeastern Florida (most of Miami-Dade County and southeastern Broward County) and in limited parts of east-central Florida (Miller, 1986, pl. 9); it attains a maximum thickness exceeding 400 ft in the southwestern and west-central Florida (Miller, 1986, pl. 9). In west-central Florida, the Ocala Limestone becomes dominated by carbonate mud-rich lithofacies (Loizeaux, 1995; Budd, 2001; Ward and others, 2003). Because of this mud-rich lithofacies, the hydraulic conductivity of the Ocala Limestone in west-central and southwestern Florida can be much lower than in areas to the east, such as the Upper East Coast Planning area (fig. 2). Interparticle porosity and permeability in the Ocala Limestone is common in most of the study area. Porosity is vuggy or cavernous in the northern part of central Florida and east coast areas north of and including the Upper East Coast Planning area.

The Suwannee Limestone of early Oligocene age (Wingard and others, 1994) in southwestern and west-central Florida predominantly consists of pale-orange to tan, fossiliferous, medium-grained calcarenite (carbonate packstone to grainstone) with minor amounts of quartz sand and rare-to-absent phosphate mineral grains; in Lee and western Collier Counties, it is well developed and can be as thick as 600 ft (Reese, 2000). Characteristic porosity and permeability in the Suwannee Limestone is interparticle to moldic or vuggy. This formation is mapped as being absent by truncation in virtually all of east-central Florida (Miller, 1986).

In southeastern Florida, there have been opposing interpretations concerning the presence or absence of the Suwannee Limestone. The Suwannee Limestone has been interpreted by some investigators to be absent or truncated in some parts of southeastern Florida (Mooney, 1980; Shaw and Trost, 1984; Miller, 1986), whereas others (Lichtler, 1960; Schiner and others, 1988; Lukasiewicz, 1992) have mapped this geologic unit in Martin, St. Lucie, and adjacent counties. Mooney (1980) describes a limestone unit, known as the Suwannee Limestone by others, as consisting of gray, sandy, calcilutite with minor phosphorite. This unit may be a basal unit of the Hawthorn Group, as suggested by Mooney (1980), who refers to it as the unnamed limestone unit. Shaw and Trost (1984) place this unit within the Hawthorn Group, at its base, in the southern part of the Kissimmee Basin Planning Area (fig. 2), an area that overlaps with the area studied by Mooney (1980). Based on analysis of a continuous core in Indian River County, this unit, which lies on top of the Ocala Limestone of late Eocene age, is referred to as the "unnamed limestone of early Oligocene age" (Weedman and others, 1995). In Martin and St. Lucie Counties, a basal limestone unit of the Hawthorn Group thickens to the east and contains only minor to trace amounts of phosphate and quartz grains near the coast. In these areas near the coast, this unit could be equivalent to the Suwannee Limestone (Reese, 2004).

The Hawthorn Group includes the lower Arcadia Formation and the upper Peace River Formation and consists of an interbedded sequence of widely varying lithologies and components that include limestone, mudstone, dolomite, dolosilt, shell, quartz sand, clay, abundant phosphate grains, and mixtures of these materials. The characteristics that distinguish the Hawthorn Group from underlying units are (1) high and variable siliciclastic and phosphatic content; (2) color, which can be green, olive-gray, or light gray; and (3) gamma-ray log response. Intervals high in phosphate sand or gravel content are present and have high gamma-ray log activity, with peaks of 100 to 200 API standard units or more.

Geologic units that overlie the Hawthorn Group include the Tamiami Formation of Pliocene age, units of Pleistocene age in southeastern Florida such as the Fort Thompson Formation, the Anastasia Formation, and the Miami Limestone, and undifferentiated sediments of Holocene age (fig. 8).

Time-Stratigraphic Framework

As discussed earlier, two stratigraphic marker horizons within the Floridan aquifer system originating from work by Duncan and others (1994a, b) and a stratigraphic marker unit near the top of the Floridan aquifer system (lower Hawthorn marker unit) were delineated and mapped in this study to provide stratigraphic guidance in the identification of aquifers and confining units. These markers are believed to be approximately time stratigraphic in nature. Four stratigraphic sections are presented herein in support of correlation of these markers and the marker unit, and contour maps of the two marker horizons are presented to indicate geologic structure in the Floridan aquifer system.

Duncan and others (1994a) describe the upper marker horizon, which they refer to as the "B" marker bed, as separating the "more thinly bedded strata of the upper Avon Park Formation from more thickly bedded and massive units of the lower Avon Park Formation," and refers to it as "an excellent reference datum for correlation throughout Brevard County." The lower marker horizon is at the top of distinctive glauconitic limestone beds at the top of the Oldsmar Formation. Duncan and others (1994b, fig. 14) demonstrated the continuity of these marker horizons between Brevard and Palm Beach Counties using gamma-ray and sonic log curves. They mapped the top of the lower marker horizon in their study area and illustrated the position of both marker horizons on two structural cross sections. In the present study, these two horizons are referred to as the middle Avon Park (MAP) and glauconite (GLAUC) marker horizons.

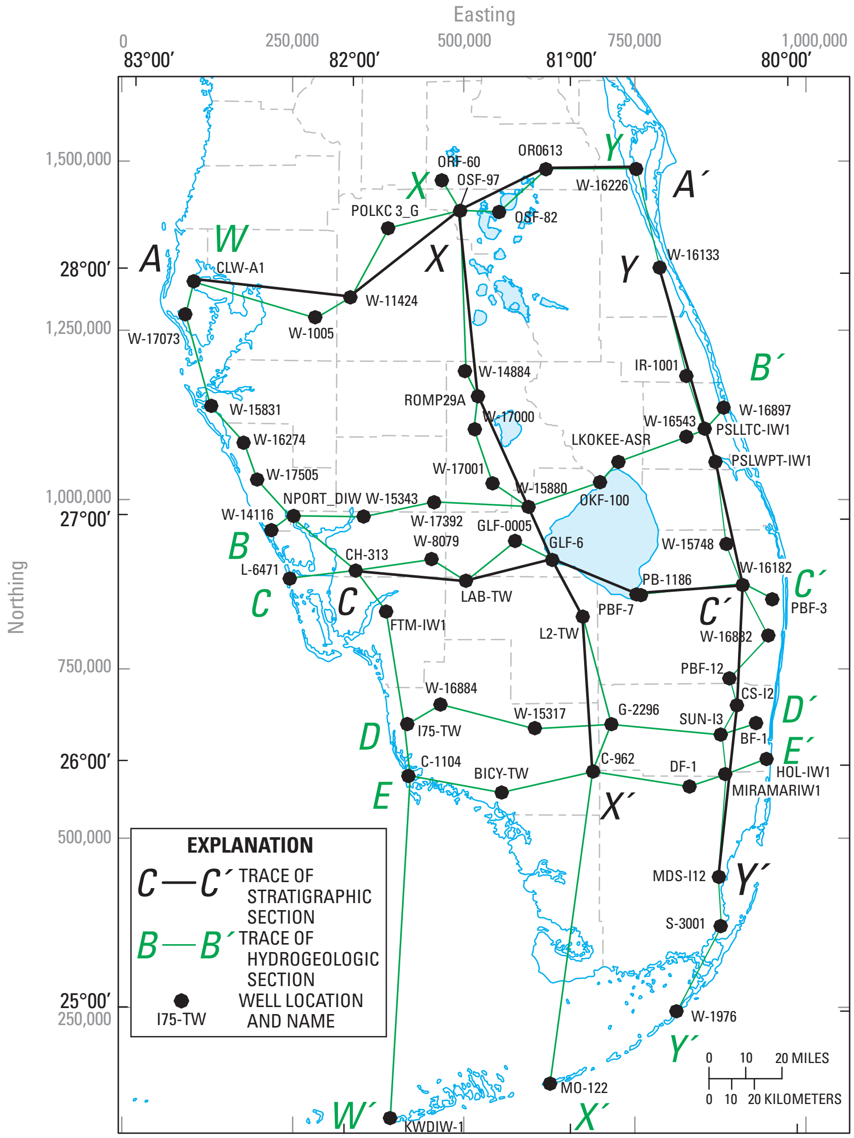
As discussed earlier, the MAP and GLAUC marker horizons do not necessarily have distinguishing lithologic characteristics or a characteristic gamma-ray log pattern, and in this study they are considered to be "correlation marker horizons" rather than "marker beds." The MAP marker horizon, however, is commonly at the base or top of a thin (10-30 ft) lithologic unit (or units) that may be evident on gamma-ray curves because of its lower gamma-ray activity. Also, in south-central Florida (around Lake Okeechobee), the MAP marker horizon is commonly present at the top of a thick zone of dolostone, with limestone or dolomitic limestone above it. The GLAUC marker horizon is commonly associated with one or a series of high gamma-ray log activity peaks. Because lithologic descriptions from deep injection well consulting reports are commonly cursory or incomplete, glauconite in limestone if present at or near the GLAUC marker horizon usually is not confirmed in these wells. Based on lithologic descriptions of drill cuttings, glauconite in Eocene-aged rocks of the study area occurs only along the east coast of Florida as far south as Palm Beach County and in one well in western Polk County of west-central Florida (Winston, 1993). Based on FGS descriptions, wells W-16226, W-16133, IR-1001, and W-16882 on section *Y-Y′* (fig. 4) have glauconitic carbonate first occurring at a depth close to that of the GLAUC marker horizon determined by gamma-ray log correlation.

The first regional gamma-ray log correlation loop establishing the position of the two marker horizons started along the east coast in Brevard County, then extended southward into Palm Beach County, westward into southwestern Florida, northward into west-central Florida, and finally eastward across the northern part of central Florida back to the east coast; it approximately followed the section lines *Y-Y′*, *C-C′*, *W-W′*, and *A-A′* (fig. 4). This important loop extends over about 400 mi, and correlated with a closure error of only 15 to 30 ft, supporting the viability of this approach. Correlation loops in the southern part of southern Florida indicate error could be higher in some cases (as high as 50 ft) because of thickening of the section, more uniform lithologic character, and less gamma-ray log activity.

A marker unit in the Arcadia Formation of the Hawthorn Group, referred to as the lower Hawthorn marker unit (fig. 8), has been mapped in Lee, Hendry, and Collier Counties (Reese, 2000), Palm Beach County (Reese and Memberg, 2000), and Martin and St. Lucie Counties (Reese, 2004). This unit lies at the top of a basal Hawthorn unit that usually contains the first permeable zone of the Floridan aquifer system (fig. 8). The characteristic pattern of the marker unit shown by gamma-ray logs remains consistent over large parts of southern Florida, and the thickness of this unit generally ranges from 50 to 150 ft.The marker unit commonly consists of micritic limestone, marlstone, or clay with minor to trace amounts of phosphate grains, and beds within it and near its boundaries may have been synchronous in their deposition over large areas (Reese, 2000).

Stratigraphic Sections

Stratigraphic sections were constructed to demonstrate support for stratigraphic correlations between central and southern Florida, and across the peninsula between the west and east coasts. Four stratigraphic sections were constructed using gamma-ray log curves along the same traces as hydrogeologic sections *A-A′* and *C-C′*, *X-X′* and *Y-Y′* shown in figure 4, and the MAP marker horizon was used as the datum (figs. 9 and 10a-d; pls. 1-4). In figures 10a-d, only five approximately equally spaced wells per trace were selected, but on plates 1 to 4, all of the wells with gamma-ray logs along these four hydrogeologic section traces are shown. Also, for figures 10a–d, the entire depth of the wells is not shown, as it is for most wells on the plates. In the figures, the section shown generally only extends from midway in the Hawthorn Group to 100 to 200 ft below the GLAUC marker horizon.



Base from South Florida Water Management District State Planar Coordinates
Datum NAD 83

Figure 9. Trace of stratigraphic and hydrogeologic sections used in the study.

Four additional correlation horizons were determined for these sections in support of the placement of the MAP and GLAUC marker horizons (figs. 10a-d and pls. 1-4). These additional correlative horizons are described as follows in order of increasing depth:

- LHMU: a correlation horizon located at the base of the lower Hawthorn marker unit that was described in a previous section.
- SUW: The origin of this correlation horizon is located in well W-16182 on sections *C-C′* (fig. 10b, pl. 2) and *Y-Y′* (fig. 10d, pl. 4) near the east coast in Palm Beach County. In well W-16182, this horizon is approximately at the top of clean limestone as indicated by the gamma-ray curve (reduced gamma-ray activity), near the upper contact of the Avon Park Formation, and near the base of what may be considered to be the Suwannee Limestone (Reese and Cunningham, 2000).
- UAP: Located about midway between SUW and the MAP marker horizon.
- LAP: Located between the MAP and GLAUC marker horizons.

Geologic units, including the Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone, and Hawthorn Group are shown on the sections for the purpose of comparison with correlations (figs. 10a-d). Geologic unit contact depths and their sources are provided in the DBHYDRO database; the FGS is the primary source for these depths. Not all formation contacts have been determined in each well. For example, the top of the Oldsmar Formation has not been determined in well W-15880 on section *X-X′* (fig. 10c and pl. 3). Aquifer or subaquifer boundaries within the Floridan aquifer system, which will be discussed in the following sections, are also shown on plates 1 to 4.

The LHMU correlation horizon shows the continuity of the lower Hawthorn marker unit in southern Florida and in the southern part of east-central Florida, as indicated by characteristic gamma-ray log patterns. The full vertical extent of this unit is shown in wells PBF-7, W-15880, and W-15748 on sections *C-C′* (fig. 10b, pl. 2), *X-X′* (fig. 10c, pl. 3) , and *Y-Y′* (fig. 10d, pl. 4), respectively. This unit probably does not extend into the northern part of the study area, particularly in the northern part of east-central Florida (fig. 10a, pl. 1).

The MAP marker horizon, as described above, commonly is at the base or top of a thin (10-30 ft) lithologic unit (or units) that may be evident on the gamma-ray curve because of its lower gamma-ray activity. This unit (or units) is evident, for example, in wells CH-313, LAB-TW, and PBF-7 (and PB-1186 on pl. 2) on section *C-C′* (fig. 10b). In some cases, this unit of low gamma-ray activity has a somewhat distinctive gamma-ray curve signature that may be caused by extreme borehole washout, probably due to fracturing, as indicated on caliper logs—for example, in well LAB-TW on section *C-C′* (not shown in fig. 10b). Examples of the high gamma-ray activity peaks associated with the GLAUC marker horizon are shown in wells PSLWPT-IW1, CS-I2, and MDS-I12 on section *Y-Y′* (fig. 10d).

Assuming that the marker horizons and the other correlation horizons approximate chronostratigraphic surfaces (time lines), then the stratigraphic sections indicate that the formation boundaries transgress time and that the Avon Park Formation and Ocala Limestone may not be chronostratigraphically restricted to the middle and late Eocene, respectively. For example, the entire Ocala Limestone is indicated to grade into the Avon Park Formation to the east into the Lower East Coast Planning Area of southeastern Florida (fig. 2) between wells GLF-6 and W-16182 on section *C-C′* (fig. 10b, pl. 2) and to the south into the same area of southeastern Florida (fig. 2) between wells PSLWPT-IW1 and W-16182 on section *Y-Y′* (fig. 10d, pl . 4).

Microfaunal data indicate the occurrence of lateral and vertical facies changes and interfingering between the Avon Park Formation, Ocala Limestone, and Suwannee Limestone in southern Florida (Winston, 1993; 1995). This evidence, based on descriptions of drill cuttings, may contradict the interpretation that deposition of the Avon Park Formation and Ocala Limestone was restricted to certain periods of time (Miller, 1986, pl. 2). The absence of the Ocala Limestone in southeastern Florida because of a facies change into the Avon Park Formation has been interpreted by Winston (1993). Miller (1986) implies that rocks of late Eocene age (Ocala Limestone) in the southern part of southeastern Florida are absent because of erosion.

Apparent truncation of the Ocala Limestone in central Florida in comparison with southern Florida is indicated by stratigraphic section *X-X′* (fig. 10c, pl. 3). The top of the Ocala Limestone has been interpreted to be an unconformity in east-central Florida, and this formation is absent due to erosion in parts of northwestern Osceola County and southwestern Orange County (Miller, 1986, pl. 9).

The top of the Oldsmar Formation, as indicated by the GLAUC marker horizon, could be much deeper than previously determined in southern Florida (pls. 3 and 4). For example, the GLAUC marker horizon is about 700 ft deeper than the previously determined top of this formation in well CS-I2 on section *Y-Y′* (fig. 10d, pl. 4).

Marker Horizon Structure Maps

Maps of the altitude of the MAP (figs. 11 and A2) and GLAUC (figs. 12 and A3) marker horizons should indicate structure in the Floridan aquifer system better than formation or aquifer boundary maps because of their approximate time-stratigraphic nature. Generally, these maps indicate a broad structural nose dipping from the center of the peninsula in northern east-central Florida to the south to about Lake Okeechobee, and then a flattening of structure farther to the south in southern Florida. The broad structural nose approximately coincides with or parallels the regional structural feature referred to as the “peninsular arch” (fig. 11; Winston, 1993). A broad structural depression centered in southeastern Florida occupies most of Broward County and parts of Palm Beach, Miami-Dade, Collier, and Monroe Counties, with relief of 100 to 200 ft (fig. 11). The “south Florida basin” (fig. 11; Winston, 1993) is a structural feature in a similar area as this depression, but it encompasses a larger area. A more pronounced structural depression (or trough) with as much as 200 to 300 ft of relief is indicated to be present in southwestern Florida, specifically, southeastern Charlotte, northeastern Lee, northwestern Hendry, and northern Collier Counties. This trough appears to trend northwest-southeast in figure 11, but more north-south in figure 12, although fewer control points are available in this area for the GLAUC marker horizon. A northwest-southeast trending trough was also mapped in the same general area at the top of the lower Hawthorn marker unit (Reese, 2000, fig. 6), and relief along this depression was similar (as much as 200 ft). The parameters used in the statistical models for generating these two surfaces were discussed earlier in the “Methods of Evaluation” section of this report.

EXPLANATION
(see figures 10 a-d)

GEOLOGIC UNITS

HAWTHORN GROUP
SUWANNEE LIMESTONE
OCALA LIMESTONE
AVON PARK FORMATION
OLDSMAR FORMATION

Formation contacts are from various sources, primarily the Florida Geological Survey

CORRELATION HORIZONS

LHMU	Base of the lower Hawthorn marker unit
SUW	Origin is near the upper contact of the Avon Park Formation in well W-16182 near east end of section C-C′
UAP	Located about midway between SUW and MAP
MAP	MIDDLE AVON PARK MARKER HORIZON - DATUM
LAP	Located between MAP and GLAUC
GLAUC	GLAUCONITE MARKER HORIZON
?	Position of correlation horizon beyond this well is uncertain
*	Section appears to be truncated at this point

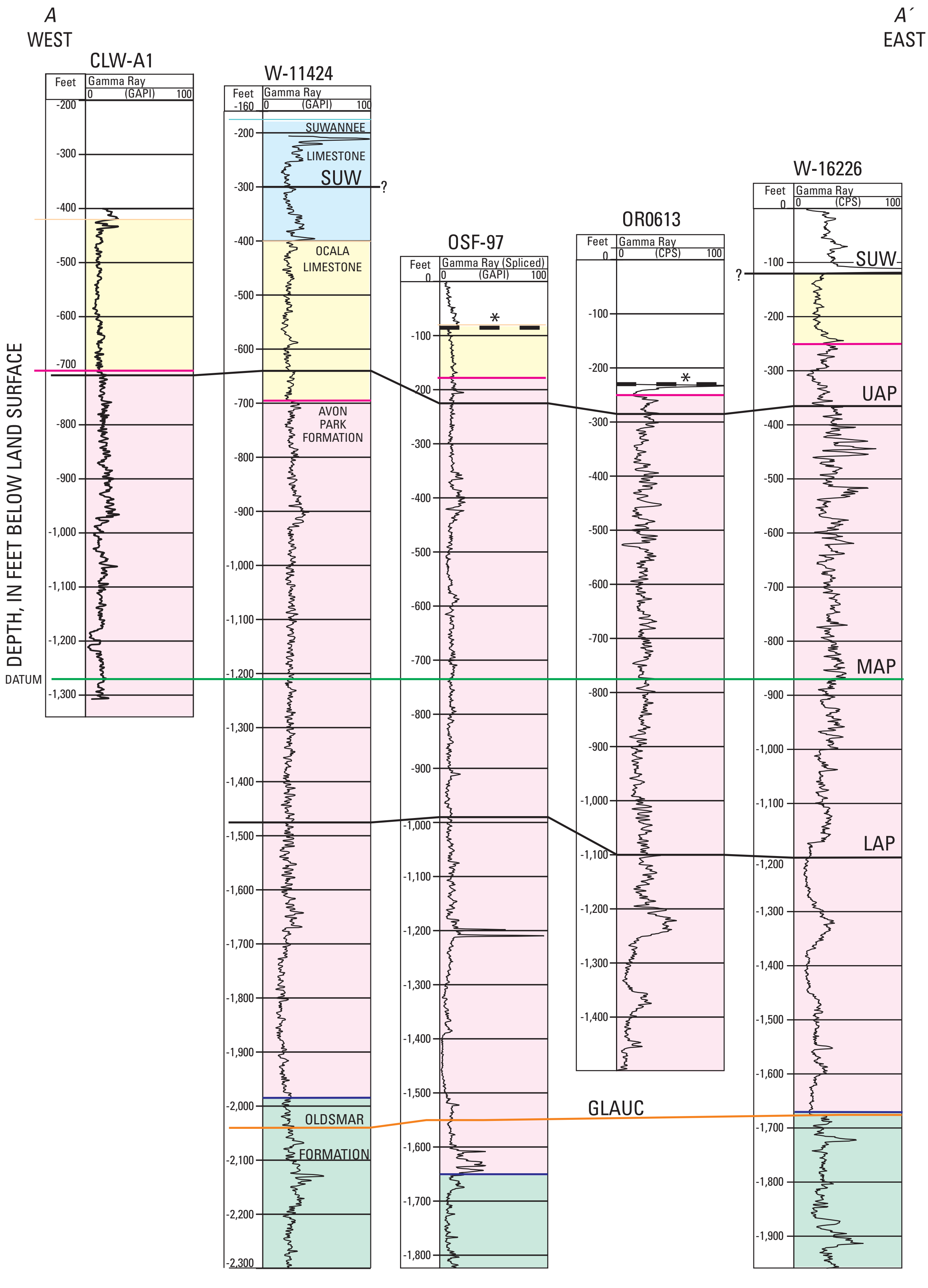


Figure 10a. Stratigraphic section *A-A′*. Trace of section shown in figure 9.

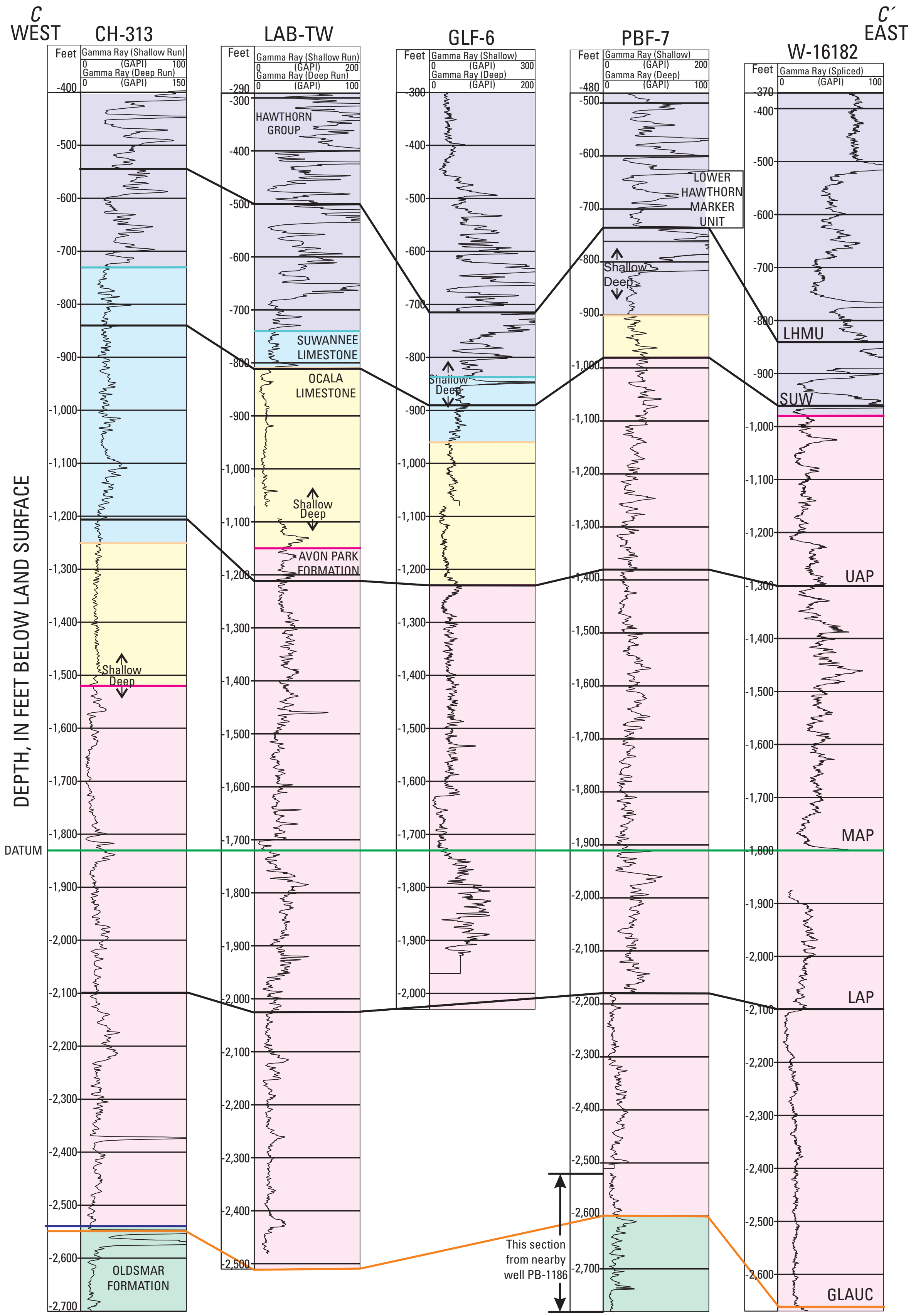


Figure 10b. Stratigraphic section *C-C′*. Trace of section shown in figure 9.

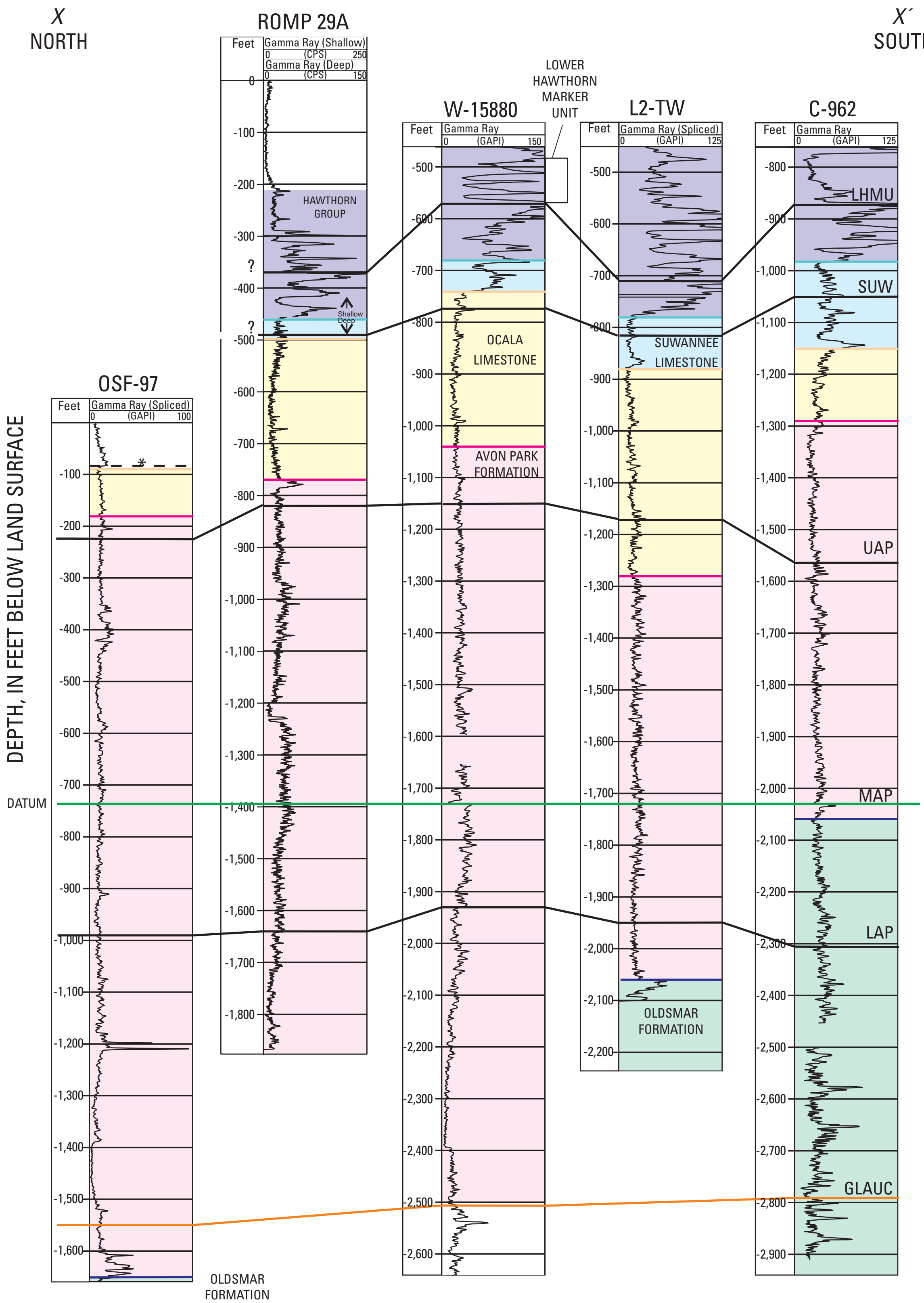


Figure 10c. Stratigraphic section *X-X′*. Trace of section shown in figure 9.

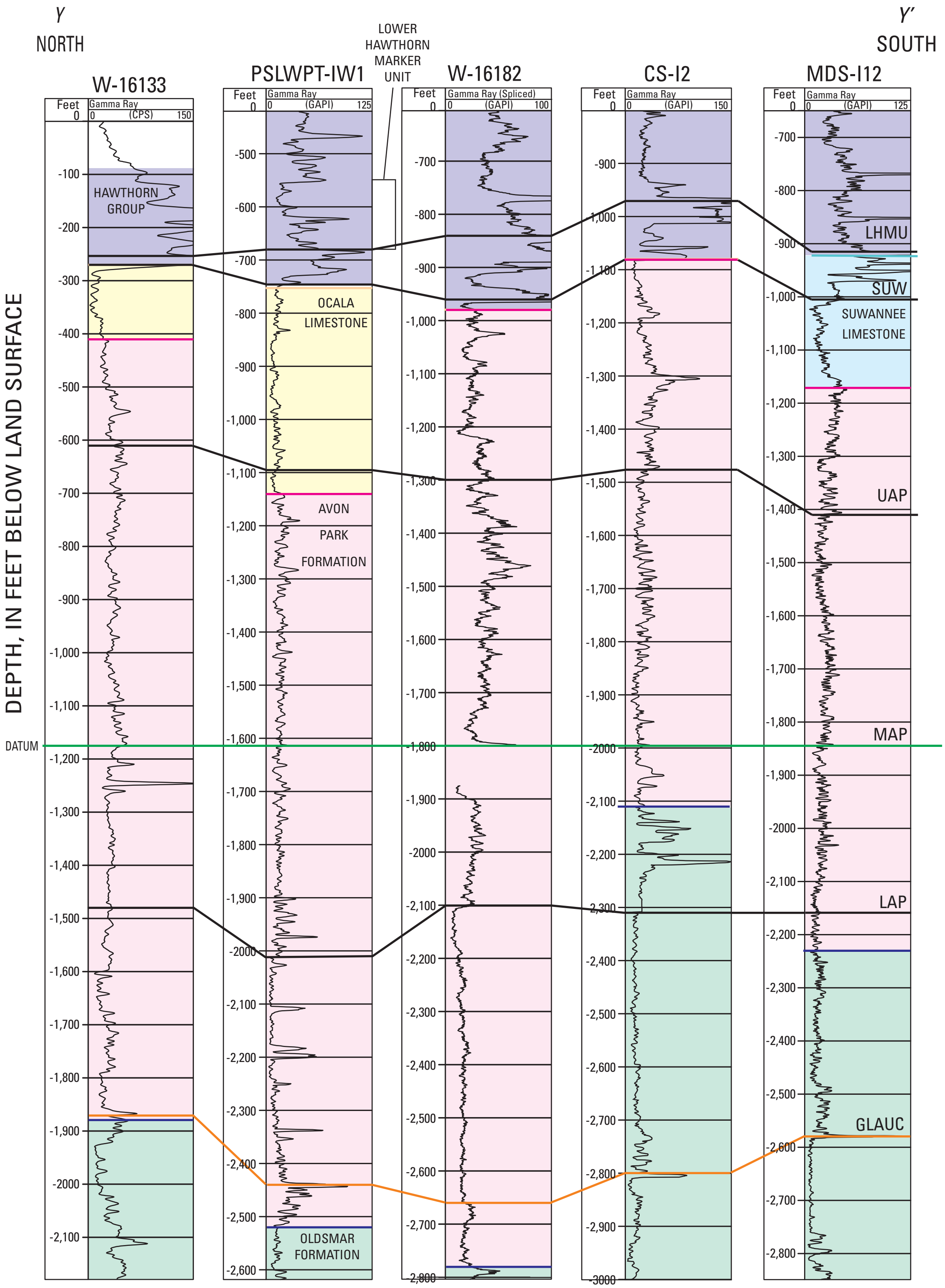


Figure 10d. Stratigraphic section *Y-Y′*. Trace of section shown in figure 9.

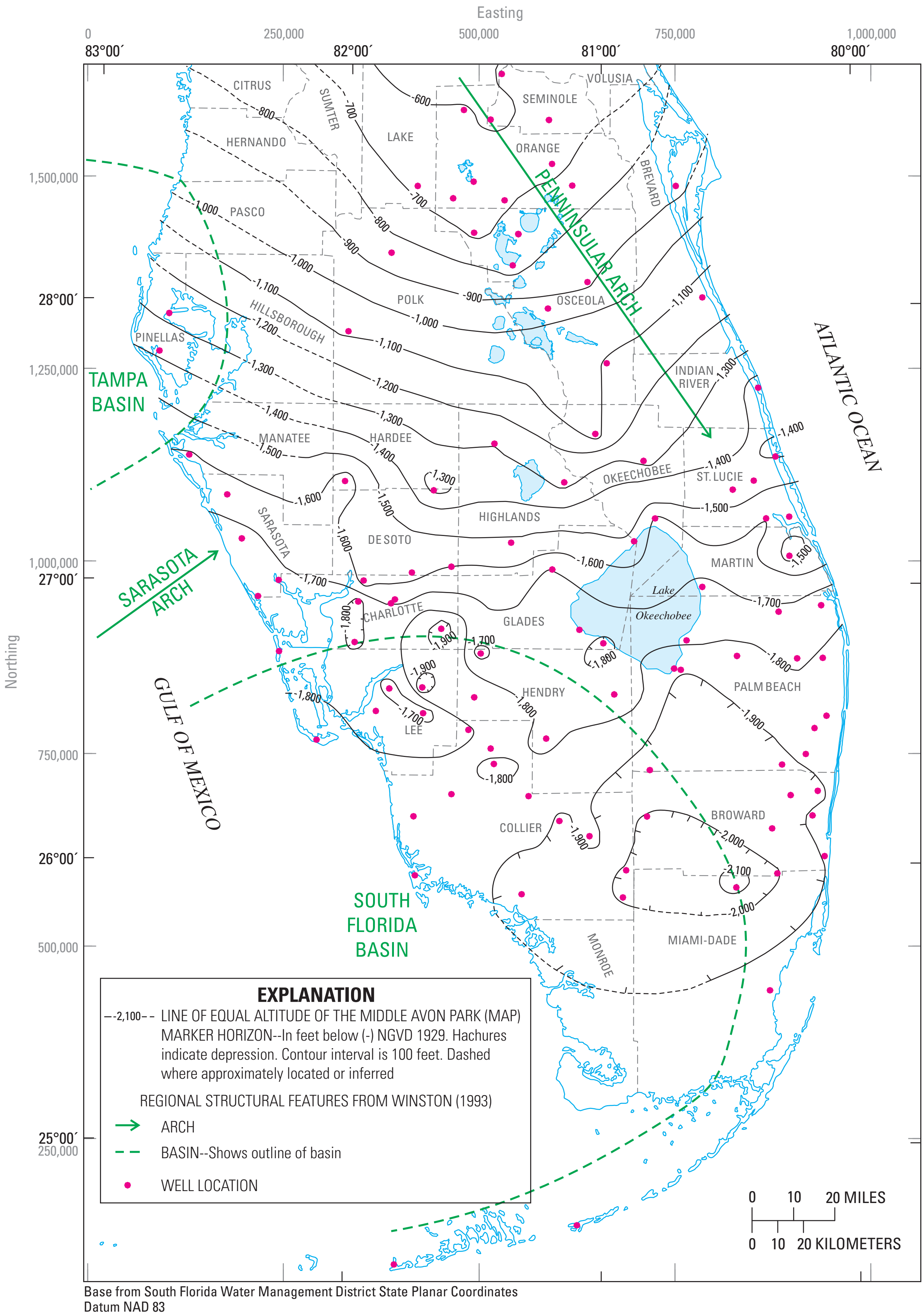


Figure 11. Altitude of the middle Avon Park marker horizon.

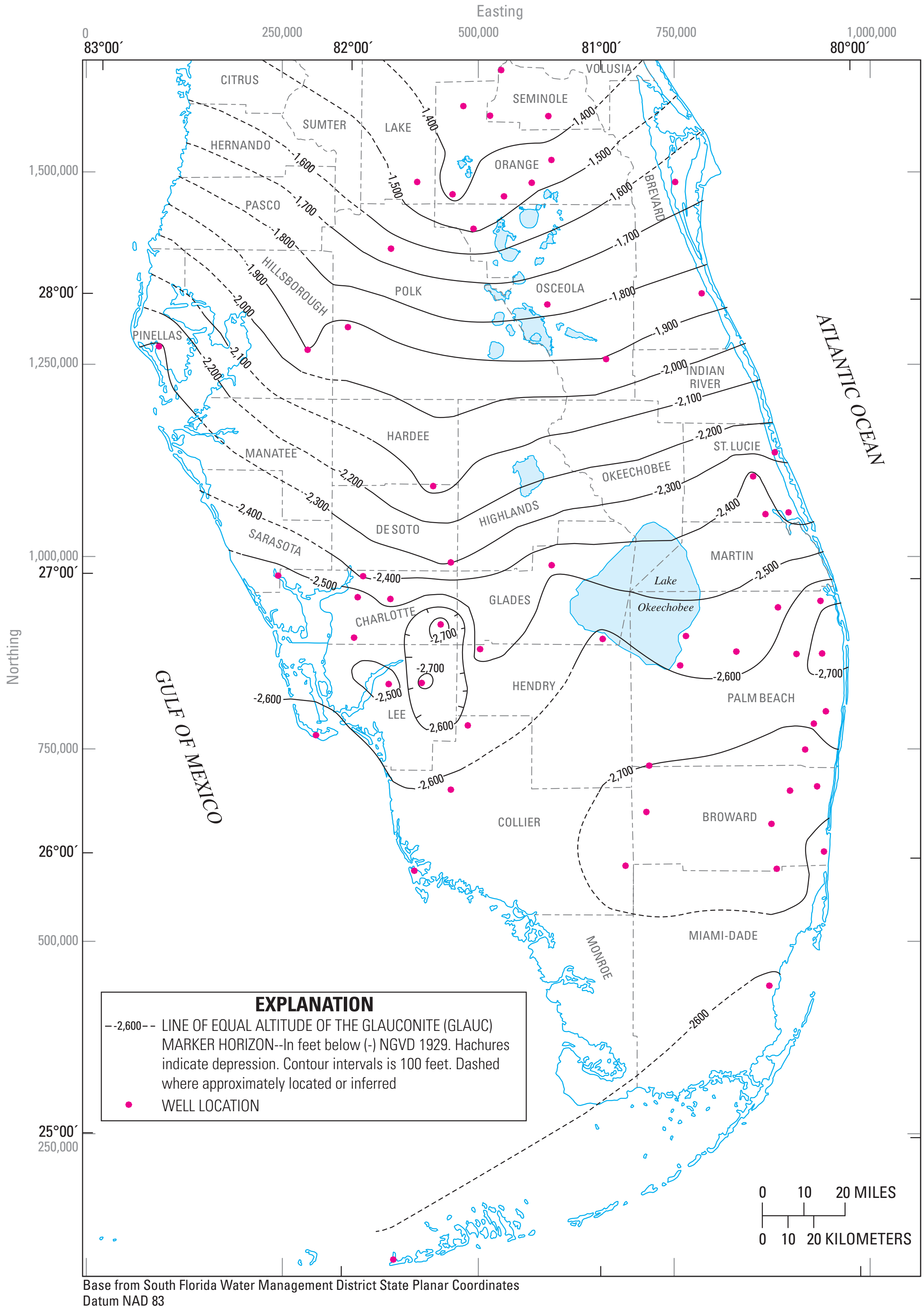


Figure 12. Altitude of the glauconite marker horizon.

Hydrogeologic Framework

The three principal hydrogeologic units present in the study area are the surficial, intermediate, and the Floridan aquifer systems (fig. 8). The Floridan aquifer system formally consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer. In this report, a new water-bearing zone referred to as the "Avon Park permeable zone" that is usually contained within the middle confining unit (fig. 8) has been delineated and mapped, and this zone is referred to as a subaquifer.

A review of the available literature on the Floridan aquifer system within the study area reveals that there are provincial hydrogeologic nomenclatures in use. Hydrogeologic units having common names may not necessarily be equivalent. Therefore, care was required in utilizing hydrogeologic unit boundaries from previous local studies. The eight hydrogeologic sections constructed for this study extend across political and county boundaries, and therefore, provide the context for comparing physical and nomenclatural similarities and differences in separate regions.

The hydrogeologic nomenclature used in this study was schematically compared to previous regional or subregional studies (fig. 13). Because of differences of the how the nomenclature used in this study compares with regional mapping done by Miller (1986), two different nomenclatures are shown for Miller (1986), one for west-central and southwestern Florida and one for east-central and southeastern Florida.

As previously discussed, available geophysical logs and a lithologic column were plotted on working copies of the hydrogeologic sections. Examples of these plots for three of the wells on the hydrogeologic sections for the Floridan aquifer system interval penetrated are shown in figures 14 to 16. All three wells are recent SFWMD test wells with a full suite of geophysical logs and represent different parts of the study area.

Diagrammatic plots of all eight of the hydrogeologic sections were constructed to scale using Viewlog™ software (figs. 17a-h), and illustrate the principal aquifers, subaquifers, and confining units within the Floridan aquifer system. The upper boundary of the Upper and Lower Floridan aquifers, the interpreted extent of the Avon Park permeable zone and the MAP and GLAUC marker horizons are also included. The position of the marker horizon lines are based on the interpolated surfaces for these marker horizons (figs. 11 and 12), and their purpose is to show the relations between the stratigraphic framework and the interpreted hydrogeologic units in the wells. As discussed in the following sections, the MAP and GLAUC marker horizons are used to guide in the identification of the main aquifers and subaquifers.

Surficial Aquifer System

The surficial aquifer system consists of quartz sand, silt, clay, shell beds, coquina, calcareous sandstone, and sandy, shelly limestone. The base of the aquifer system commonly is defined where sediments grade from sand into clayey sand or clay; however, basal sediments also can consist of limestone. The thickness of the surficial aquifer system varies from 20 ft to about 400 ft in the study area, with the greatest thickness in southeastern Florida occurring along the east coast (fig. 8). The aquifer system overlies and adjoins the Floridan aquifer system in the northern part of west-central Florida where the Upper Floridan aquifer is unconfined.

Intermediate Confining Unit or Aquifer System

The intermediate confining unit or aquifer system extends from the base of the surficial aquifer system to the top of the Floridan aquifer system (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). The upper contact of the uppermost confining unit in the intermediate confining unit or aquifer system is commonly equivalent to the upper Hawthorn Group contact, but can extend into the overlying Tamiami Formation. Water-bearing rocks in the intermediate aquifer system of west-central and southwestern Florida grade or pinch out to the east and, in east-central and southeastern Florida, the intermediate aquifer system becomes the intermediate confining unit. The lithology of the confining unit is variable and includes fine-grained sediments, such as clay, marl, micritic limestone, and silt, which provide good confinement. The thickness of the intermediate confining unit/aquifer system varies from absent to 900 ft in the study area, with the greatest thickness occurring in southeastern Florida.

Aquifers developed within the intermediate aquifer system in southwestern Florida include the sandstone and mid-Hawthorn aquifers (fig. 8). Aquifers in this system farther north in west-central Florida include the permeable zones PZ1, PZ2, and PZ3 (Barr, 1996; Torres and others, 2001) (fig. 8). Aquifer tests at some wells show that PZ3, at the base of the system, is hydraulically separate from the Floridan aquifer system (Torres and others, 2001), and Knochenmus (2006) also generally indicates that PZ3 is separate from the Floridan aquifer system. PZ3 is probably equivalent to the lower Hawthorn aquifer or producing zone in southwestern Florida, which in contrast, is generally accepted as being part of the Floridan aquifer system (Reese, 2000). PZ2, a permeable zone near the top of the Arcadia Formation (Torres and others, 2001), is probably equivalent to the mid-Hawthorn aquifer (Knochenmus, 2006), which is in a similar stratigraphic position (Reese, 2000).

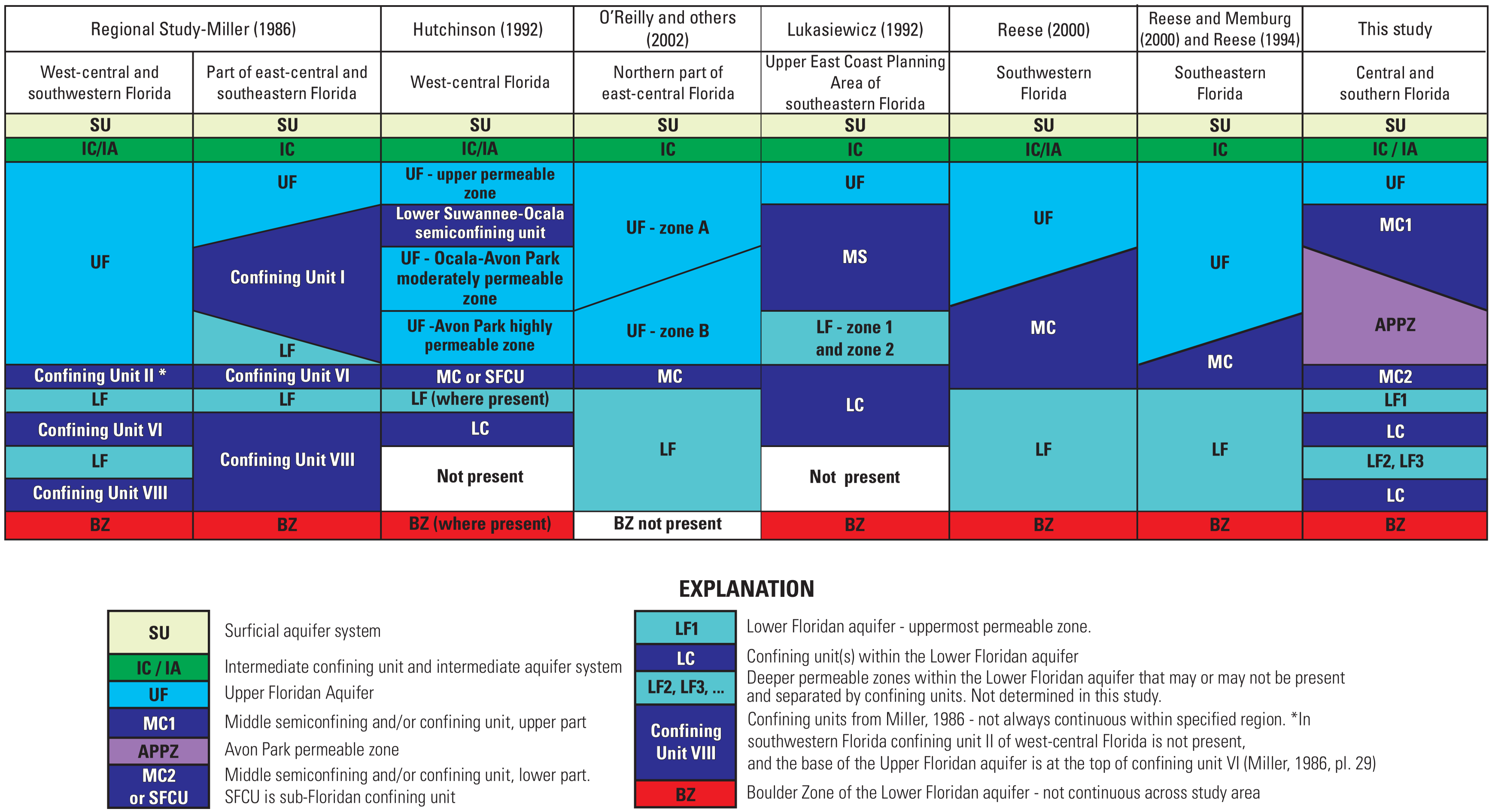


Figure 13. Schematic comparison of hydrogeologic nomenclature used in this study with previous studies.

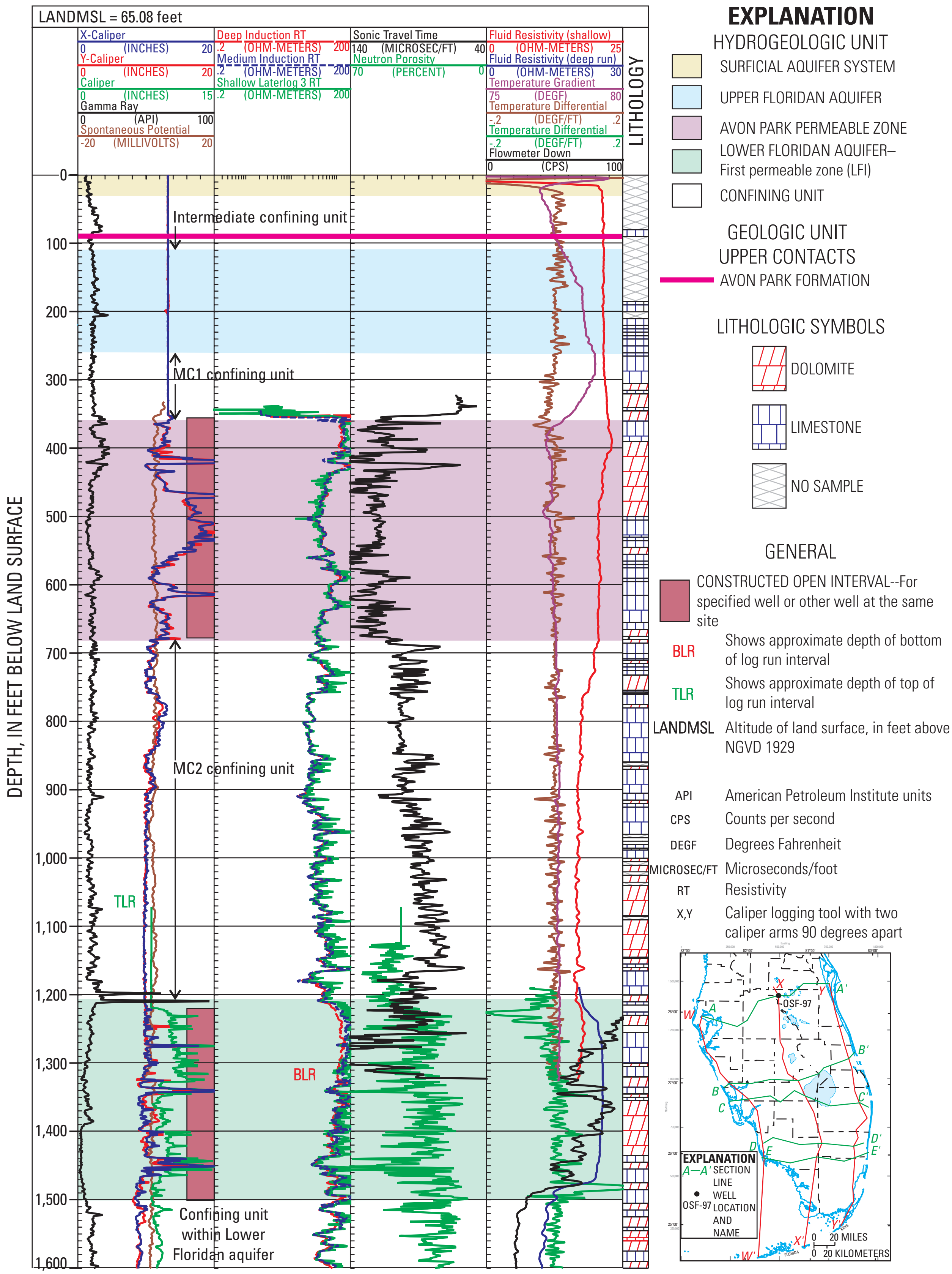
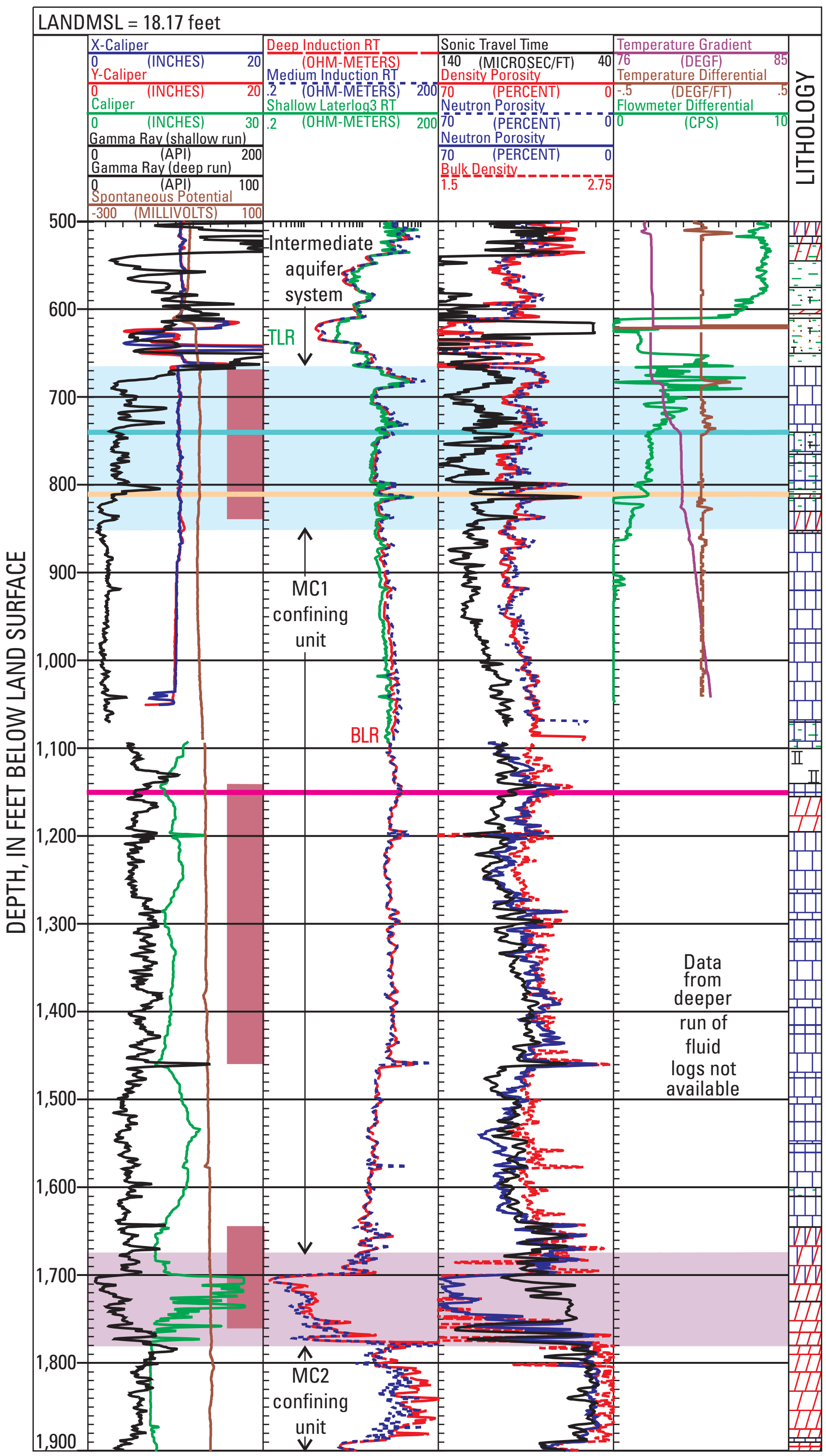


Figure 14. Geophysical logs, lithology, and hydrogeologic units for well OSF-97 on sections *A-A′* and *X-X′* representing the north-central part of the study area.



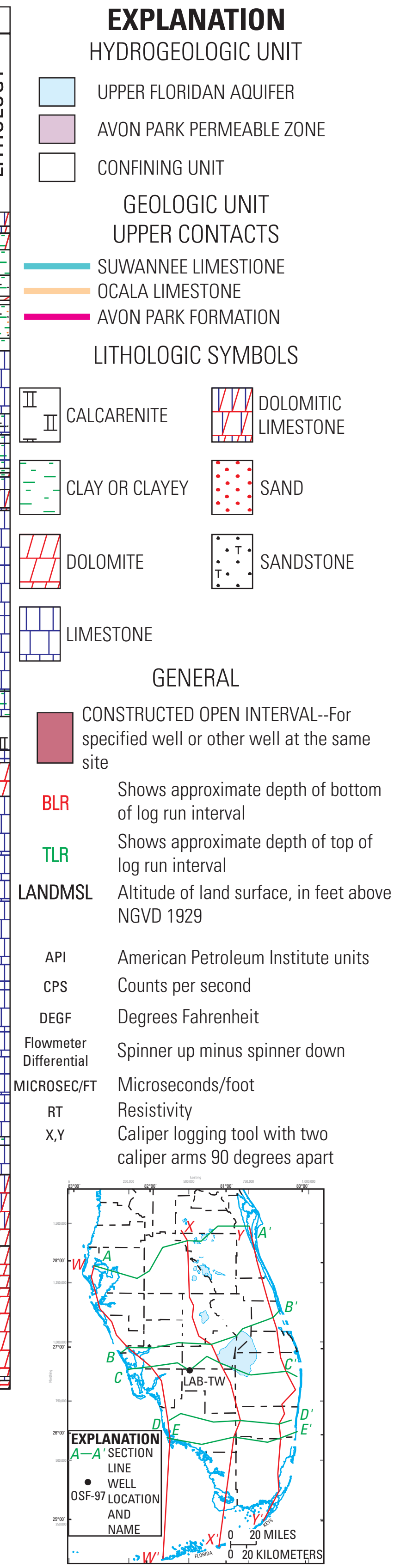


Figure 15. Geophysical logs, lithology, and hydrogeologic units for well LAB-TW on section *C-C'* representing the southwestern part of the study area.

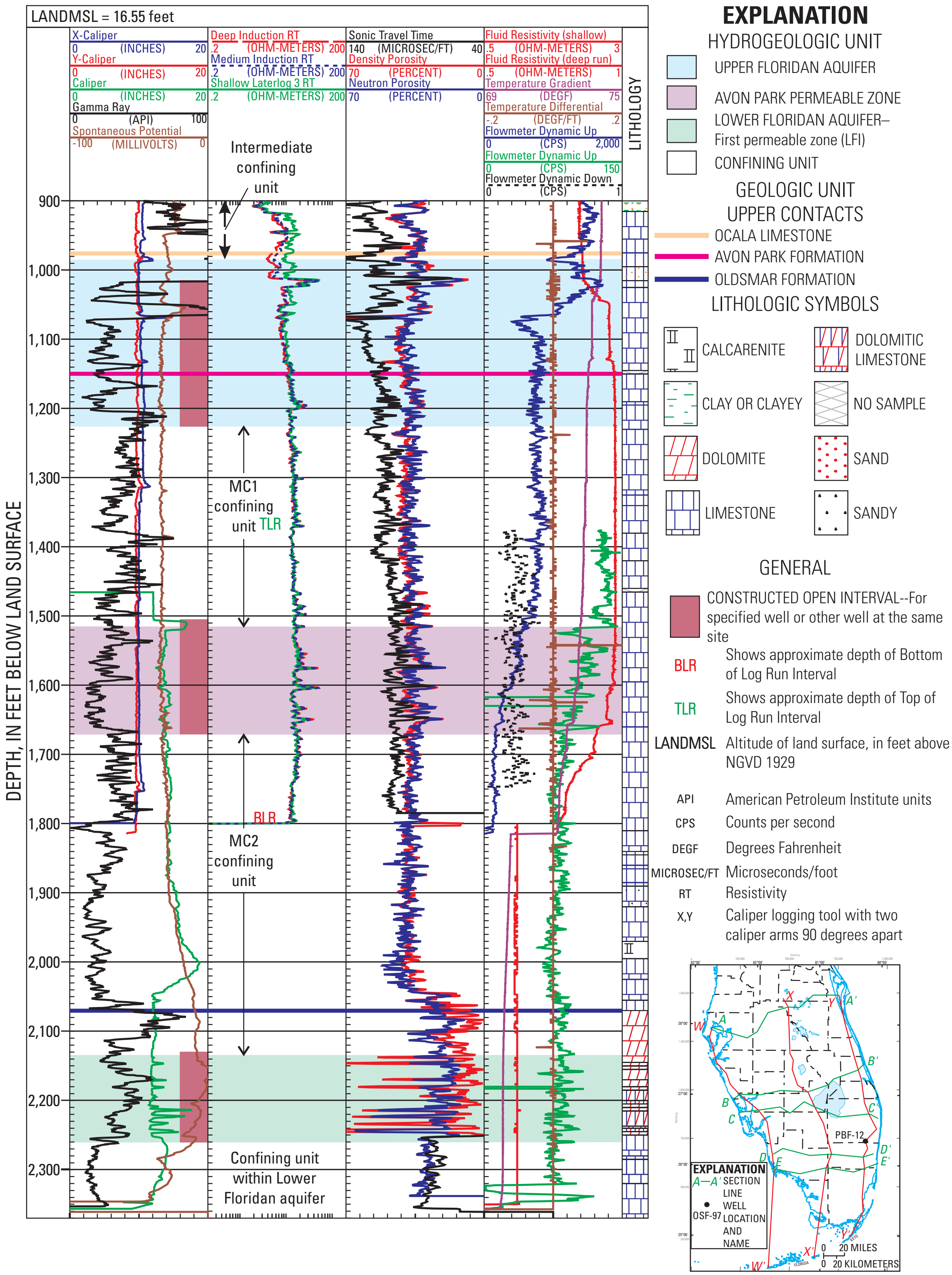


Figure 16. Geophysical logs, lithology, and hydrogeologic units for well PBF-12 on section *Y-Y′* representing the southeastern part of the study area.

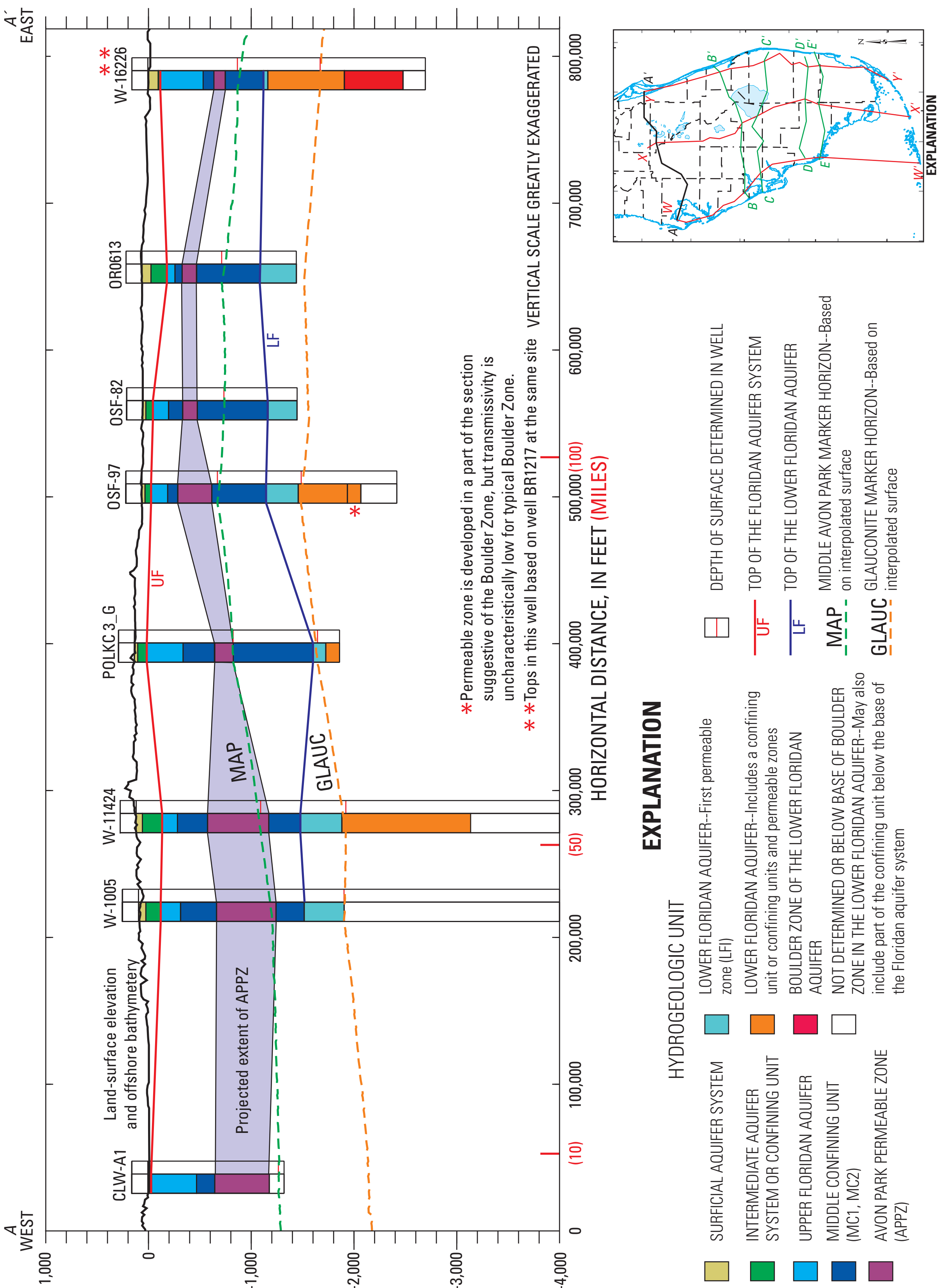


Figure 17a. Hydrogeologic sections *A-A′*.

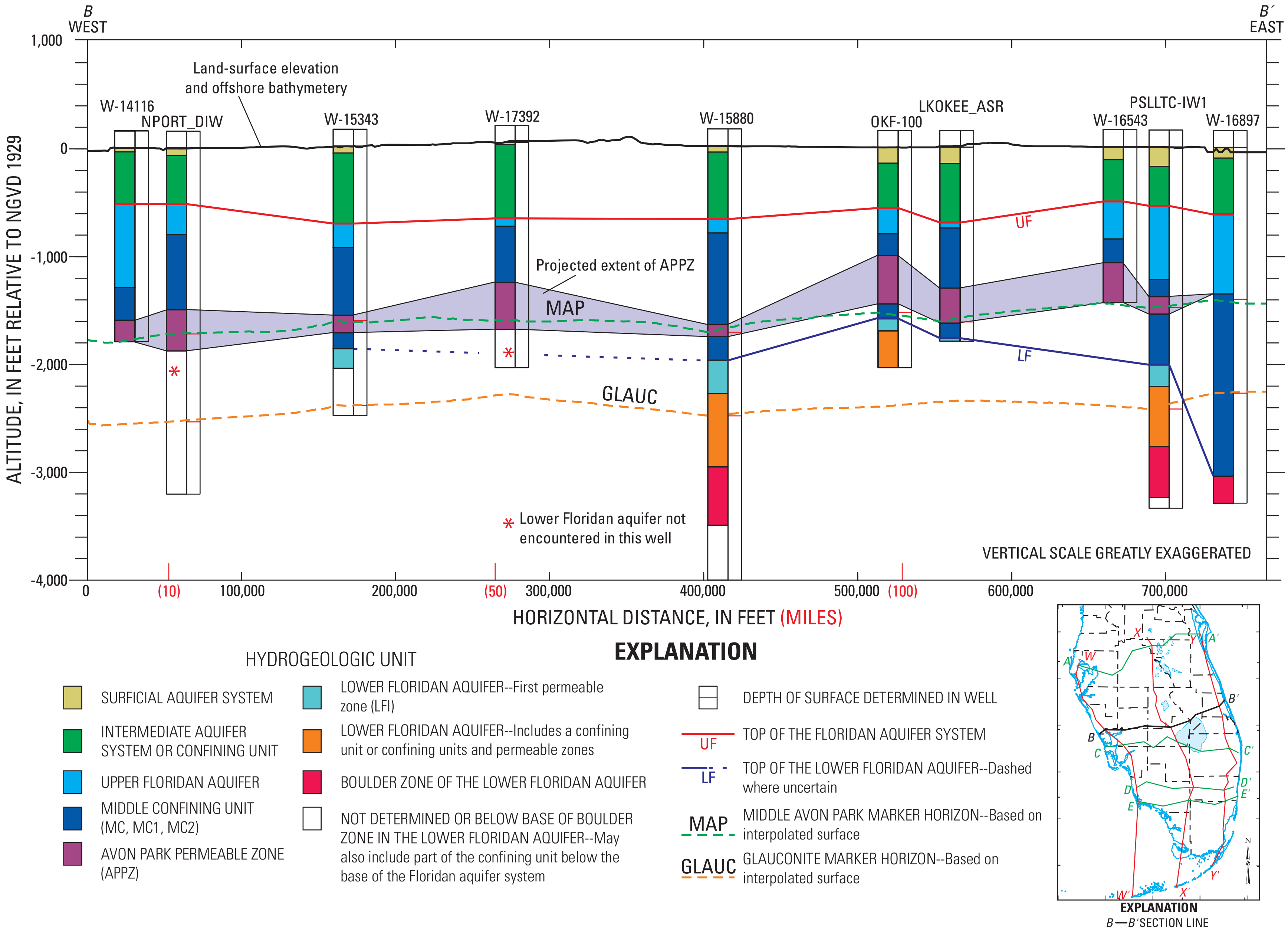


Figure 17b. Hydrogeologic sections *B-B′*.

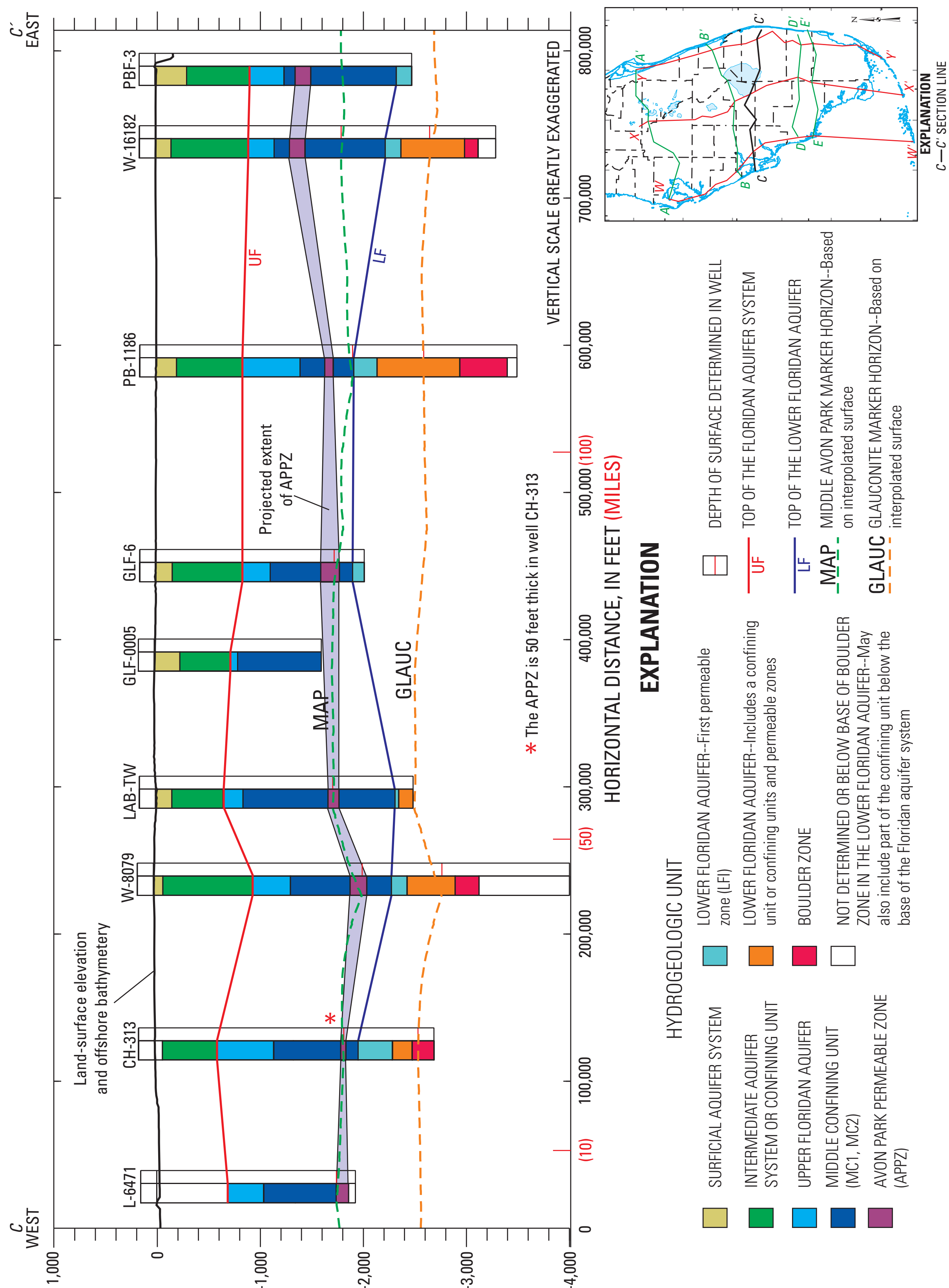


Figure 17c. Hydrogeologic sections *C-C′*.

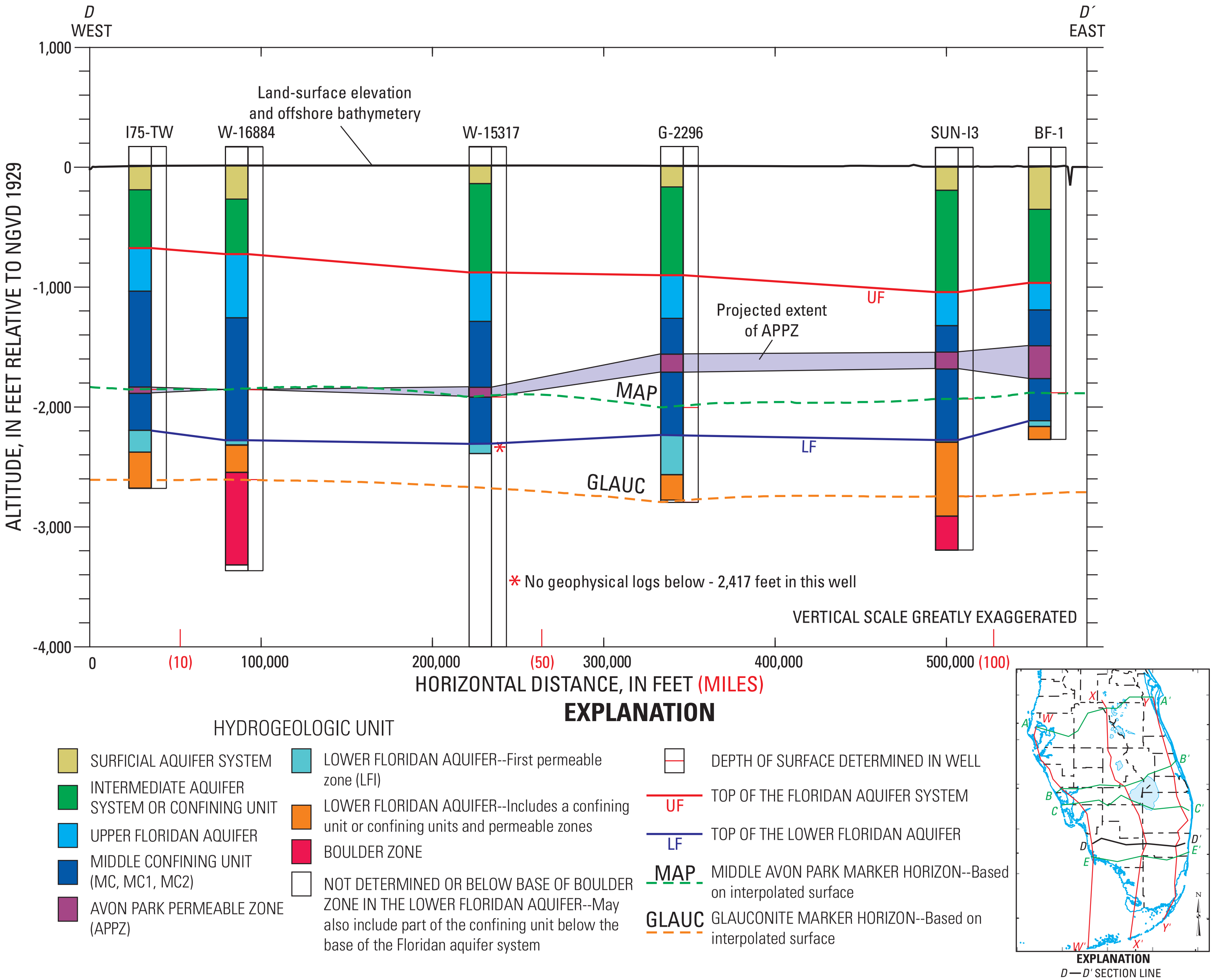


Figure 17d. Hydrogeologic sections *D-D′*.

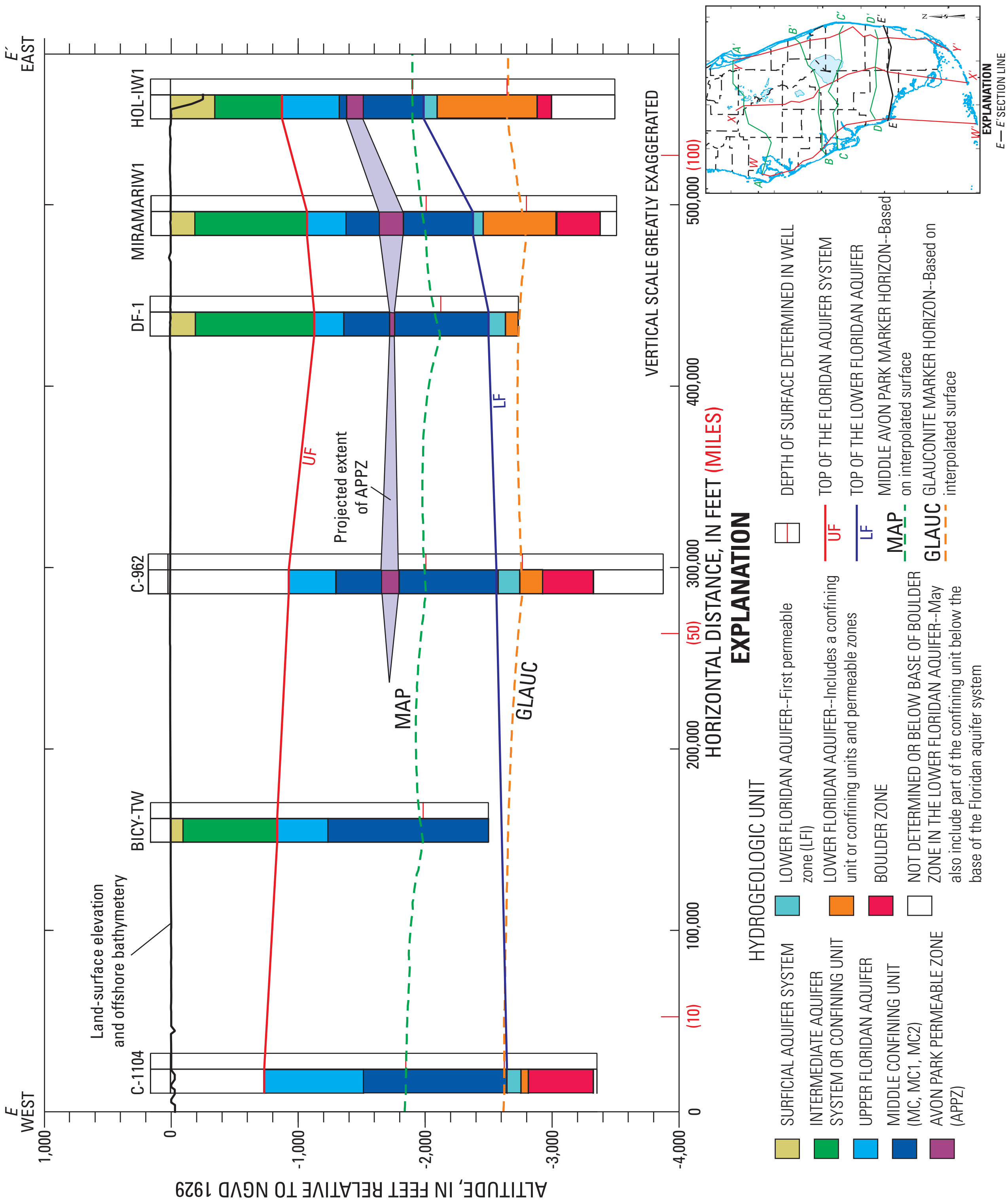


Figure 17e. Hydrogeologic sections *E-E′*.

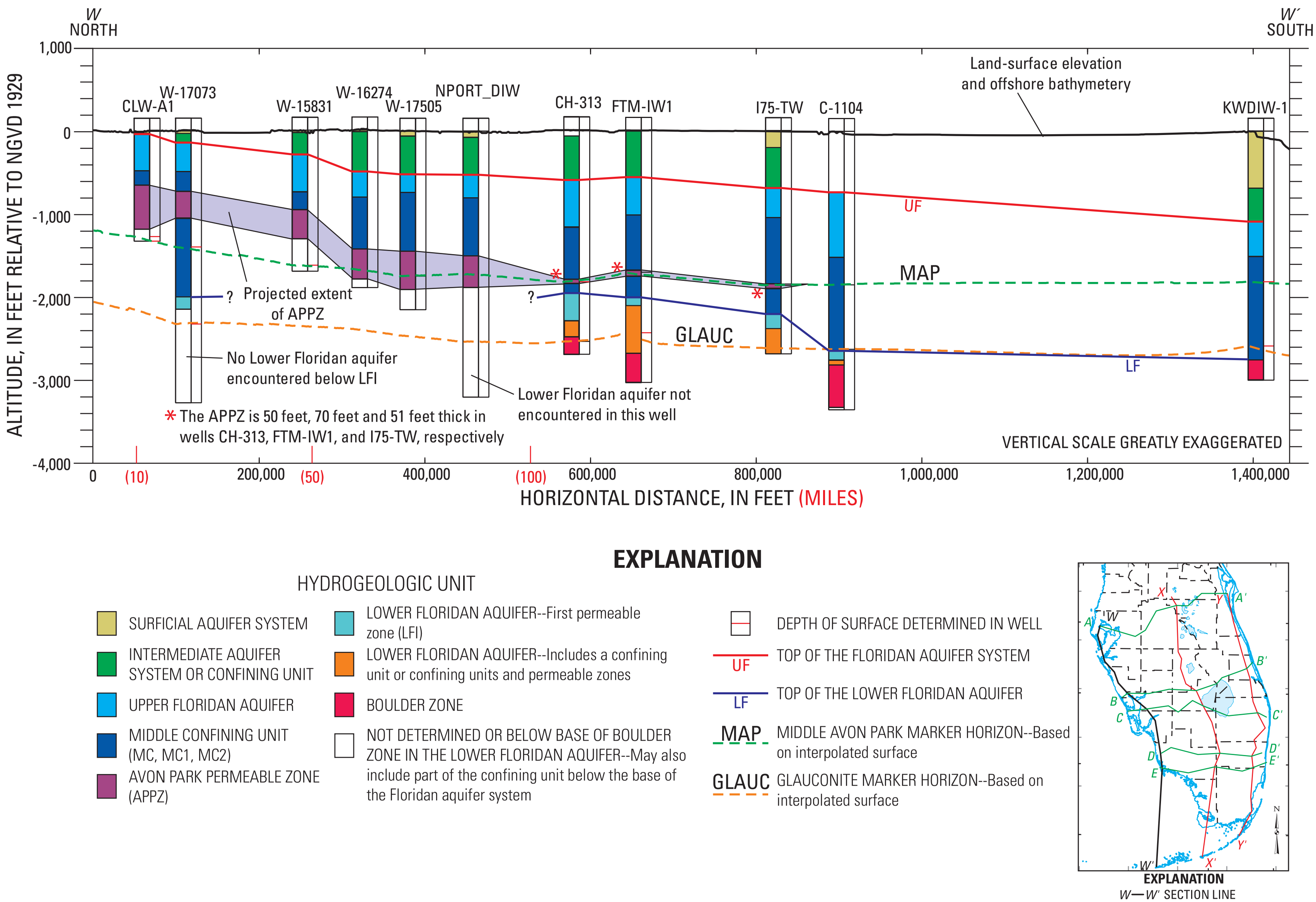


Figure 17f. Hydrogeologic sections *W-W′*.

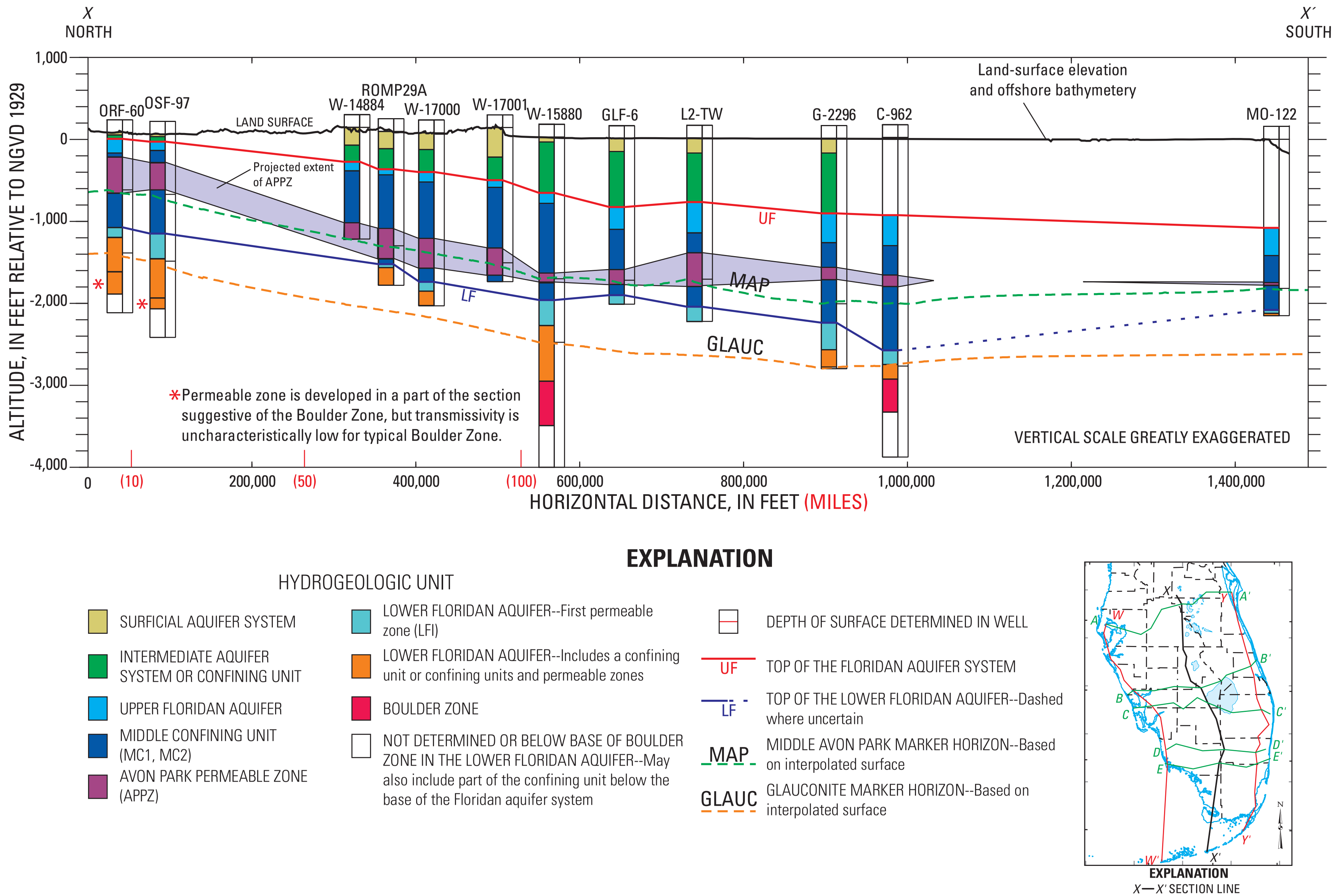


Figure 17g. Hydrogeologic sections *X-X′*.

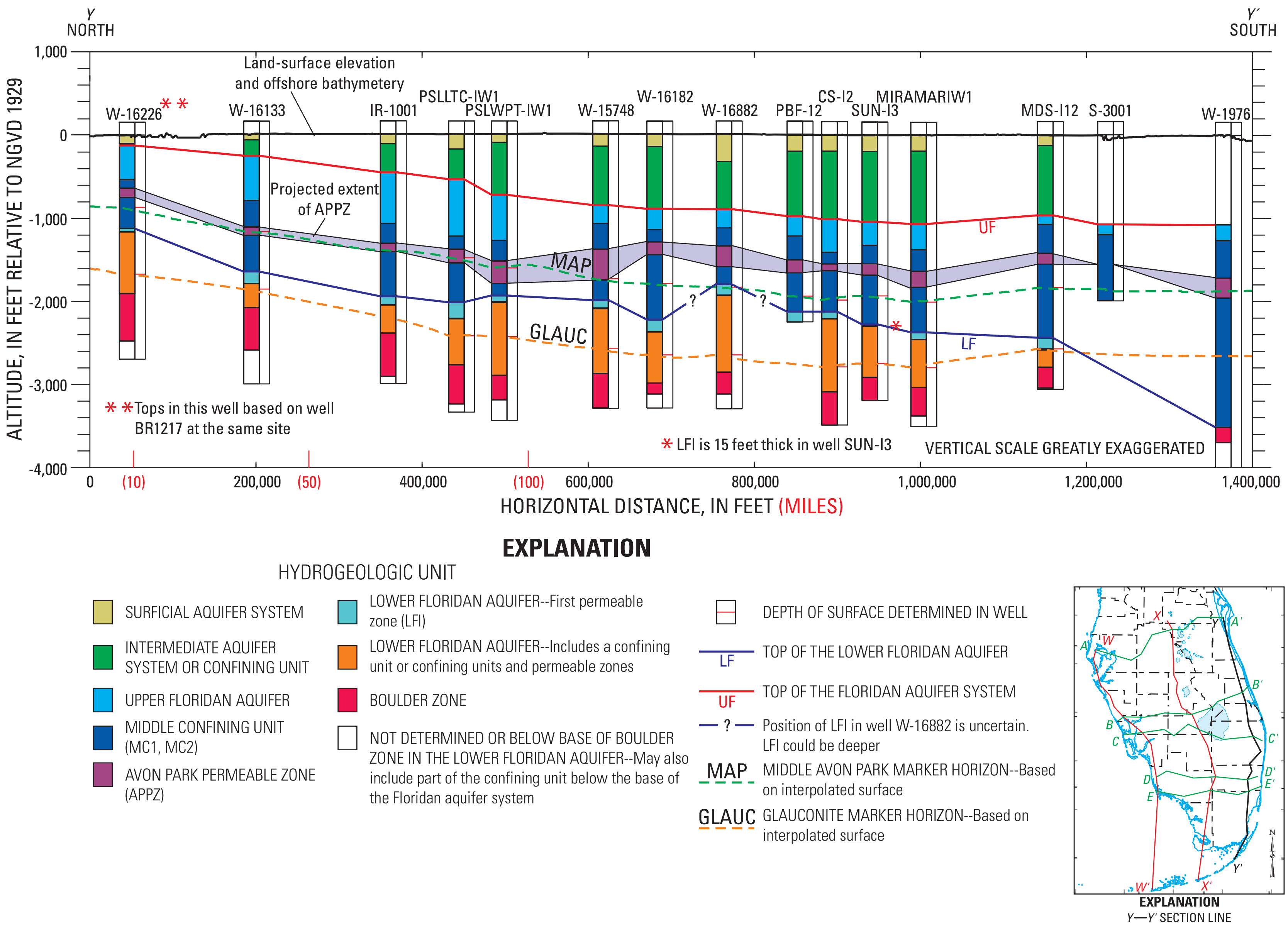


Figure 17h. Hydrogeologic sections *Y-Y′*.

Upper Floridan Aquifer

The Upper Floridan aquifer is continuous throughout the study area. The subsequent discussion of the Upper Floridan aquifer is divided into three sections that describe the following: (1) characteristics and stratigraphic position of the aquifer; (2) boundaries, thickness, transmissivity, and confinement of the aquifer; and (3) uses of the aquifer that relate to the purpose of this report and the new conceptual hydrogeologic framework.

Characteristics and Stratigraphic Position

The uppermost surface of the Upper Floridan aquifer is marked by drilling characteristics, such as a lost-circulation zone or drilling break (a sudden increase in the rate of penetration). Additionally, the Upper Floridan aquifer is well confined in southern Florida, where it is characterized by its artesian pressure or a large increase in hydraulic head that can cause water flows, which cut the drilling mud. Geophysical log characteristics include a decrease in gamma-ray log activity, increased electrical formation resistivity and porosity, anomalous caliper log readings (spikes) indicating abrupt borehole enlargements, or thin zones of in-gage borehole where well-cemented but permeable limestone or dolostone may be present. Additionally, a large flow zone in terms of flow rate (as much as hundreds of gallons per minute) or contribution to total flow, as observed in borehole flowmeter logs or flow to the surface during drilling, commonly marks the top of the Upper Floridan aquifer. Lesser flow zones can occur above this large flow zone; however, these lesser zones may or may not be included in the Upper Floridan aquifer, depending on their head, permeability, and the degree of confinement provided by the unit(s) separating them from the large flow zone.

Porosity and permeability in the Upper Floridan aquifer vary widely depending on location and formation. Common forms are interparticle, moldic to vuggy, and karstic to cavernous. The karstic to cavernous permeability is most common in the upper part of the aquifer in the northern part of the central Florida, where the aquifer becomes unconfined to thinly confined. Permeability associated with fracturing does not seem to be common.

In southern Florida, the Upper Floridan aquifer consists of several thin water-bearing zones of high permeability (flow zones) interlayered with thicker, low-permeability zones. Commonly, one or two major flow zones provide most of the productive capacity. These flow zones, commonly less than 20 ft thick, occur within the upper part of the Upper Floridan aquifer, typically within the lower Hawthorn producing zone, and uppermost Suwannee Limestone, the Ocala Limestone, or the Avon Park Formation. Unconformities present at the top of the Suwannee Limestone, Ocala Limestone, or Avon Park Formation (Miller, 1986) are associated with zones of dissolution and increased permeability (Meyer, 1989).

The top of the Upper Floridan aquifer typically coincides with a formation boundary such as the top of the Suwannee Limestone; however, this aquifer boundary can occur over a wide range within the geologic section, from the lower part of the Hawthorn Group (lower Arcadia Formation) down to the upper part of the Avon Park Formation (fig. 8). The youngest stratigraphic unit that forms part of the Floridan aquifer system, at least in southern Florida and possibly in some of the rest of the study area, is the basal Hawthorn unit defined by the overlying lower Hawthorn marker unit previously described (fig. 8). Where present, this marker unit is included within the section providing good confinement above the Upper Floridan aquifer.

The hydrogeology of the Upper Floridan aquifer in southern Florida varies between southwestern and southeastern Florida. In southwestern Florida, the aquifer typically includes only a well developed and distinct lower Hawthorn producing zone and a thick and well developed Suwannee Limestone. In some areas, however, the aquifer may extend down into the upper part of the Ocala Limestone. In contrast, in southeastern Florida, the aquifer has been interpreted by many to include a thinner Suwannee Limestone (for example, Bennett and others, 2001), and the aquifer usually extends well down into the Avon Park Formation. An alternate interpretation for most of southeastern Florida is that the aquifer begins in the basal Hawthorn unit, and the Suwannee Limestone is absent (Reese and Memberg, 2000). Confinement is typically better (lower vertical hydraulic conductivity) between flow zones in southwestern Florida than in southeastern Florida. Some permeable zones in southwestern Florida have been referred to as separate aquifers or subaquifers, for example, Lower Hawthorn zones I and II, Suwannee zones I and II, and Ocala zones I and II (Water Resources Solutions, Inc., 2000).

The position of the Upper Floridan aquifer also varies stratigraphically between west-central and southwestern Florida. Where the lower Hawthorn producing zone is developed in southwestern Florida, this zone is included in the aquifer. To the north of Lee and Hendry Counties in west-central Florida, however, this lowermost Hawthorn producing zone, referred to as zone PZ3, is included in the intermediate aquifer system (Torres and others, 2001; Knochenmus, 2006). In west-central Florida, the Upper Floridan aquifer as defined in this study principally includes the Suwannee Limestone but also an upper part of the Ocala Limestone in some areas (figs. 8 and 13).

In east-central Florida, the Upper Floridan aquifer as defined in this study includes only zone A of zones A and B of the Upper Floridan aquifer (O’Reilly and others, 2002) (fig. 13). McGurk and Presley (2002) also divide the Upper Floridan aquifer in east-central Florida into the same two zones and make each zone a separate layer in their model construction.

Boundaries, Thickness, and Confinement

The altitude of the top of the Upper Floridan aquifer varies considerably within the study area, ranging from above NGVD 1929 in the northern part of west-central Florida to more than 1,100 ft below NGVD 1929 in Miami-Dade County of southeastern Florida (figs. 18 and A4). In southwestern Florida, unusually high local relief (several hundred feet) marks this upper surface; this relief results in part from the discontinuous nature of the lower Hawthorn producing zone within the aquifer. For example, in central Hendry County, the top of the aquifer was determined to be about 600 ft below NGVD 1929 in well W-15371 (USGS local number HE-1104) and 1,020 ft below NGVD 1929 in well HE-1103, located about 8 mi to the north (the station names of these two wells are labeled in fig. A4 and app. 2). The lower Hawthorn producing zone appears to be thick and well developed in W-15371, but lithologic description suggests development of this zone in HE-1103 is poor (Reese, 2000, pl. 4). The top of the Upper Floridan aquifer in W-15371 was placed at the top of the lower Hawthorn producing zone, whereas it was placed at the top of the Suwannee Limestone in HE-1103. The two pronounced depressions in the top of the Upper Floridan aquifer in Hendry County, one in central Hendry and one in southeastern Hendry, are uncertain (shown by dashed contour lines with an altitude of 800 ft below NGVD 1929 or deeper), because they are based on oil test wells that have only lithologic descriptions or poor quality geophysical log data and lithologic descriptions.

The basal boundary of the Upper Floridan aquifer commonly appears to be gradational with the middle confining unit and difficult to define objectively. If fluid logs are not available, or were not conducted under stressed conditions, other geophysical logs such as sonic, resistivity, and caliper, can be used in combination with lithologic data to determine the boundary. Depending on the lithology and nature of the sonic curve, a decrease in travel time below 120 microseconds per foot can be used to estimate the boundary. This value of sonic travel time equates to a high porosity (43-45 percent) in the Floridan aquifer system in southern Florida (Reese, 2000). The caliper and resistivity logs and lithology can also be used to determine the lower boundary. The base is commonly placed above a thick limestone unit that shows gradual but substantial borehole enlargement on the caliper log. This caliper log signature is indicative of fine-grained, poorly cemented limestone of relatively low permeability.

The thickness of the Upper Floridan aquifer ranges from less than 100 ft in some small areas of central Florida to greater than 700 ft in several coastal areas principally in southern Florida: southern Sarasota, western Collier, and northeastern St. Lucie Counties (figs. 19 and A5). A large area where thickness is less than 200 ft extends from the northern part of east-central Florida down the center of the peninsula to Lake Okeechobee. The thickness along the coast of southeastern Florida, excluding St. Lucie County, ranges from about 100 to greater than 400 ft.

Transmissivity of the Upper Floridan aquifer is highest in west-central Florida where it is greater than 100,000 ft^2/d in northern Hillsborough and northwestern Polk Counties and as high as about 300,000 ft^2/d in Pinellas County (unpublished data, 2004); a region of low transmissivity (less than 10,000 ft^2/d) exists in a large central peninsular area that extends from southeastern Polk to northwestern Miami-Dade Counties and has a maximum west to east extent in an area including Hardee, Highlands, and most of Okeechobee Counties.

The Upper Floridan aquifer is unconfined to thinly confined above (less than 100 ft, breached, or both) in the northern part of the study (fig. 18). In parts of Hillsborough, Polk, Osceola, and Brevard Counties and to the south, confinement is generally greater than 100 ft and unbreached (Miller, 1986).

Water Use

Uses of the Upper Floridan aquifer include withdrawals for agricultural and public supply and aquifer storage and recovery. Ground water is withdrawn for public supply from the Upper Floridan aquifer within most of the study area. Ground water withdrawn in southeastern and southwestern Florida (fig. 1), however, is brackish and requires desalinization prior to public consumption. Agricultural use is also common in most of the study area. In the Upper East Coast Planning Area of southeastern Florida and in Indian River County, large brackish-water withdrawals are made from this aquifer for agricultural purposes. Withdrawals of brackish water from the Upper Floridan aquifer for agricultural supply are also made in southwestern Florida. Brackish water withdrawn for agricultural use is not treated, other than blending with fresh surface water.

The Upper Floridan aquifer is the primary aquifer used for ASR in southern Florida (fig. 1). Twenty-nine of 30 Floridan aquifer system ASR sites in southern Florida have their storage zone completed within or planned for the Upper Floridan aquifer as defined in this study, and the remaining site has a storage zone in the Avon Park permeable zone (Reese and Alvarez-Zarikian, 2007).

Middle Confining Unit

The middle confining unit of the Floridan aquifer system underlies the Upper Floridan aquifer, and in most of the study area, is divided into upper (MC1) and lower (MC2) parts that are separated by the Avon Park permeable zone (discussed below) (fig. 13). Despite the name, in most of the study area the middle confining unit is semiconfining or leaky in nature and generally consists of micritic limestone (wackstone to mudstone), dolomitic limestone, and dolomite or dolostone.

In most of west-central Florida including Highlands County and parts of southwestern Florida, where the Ocala Limestone is fine grained and micritic in nature, the upper

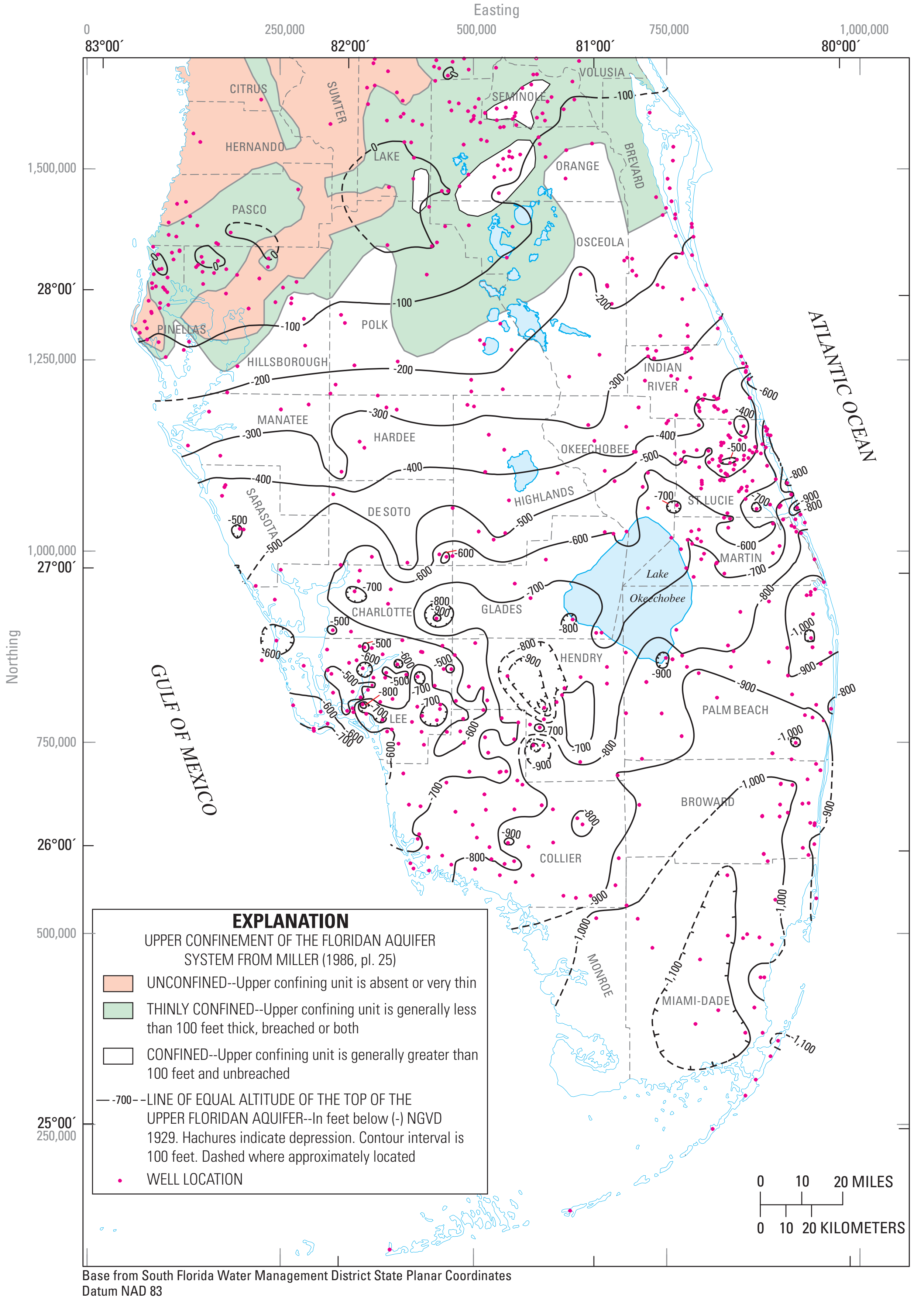


Figure 18. Altitude of the top of the Upper Floridan aquifer and areas where the aquifer is unconfined or thinly confined.

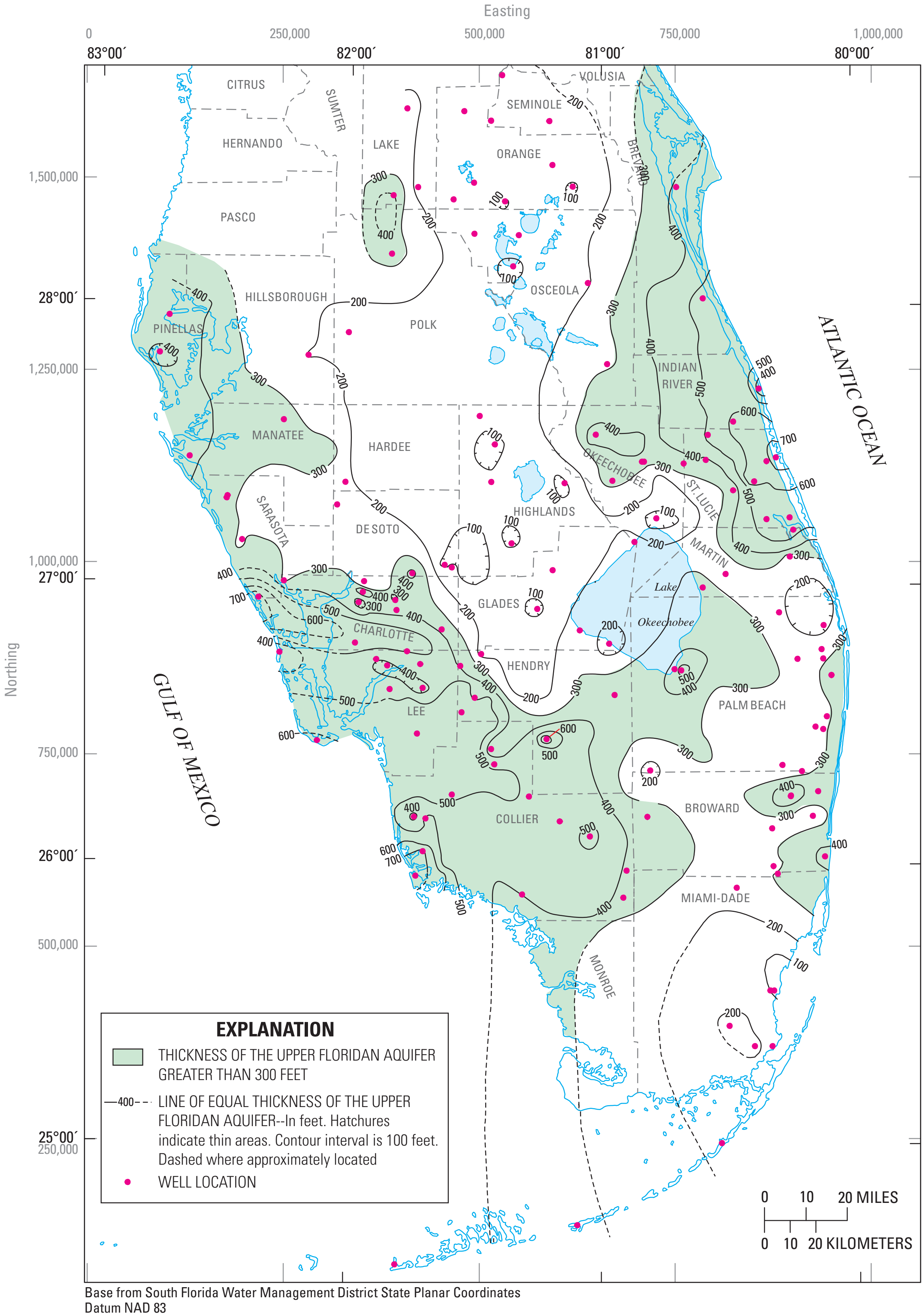


Figure 19. Thickness of the Upper Floridan aquifer.

boundary of the middle confining unit is placed at or near the upper contact of the Ocala Limestone. Previous researchers that have described the Ocala Limestone as a semiconfining unit in west-central Florida are Hutchinson (1992), Ward and others (2003), Hydrogeologic Inc. (2002), and Hancock and Basso (1993). Hutchinson (1992) refers to this semiconfining unit as the "lower Suwannee-Ocala semiconfining unit" (fig. 13). An example of a well in which the Upper Floridan aquifer-middle confining unit boundary approximately corresponds with the upper Ocala Limestone contact is LAB-TW (fig. 15).

The altitude of the top of the middle confining unit is based on fewer points of control and exhibited greater variability than the top of the Upper Floridan aquifer (figs. 5, 6, 20, and A6; tables 1 and 2). Part of this variability may be due to the difficulty in determining this boundary as previously described. Many of the wells that penetrate the boundary have incomplete information available for reliable determination, and in west-central Florida, the upper Ocala Limestone contact was used as a proxy for the Upper Floridan aquifer-middle confining unit boundary in 34 wells (table A2). This formation contact in these wells was determined by the FGS, and these wells are identified in figures 20 and A6. The thickness of MC1 ranges from less than 100 ft in the northern part of east-central Florida to greater than 800 ft in the parts of Glades and Hendry Counties, west of Lake Okeechobee (figs. 21 and A7). MC1 thins along the coast in southeastern Florida where it commonly is less than 200 ft thick, and in two wells, less than 100 ft thick. MC1 reaches a thickness of greater than 800 ft in well LAB-TW (figs. 15 and 17c) on section *C-C′*. MC1 combines with MC2 to form a single sequence where the Avon Park permeable zone is absent in southern Collier County and most of Monroe County (fig. 21).

The efficacy of the MC1 confining unit in the northern part of east-central Florida has not been previously substantiated. MC1 in this area, as defined in this study, is present between zones A and B of the Upper Floridan aquifer as defined by O'Reilly and others (2002) (fig. 13). Because of a thickness in this area of 100 ft or less (fig. 21) and its semiconfining nature, MC1 could be included within the Upper Floridan aquifer, which can be considered to be a thick complex sequence containing multiple flow zones separated by semiconfining intervals. MC1 is 100 ft thick in OSF-97 (fig. 14) as interpreted by Bennett and Rectenwald (2003a).

The thickness and effectiveness of MC1 as a confining unit could be important to the freshwater recovery performance of ASR wells in the brackish-water Upper Floridan aquifer. The semiconfining nature of MC1 in southern Floridan has been demonstrated by multiwell aquifer tests (Reese, 2002). If vertical hydraulic conductivity is high or the unit is thin, saline upconing from the Avon Park permeable zone might occur during withdrawal of injected water, reducing recovery. In southern Florida, this zone is, in general, more saline than the Upper Floridan aquifer (Bennett, 2003; Reese, 2004).

Avon Park Permeable Zone

The Avon Park permeable zone usually lies between the Upper and Lower Floridan aquifers and within the middle confining unit as defined in this study (figs. 8 and 13). The name of this zone derives from the description of this zone as the "Avon Park highly permeable zone" in west-central Florida (Hutchinson, 1992). This zone is the same as a highly productive zone in northeastern Palm Beach County that lies within the middle confining unit and was informally described as the "middle Floridan aquifer" at a Floridan reverse-osmosis well field (ViroGroup, Inc., 1994). This zone has also been described as the "middle Floridan aquifer" at several SFWMD test well sites (Bennett, 2003; Lukasiewicz, 2003a; 2003b).

Characteristics and Stratigraphic Position

The Avon Park permeable zone occurs within the middle to upper part of the Avon Park Formation; its occurrence is either near the MAP marker horizon or includes a thick part of the section extending several hundred feet above the MAP marker horizon (figs. 17a-h). This zone characteristically contains thick beds or units of dolostone with interbedded limestone and dolomitic limestone; only limestone is common in the upper part. In a large part of southern Florida, however, the zone is usually composed of all limestone (for example, in wells on section *Y-Y′* south of and including PBF-12 in southern Palm Beach County, figs. 16 and 17h). Permeability in the Avon Park permeable zone is primarily associated with fracturing, but cavernous or karstic, intergrain, and intercrystalline permeability can also be present. The dolomite in this zone varies from poorly to moderately consolidated and sucrosic to dense, hard, and massive, with a gradation from the former to the later commonly occurring with increasing depth.

Geophysical log signatures for the Avon Park permeable zone include: (1) an in-gage (similar to drill bit size) or nearly in-gage hole with numerous abrupt and large hole enlargements due to fracturing and dissolution; (2) high electrical resistivity rapidly changing to anomalously low resistivity in fractured zones; (3) erratic low and high porosity curve spikes, including anomalously high sonic log travel time spikes caused by fracture-related cycle skipping; (4) some increase in gamma-ray log activity associated with the dolostone; and (5) some SP curve activity (figs. 14-15). High transmissivity and the fractured nature of the Avon Park permeable zone commonly results in borehole enlargement and lost circulation zones during drilling. Borehole flowmeter logs can indicate large flow zones within the Avon Park permeable zone, and these zones can also be marked by large temperature or fluid resistivity curve deflections, in addition to a large increase in flow.

The Avon Park permeable zone has been identified in previous studies as being either part of the Upper or Lower Floridan aquifer. This zone has been identified as: (1) the lower part of the Upper Floridan aquifer in Palm Beach,

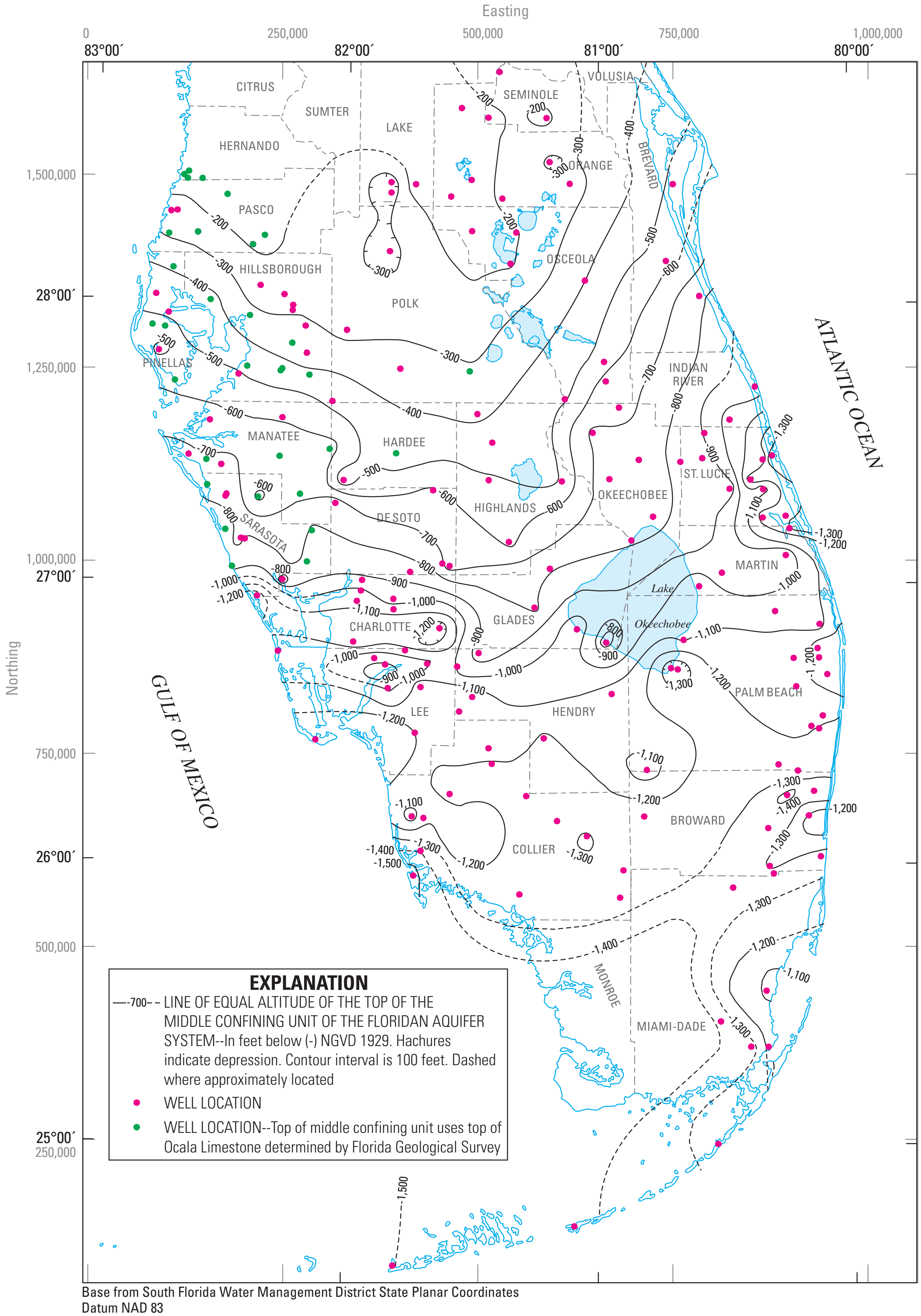


Figure 20. Altitude of the top of the middle confining unit (MCI) of the Floridan aquifer system.

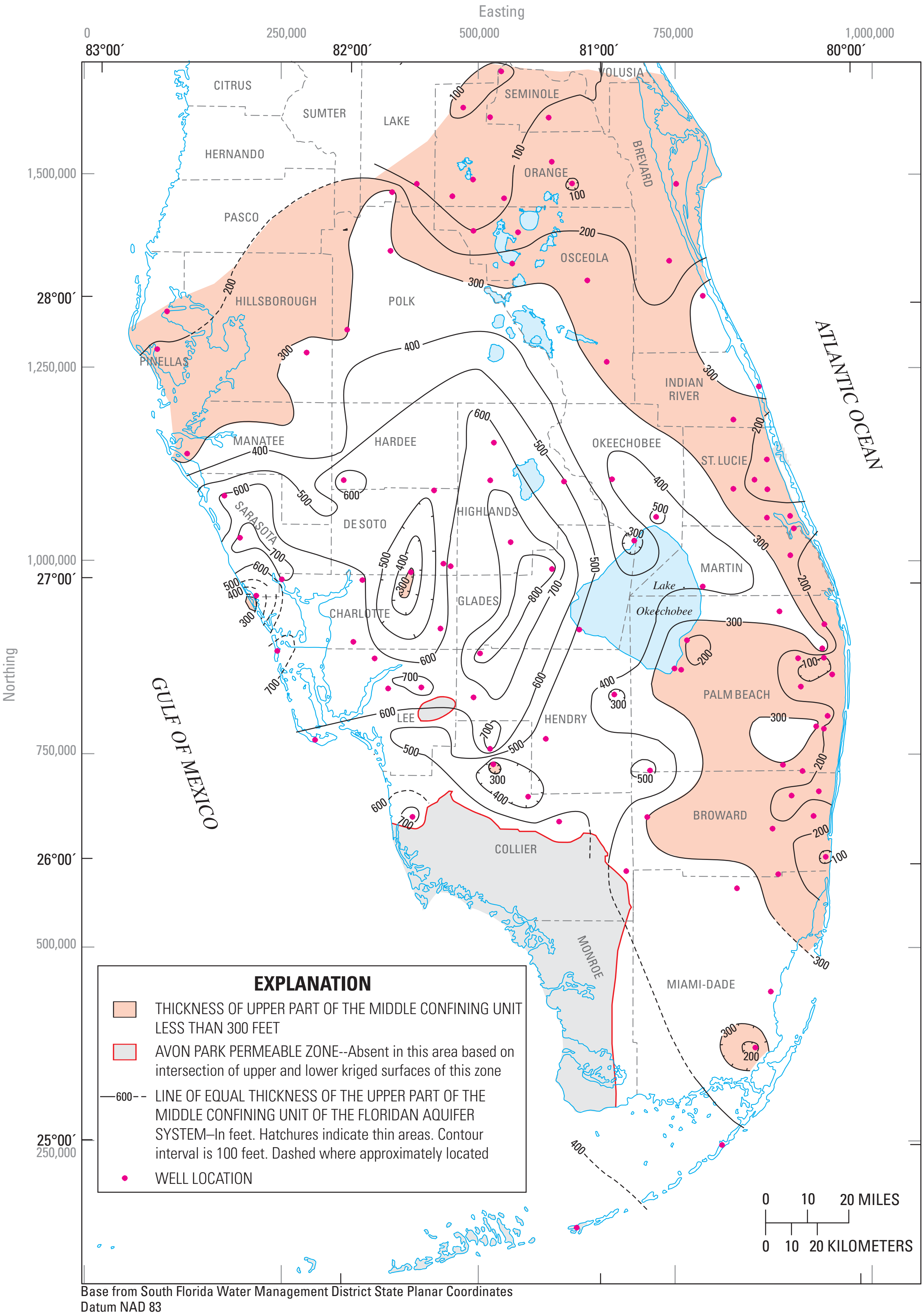


Figure 21. Thickness of the upper part of the middle confining unit (MCI) of the Floridan aquifer system.

Broward, and Miami-Dade Counties (Reese, 1994; Reese and Memberg, 2000), in west-central Florida (Miller, 1986; Hutchinson, 1992), and in the northern part of east-central Florida (O'Reilly and others, 2000) (fig. 13); or (2) the upper part of the Lower Floridan aquifer in Okeechobee, St. Lucie, and Martin Counties (Lukasiewicz, 1992) and in Highlands, Glades, and central-south Florida (western Palm Beach, western Broward, eastern Hendry, and eastern Collier Counties (Miller, 1986, pl. 31) (fig. 13). This last comparison to Miller (1986) includes most of the area through which hydrogeologic section *X-X′* (fig. 17g) extends.

Boundaries, Thickness, Confinement, and Continuity

The altitude of the upper boundary of the Avon Park permeable zone deepens to the south-southeast, ranging from about 200 ft below NGVD 1929 in the northern part of east-central Florida to more than 1,800 ft below NGVD 1929 in southern Florida (figs. 22 and A8). The altitude of the top of the this zone mapped herein in west-central Florida is similar to the top of the "highly permeable dolomite zone" of the Floridan aquifer mapped in the same area (Wolansky and others, 1980). These two surfaces are usually no more than 100 ft different in altitude. Wolansky and others (1980) describe the permeable zone they map as "a thick bed of massive, hard, dark-brown dolomite occurring in the Avon Park Limestone." Wells used to map this zone were not identified, making it difficult to directly compare interpreted boundaries provided by Wolansky and others (1980) and this investigation.

Locally, the effective (hydraulic) top of the Avon Park permeable zone in west-central Florida may extend higher than mapped, to near or above the top of the Avon Park Formation and include the "Ocala-Avon Park moderately permeable zone" of the Upper Floridan aquifer described by Hutchinson (1992) (fig. 13). An example is given by well NPORT-DIW on sections *B-B′* and *W-W′* (fig. 4). A highly permeable zone contained within the upper part of the Avon Park Formation at 1,100 to 1,220 ft below land surface in this well is considered interconnected (CH2M HILL, 1988) with the Avon Park permeable zone mapped in this study that extends from a depth of 1,500 to 1,880 ft below land surface. The Ocala Limestone is 300 ft thick in this well and is considered to be a semiconfining unit (CH2M HILL, 1988).

The altitude of the upper boundary of the Avon Park permeable zone can vary greatly over relatively short distances. This variability can occur in most of the study area where the zone is present, but it is commonly seen in St. Lucie, Martin and Palm Beach Counties of southeastern Florida. In this area, altitude of the top of this zone generally decreases from north to the south from 1,200 to 1,500 ft below NGVD 1929, respectively, but locally it can change by about 200 to 300 ft or more between wells. An extreme example is in eastern Martin County indicated by wells TFRO-1 and M-1352, located about 6 mi apart. The top of the zone is more than 400 ft shallower in TFRO-1 than in M-1352 (1,132 ft compared to 1,592 to below NGVD 1929, respectively, figs. A1 and A8). Occurrence of permeable dolostone higher in the stratigraphic section can greatly affect the location of the upper boundary of this zone, and this occurrence appears to be highly localized in some areas.

The upper boundary of the Avon Park permeable zone generally occurs shallower within the stratigraphic section as it extends from southern Florida to west-central Florida and east-central Florida (*W-W′*, fig. 17f; *X-X′*, fig. 17g, respectively), and this zone is interpreted to be zone B of the Upper Floridan aquifer as defined by O'Reilly and others (2002) in east-central Florida (fig. 13). The stratigraphic section is defined using the MAP marker horizon, deeper and shallower correlation horizons, and the lower Hawthorn marker unit (figs. 10a-d). The shallowing of the top of the Avon Park permeable zone within the section to the north coincides with stratigraphic shallowing of a thick zone of dolomite that contains this zone. The top of this thick zone of dolomite occurs as shallow in the section as the upper contact of the Avon Park Formation in west-central Florida in the three northernmost wells on section *W-W′* (wells W-15831, W-17073, and CLW-A1); the top of the Avon Park permeable zone in these three wells is placed approximately at this upper formation contact. Maliva and Walker (1998) observed stratigraphic shallowing in the occurrence of dolomite in the stratigraphic section within the Oldsmar and Avon Park Formations along the west coast from Collier County to northern Charlotte County based on deep wastewater injection well data.

The thickness of the Avon Park permeable zone varies from absent to more than 500 ft; its greatest thickness occurs in west-central Florida; it is generally more than 200 ft thick in (1) almost all of west-central Florida, (2) the southwestern part of east-central Florida, (3) most of the Upper East Coast Planning Area of southeastern Florida, and (4) northern Palm Beach County (figs. 23 and A9). The Avon Park permeable zone generally thins to 100 ft thick or less in southwestern Florida area and is absent in most of Collier and Monroe Counties. This zone also appears to pinch out, or possibly merge, with the Upper Floridan aquifer to the east along the east coast of southeastern Florida as shown on sections *B-B′* (fig. 17b) and E-E′ (fig. 17e). The zone is absent in areas close to the east coastline of southeastern Florida and the Florida Keys; for example, it is absent in wells W-16897 (fig. 17b), KWDIW-1 (fig. 17f), and S-3001 (fig. 17h). In some of these east coast areas, the thinning or loss of this zone appears to be due to the grading of dolostone into limestone in a coastward direction.

The area of poor development of the Avon Park permeable zone in southern Florida, where the thickness of this zone is less than 100 to 200 ft and limestone is the predominant lithology (fig. 23), could be related to structure in the Floridan aquifer system as shown by the altitude of the MAP marker horizon (fig. 11); this area of poor development tends to coincide with the broad structural depression in southern Florida

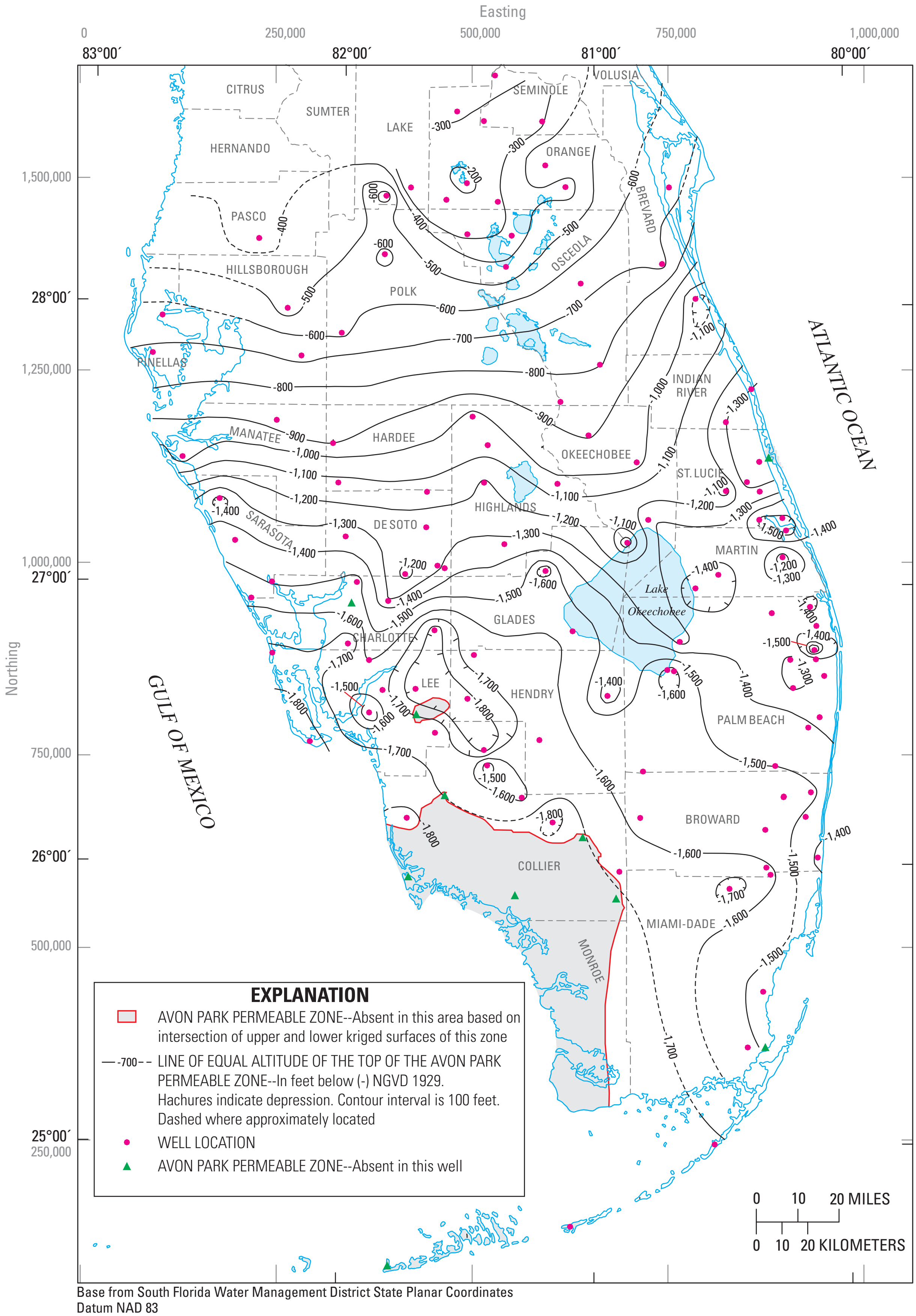
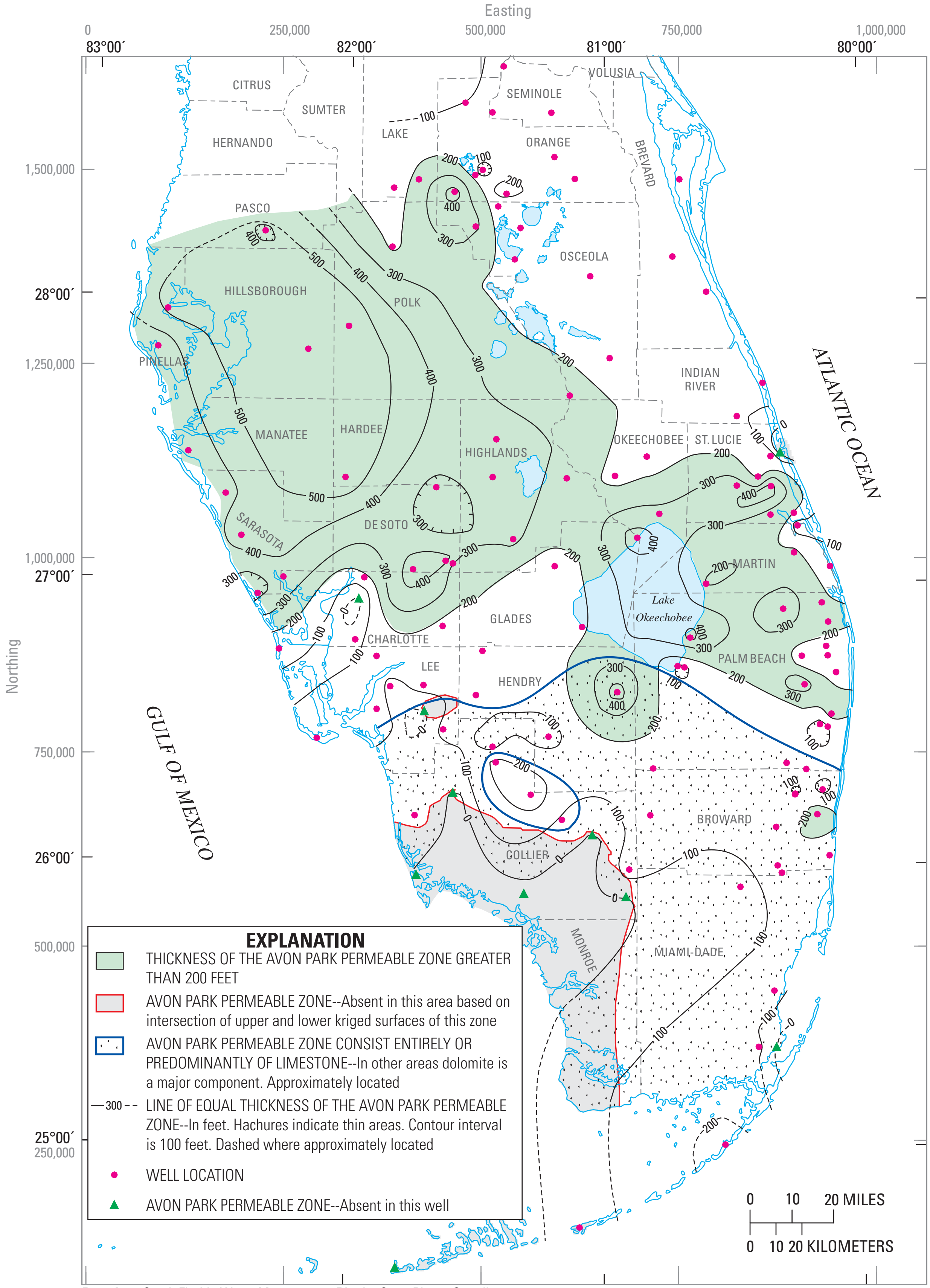


Figure 22. Altitude of the top of the Avon Park permeable zone of the Floridan aquifer system.



Base from South Florida Water Management District State Planar Coordinates
Datum NAD 83

Figure 23. Thickness of the Avon Park permeable zone.

that occupies part of the south Florida basin. Development of dolomite in the Avon Park permeable zone in west-central Florida took place contemporaneously with deposition in very shallow marine water (Tihansky, 2005), Therefore, water depth during deposition in this broad structural depression in southern Florida could have been too great for development of dolomite.

Transmissivity of the Avon Park permeable zone is as high as 1,600,000 ft^2/d in DeSoto County of west-central Florida and less than 100,000 ft^2/d in the southern part of southern Florida and a large inland area of central Florida (including eastern Hillsborough, Polk, western Osceola, and northern Highlands Counties; unpublished data, 2004). The area with transmissivity less than 100,000 ft^2/d in southern Florida tends to coincide with the area where limestone is predominant in the Avon Park permeable zone (fig. 23).

MC1 provides moderate to poor confinement or semi-confinement between the Avon Park permeable zone and the Upper Floridan aquifer. The relatively poor confinement between this zone and the Upper Floridan aquifer in the northern part of east-central Florida has been previously discussed, and confinement probably is also poor in some areas along the east coast in southeastern Florida.

O'Reilly and others (2002) differentiate between the middle semiconfining unit and the middle confining unit in east-central Florida, both of which separate the Upper and Lower Floridan aquifers and are both included in the MC2 unit defined in this study (fig. 13). The middle confining unit of O'Reilly and others (2002) underlies the middle semiconfining unit; the former provides much better confinement and is nonleaky because, unlike the semiconfining unit, it contains pore-filling, intergranular gypsum and anhydrite. Where the Lower Floridan aquifer does not exist in some parts of west-central Florida (discussed later), the MC2 confining unit below the Avon Park permeable zone becomes the sub-Floridan confining unit (fig. 13).

Hydraulic connectivity within the Avon Park permeable zone, is more uncertain between some wells and areas than others. The connectivity of this zone between southern Florida and east-central Florida, as mapped, seems likely (section *X-X′*, fig. 17g). Proof of this connection, however, through hydraulic head and hydrogeochemical data is beyond the scope of this study. In west-central Florida, the top of the Avon Park permeable zone becomes almost 500 ft shallower to the north between wells W-16274 (ATL-MW) and W-15831 on section *W-W′* (fig. 17f), which are about 13 mi apart, even though the MAP marker horizon between these two wells is only 40 ft shallower and the top of the Avon Park Formation is only about 140 ft shallower; the thickness of the zone is about 360 ft in both wells. Hydraulic connectivity between these two wells in the Avon Park permeable zone could exist if the dolomitized zone containing this zone is vertically connected by networks of open fractures or karst features, and this dolomitized zone is continuous between the two wells.

Hydraulic connectivity in the Avon Park permeable zone is also less certain between some wells in southeastern Florida along the east-west sections. The zone is from 100 to 200 ft stratigraphically shallower between some wells from west to east, where the zone is only 100 to 200 ft thick or less (section *C-C′*, fig. 17c; section *D-D′*, fig. 17d; section *E-E′*, fig. 17e).

Although the physical boundaries of the Avon Park permeable zone were determined on the basis of it representing a major separate permeable zone within the Floridan aquifer system, vertical hydraulic connectivity within this zone is uncertain in some areas, particularly where the zone is thick and consists of several discrete flow zones. Interconnectivity within the zone depends on the presence of extensive, open, vertical fracture networks; a layer of dense, unfractured dolomite could provide areas of confinement within the zone. Some evidence for confinement was found between the two major flow zones within the Avon Park permeable zone in well W-16543 on section *B-B′* in St. Lucie County (Lukasiewicz, 1992), where this zone is thick and well developed. This evidence came from water-quality data, geophysical logs, and packer tests. These flow zones are developed at the top and base of the Avon Park permeable zone and are separated by a 250-ft-thick semiconfining unit. Lukasiewicz (1992), however, referred to all of the Avon Park permeable zone in this well as being in the upper part of the Lower Floridan aquifer.

Water Use

The Avon Park permeable zone, as defined in this study, is a major public water-supply source where it is potable and transmissive. In east-central Florida, this zone (locally referred to as the lower zone or zone B of the Upper Floridan aquifer) has been described as being more productive than the Upper Floridan aquifer of this study (zone A; McGurk and Presley, 2002; O'Reilly and others, 2002). In west-central Florida, the Avon Park permeable zone (Avon Park highly permeable zone of Hutchinson, 1992 and Avon Park producing zone of Tihansky, 2005) is also a major public source inland from the coast and above the saltwater-freshwater interface (Tihansky, 2005). In the Upper East Coast Planning Area and Palm Beach County of southeastern Florida, the Avon Park permeable zone is less potable and is the primary production zone for supply to reverse-osmosis water-treatment plants (Reese, 2004). The largest municipal reverse-osmosis well field in this area is the Jupiter Water System in northeastern Palm Beach County, where an average of 5.2 Mgal/d was withdrawn during 2000.

Where the Avon Park permeable zone is below the saltwater-freshwater interface and contains nonpotable water, it is also used for injection of treated wastewater in west-central Florida (Hutchinson, 1992). The area of injection is close to the coast (fig. 3), and the injection zone includes the Avon Park permeable zone and, in some cases, an overlying Ocala-Avon Park "moderately permeable" zone (fig. 13; Hutchinson, 1992). The six wells on section *W-W′* north of and including NPORT_DIW are all at wastewater injection well sites, and the injection zone at these sites primarily includes

the Avon Park permeable zone (fig. 17f). Farther south along the west coast, the Avon Park permeable zone is poorly developed or not present (figs. 17d-f and 23), and the injection zone includes the Boulder Zone of the Lower Floridan aquifer in the Oldsmar Formation (Maliva and Walker, 1998).

Lower Floridan Aquifer

The Lower Floridan aquifer is a thick sequence of carbonate rocks that contains several permeable zones separated by thick semiconfining units (Miller, 1986). The semiconfining units tend to be much thicker than the permeable zones, with the exception of the Boulder Zone in the lower part of the aquifer (fig. 8). The permeable zones or subaquifers in the Lower Floridan aquifer above the Boulder Zone are listed from the highest to lowest in this study, beginning with LF1 and continuing with LF2, LF3, and so forth (fig. 13). In some areas, only LF1 is present. The confining unit below LF1 and the ones between deeper permeable zones are referred to as LC.

The base of the Floridan aquifer system in southern and east-central Florida is marked by impermeable, massive anhydrite beds of the Cedar Keys Formation (Miller, 1986). In some of the coastal areas of west-central Florida, such as southwestern Sarasota and west Charlotte Counties, the Lower Floridan aquifer is entirely absent due to occlusion of pore space by intergranular evaporates (Hutchinson, 1992), for example, well NPORT_DIW on section *W-W′* (fig. 17f). Well W-17073 (South Cross Bayou injection test well E-1 in Pinellas County, fig. 17f) has a minor Lower Floridan aquifer permeable zone from a depth of 2,000 to 2,150 ft. However, a transmissivity estimate of only 2,000 to 3,000 ft^2/d was reported for the entire open interval from a depth of 1,853 to 3,280 ft in this well that included this zone (Hickey, 1982). Normally, transmissivity of the uppermost permeable zone in the Lower Floridan aquifer is higher by one to two orders of magnitude (unpublished data, 2004).

Upper Permeable Zone

Only the tops and bases of the uppermost permeable zone or subaquifer of the Lower Floridan aquifer (LF1) and the Boulder Zone were determined in this study (tables 1, 2 and A2, app. 1). These two permeable zones in the Lower Floridan aquifer are shown on the eight hydrogeologic sections (figs. 17a-h).

Characteristics and Stratigraphic Position

LF1 is within the lower part of the Avon Park Formation; it is defined herein as representing the first major permeable zone that occurs below the MAP marker horizon; usually, it is above the GLAUC marker horizon (figs. 17a-h). Characteristics of the LF1 are similar to the Avon Park permeable zone. The LF1 occurs in fractured dolostone units, the LF1 geophysical log signatures are similar to those for the Avon Park permeable zone, and it also contains limestone and dolomitic limestone. The dolostone, however, is consistently more dense and massive in LF1 than in the Avon Park permeable zone. Examples of the geophysical log and lithologic characteristics of LF1 are shown in figures 14 and 16.

Abrupt shifts in the depths of the top of the Lower Floridan aquifer and base of the Upper Floridan aquifer from west to east across the peninsula were mapped by Miller (1986), but evidence for these shifts was not found in this study. Miller (1986) mapped an abrupt shift in depth of the top of the Lower Floridan aquifer, varying from about 300 to 900 ft and down to the west. This vertical shift is shown by a boundary line on the top of the Lower Floridan aquifer contour map (Miller, 1986, pl. 31) that trends northwest through western Glades County, western Highlands County, and central Polk County. This shift and a similar shift in the depth of the base of the Upper Floridan aquifer is provided by discontinuous confining units that do not have sharp lateral boundaries (Miller, 1986, sections *G-G′* and *H-H′*, pls. 23, 24). The uppermost permeable zone of the Lower Floridan aquifer of Miller (1986) in parts of east-central and southeastern Florida is defined as the Avon Park permeable zone in this study. Sections *A-A′* through *E-E′* illustrate the west-east physical relation between Avon Park permeable zone and LF1; LF1 occurs in approximately the same part of the stratigraphic section between western and eastern areas (figs. 17a-e).

Thickness, Confinement, and Continuity

The thickness of LF1 ranges from absent to greater than 400 ft, and it appears to grade into rocks of low permeability near the coast in some areas. Examples include well W-16897 on the east coast (section *B-B′*, fig. 17b), KWDIW-1 in the lower Florida Keys (section *W-W′*, fig. 17f), and well W-1976 in the upper Florida Keys (section *Y-Y′*, fig. 17h).

Transmissivity of LF1 is substantial in southern Florida and in the northern part of east-central Florida. In these areas, transmissivity generally ranges from greater than 10,000 ft^2/d to as high as almost 700,000 ft^2/d in Orange County (unpublished data, 2004).

The degree of confinement above and below LF1 in terms of thickness and rock type is variable. In some areas, confinement between Avon Park permeable zone and LF1 by MC2 may be poor. For example, MC2 is only 130 ft thick and consists of dolostone in well GLF-6 in Glades County (section *C-C′*, fig. 17c); the caliper log from this well suggests that this dolostone interval contains fractures. The thickness of MC2 generally ranges from about 100 to 900 ft where both the Avon Park permeable zone and LF1 are present and were penetrated; however, in well L-6461 in Lee County, thickness is only 20 ft.

Confinement provided by the confining unit (LC) below LF1 can be very good in central Florida due to pore-filling anhydrite and gypsum (for example, well OKF-100 on section *B-B′*). Good confinement in MC2 and LC could also be provided by dense unfractured dolostone in some areas.

Maliva and Walker (1998) found evidence in southwestern Florida that indicates dense unfractured dolomite beds provide the primary confinement that prevents upward migration of injected buoyant wastewater. The measured vertical hydraulic conductivities of core samples for dolomite from the middle confining unit and Lower Floridan aquifer were substantially lower than those for limestone (Maliva and Walker, 1998). Forty percent of dolomite core samples had conductivities of 10^{-8} cm/sec ($3x10^{-5}$ ft/d) or less; whereas limestone samples had a modal conductivity of 10^{-5} to 10^{-6} cm/sec ($3x10^{-2}$ to $3x10^{-3}$ ft/d), and all samples had a conductivity of more than 10^{-8} cm/sec ($3x10^{-5}$ ft/d).

The hydraulic connectivity of LF1 is more uncertain between wells in some areas. The location of LF1 appears to vary within the section in some areas, particularly near the coast. For example, in well C-1104 on sections *E-E′* and *W-W′* (figs. 17e and 17f), LF1 is not developed above the GLAUC marker horizon and is placed deeper in the section. Another example is shown on section *E-E′* (fig. 17e) in well HOL-IW1, in which LF1 is several hundred feet higher in the section than in well MIRAMARIW1—the next well to the west on the section.

The position of LF1 is uncertain in well W-16882 on *Y-Y′* (fig. 17h). The top and base of LF1 in this well were placed high in the section just above and below the MAP marker horizon, respectively, at a position several hundred feet higher than adjacent wells on the section. An alternate interpretation for well W-16882 is that the zone interpreted to be LF1 is part of the Avon Park permeable zone and LF1 is a deeper permeable zone not shown in figure 17h. LF1 was placed at the position shown in well W-16882 in figure 17h primarily because of a large and anomalous temperature log break at the top of this zone, which could indicate separation between this zone and higher permeable zones. A temperature log break is a rapid change in borehole fluid temperature with depth under flowing or pumping conditions.

Boulder Zone

The Boulder Zone (Kohout, 1965) is a thick, highly permeable zone consisting primarily of fractured dolostone and is commonly used for the disposal of treated wastewater in deep injection wells in the study area (fig. 3). Transmissivity for the Boulder Zone in southern Florida is generally greater than all other permeable zones or aquifers in the Floridan aquifer system and on the order of 10^6 to 10^7 ft^2/d (Meyer, 1974, and Singh and others, 1983).

The top of the Boulder Zone was found in this study to occur in the Oldsmar Formation at a similar stratigraphic position, one to several hundred feet below the GLAUC marker horizon (figs. 17a-h). Of the 64 wells in which this top was determined (tables 1 and A2, app. 1), in only two was the top of Boulder Zone shallower than the GLAUC marker horizon, and in these two the difference was only 60 ft. Miller (1986), however, describes a “boulder zone,” a term adopted from drillers, as having no stratigraphic significance and as not “developed over a wide area at the same depth or at the same stratigraphic position.” Additionally, “the stratigraphic position and depths of high transmissivity injection zones” in southwestern Florida, including the Boulder Zone, “are highly variable, and cannot be predicted with any confidence” (Maliva and Walker, 1998).

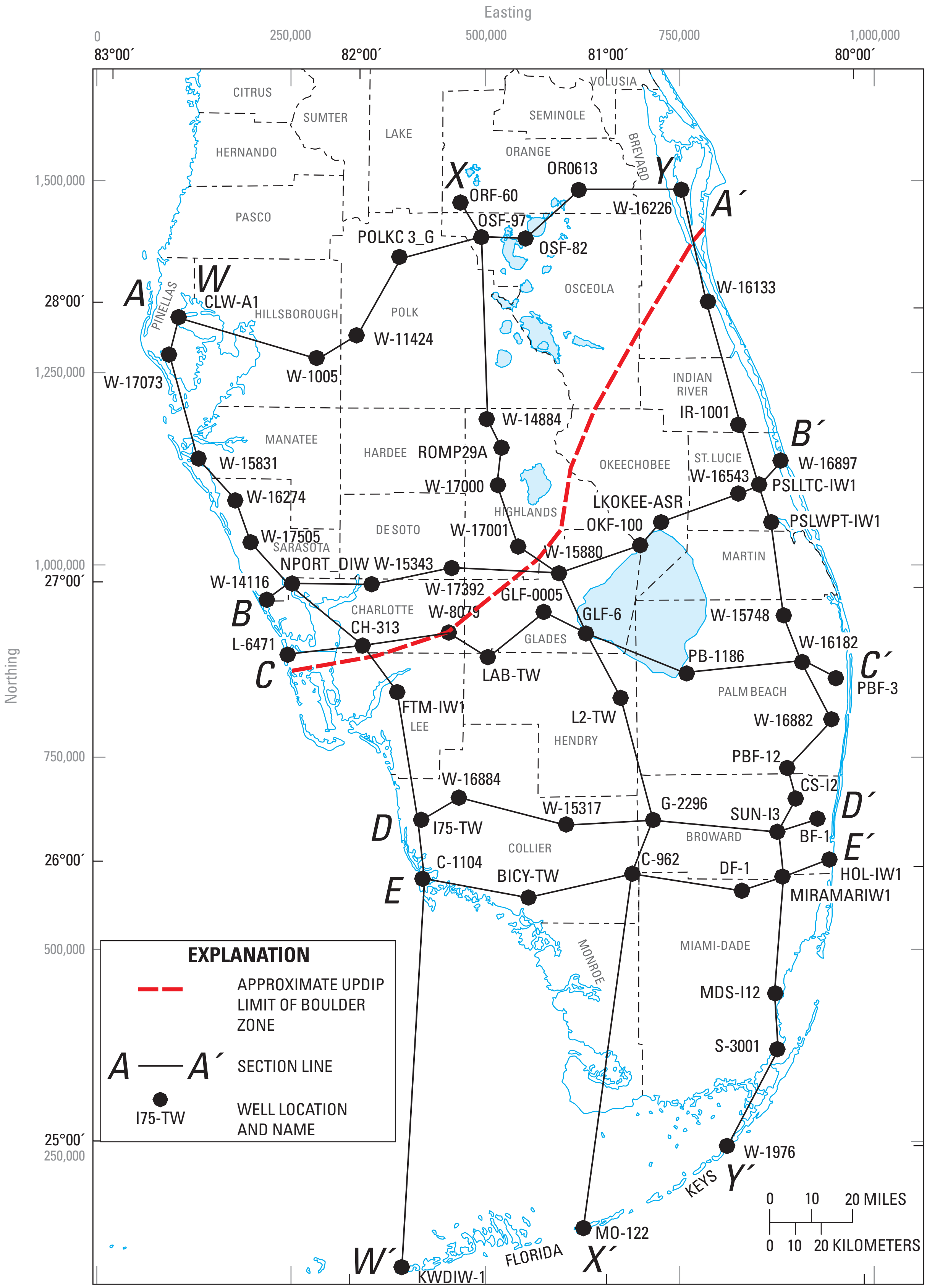
The top of the Boulder Zone commonly coincides with the top of a thick interval of massive dolostone, but the effective top can differ from this lithologic boundary; it is defined as occurring at the top of anomalously permeable fractured zones, which are best determined using geophysical logs such as the caliper, sonic, formation resistivity, and borehole fluid logs. The top of the Boulder Zone was usually determined using data from consulting reports and tends to coincide with the top of the injection zone used for the disposal of treated municipal wastewater or reverse-osmosis reject water.

The Boulder Zone can be as thick as 700 ft, and the nature of the permeability in this zone ranges from fractured to cavernous, with open fracture networks probably providing most of the permeability (Duerr, 1995; Maliva and Walker, 1998); both fractured limestone and dolostone can be present. The base of this zone was indeterminate in some wells because they were not drilled deep enough.

The Boulder Zone was found to occur over a larger area than mapped by Miller (1986), and a permeable zone of much lower transmissivity can occur at a stratigraphic position similar to the Boulder Zone in a part of east-central Florida far from the mapped extent of the Boulder Zone. The Boulder Zone occurs in all of southern Florida and part of east-central Florida but not in west-central Florida (fig. 24; Miller, 1986). In this study, however, the zone was identified in southern Charlotte County in west-central Florida (fig. 17c) and has been reported in an injection well in northern Charlotte County (East Port Wastewater Treatment Plant; Maliva and Walker, 1998). In the north-central part of the study area (northwestern Osceola and southwestern Orange Counties), a permeable zone occurs at a stratigraphic position similar to the Boulder Zone and is about 100 to 200 ft thick (wells ORF-60 and OSF-97 on section *X-X′*; fig. 17g). The transmissivity of this zone in these two wells, however, is indicated to be low to moderate and not on the same order of magnitude as is commonly found for the Boulder Zone (Bennett and Rectenwald, 2003a,b).

Summary and Conclusions

The carbonate Floridan aquifer system of central and southern Florida (south of a latitude of about 29 degrees north) is an invaluable resource with a complex framework that has previously been mapped and managed primarily in a subregional context according to geopolitical boundaries. As interest and use of the Floridan aquifer system of this area increases, a consistent regional hydrogeologic framework is needed for effective management across these boundaries.



Base from South Florida Water Management District State Planar Coordinates
Datum NAD 83

Figure 24. Location of the approximate updip limit of the Boulder Zone (from Miller, 1986), trace of hydrogeologic sections, and location of wells used on sections.

Many aquifer storage and recovery (ASR) facilities have been constructed in this system, and withdrawal of brackish water with treatment by reverse osmosis for public supply has increased rapidly in recent years. Due to high population growth, the number of Floridan aquifer system wastewater injection facilities is also rapidly expanding. To prevent water-level and water-quality conflicts between these potentially competing uses, a clear understanding of the hydrogeology of the aquifer system is required.

This study was undertaken to provide a synthesis of previous studies and disparate data sources, and to update the hydrogeologic framework for the Floridan aquifer system, including linkage of central and southern Florida and west and east coastal areas. The approach used in this study included: (1) thorough review of previous studies; (2) identification of differences in hydrogeologic nomenclature and interpretations across the study area; (3) collection, processing, archiving, and interpretation of available data; (4) development of a correlative or time-stratigraphic framework; and (5) development of a preliminary hydrogeologic framework with consistent nomenclature based on the stratigraphic framework and delineation and mapping of the bounding surfaces of major aquifers, subaquifers or thick permeable zone, and confining units.

The review of previous studies in the study area, both regional and subregional in scope, found significant differences in the naming and definition of hydrogeologic units within the Floridan aquifer system. To make use of the data from these studies, it was necessary to identify these conflicts; and to guide this effort and develop a unified conceptual hydrogeologic framework, it was necessary to: (1) construct eight regional hydrogeologic sections through key wells, delineating major aquifers, subaquifers, and confining units across the study area north to south and west to east; and (2) develop an approximately correlative or approximate time-stratigraphic framework including construction of four stratigraphic sections. The differences in hydrogeologic nomenclature and interpretation across the study area from previous studies were identified and resolved within the unified conceptual hydrogeologic framework. Based on that conceptualization, data from previous studies of the Floridan aquifer system were extracted, archived, and utilized in conjunction with boundary depth determinations made for this study to map the boundaries and thicknesses of hydrogeologic units.

Development of an approximately correlative stratigraphic framework included delineation of a marker unit and marker horizons. The horizons are correlative points in the stratigraphic section rather than a unit with upper and lower boundaries. This approximate time-stratigraphic framework differed from the formation-based stratigraphy and provides a basis for better understanding the vertical and lateral extent of formations. Formations included in the Floridan aquifer system in ascending order include the upper part of the Cedar Keys Formation, Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone, and the lower part of the Hawthorn Group.

Two correlative stratigraphic marker horizons within the Floridan aquifer system and a marker unit near the top of the aquifer system were delineated or mapped to provide stratigraphic guidance in the identification and determination of aquifers and confining units and in the delineation of their lateral continuity. The two marker horizons originated from two previous studies of east coast Lower Floridan aquifer injection wells, where they are based on lithology and correlation of geophysical log (natural gamma-ray and sonic) signatures observed in boreholes. One marker horizon is near the middle of the aquifer system in the middle part of the Avon Park Formation (MAP marker horizon); the second is in the lower part of the system and marks the top of distinctive glauconitic limestone beds that can be present at the top of the Oldsmar Formation (GLAUC marker horizon). The depths of these same two marker horizons were extended throughout the study area by correlation of natural gamma-ray logs between wells. The marker horizons do not have distinguishing lithologic characteristics or a characteristic gamma-ray log pattern in all areas but are still believed to be valid because of correlation of the entire section and correlation of all sufficiently deep wells with gamma-ray logs. The correlative marker unit near the top of the aquifer system is in the Hawthorn Group and has been previously identified and mapped in southern Florida. It is referred to as the lower Hawthorn marker unit and provides a stratigraphic constraint for the top of the Floridan aquifer system.

An approximate time-stratigraphic framework based on the lower Hawthorn marker unit and the GLAUC and MAP marker horizons was compared with previously determined formation tops using stratigraphic sections. The Ocala Limestone appears to be absent in southeastern Florida because of a facies change of the entire Ocala Limestone into the Avon Park Formation from the west and north into this area. Based on this observation in this area either the Ocala Limestone is substantially older than late Eocene, the commonly accepted age of this unit, or the upper part of the Avon Park Formation is younger than middle Eocene.

The three principal hydrogeologic units in the study area are the surficial, intermediate, and Floridan aquifer systems. The Floridan aquifer system formally consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer. This study introduces a new major regional productive zone or subaquifer, referred to as the Avon Park permeable zone. This zone is contained within the middle confining unit and synthesizes an extensive zone that has been referred to differently in different parts of the study area in previous studies.

Top and bottom surfaces for the Upper Floridan aquifer and Avon Park permeable zone and the two stratigraphic marker horizons within the Floridan aquifer system were generated by fitting data to a statistical model using ordinary kriging. Thickness maps of these two aquifers and the upper part of the middle confining unit that separates them were produced from the aquifer boundary surfaces. Surface altitude and thickness contours were manually smoothed and forced to honor all data points.

The mapping done in this study indicates that the Upper Floridan aquifer is continuous throughout the study area. The top of the aquifer commonly coincides with a formation boundary, such as the top of the Suwannee Limestone; however, this top can occur over a wide range within the stratigraphic section, from a basal Hawthorn unit down to the upper part of the Avon Park Formation, and the depth of this top was found to be relatively consistent with previous studies. The lower Hawthorn marker unit provides part of the upper confinement at the top of the Upper Floridan aquifer, at least in southern Florida. The altitude of the top of the Upper Floridan aquifer varies over a wide range, from above NGVD 1929 in the northern part of west-central Florida to more than 1,100 ft below NGVD 1929 in Miami-Dade County of southeastern Florida due to dip into the south Florida basin. The thickness of the Upper Floridan aquifer ranges from less than 100 ft in parts of east-central Florida to greater than 700 ft in several coastal areas within southwestern Florida.

The Upper Floridan aquifer is separated from the Avon Park permeable zone by the semiconfining upper part of the middle confining unit, referred to as MC1. In this study, the top of MC1 is placed near the top of the Ocala Limestone in most of west-central Florida and parts of southwestern Florida. Part or all of the Ocala Limestone is semiconfining in these areas because it becomes dominated by fine-grained, carbonate mud-rich lithofacies of low permeability. The thickness of MC1 ranges from less than 100 ft in the northern part of east-central Florida to greater than 800 ft in the parts of Glades and Hendry Counties west of Lake Okeechobee. The thickness of MC1 commonly is less than 200 ft along the coast in southeastern Florida. The thickness and confining nature of MC1 may affect the freshwater recovery performance of ASR wells with storage zones in the Upper Floridan aquifer. Pumping during recovery could cause the upconing of brackish to saline water from the Avon Park permeable zone below the ASR storage zone, reducing recovery efficiency.

The name of the Avon Park permeable zone derives from the description of this zone as the “Avon Park highly permeable zone” in west-central Florida in a previous study. Additionally, this zone has been identified previously in southeastern Florida as the “middle Floridan aquifer.” The Avon Park permeable zone is separated from the Lower Floridan aquifer by the lower part of the middle confining unit (MC2). MC2 is semiconfining to confining.

The Avon Park permeable zone occurs within the Avon Park Formation, and its occurrence is either near the MAP marker horizon or within a thick part of the section extending several hundred feet above the marker horizon. This subaquifer is present in most of the study area. It characteristically consists of thick dolostone units with interbedded limestone and limestone in its upper part, and permeability is primarily associated with fracturing. This zone is well developed in west-central Florida, parts of east-central Florida, and the northern part of southeastern Florida (in parts of St. Lucie, Martin and Palm Beach Counties). In the southern part of southern Florida, however, it is usually composed of all limestone. The zone has been identified in previous studies as the upper part of the Lower Floridan aquifer in the northern part of southeastern Florida and in a central peninsular area, or as the lower part of the Upper Floridan aquifer in west-central Florida, the northern part of east-central Florida, and the southern part of southeastern Florida. The Avon Park permeable zone is interpreted to be the lower zone B of the Upper Floridan aquifer as defined in a previous study of east-central Florida, and the Upper Floridan aquifer of this study is equivalent to upper zone A of the Upper Floridan aquifer in the same previous study. In west-central Florida the Upper Floridan aquifer as defined in this study principally includes the Suwannee Limestone but also an upper part of the Ocala Limestone in some areas.

The upper boundary of the Avon Park permeable zone commonly appears to correspond with the top of a thick section of mostly dolomite that transgresses chronostratigraphic boundaries, and this boundary can become progressively younger as the zone extends northward from southern Florida to central Florida. The Avon Park permeable zone occurs in the section as high as the top of the Avon Park Formation in west-central Florida. Occurrence of permeable dolostone higher in the stratigraphic section appears to be highly localized in some areas, causing large variations in the top of the zone (from one to several hundred feet) over relatively short distances (6 mi or less).

The thickness of the Avon Park permeable zone ranges from 0 to greater than 500 ft; it is generally greater than 200 ft thick in west-central Florida, in the southwestern part of east-central Florida, and in the northern part of southeastern Florida. The aquifer reaches its maximum thickness in west-central Florida. It generally thins to 100 ft thick or less in southwestern Florida area and is absent in the southern part of this area (most of Collier and Monroe Counties). The aquifer also appears to pinch out, or merge with the Upper Floridan aquifer, to the east in places along the east coastline. Transmissivity of the Avon Park permeable zone is generally an order of magnitude higher than transmissivity in the Upper Floridan aquifer, and ranges from less than 100,000 to greater than 1,000,000 ft^2/d. A large area in southern Florida, where limestone is the predominant lithology in the zone, tends to coincide with an area where transmissivity is less than 100,000 ft^2/d. Development of dolomite as a major component in the zone to the north of this area appears to be related to structure, as indicated by the altitude of the MAP marker horizon.

Hydraulic connectivity in the Avon Park permeable zone as mapped is more uncertain between some wells than others because of the rapid change in stratigraphic position of the top of the aquifer from one to several hundred feet. Hydraulic connectivity between two wells that exhibit a stratigraphic offset in the position of the aquifer could exist if the zone of dolomitization or permeable limestone containing the aquifer is connected vertically throughout by a network of open fractures or karst features, and the vertical shift in this zone is

continuous between the wells. Vertical hydraulic connectivity within the Avon Park permeable zone is also uncertain in some areas, particularly where the aquifer is thick and consists of several flow zones.

The uppermost permeable zone or subaquifer of the Lower Floridan aquifer (LF1) occurs in the lower part of the Avon Park Formation and is defined herein as the first major permeable zone below the MAP marker horizon. Similar to the Avon Park permeable zone, the LF1 occurs primarily in fractured dolostone units. The thickness of LF1 ranges from 0 to greater than 400 ft and, similar to the Avon Park permeable zone, it appears to pinch out coastward in some areas. LF1 and the entire Lower Floridan aquifer are absent in some coastal areas of west-central Florida due to the occlusion of pore space by intergranular evaporites.

Confinement above and below LF1 is variable. In some areas, confinement between the Avon Park permeable zone and LF1 by MC2 may be poor because of thinning of the MC2 (as little as 100 ft) and the unknown extent of vertical fracturing that may be present in MC2. Confinement provided by the lower part of MC2 and the confining unit below LF1 is very good in western areas of east-central and west-central Florida because of pore-filling anhydrite and gypsum. Good confinement in MC2 and the unit below LF1 may also be provided by dense unfractured dolostone in some areas. Hydraulic connectivity of LF1 between wells in some areas is uncertain; LF1 appears to develop in different parts of the stratigraphic section in some areas, particularly in coastal areas.

The Boulder Zone is a thick highly permeable zone in the lower part of the Lower Floridan aquifer. It consists mostly of dolostone, can be as thick as 700 ft, and permeability in this zone ranges from fractured to cavernous, with open fracture networks probably providing most of the permeability. Although previous studies indicate the Boulder Zone is not necessarily developed at the same stratigraphic position, in this study the top of this zone typically was found to occur at a similar stratigraphic position in the Oldsmar Formation, one to several hundred feet below the GLAUC marker horizon. In southern Florida, this zone is the primary target for underground injection of treated wastewater, but along the west coast the wastewater injection zone varies considerably within the stratigraphic and hydrogeologic section. In west-central Florida north of southern Charlotte County the Boulder Zone is not present, and the wastewater injection zone includes the Avon Park permeable zone and, in some cases, a moderately permeable zone that extends up into the lower part of the Ocala Limestone. In these coastal wastewater injection areas of west-central Florida, the Avon Park permeable zone is below the saltwater-freshwater interface.

This report provides an improved understanding of the hydrogeologic linkage within the Floridan aquifer system between central and southern Florida and between west and east coastal areas; however, the hydraulic connectivity of the aquifers and permeable zones mapped, particularly those below the Upper Floridan aquifer, remains uncertain in some areas. The degree of confinement provided by confining units mapped between these permeable zones in some areas is also uncertain. Additional data and studies are needed to confirm connectivity, including collection of hydraulic head, hydrogeochemical, and water temperature data and their three-dimensional mapping and interpretation.

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