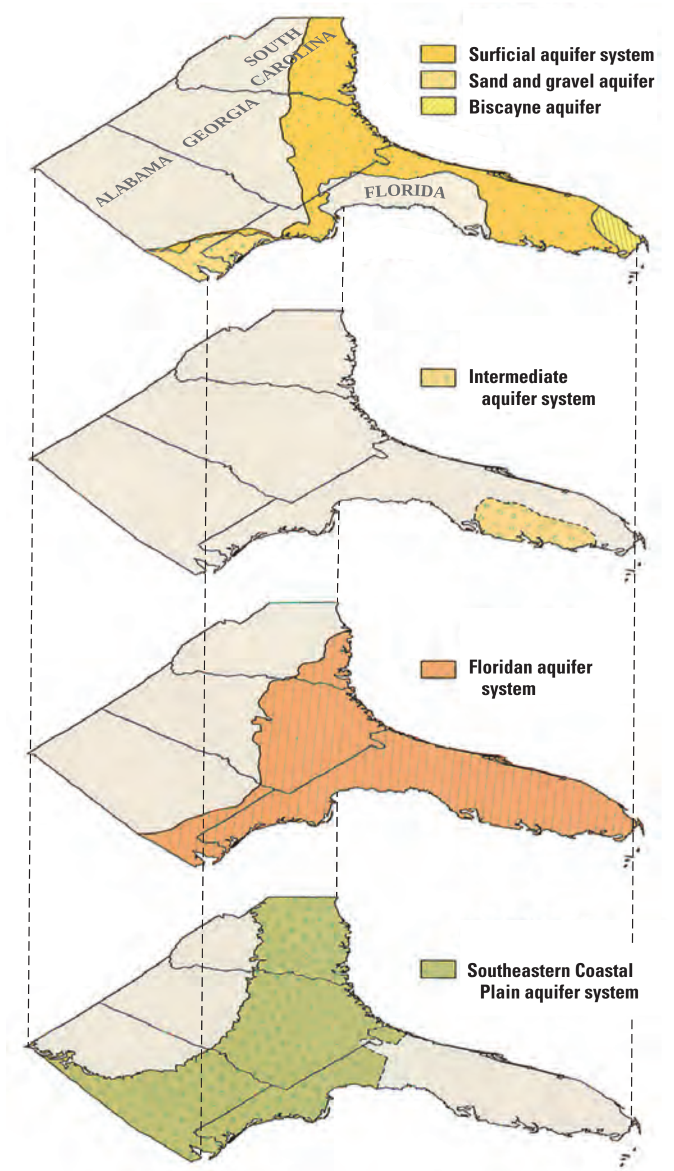
Groundwater Resources Program

Revised Hydrogeologic Framework of the Floridan Aquifer System in Florida and Parts of Georgia, Alabama, and South Carolina



Professional Paper 1807

Version 1.1

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

Cover. Photographs: top, center-pivot irrigation (Jeff Vanuga, United States Department of Agriculture, Natural Resources Conservation Service; middle, Yates Springs, Decatur County, Georgia (Alan M. Cressler, USGS); bottom, Arch Cave, Jackson County, Florida (Alan M. Cressler, USGS). Sequence of maps: shows the extent of each aquifer or aquifer system. Comparison of the maps shows the places where aquifers are stacked upon each other (Miller, 1990).

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By Lester J. Williams and Eve L. Kuniansky

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Contents

Plates (available at http://pubs.usgs.gov/pp/1807/)

Figures

Tables

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Ggal/d)	43.81	cubic meter per second (m^3/s)
	Discharge	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above 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.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

APPZ	Avon Park permeable zone
ASCII	American Standard Code for Information Interchange
ATV	acoustic televiewer
BCCU	Bucatunna clay confining unit
FGS	Florida Geological Survey
LAPPZ	lower Avon Park permeable zone
LISAPCU	Lisbon-Avon Park composite unit
MAPCU	middle Avon Park composite unit
MCUI–VIII	middle confining units I–VIII (of Miller, 1986)
NED	National Elevation Dataset
NMR	nuclear magnetic resonance
NWFWMD	Northwest Florida Water Management District
OCAPLPZ	Ocala-Avon Park lower permeability zone
RASA	Regional Aquifer System Analysis
SFWMD	South Florida Water Management District
SJRWMD	St. Johns River Water Management District
SRWMD	Suwannee River Water Management District
SWFWMD	Southwest Florida Water Management District
TDS	total dissolved solids
USGS	U.S. Geological Survey

Revised Hydrogeologic Framework of the Floridan Aquifer System in Florida and Parts of Georgia, Alabama, and South Carolina

By Lester J. Williams and Eve L. Kuniansky

Abstract

The hydrogeologic framework for the Floridan aquifer system has been revised throughout its extent in Florida and parts of Georgia, Alabama, and South Carolina. The updated framework generally conforms to the original framework established by the U.S. Geological Survey in the 1980s, except for adjustments made to the internal boundaries of the Upper and Lower Floridan aquifers and the individual higher and contrasting lower permeability zones within these aquifers. The previously numbered middle confining units (MCUI–VIII) and the naming convention for units and zones were substantially revised. The revised boundaries of the Floridan aquifer system were mapped by considering results from local studies and regional correlations of lithostratigraphic and hydrogeologic units or zones. Additional zones within the aquifers have been incorporated into the framework to allow finer delineation of permeability variations within the aquifer system. These additional zones can be used to progressively divide the system for assessing groundwater and surface-water interaction, saltwater intrusion, and offshore movement of groundwater at greater detail if necessary. The extent and altitude of the freshwater-saltwater interface in the aquifer system has been mapped to define the freshwater part of the flow system. The revised framework is a regional work product intended for regional-scale (greater than 10,000 square miles) and subregional (1,000 to 10,000 square miles) investigations, rather than site-scale (less than 1 square mile) investigations intended for regulatory purposes.

The Floridan aquifer system behaves as one aquifer over much of its extent; although the system is subdivided vertically into two aquifer units, the Upper and Lower Floridan aquifers. In the previous framework, discontinuous numbered middle confining units (MCUI–VII) were used to subdivide the system. Some of these individually numbered middle confining units overlapped each other vertically. Previously, where units overlapped the least permeable rock unit within the middle part of the system was used to subdivide the system. In areas where less-permeable rocks do not occur within the middle part of the system, the system was previously considered one aquifer and named the Upper Floridan aquifer. In intervening years, more detailed data have been collected in local areas, resulting in some of the same lithostratigraphic units in the Floridan aquifer system being assigned to the Upper or Lower Floridan aquifer in different parts of the State of Florida. Additionally, some of the numbered middle confining units are found to be semiconfining, very leaky, or have hydraulic properties within the same order of magnitude as the aquifers above, below, or both above and below. Although the term “confining unit” is not totally abandoned within the revised framework, a new term “composite unit” is introduced for lithostratigraphic units that cannot be defined as either a confining or aquifer unit over their entire extent. This naming convention is a departure from the previous framework of the late 1980s, in that stratigraphy is used to consistently subdivide the aquifer system into upper and lower aquifers across the State of Florida. This lithostratigraphic mapping approach does not change the concept of flow within the system. Areas of differing hydraulic properties of composite units are delineated to indicate where the Upper and Lower Floridan aquifers behave as one aquifer system. The revised framework uses stratigraphic names for the composite units within the middle part of the Floridan aquifer system rather than numbers. Additionally, distinctly different permeability zones are mapped within the Upper and Lower Floridan aquifers and stratigraphic names are used for those zones.

The surficial aquifer system overlies the Floridan aquifer system over about half of the study area but is only thick and productive in two areas; in southern Florida it is known as the Biscayne aquifer and in the westernmost panhandle of Florida it is named the sand and gravel aquifer. Elsewhere, the surficial aquifer system forms a thin irregular blanket of terrace and alluvial sands that can act as an important source-sink layer for temporary storage of groundwater that may

ultimately recharge the underlying Floridan aquifer system. An updated map showing the extent and thickness of the undifferentiated sediments that compose the surficial aquifer system was created as part of this study.

The boundaries (top and base) of the Floridan aquifer system were updated on the basis of data compiled from previous studies and from databases of the U.S. Geological Survey, Florida Geological Survey, and Florida's water management districts. The top of the uppermost vertically continuous carbonate rock section forms the upper surface (top) of the aquifer system. This upper surface is irregular, owing in part to karstification in the unconfined or thinly confined areas of the system. The base of the aquifer system was mapped and extended in depth and areal extent in the northern part of the study area to incorporate hydraulically connected coastal plain aquifers that are equivalent to the Lower Floridan aquifer. In peninsular Florida, the base was not revised substantially and is mapped at the top of a distinctive massive bedded anhydrite that is easily recognized in geophysical logs. A lower permeability unit located just above the massive anhydrite sequence was identified, however, and may locally form the base of the active groundwater flow system.

The lateral extent of the updip boundary of the Floridan aquifer system is modified from previous work based on newer data and inclusion of parts of the updip clastic facies. The carbonate and clastic facies form a gradational sequence, generally characterized by limestone of successively younger units that extend progressively farther updip. Because of the gradational nature of the carbonate-clastic sequence, some of the updip clastic aquifers have been included in the Floridan aquifer system, the Southeastern Coastal Plain aquifer system, or both. Thus, the revised updip limit includes some of these clastic facies. Additionally, the updip limit of the most productive part of the Floridan aquifer system was revised and indicates the approximate updip limit of the carbonate facies.

Within the Upper Floridan aquifer of central and southern Florida, a subregionally extensive, highly fractured and cavernous interval called the Avon Park permeable zone is mapped as an aggregate of several permeable zones in the upper part of the Avon Park Formation. The aggregate Avon Park permeable zone is overlain everywhere by a less-permeable carbonate zone named by others the "Ocala-Avon Park lower permeability zone" (a lower permeability zone within the Upper Floridan aquifer) and underlain by lower permeability confining to semiconfining evaporitic and non-evaporitic rocks of the newly mapped middle Avon Park composite unit (previously all or parts of MCUI–III and VI). The Ocala-Avon Park lower permeability zone is, in turn, overlain by the uppermost permeable carbonates of the Floridan aquifer system, including parts of the Suwannee and Ocala Limestones, and parts of the Hawthorn Group.

The MCUI–VII of the Floridan aquifer system in the current revision have been abandoned, remapped, or reassigned to one or both of the composite units or divided into one of the composite units and one of the aquifer zones. The composite units were delineated through the use of borehole geophysical logs and lithologic logs rather than relying on hydraulic testing or lithologic description alone. A composite unit is defined herein as a narrow lithostratigraphic interval within the middle part of the Floridan aquifer system that is composed of lower permeability units over much of its extent, but can be confining, semiconfining, or have permeability within the same order of magnitude as the Upper or Lower Floridan aquifers. The Lisbon-Avon Park composite unit is present in the northern part of the system, extending into the northern peninsula of Florida. The middle Avon Park composite unit extends through central and southern Florida and the southeastern part of Georgia. The Lisbon-Avon Park composite unit is used to subdivide the system in Georgia, northern Florida, eastern Alabama and western South Carolina. The Bucatunna clay confining unit is present in the southern panhandle of Florida and southwestern Alabama and is used to subdivide the system in that area. The middle Avon Park composite unit subdivides the system in peninsular Florida. The Lisbon-Avon Park composite unit also contains the Claiborne, Gordon, and Lisbon confining units and upper part of MCUI and has aquifer properties in part of western peninsular Floridan (no previously mapped MCU). The middle Avon Park composite unit contains the lower part of MCUI, MCUII, MCUIII, and MCUVI and is confining in western peninsular Florida (MCUII) and leaky or semiconfining over most of its extent. The Bucatunna clay confining unit contains MCUV and is a low permeability confining unit. These three units are used in different parts of the study area to subdivide the Floridan aquifer system into the Upper and Lower Floridan aquifers.

A new basal permeable zone is mapped throughout the Florida peninsula and slightly into southeastern Georgia, within the Lower Floridan aquifer. The new basal zone incorporates the previously established Boulder Zone and Fernandina permeable zone into a more extensive unit called the Oldsmar permeable zone. The Oldsmar permeable zone appears to be fairly transmissive far beyond the cavernous areas of the previously mapped Boulder and Fernandina permeable zones and contains freshwater in central peninsular Florida. This extensive basal unit may influence the movement of freshwater through the deepest part of the aquifer system toward diffuse discharge areas near the coast. The zone is of interest because it may be an important alternate source of water where it is confined (and isolated) beneath the Upper Floridan aquifer and may be important to the offshore movement of previously unmapped fresh groundwater.

The Oldsmar permeable zone is overlain by another new unit introduced herein as the glauconite marker unit, which derives its name from a gamma-ray marker that was first used in southeastern Florida to map a glauconitic, fine-grained low-permeability unit above the Boulder Zone. The gamma-ray marker was found to be subregionally extensive, and when coupled with a low-resistivity response, it forms a distinct mappable horizon within the Lower Floridan aquifer. The glauconite marker unit typically is considered to be a semiconfining unit but may locally contain zones of high permeability.

The regional extent and altitude of the freshwater-saltwater interface was mapped using geophysical logs, water-quality data from deep wells, and selected time-domain electromagnetic soundings. The interface is represented by the approximate location of the 10,000-milligrams-per-liter total-dissolved-solids concentration boundary that separates mostly fresh and brackish water from underlying saline water. Because the new map is based on well-log data rather than a calculated interface using a theoretical density contrast, geologically controlled salinity variations can be portrayed within the aquifer. Additional salinity calculations from geophysical logs were used to create salinity profiles across the thick sequence of carbonate rocks that compose the aquifer system. Many of the profiles indicate zones of fresher water may be present beneath more saline water, along the deep transmissive part of the aquifer system.

Two subregional salinity features are identified from the salinity mapping. The first is informally named the “Apalachicola salinity feature” in the vicinity of a thick accumulation of fine-grained carbonate rocks in the Southwest Georgia embayment (also known as Apalachicola embayment). In that area, saltwater is contained in the lower part of the Floridan aquifer system and the effective thickness of the freshwater flow system is greatly reduced compared to that of previously published maps. The second feature is a previously unmapped disconnected zone of brackish to saline water that lies near the base of the aquifer system in the vicinity of the central part of the Georgia-Florida state line. Because of its shape and position, this disconnected zone is probably trapped connate water in fine-grained carbonate rocks near the base of the system isolated from higher permeability rocks above. High-salinity zones are indicated in other parts of the aquifer system, such as near Brunswick, Georgia, and Fernandina Beach, Florida, or associated with previously mapped low-permeability units.

The hydraulic properties of the hydrogeologic or lithostratigraphic units established for the Floridan aquifer system were compiled from aquifer testing at individual well sites, packer testing along discrete intervals of open borehole, and from laboratory analysis of core samples. These data indicate a high degree of variability reflective of local changes in lithology and development of secondary porosity from dissolution of the carbonate rocks of the aquifer system. Small-scale variations observed in nearly all of the hydrogeologic units or zones mapped in the Floridan make it difficult to establish subregional or local properties of these units, and thus such properties must be determined on a well-by-well basis. Additionally, post-depositional changes, such as collapse features, can affect vertical flow between any unit or zone.

Large-scale variations of regional permeability of the individual rock units that compose the Floridan aquifer system are the result of many different but closely related hydrogeologic factors, including (1) rock type and texture; (2) degree of relative confinement and proximity to recharge and circulation of freshwater through the rocks; (3) presence of structures such as joints, fractures, and weaknesses along bedding planes along which dissolution and collapse features occur, and (4) post-depositional diagenesis, which can greatly increase or decrease rock permeability through dissolution or dolomitization. Collectively, these factors indicate that local variation in permeability is extremely complex and depends partly on the texture of the limestone and its depositional environment and partly on the post-depositional history of the rock.

Introduction

In 2005, the U.S. Geological Survey (USGS) Groundwater Resources Program initiated studies to assess groundwater availability of the Nation’s principal aquifers. The Floridan aquifer system was the sixth such study, starting in the fall of 2009. Although the objective of these regional studies varies (http://water.usgs.gov/ogw/gwrp/activities/regional.html), each has the overall goal of providing information about the current status of groundwater resources in principal aquifers and developing tools and datasets to assist State, county, municipal, and special districts formed for water-resources management in making long-term decisions (years to decades) about groundwater management (Reilly and others, 2008). A major focus at the beginning of each study was to update the hydrogeologic framework and conceptual model, upon which regional groundwater-flow simulations and water availability assessments are based.

The Floridan aquifer system is complex, consisting mostly of permeable Tertiary carbonate rocks and some equivalent clastic units in the updip areas of Alabama, Georgia, and South Carolina. In Georgia and Florida, the aquifer system is the principal source of freshwater for agricultural irrigation, industrial, mining, commercial, and public supply (Maupin and Barber, 2005; Miller, 1986). The Floridan aquifer system also locally yields abundant water supplies in southeastern Alabama and South Carolina. Together in all four States, the aquifer system covers approximately 100,000 square miles (mi^2). The approximate extent of the aquifer system is shown in figure 1. The system dips steeply into southeastern Mississippi and contains poor quality water; thus, it is not utilized for water supply in Mississippi and not mapped by Miller (1986) or herein. However, this extent includes some of the updip clastic facies that have been included in either the Southeastern Coastal Plain aquifer system, Floridan aquifer system, or both. Additionally, the updip limit of the most productive part of the Floridan aquifer system was revised and indicates the approximate updip limit of the carbonate facies (former extent of Miller, 1986). The system includes Miocene to Paleocene rocks that combine to form a vertically continuous sequence of mostly carbonate rocks that are interconnected to varying degrees vertically and horizontally within the system (Miller, 1986). In this revision, some upper Cretaceous rocks where permeable and hydraulically connected to Paleocene rocks are part of the system.

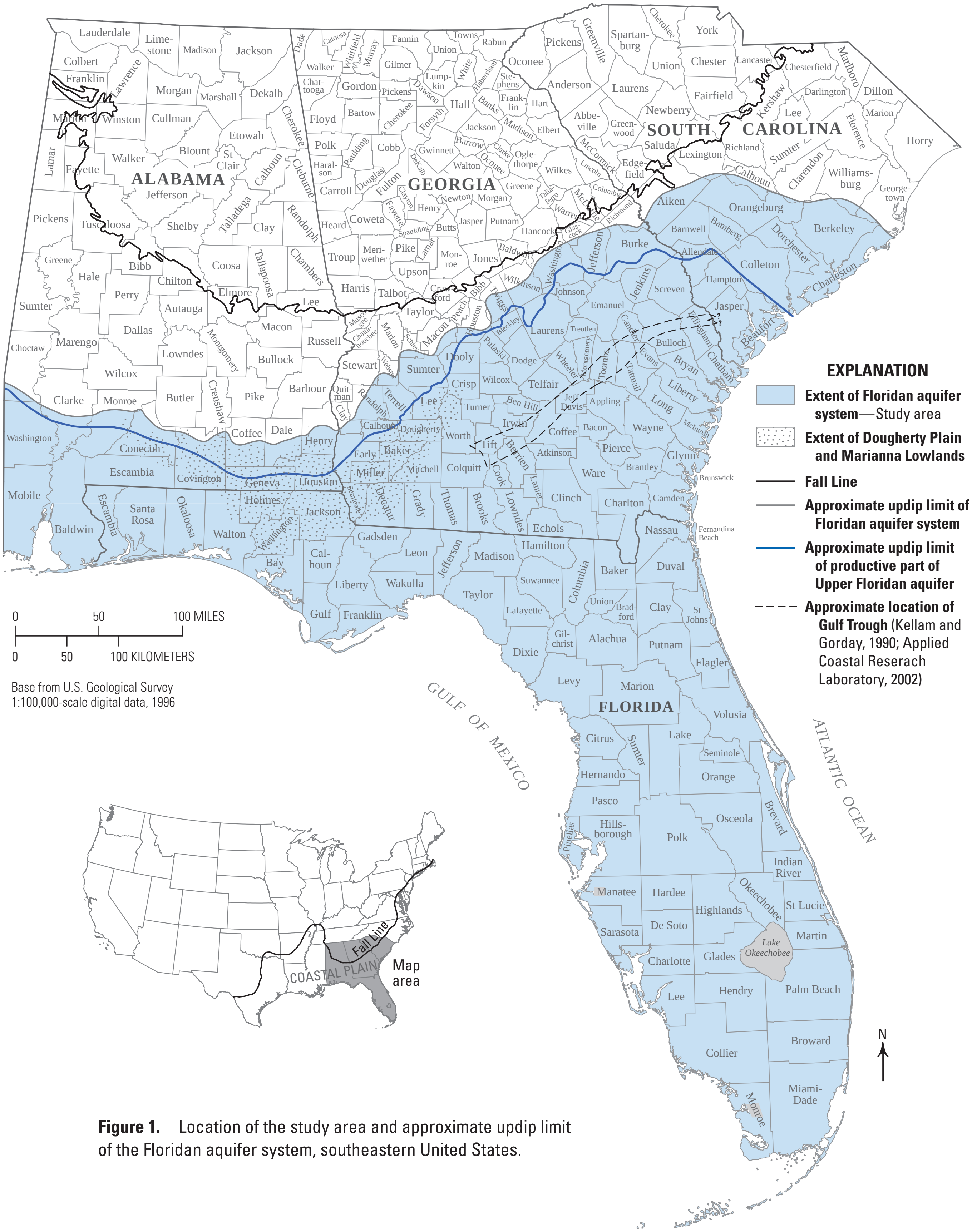


Figure 1. Location of the study area and approximate updip limit of the Floridan aquifer system, southeastern United States.

Purpose and Scope

This report describes a revised hydrogeologic framework of the Floridan aquifer system for Florida, and parts of Georgia, Alabama, and South Carolina. The revised framework is considered regional in scope and its intended use is for investigations covering over 10,000 mi^2. Caution should be exercised in using the revised regional framework for site-scale investigations related to regulatory water-management and water-quality issues. For site-scale investigations, local water-resource, geologic, and other data and associated information should be obtained to supplement the information contained in this report.

Within the revised framework, the altitude, thickness, and extent of the aquifers, confining units, and composite units that compose the system are defined and variations in permeability are described. The framework primarily is based on subsurface mapping and correlations of hydrogeologic or lithostratigraphic units derived from geophysical logs obtained from 958 wells and supplemented with information from an additional 3,300 wells regarding the thickness of the undifferentiated surficial deposits and upper confining unit as well as the depth to the top of the Floridan aquifer system.

Discussions of stratigraphy primarily concentrate on those rock units that are part of the Floridan aquifer system, its updip permeable clastic equivalents, and the upper and lower confining units of the system. The abbreviated discussions of stratigraphy in this report are, in part, condensed from Miller (1986) and Renken (1996).

This report builds upon and updates the hydrogeologic framework of Miller (1986) to

1. define the major and minor hydrogeologic or lithostratigraphic units and zones that compose the regional Floridan aquifer system, including descriptions of new units and zones established within the aquifer system and the revised nomenclature for these units and zones;

2. describe the influence of rock type, geologic structure, and position of permeable strata with respect to the movement of groundwater through the aquifer system;

3. delineate the approximate freshwater-saltwater interface as determined from well logs and represented by the altitude of water containing greater than 10,000 milligrams per liter (mg/L) total dissolved solids (TDS) concentration; and

4. describe variations in regional permeability of the aquifer system on the basis of rock type, aquifer performance test results, salinity variation, and water-level responses to stresses for incorporation into regional groundwater flow simulations.

This revision of the hydrogeologic framework includes (1) hydrogeologic data for selected well sites in the study area; (2) maps depicting the top, base, and thickness of the Floridan aquifer system and its two regional aquifers; (3) maps depicting the altitude and extent of subregional confining, semiconfining, and composite units and zones within the system; (4) a description of the freshwater-saltwater interface that defines the boundary of the freshwater flow system and internal flow boundaries; (5) hydrogeologic cross sections showing the relation among various units and zones; (6) tables and graphs summarizing hydraulic properties of aquifers, composite units, and confining units and zones; and (7) discussions of regional aquifer permeability and aquifer interconnection.

Previous Studies

Numerous geologic and hydrogeologic studies of water resources pertaining to the Floridan aquifer system have been published by the USGS, State Geologic Surveys, and by Florida's five water management districts. In addition, hundreds of well drilling and aquifer test reports have been completed throughout the region.

Reports describing the regional surface and subsurface geology include Applin and Applin (1967), Arthur and others (2008), Chen (1965), Clarke and others (1990), Cooke (1943, 1945), Herrick (1961), Herrick and Vorhis (1963), Miller (1986), Puri (1957), Scott (1988, 1990), and Scott and others (2001). Geologic maps and outcrop data used in this report were obtained from Dickson and others (2005), Geological Survey of Alabama (2006), Georgia Geologic Survey (1976), and Scott and others (2001).

Reports concerning the regional hydrogeology of the Floridan aquifer system include early works by Stringfield (1936, 1966) and Warren (1944) and a subsequent series of reports published as part of the USGS Regional Aquifer System Analysis (RASA) Program (Jen Sun and others, 1997). The RASA program reports focused on subregional areas, including coastal Georgia (Krause and Randolph, 1989), southwestern Georgia and parts of the Florida panhandle (Maslia and Hayes, 1988), west-central Florida (Ryder, 1985), and east-central Florida (Tibbals, 1990). Meyer (1989) and Hutchinson (1992) also described aspects of the deeper flow system in southern Florida. Although published later, preliminary results of these subregional investigations were synthesized into a description of the regional hydrogeologic framework by Miller (1986) and a description of the regional groundwater hydraulics and flow simulation by Bush and Johnston (1988). Recently, Kuniansky and Bellino (2012) tabulated aquifer tests for the entire Floridan aquifer system, and Kuniansky and others (2012) provided an updated transmissivity map of the Upper Floridan aquifer (as defined by Miller, 1986).

Other notable reports covering subregional areas of the Floridan aquifer system include a synthesis of hydrogeologic data for southern Florida (Reese and Richardson, 2008) and an extensive report on the hydrogeology in west-central and southwestern Florida in the Southwest Florida Water Management District (SWFWMD) (Arthur and others, 2008). Clarke and others (1990), Falls and others (2005a), and Williams and Gill (2010) describe the geology and hydrogeology in the coastal region of Georgia; Aadland and others (1995) and Gellici and Lautier (2010) describe the hydrogeology in the contiguous coastal areas of South Carolina.

In southwestern and south-central Georgia, Torak and others (1996), Torak and Painter (2006), and Torak and others (2010) describe the hydrogeology in those areas. Gillett and others (2004) and Gillett and others (2000) describe the hydrogeology in southwestern and southeastern Alabama.

Reports describing updip clastic units that are stratigraphic and hydraulic equivalents to the Floridan aquifer system include those by Aucott (1996), Barker and Pernik (1994), Faye and Mayer (1997), and Renken (1996). Additionally, several reports of importance related to updip areas of the Floridan aquifer system include McFadden and Perriello (1983), which describes the Claiborne aquifer in southwestern Georgia, Brooks and others (1985), which describes the Gordon aquifer in eastern Georgia, and Gillett and others (2004), which describes the Lisbon aquifer in southeastern Alabama.

Methods of Investigation

The hydrogeologic framework of the Floridan aquifer system was updated by compiling and synthesizing hydrogeologic data from previous reports and from State and USGS data. The process included compiling and interpreting geophysical logs, lithologic data, hydraulic testing data, and water-quality data. No new wells were drilled, nor were specific data collected as part of this study; however, incorporation of ongoing drilling and testing data from State agencies was critical to updating the framework presented in this report.

Approach

Because the Floridan aquifer system largely is composed of a vertical sequence of carbonate rocks, the general approach involved using borehole geophysical logs and flowmeter data to define parts of the aquifer system that transmit most of the water within the main body of the aquifer system and those parts that restrict movement within the system. Extending the relatively permeable and less permeable zones was done using geophysical log patterns to identify characteristic rock sequences whose physical properties relate to permeability. Once a geophysical log pattern was established as representative of a permeability zone, this property was considered to remain consistent within the geographic area.

In any given area, a major objective was to first determine the presence of zones of enhanced permeability, usually supported by one or more flowmeter logs or other ancillary data (such as large changes in hydraulic head or discharge from a well) and, secondly, to relate the geophysical log pattern to those zones. For example, in the northern coastal regions of Georgia and South Carolina, the original flowmeter data from McCollum and Counts (1964) were obtained from USGS files and reanalyzed and combined with the resistivity and gamma-ray logs from the same or nearby wells. Once all of the geophysical log data were compiled, flow zones were plotted onto working cross sections and then onto more detailed stratigraphic cross sections to evaluate the position of flow zones with respect to stratigraphic units. Although this approach is similar to that used by Miller (1986), as well as many other workers, the process of correlating geophysical log response to general aquifer permeability characteristics is difficult and not without potential flaws.

The upscaling and grouping of local flow zones into the major aquifers or subregional “zones” was an important second step used in mapping the regional flow system and developing a manageable representation (or layering) for a regional groundwater flow simulation. The basic abstraction used for the aquifer system is essentially the same as described by Miller (1986), with permeable zones grouped into two main aquifers, namely the Upper and Lower Floridan aquifers. Because of the greater thickness of both aquifers in central and southern Florida, however, additional zonation was established to better define variations in permeability in the two regional aquifers in those areas.

The grouping of local flow zones, and likewise the establishment of less-permeable zones within the main body of the Floridan aquifer system, can be somewhat subjective depending on the quality of the well-log data, the vertical separation between flow zones, and the lateral continuity of the zones. If zones are closely spaced, judgment must be exercised to determine whether to include or exclude permeable zones from one aquifer or another. A local permeable zone that is not present elsewhere may be included within an otherwise lower permeability confining or composite unit or zone in some cases. This leads to inconsistencies in aquifer subdivision depending on how zones are grouped by different workers. Therefore, in this report, the individual flow zones defined herein may not necessarily match a local zone or aquifer designation in previously published reports. For example, many of the flow zones originally mapped as part of the Lower Floridan aquifer in southern Florida are now grouped into the Avon Park permeable zone or the middle Avon Park composite unit (Reese and Richardson, 2008). Similarly, some of the permeable zones tapped by deep injection wells in southern Florida that are part of the Boulder Zone can now be differentiated into distinct flow zones within the Lower Floridan aquifer for local studies but are part of the Oldsmar permeable zone in this study.

Vertical hydraulic head differences within well clusters also were used to assess the relative leakiness of confining and semiconfining units; over 1,100 wells at 350 well cluster sites were used in the analysis (pl. 1). Most of the sites used in this analysis are located in central and southern Florida where the St. Johns River Water Management District (SJRWMD) and South Florida Water Management District (SFWMD) have installed a number of well clusters, each comprising a group of wells tapping individual hydrogeologic zones of interest. In other areas, periodic water levels measured at wells in close proximity to each other were used to gain insight into the general hydraulic head differences across confining and semiconfining units.

Sources of Data and Key Well Locations

The locations of key wells used for constructing the various maps and cross sections are shown on plate 1. Initially, available files from approximately 600 wells that were the basis for the original hydrogeologic framework by Miller (1986) were compiled and used to evaluate geophysical log and lithologic log characteristics of permeability zones in the Floridan aquifer system. Copies of well logs and geophysical logs annotated with correlation information were scanned into .tiff images to make them easier to overlay onto cross sections and for comparison with newer logs. In addition, the structural surfaces developed from the original framework of Miller (1986) were digitized and put into raster surfaces (Bellino, 2011) to allow direct comparison with newer reports and well logs compiled as part of this study.

In addition to the data compiled from Miller (1986), borehole geophysical logs and lithologic data were obtained from several additional sources, including the SFWMD database (DBHYDRO), SJRWMD database, SWFWMD database, files from USGS offices in Florida and Georgia, and files from the Florida Geological Survey (FGS), Geologic Survey of Alabama, and Georgia Environmental Protection Division. Paper copies of these logs were scanned, or if available, digital log data were obtained and placed into the study database. In some areas of the Floridan aquifer system, the density of well-log data far exceeded the needs of the present study, particularly in oil-producing areas such as Escambia and Santa Rosa Counties, Fla.

Not all of the original files used to develop the original framework of Miller (1986) could be located, making it difficult to evaluate hydrogeologic boundaries in certain areas. In such cases, data from either newer wells or nearby existing oil and gas test wells were obtained and used for regional correlation. In areas where previously used logs were of limited depth or poor quality, deeper higher quality well logs were obtained.

Lower permeability areas of the Upper Floridan aquifer in the vicinity of the Gulf Trough were mapped during this study using drilling records from the Georgia Environmental Protection Division's Agricultural Permitting Unit (Edward Rooks, written commun., 2010) and from records of the USGS. Few, if any, large-capacity (greater than 100 gallon per minute [gal/min]) wells that tap the Upper Floridan aquifer have been successfully completed in the Gulf Trough. Within these areas, the presence of either lower yield shallow wells tapping overlying units, usually sandy beds in the Hawthorn Group, or much deeper wells tapping the underlying Claiborne aquifer or equivalent clastic aquifers, also were used as an indication of low permeability in the Upper Floridan aquifer.

Hydrogeologic Cross Sections

A series of hydrogeologic cross sections were constructed to depict the major and minor units of the Floridan aquifer system; locations of the cross-section lines are shown on plate 1 and in figure 2. In the northern half of the study area, cross sections *A–A′* through *F–F′* were constructed to show the updip part of the aquifer system and generally are oriented parallel to the structural dip toward the Atlantic Ocean or Gulf of Mexico. Section *G–G′* extends from southeastern South Carolina to northeastern Florida along the coastal areas of the Atlantic Ocean. Sections *H–H′* and *I–I′* generally are oriented perpendicular to the major structural features of the system in the central Florida panhandle, southern Georgia, and northern Florida. In the southern half of the study area, cross sections *J–J′* through *M–M′* are oriented north-to-south and show the relationship of the hydrogeologic units generally parallel to the dip extending into southern Florida and then into a relatively flat-lying area in south-central and southeastern Florida. Sections *N–N′* through *Q–Q′* are oriented west-to-east across the peninsula and show the relationships of the hydrogeologic units along geologic strike and across major structural features. No dip-oriented cross sections are included in this report for the northern coastal region of Georgia and South Carolina, and the reader is therefore referred to previously published cross sections in those areas (Gellici and Lautier, 2010; Williams and Gill, 2010).

Stratigraphic Data

Most of the stratigraphic data shown in the cross sections and described in this report are derived from the work of Miller (1986) and Renken (1996), which are the primary sources of regional-scale information about Tertiary and younger deposits. In addition, digital datasets for the Floridan aquifer system (Bellino, 2011) and Southeastern Coastal Plain aquifer system (Cannon and others, 2012) were used extensively in this study.

Salinity Mapping

To simulate groundwater flow and the movement of the freshwater-saltwater interface, the approximate depth and extent of brackish and saline water was mapped in the aquifer system. The mapping primarily involved estimating variations in TDS concentration using borehole geophysical logs supplemented with (1) water samples collected from deep test wells, (2) water samples collected from packer tests, or (3) water samples collected from the reverse-air discharge during the drilling of test holes. In addition, data from selected time-domain electromagnetic soundings were used in some areas to refine the position of salinity boundaries (Patrick Burger, St. Johns River Water Management District, written commun., 2013). Reese (2000) calculated log-derived TDS concentrations using deep induction and either density or sonic porosity logs in southwestern Florida. Sources of error in calculating TDS concentrations from well logs included the selection of representative porosity values and a cementation exponent for the intervals being analyzed, and possible errors associated with large-diameter boreholes common in

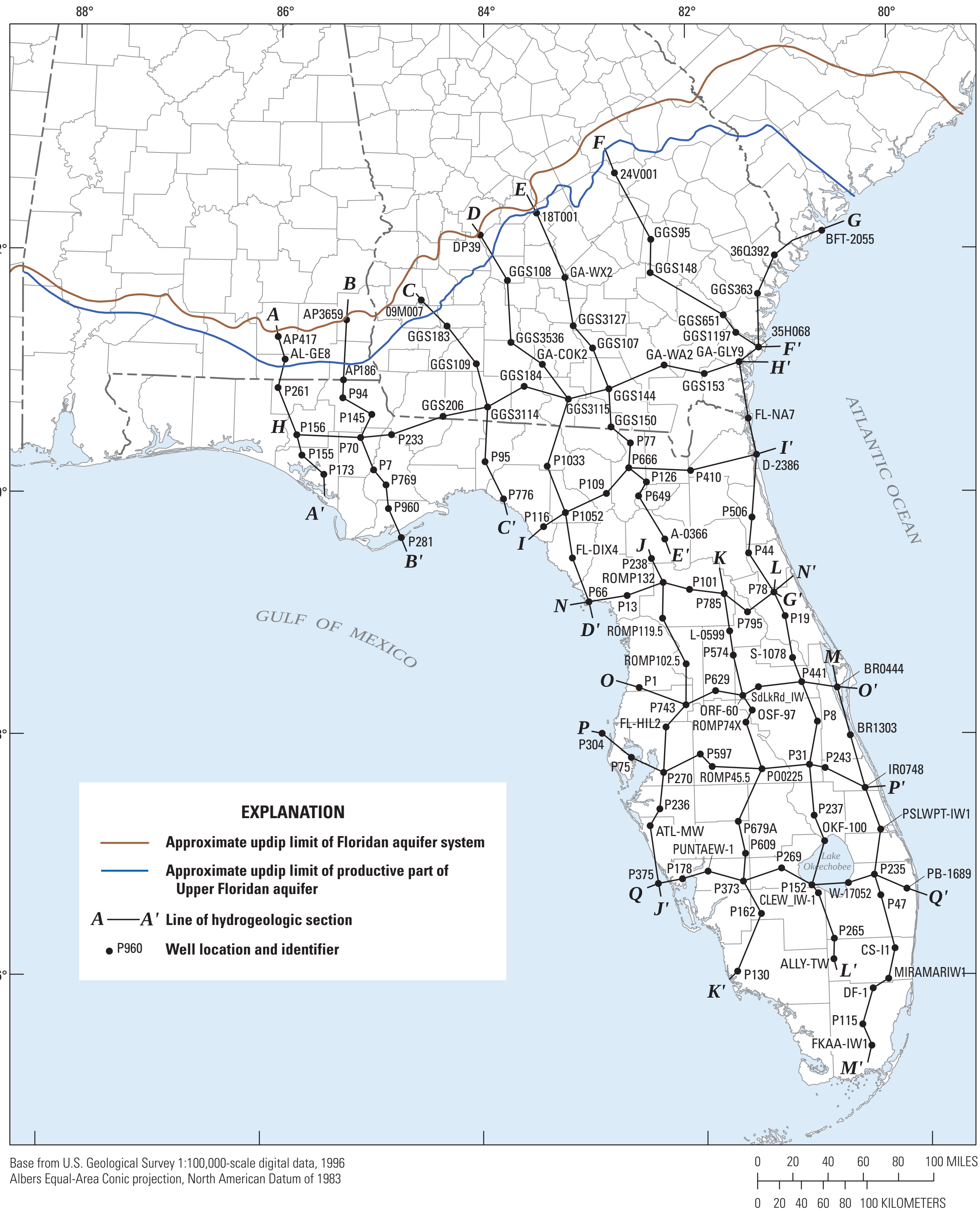


Figure 2. Locations of hydrogeologic cross-section lines and selected wells in the Floridan aquifer system, southeastern United States.

the study area. Other studies in southeastern Florida produced similar results using similar methods (Reese, 1994; Reese and Memberg, 2000; and Reese, 2004).

Salinity variations are described in this report using a classification scheme modified from Reese (1994) and used in Reese (2000) and Reese and Memberg (2000). The scheme has five salinity zones and six salinity classes for describing salinity on the basis of estimated TDS concentration (table 1). However, only salinities greater than 10,000 mg/L TDS are mapped or shown in cross section.

Salinity mapping units include the freshwater, brackish-water, salinity-transition, saline-water, and brine-water zones (table 1). Of greatest interest to this study was the definition of the brackish-water zone between 1,000 and 10,000 mg/L TDS concentration, the salinity transition zone between 10,000 and 35,000 mg/L TDS concentration, and the saline-water zone between 35,000 and 100,000 mg/L TDS concentration. Because salinity increases rapidly through the salinity transition zone, usually across tens of feet to several hundred feet, as described by Reese (1994), the base of the brackish-water zone was used to approximate the boundary of the freshwater-saltwater interface. This approach differs slightly from that used to develop the freshwater-saltwater interface map of Sprinkle (1989) who used chloride data from widely spaced deep wells and approximated the remaining areas of the interface using the Hubbert (1940) formula and known (or estimated) predevelopment freshwater hydraulic heads. Sprinkle (1989) defined the base of freshwater to be the midpoint of the freshwater-saltwater transition zone or at a chloride concentration of 10,000 mg/L. Although salinity boundaries other than the base of the brackish-water zone were calculated from well logs used in this study, these other zones were not mapped because of the similar configuration of these zones on a regional scale. It should be noted that the base of the brackish-water zone may or may not approximate the freshwater-saltwater interface because of density equilibrium and it is assumed that the salinity boundaries have changed little during the last 40 to 60 years when the well-log and water-sample data used to develop the map were collected. This seems true for southern Florida (Reese, 2004), as well as the coastal areas of the Floridan aquifer system in Georgia (Peck and others, 2011), where little change in chloride concentrations have been reported over the past few decades.

Table 1. Salinity zones and classes used for describing salinity on the basis of estimated total dissolved solids concentration.

[mg/L, milligrams per liter; classification of water based on total dissolved solids modified from Reese (1994, 2000) and Reese and Memberg (2000)]

Salinity zone	Salinity class	Total dissolved solids concentration (mg/L)
Freshwater	Fresh	0–1,000
Brackish water	Slightly brackish	1,000–3,000
	Brackish	3,000–10,000
Salinity transition	Moderately saline	10,000–35,000
Saline water	Saline	35,000–100,000
Brine water	Brine	>100,000

Unique Well Identifiers

Wells used in constructing the revised hydrogeologic framework were designated with unique well identifiers that are used throughout this report. Previously assigned well identifiers of Miller (1986) were updated to the State permit number or local identifier wherever possible. In Florida, permitted oil and gas test wells were designated with a “P” followed by the associated permit number (P1, for example). In Georgia, permitted oil and gas logs were designated with “GGS” followed by the number assigned by the Georgia Geological Survey (GGS3114, for example). A few oil and gas test wells in Georgia that do not have an assigned GGS number were designated as “DP” followed by the Georgia Environmental Protection Division permit number. In Alabama, permitted oil and gas test wells were designated with “AP” followed by the permit number (AP1111, for example). Deep test wells drilled for water-related investigations were identified using previously assigned water management district or State geologic survey identifiers. The uniqueness of the identifiers across project databases was checked to prevent duplication of the well identifiers used in this study.

Digital Log Database

A database of borehole geophysical logs and other types of data files was compiled during this study and another ongoing study of brackish-water resources in the southeastern United States (Williams and others, 2013). The database contains logs from 1,244 wells in Florida, Georgia, Alabama, and South Carolina and a limited number of logs from offshore wells in the eastern Gulf of Mexico and the Atlantic Ocean. A primary site table in the database contains well location information and measuring point elevations (referenced to the Kelly bushing, drilling floor, or land surface elevation). This table is linked to a data folder that contains the individual .tiff images of the well logs, log ASCII (American Standard Code for Information Interchange) standard digital file data for individual curves, and other related documents for each well. The reader is referred to this source of data to access hand-annotated logs and other data upon which the revised Floridan hydrogeologic framework is based.

Digital Data Report

Digital data for structural surfaces and thickness maps presented in this report are provided in a separate downloadable digital data report (Williams and Dixon, 2015). The datasets contain extent polygons, contours, outcrop areas, and data tables with hydrogeologic point values. The term "hydrogeologic point values" refers to the altitude of the interpreted tops and bottoms of hydrogeologic or composite units upon which the structural surfaces and thickness maps are based. The tabulated hydrogeologic point values can be used to produce finer or coarser interpolated grids as needed. For the purpose of this report, all digital surfaces were developed by interpolating values from individual hydrogeologic points using the Australian National University Digital Elevation Model method (Hutchinson, 1988, 1989) within 1,000-meter grid cells. Thickness raster surfaces also were constructed using the same interpolation scheme and grid size.

Hydrogeologic Framework of the Floridan Aquifer System

The hydrogeology of the study area can be subdivided based on depositional environment. Coastal Plain deposits in this area are grouped into two principal facies: (1) predominantly warm, shallow marine, platform carbonate rocks that have been deposited in a thick continuous sequence beneath southeastern Georgia and the Florida peninsula; and (2) predominantly near-shore clastic rocks that have been deposited along the Coastal Plain extending from the Fall Line southward and eastward toward the Gulf of Mexico and the Atlantic Ocean (fig. 3). These two major facies are respectively divided into the mostly carbonate Floridan aquifer system and the underlying, mostly clastic Southeastern Coastal Plain aquifer system.

In Georgia and parts of northern Florida, the carbonate and clastic facies form a gradational sequence, generally characterized by limestone of successively younger units that extend progressively farther updip. Miocene and younger sediments of mostly clastic origin overlie the older carbonate rocks in most areas, except where the clastic sediments have been removed by erosion or were never deposited.

Because of the gradational nature of the carbonate-clastic sequence, some of the updip clastic aquifers have been included in either the Floridan aquifer system, the Southeastern Coastal Plain aquifer system (fig. 3), or both, as needed to portray major elements of the groundwater flow system (Barker and Pernik, 1994; Bush and Johnston, 1988; Campbell and Coes, 2010; Krause and Randolph, 1989; Maslia and Hayes, 1988; Payne and others, 2005). In southwestern and east-central Georgia, the Claiborne and Gordon aquifers that are part of the regional Pearl River aquifer of the Southeastern Coastal Plain aquifer system (Renken, 1996) grade laterally into the lower part of the Floridan aquifer system. In the part of the system farthest updip, it is difficult to distinguish the aquifers as separate units and they may behave as a single hydrogeologic unit. Farther downdip, deeper aquifers of the Southeastern Coastal Plain aquifer system become progressively more isolated from the Floridan aquifer system. A generalized correlation between stratigraphic units and the regional aquifer systems is shown in figure 4. This chart shows many of the formations that are mentioned in this report and how they are grouped into the major aquifer systems in the southeastern United States. A detailed correlation of units is provided on plate 2.

Nomenclature

Over time, as more test drilling and hydraulic testing have been completed, the number of hydraulically connected formations included in the Floridan aquifer system has increased (fig. 5). Early terms used to describe the aquifer system include the "principal artesian formations" of Stringfield (1936), "Floridan aquifer" of Parker and others (1955) and the "principal artesian aquifer" of Stringfield (1966). In each of these revisions, test drilling revealed that deeper carbonate formations were hydraulically connected to the main body of the system and, hence, the base was progressively moved downward to include these deeper rocks within part of the Cedar Keys Formation, where hydraulically connected. The top and base of the Floridan aquifer system, as used in the current revision, is essentially unchanged from Miller (1986).

The nomenclature in this report builds upon that of Miller (1986). During that study, it was shown that (1) regional aquifers included many formations and rock types, (2) aquifers could cross formational boundaries, and (3) no single formation was completely representative of the Floridan aquifer system across the region. Hence, the lateral extent and tops and bottoms of the aquifer system and its individual aquifers were based on the relative permeability of hydraulically connected rocks, regardless of their age or formation designation.

Although Miller (1986) showed that zones of distinctly different permeability in the Floridan aquifer system cross formational boundaries, for correlation purposes, hydrogeologists working on a local scale have tended to use stratigraphically associated terminology to describe permeability variations. Accordingly, as more data have been collected with respect to aquifer system properties, the Floridan aquifer system has been further subdivided into layers or zones. This more refined subdivision has resulted in some conflicts in the naming conventions of regional- and local-scale units and zones.

In Miller (1986), the Floridan aquifer system was subdivided into two aquifers, which is essentially the same hierarchy used herein. The current revision increases the

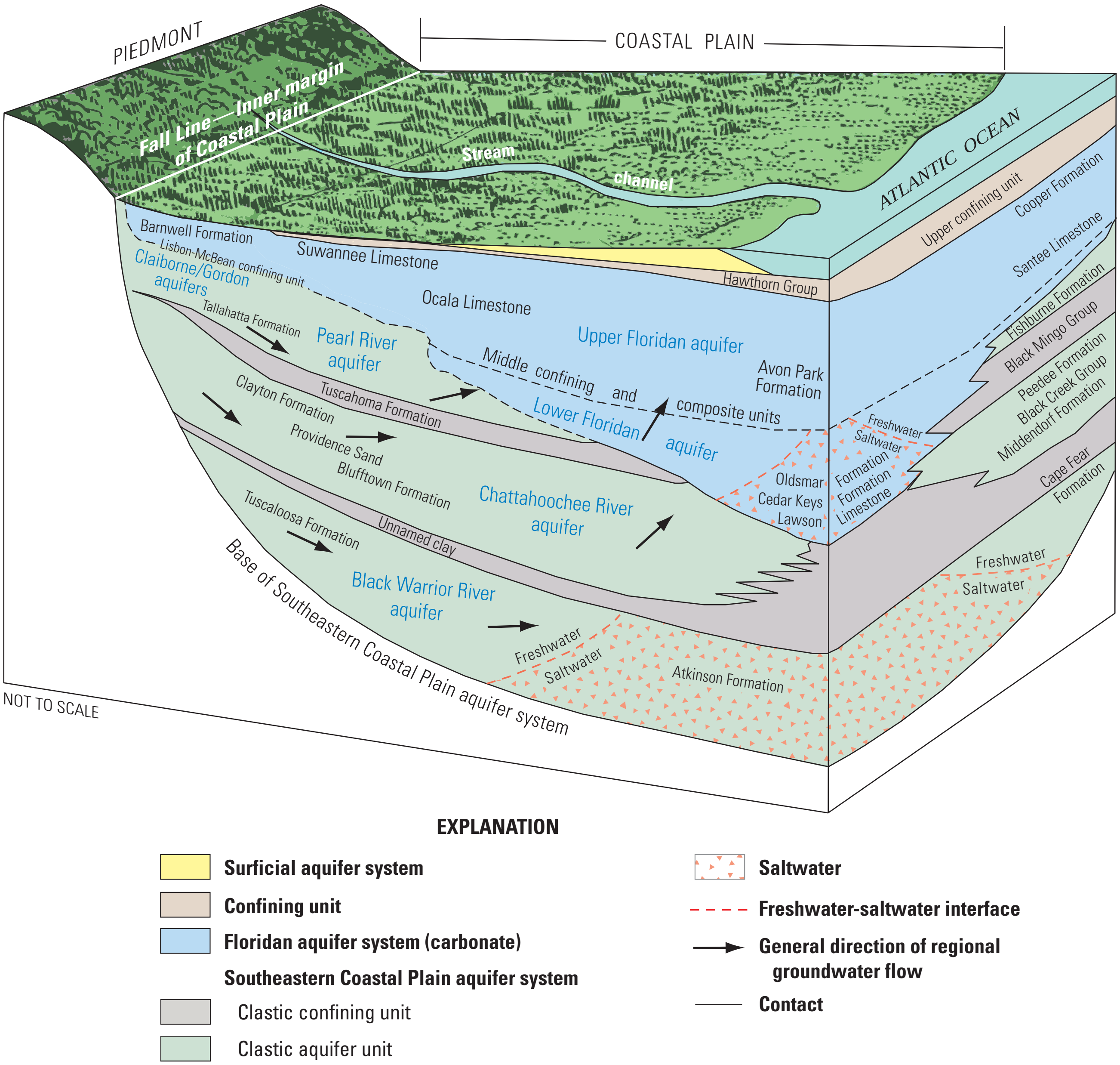


Figure 3. Generalized block diagram showing the hydrogeologic relation between the Floridan aquifer system and the Southeastern Coastal Plain aquifer system in east-central Georgia (modified from Barker and Pernick, 1996; Renken, 1996).

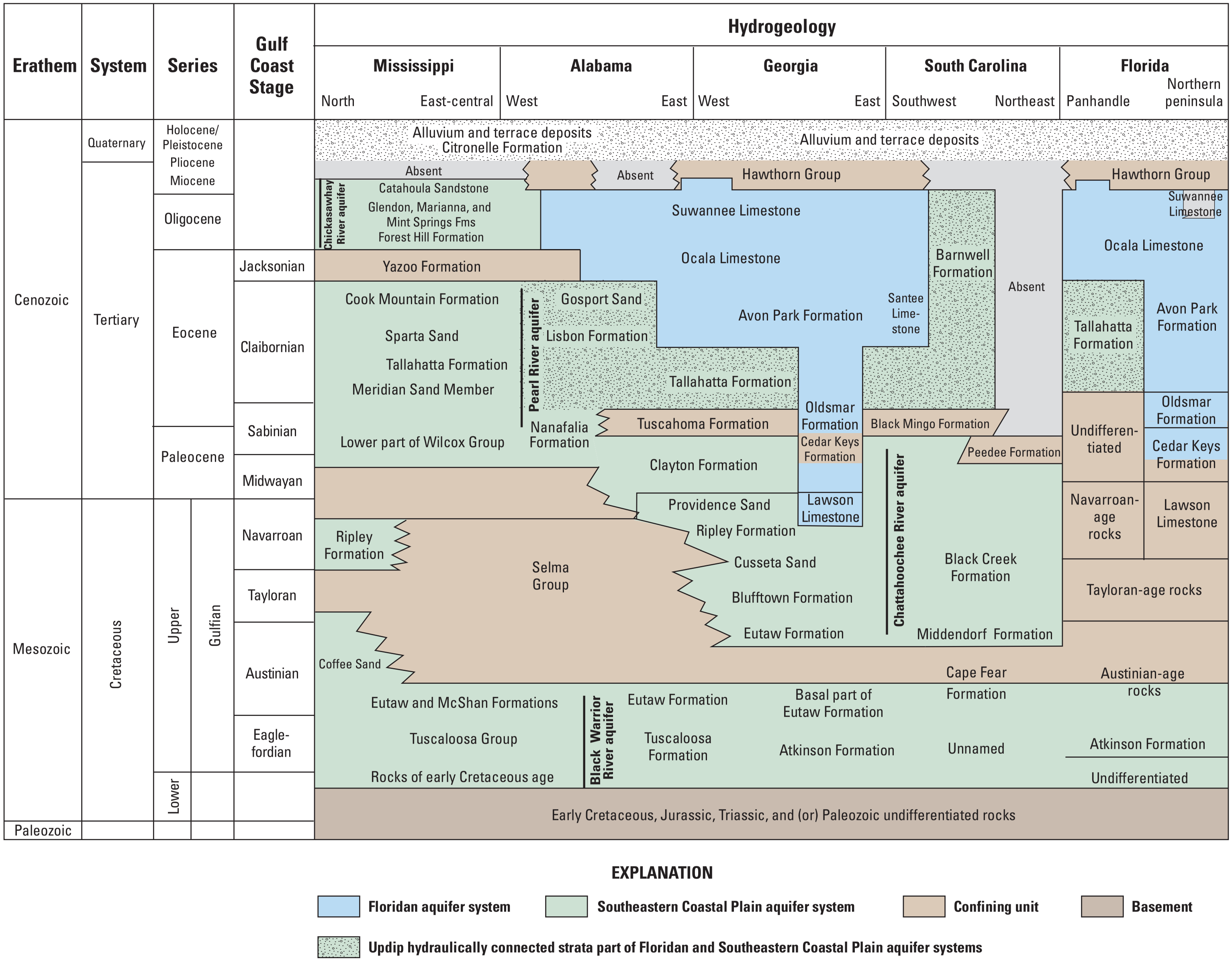


Figure 4. Generalized correlation chart showing stratigraphic units and hydrogeologic units of the Floridan and Southeastern Coastal Plain aquifer systems (modified from Renken, 1996).

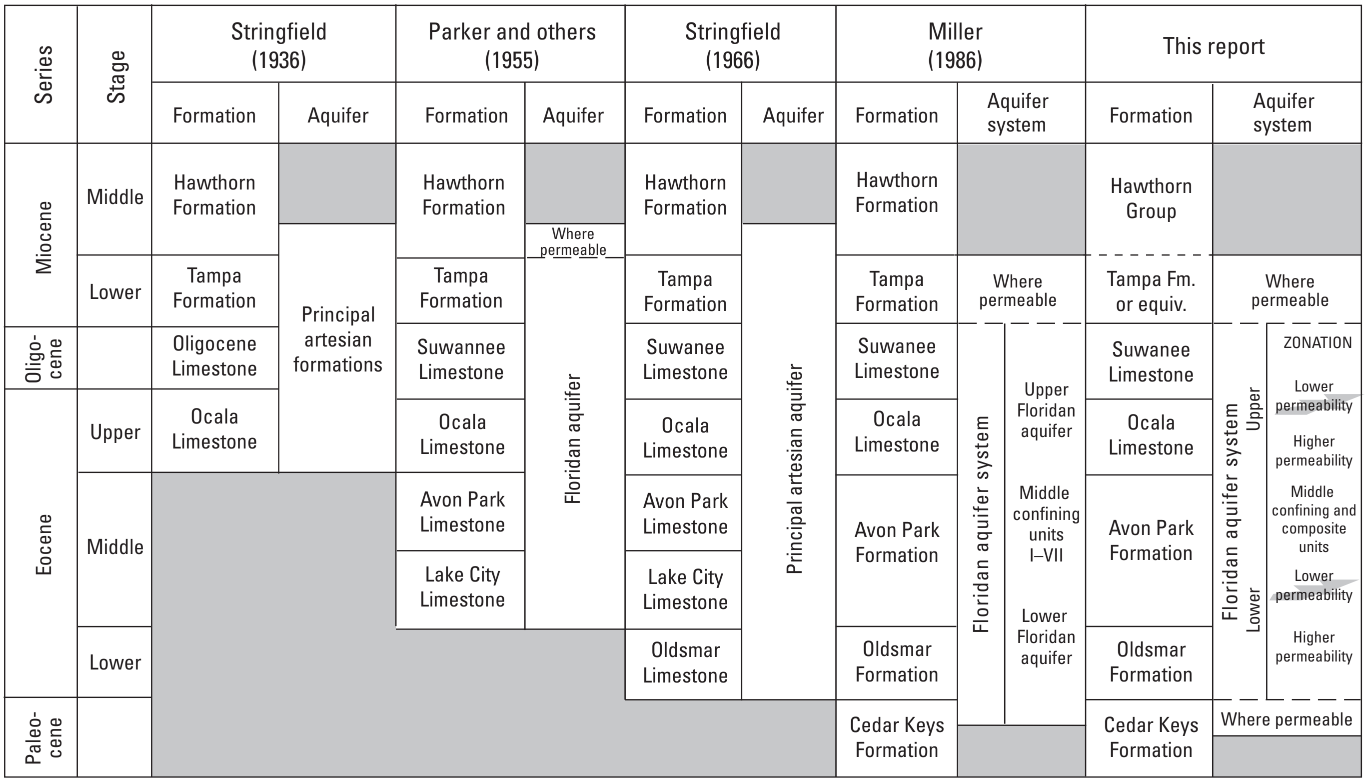


Figure 5. Comparison of hydrogeologic terminology used for the Floridan aquifer system in this study and previous studies (modified from Miller, 1986).

number of zones to delineate hydraulic conductivity characteristics of narrow stratigraphic intervals that have distinctly different hydraulic conductivity from the surrounding rocks within the Upper and Lower Floridan aquifers. For example, the Fernandina permeable zone (Miller, 1986) is a cavernous interval within the Lower Floridan aquifer that has much higher hydraulic conductivity than the surrounding rock. Similarly, some of the previously defined middle confining units could be considered zones having slightly or substantially lower hydraulic conductivity than the surrounding rock, thus restricting the movement of groundwater from the upper to the lower part of the aquifer system or even within a single aquifer.

To reduce the ambiguity in defining units and zones within the aquifer system, an attempt was made to group higher or lower permeability zones along narrower stratigraphic intervals. In a regional context, it may have been necessary to group one or more geologic formations to represent an important subregional or regional zone or unit within the Floridan aquifer system while attempting to stay within the narrowest stratigraphic interval possible.

Important considerations during revision of the framework include

- the mappability of units and zones, using the methods discussed earlier;
- the stratigraphic position and continuity of permeable and less-permeable zones in subregional areas and the logical grouping of these zones into broader units that can be represented regionally;
- the degree of hydraulic head separation between individual zones or aquifers as determined from well cluster sites, through packer testing or inferred from changes in water quality; and
- the use of geophysical log markers to further define the positions of aquifers, confining units, and zones within the aquifer system.

The use of zones has increased greatly over the past few decades. For example, Reese and Richardson (2008) identified and mapped a subregionally extensive permeable zone in southern Florida they called the Avon Park permeable zone (APPZ). Zones also have been used to describe permeability variations in both the Upper and Lower Floridan aquifers. In SWFWMD reports, variations in permeability have been extensively described as zones and linked to the formation(s) in which they occur. One of the more extensively mapped zones is a less-permeable zone within the Ocala Limestone. This zone separates more-permeable zones of the overlying Suwannee Limestone from extremely permeable cavernous zones of the underlying Avon Park Formation.

To address the addition of subregional zones to the Floridan aquifer system nomenclature, the usage of certain terms and names is clarified as follows:

- The **Floridan aquifer system** includes the vertically continuous carbonate-rock system described by Miller (1986) and is expanded to include hydraulically connected clastic aquifers in the updip part of the aquifer system, including the Gordon aquifer (Brooks and others, 1985), Claiborne aquifer (McFadden and Perriello, 1983), and Lisbon aquifer (Gillett and others, 2004). These clastic aquifers are considered part of the Lower Floridan aquifer in this report. However, the delineation of the updip extent of the carbonate rocks is provided in this report as the approximate updip limit of the productive part of the Upper Floridan aquifer.

- The Floridan aquifer system is divided into the **Upper and Lower Floridan aquifers** similar to those described by Miller (1986). However, the boundary between the two aquifers is redefined through grouping of permeable and less-permeable zones within a lithostratigraphic interval and, therefore, is no longer strictly based on the original eight subregional middle confining units (MCUI–MCUVIII) of Miller (1986).

- **Aquifers** (upper and lower) of the Floridan aquifer system can include one or several distinctly different permeability zones potentially dividing each of the regional aquifers into two or more distinct zones of subregional or local extent. In southwestern Florida, for example, the Suwannee permeable zone, Ocala lower permeability zone, and Avon Park permeable zone are subunits within the Upper Floridan aquifer. Similarly, the first and second permeable zones of the Lower Floridan aquifer and the Fernandina permeable zone are subunits within the Lower Floridan aquifer in northeastern Florida.

- The **middle confining units** of Miller (1986) were a series of numbered discontinuous lower permeability units in the approximate middle part of the aquifer system. These middle confining units (MCUI–VII) can consist of leaky, semiconfining, and confining sediments (decreasing order of vertical hydraulic conductivity). The numbered MCU nomenclature has been abandoned in this revision, although areas of the older MCUs are shown on maps as part of what is termed a composite unit.

- Generally less-permeable lithostratigraphic units are grouped into a **composite unit** for subdividing the system into the Upper and Lower Floridan aquifers. A composite unit consists mostly of less-permeable rocks positioned along a narrow stratigraphic horizon defined by geologic and geophysical log markers. A composite unit also can contain areas of higher permeability rock along the same stratigraphic horizon; these higher permeability areas may have similar hydraulic properties to the aquifers bounding the composite unit above and below. The composite unit facilitates consistent mapping of the Upper and Lower Floridan aquifer across the State of Florida based on stratigraphic interval position. The numbered MCUs (I–VIII) of Miller (1986) have been abandoned, remapped, or reassigned to one or both composite units or become part of a zone within the Upper or Lower Floridan aquifers, as described in the section “Revised Definition and Application of the Numbered Middle Confining Units.”

- **Zones** are defined on the basis of relative permeability, stratigraphic position, and geographic distribution. Each zone can lie entirely within a single geologic formation or include parts of two or more formations that are hydraulically distinct from aquifer materials above and below. For example, the Boulder Zone is a zone of cavernous permeability developed in rocks of the Oldsmar Formation in southern Florida. A zone is not used to depict local vertical increases or decreases in permeability (such as those associated with a fault or collapse feature). The terms “zone” and “unit” are somewhat analogous, with the main difference being that a zone has a distinctly different hydraulic property than the aquifer material above and below and is used to describe permeability variations within the aquifer. In addition, individual zones mapped within a geographic region do not crosscut laterally.

- A **higher permeability zone** has distinctively higher hydraulic conductivity than the surrounding aquifer material. Examples include the APPZ, Boulder Zone, Fernandina permeable zone, and Suwannee permeable zone. In thick geologic formations with distinct thin zones of permeability, qualifiers are used to denote the stratigraphic position of the zone; for example, the terms “upper Avon Park permeable zone” and “lower Avon Park permeable zone” could be used to differentiate permeable zones in different parts of the Avon Park Formation.

- A **lower permeability zone** has distinctively lower hydraulic conductivity than the surrounding aquifer material. Less-permeable zones may form local or subregional leaky zones within the main body of the aquifer system. Appropriate modifiers are used to describe the unit as leaky or very leaky where possible. Examples include part of middle confining unit MCUI of Miller (1986), middle confining unit MC1 of Reese and Richardson (2008), and the Ocala low-permeable zone of LaRoche (2007), which are all part of the Upper Floridan aquifer in this revised framework.

- **Local zones** mapped in different geographic regions can be grouped based on formation name. For example, the Boulder Zone (cavernous) of southern Florida is grouped with other permeable zones (non-cavernous) in the Oldsmar Formation to form a new zone named the “Oldsmar permeable zone,” described later in this report. Similarly, the Ocala lower permeability zone of southwestern Florida is combined with the middle confining unit MC1 used in southern Florida to form a new zone named the “Ocala-Avon Park lower permeability zone,” (OCAPLPZ) also described later, which extends over a broader area than each of the individual local zones.

Revised Definition and Application of the Numbered Middle Confining Units

A major revision has been made to the definition and application of numbered middle confining units of Miller (1986) as well as the names used to define different regions of these units. The revision resolves inconsistencies between the names used to identify less-permeable units to those originally used to define the numbered middle confining units of Miller (1986), thereby clarifying the mapping criteria and stratigraphic position of the middle confining and composite units.

The changes to the numbered middle confining unit(s) include one or more of the following:

- Retained—The top and base of a numbered middle confining unit is remapped on the basis of hydraulic testing data and geophysical log markers; the extent and shape of the unit is either similar to that previously mapped or is expanded to include lower permeability rocks at a similar stratigraphic interval.
- Reassigned—All or part of the unit is reassigned from the numbered middle confining unit into one or more lower permeability zones in the Upper or Lower Floridan aquifer.
- Abandoned—All or part of a unit previously mapped as part of a numbered middle confining unit is found to be part of permeable aquifer material because of newer hydraulic testing data or has been reassigned to another hydrogeologic unit or zone and the name for the unit is no longer needed.

Middle confining units MCUI, MCUII, MCUIII, MCUV and MCUVI have been retained or reassigned. Further, because MCUI was originally mapped as a relatively thick unit containing permeable and less-permeable beds, part of this unit has been reassigned into a newly defined composite unit named the “Lisbon-Avon Park composite unit,” described later, and part has been reassigned to a newly defined lower permeability zone within the Upper Floridan aquifer (the OCAPLPZ, also described later). Middle confining units MCUIV and MCUVII have been abandoned.

Over parts of central Florida, two overlapping numbered confining units of Miller (1986) created areas where permeable aquifer material lies between vertically separate middle confining units. These permeable beds may locally be considered to be part of either the Upper or Lower Floridan aquifers depending on which middle confining unit is used as a separation between the two aquifers. As a convention, Miller (1986) used the shallowest middle confining unit to define the base of the Upper Floridan aquifer and, in places where no middle confining unit was mapped, the Upper Floridan aquifer was extended to the base of the aquifer system. Accordingly, the presence or absence of the middle confining unit greatly affected the thickness and structural configuration of the two aquifers within the system.

The application of the numbered middle confining units to define the Upper and Lower Floridan aquifers has been fundamentally changed herein by grouping less-permeable or lower permeability rocks in the approximate middle part of the aquifer system into narrower lithostratigraphic intervals. In areas where no middle confining unit is defined, an equivalent horizon is extended along the same stratigraphic interval and this entire lithostratigraphic interval is called a composite unit. Therefore, the base of the Upper Floridan aquifer is no longer strictly based on the top of the shallowest lower permeability unit (numbered MCU). As a result of this change, the thickness and extent of the composite units more closely follow natural rock-stratigraphic units that can be mapped with geophysical markers, which reduces the effect of abrupt structural changes in the aquifer configuration. Additionally, the division of the Floridan aquifer system into Upper and Lower Floridan aquifers is more consistent, even in areas where the units are all hydraulically connected. The lithostratigraphic mapping approach has another major advantage by allowing the position of higher and lower permeable zones within the Upper and Lower Floridan aquifers to more easily be defined using stratigraphic and geophysical markers within the regional aquifers.

To clearly show local or regional variations of vertical hydraulic conductivity in the two composite units, the corresponding maps herein are shaded. The shaded regions shown are intended to differentiate large regional differences. Smaller differences that cannot be portrayed on the regional-scale maps could be important to local studies. Exceptions to the generalized differences in unit properties of the shaded regions are possible for small intervals at individual wells and may be identified as new data are collected.

Conceptual Model, Regional Variation, and Description of New Terminology

At a regional scale, permeable rocks in the upper and lower parts of the Floridan aquifer system are grouped into the Upper and Lower Floridan aquifers, respectively. Because of the wide variation in thickness, rock types, texture, and secondary dissolution and recrystallization of the carbonate rocks in different parts of the study area, there is a correspondingly wide variation in the number of regional units and zones that could be delineated within the Floridan aquifer system. Several idealized columns are shown in figure 6 to illustrate the major and minor units and zones within the Floridan aquifer system in different regions of the study area. The aquifer system is overlain by the upper confining unit, in all regions except southwestern Georgia, southeastern Alabama, parts of central Florida, and southwestern Florida; and underlain by a lower confining unit throughout.

As shown in figure 6, the Upper and Lower Floridan aquifers are separated by the discontinuous numbered middle confining units that are now grouped within two composite units: (1) the Lisbon-Avon Park composite unit (LISAPCU), consisting of lower permeability clastic and higher to lower permeability carbonate rocks in the northern part of the study area; and (2) the middle Avon Park composite unit (MAPCU), consisting of lower permeability evaporite- and non-evaporite-bearing carbonate rocks to moderately permeable carbonate rocks in the central and southern parts of the study area. In areas where the two composite units overlap (columns 4 and 5 in fig. 6), one or the other composite unit is used as a separation between the Upper and Lower Floridan aquifers. The composite units can contain confining, semiconfining, and leaky strata that are part of several previously defined MCUs. Some of the numbered middle confining units are semiconfining or leaky (have hydraulic properties of the rocks within the same order of magnitude as the aquifers above, below, or both above and below). In these leaky areas, the exchange of water between the two regional aquifers may not be restricted and the two aquifers behave as a single aquifer. In the Florida panhandle, the Bucatunna clay confining unit (BCCU; subregional extent) divides the system into the Upper and Lower Floridan aquifers.

One area where the two regional aquifers are highly interconnected is in the northern coastal region of Georgia and South Carolina. In that area, sandy granular limestone and fine-grained argillaceous limestone form a leaky unit that separates the system into the two regional aquifers, where recent multi-well aquifer tests indicate that the hydraulic properties of the middle confining unit of Miller (1986) is similar to the Lower Floridan aquifer (Clarke and others, 2010; Clarke and others, 2011; Gonthier, 2012; Cherry and Clarke, 2013; fig. 6). Farther south, thick beds of dolostone and dolomitic limestone divide the flow system in southeastern Georgia and northeastern Florida into several permeable and less-permeable zones (fig. 6). In central, southwestern, and southern Florida, where the total thickness of the aquifer system exceeds 3,000 feet (ft), several high permeability zones are separated by lower permeability zones. The progressive thickening of the aquifer system and its various higher and lower permeability zones from north-central Florida to southern Florida is shown in figure 7.

The uppermost permeable zone forms a large part of the Upper Floridan aquifer in north-central Florida (fig. 7). Where this zone is developed exclusively in the Ocala Limestone, it is identified as the Ocala permeable zone. At the top of rocks of middle Eocene age, the upper dolostone unit separates the uppermost permeable zone from permeable zones below. The dolostone unit represents a low-porosity, relatively thick semiconfining unit in this part of the section, which is essentially middle confining unit MCUI of Miller (1986). However, this unit may not be confining everywhere, and where it is fractured or contains solution features, the unit may be part of the Floridan aquifer system.

Southward, in central Florida, the middle part of the system includes evaporite-bearing carbonate rocks of middle confining unit MCUII of Miller (1986) and lower permeability carbonate units in the lower part of middle confining unit MCUI of Miller (1986); these are combined at the same stratigraphic interval to form the MAPCU. The MAPCU forms the boundary between the Upper and Lower Floridan aquifers throughout much of central and southern Florida.

In southwestern Florida, evaporite-bearing rocks of MCUII form the largest and most confining part of the MAPCU, restricting flow between the Upper and Lower Floridan aquifers. Over much of this area, the evaporite-bearing unit is thick, continuous, and tightly confining. Southeastward toward Palm Beach County, several deeper, less-continuous evaporite-bearing units may be present below middle confining unit MCUII and extend farther south. These evaporite-bearing units represent middle confining unit MCUVI of Miller (1986), which as described earlier, has been abandoned and merged with the MAPCU. In a hydrogeologic study of the SWFWMD, Arthur and others (2008) concluded that MCUII and MCUVI could be combined to form a single more extensive middle confining unit they termed the “middle Floridan confining unit.” Although distinct evaporitic units can be mapped in this area, the generalization of evaporitic intervals into a single more continuous zone to form the MAPCU seems to be the most practical regional representation of these lower permeability rocks.

Toward the south where the Floridan aquifer system thickens, higher and lower permeability zones within the Upper Floridan aquifer are delineated. The shallowest include permeable zones within the basal part of the Arcadia Formation, within the Suwannee Limestone (Suwannee permeable zone; Hutchinson, 1992) and within an unnamed Oligocene limestone (Reese and Richardson, 2008). These zones are collectively grouped into the uppermost permeable zone and are separated from the vuggy or cavernous extremely permeable APPZ by finer-grained rocks of the OCAPLPZ. The newly designated OCAPLPZ is roughly equivalent to MC1 of Reese and Richardson (2008) and is introduced to reduce potential confusion of MC1 with MCUI of Miller (1986).

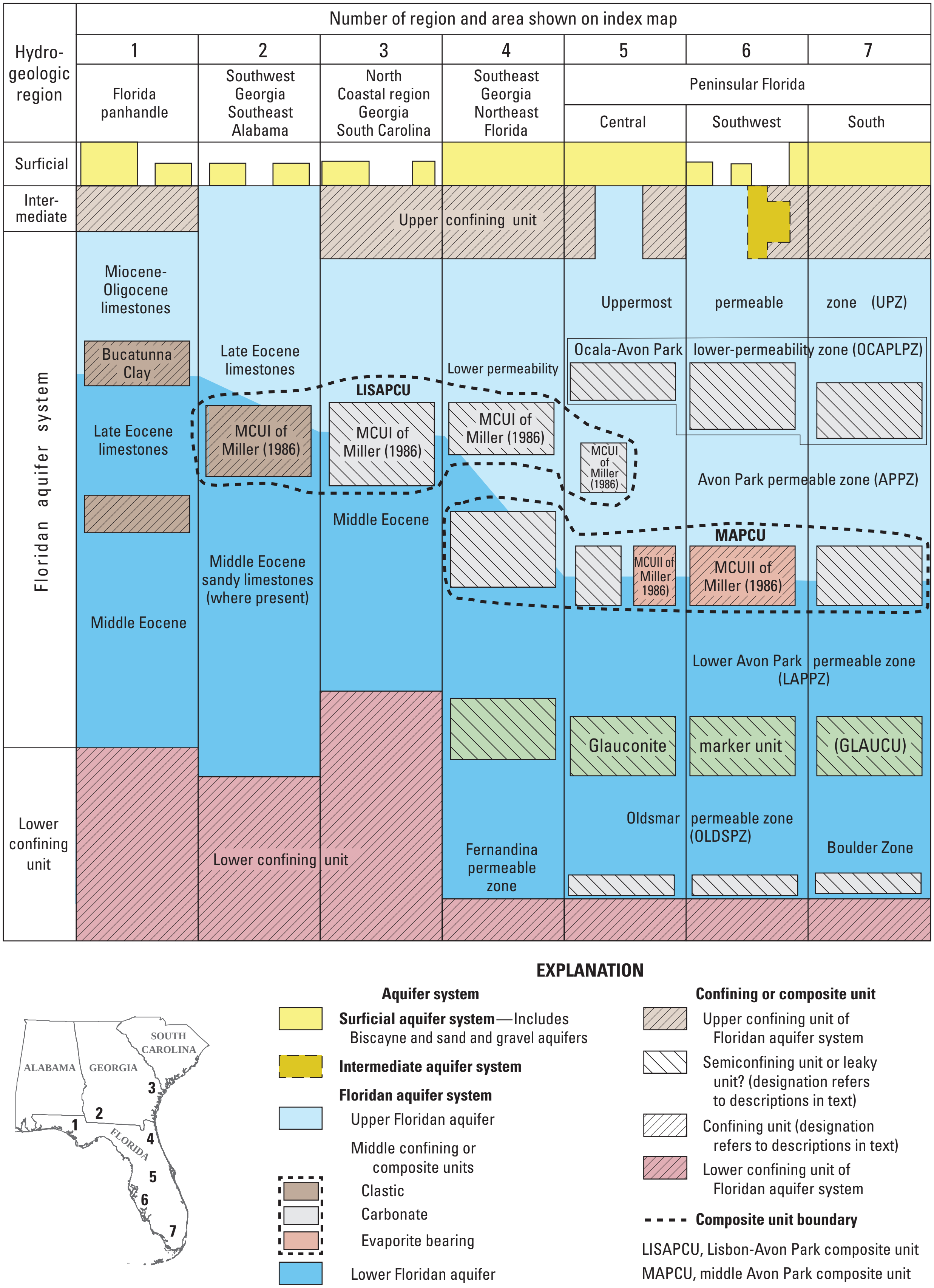


Figure 6. Aquifers, composite and confining units of the Floridan aquifer system, southeastern United States.

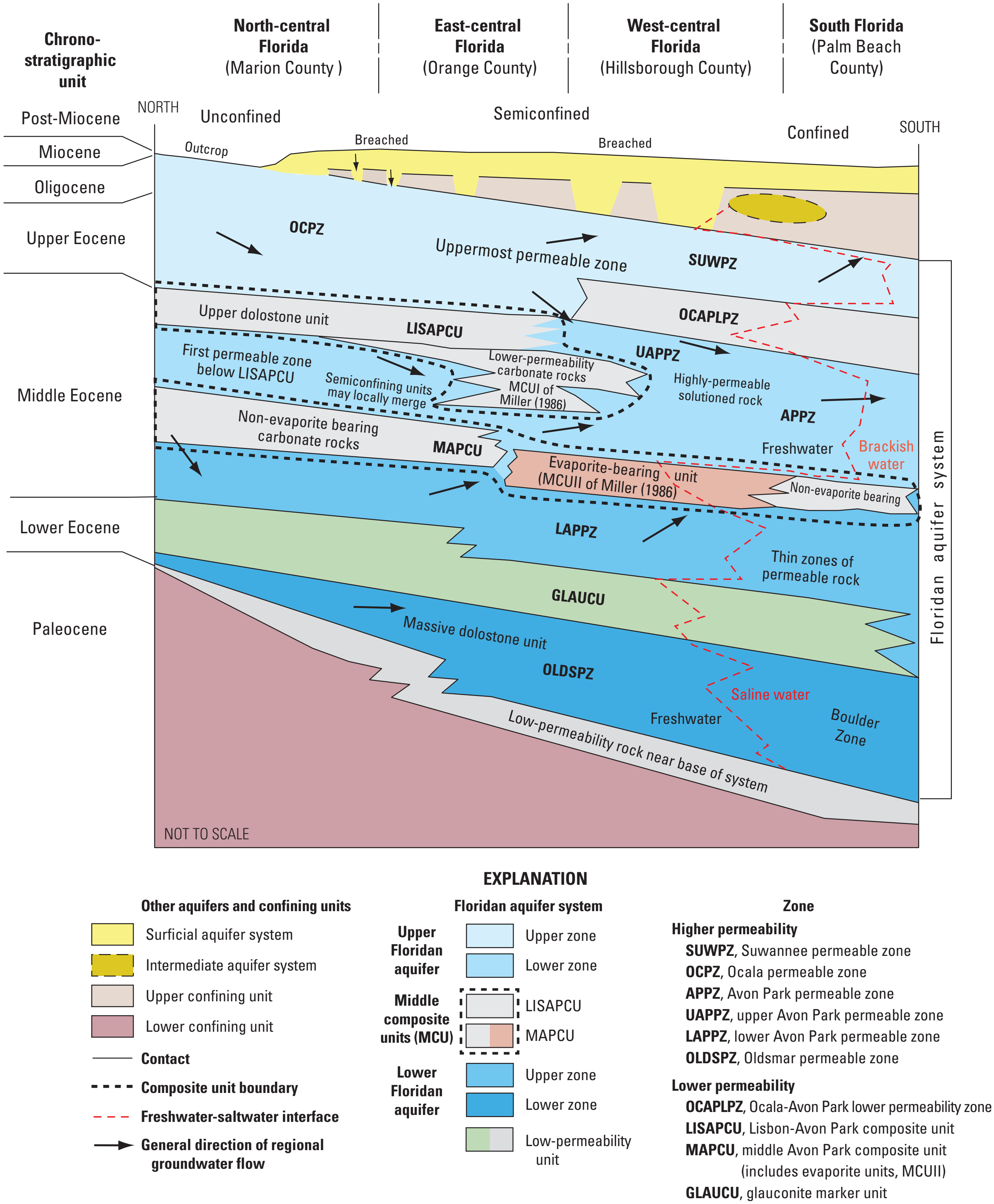


Figure 7. Schematic cross section showing transition of hydrogeologic units and zones from north-central Florida to southern Florida.

The APPZ can be qualified with the term “upper” to distinguish it from deeper zones in the lower part of the Avon Park Formation, although this qualifier generally is not used in favor of simply using the term “APPZ” (fig. 7). Because of its exceptionally large hydraulic conductivity compared to other zones in the Floridan aquifer system, the APPZ may behave as a distinct hydraulic zone and may have water of different quality than other zones in the Upper Floridan aquifer. In some areas, the APPZ was considered a separate aquifer within the middle part of the Floridan (Bennett and others, 2001; Bennett and Rectenwald, 2003; Bennett and Rectenwald, 2004). In this revision the APPZ is within the Upper Floridan aquifer.

Deeper in the Floridan aquifer system, below the evaporite-bearing units, several permeable zones are mapped within the Lower Floridan aquifer. These zones include a new unit, introduced here as the “lower Avon Park permeable zone” (LAPPZ), which is approximately equivalent to LF1 and deeper zones described by Reese and Richardson (2008) and the Oldsmar permeable zone, which incorporates cavernous intervals previously mapped as the Boulder Zone of Miller (1986) and other moderately transmissive rocks in the basal part of the system. The LAPPZ and the Oldsmar permeable zone are respectively located above and below another new unit introduced here, named the “glauconite marker unit” (GLAUCU).

Another area where new terminology is introduced covers southwestern Georgia, southeastern Alabama, and north-central Florida. The new terms, as they apply to permeable and less-permeable parts of the Floridan aquifer system, are shown in figure 8 in a north-to-south schematic cross section from Albany, Ga., to Gainesville, Fla. In the northern part of this schematic cross section, the permeable part of the aquifer system is the Upper Floridan aquifer. Here, the aquifer is recharged by (1) infiltration through a residuum unit, (2) leakage along losing stream segments, or (3) complete capture of streams into the aquifer system. In and near Albany, Ga., the Upper Floridan aquifer consists of highly permeable Miocene to late Eocene carbonate rocks. In this area, and farther north toward the outcrop area, clastic rocks of the Claiborne aquifer (McFadden and Perriello, 1983) are hydraulically connected to the Upper Floridan aquifer. In this updip location, downward hydraulic head gradients from the Upper Floridan aquifer allow for leakage to the underlying Claiborne aquifer though the Lisbon-McBean confining unit (also known as the Lisbon confining zone). Farther south, gradients become negligible or reverse as the Claiborne aquifer merges with the Floridan aquifer system along a line coincident with, or just north of, the Gulf Trough (Applied Coastal Research Laboratory, 2002; Foley and others, 1986; Kellam and Gorday, 1990; Patterson and Herrick, 1971).

In south-central Georgia, near Tifton, low-permeability rocks in the Gulf Trough greatly impede the movement of groundwater through the Upper Floridan aquifer. Farther south near Valdosta Ga., intergranular gypsum and thin and intermittent layers of evaporite minerals in middle Eocene rocks decrease the permeability in the lower part of the Floridan aquifer system. Here, the evaporite-bearing units act as lower permeability barriers to flow (fig. 8), and freshwater moving from the Claiborne aquifer in southwestern Georgia may move upward and over the evaporite units, or slowly through them, towards discharge areas. Farther south, rocks of the Upper Floridan aquifer merge with thicker extremely permeable solution zones in the unconfined areas of north-central Florida.

In a broad area of north-central Florida, the Floridan aquifer system is unconfined and consists of highly permeable rock from the top of the system to its base. In this area, groundwater may freely circulate through the entire system because of the lack of confinement within the system (Miller, 1986). Near Gainesville, Fla., the Floridan aquifer system includes permeable rocks that range from upper Eocene to Paleocene. As shown in figure 8, the upper dolostone unit of the Avon Park Formation may locally restrict flow between the upper and lower parts of the aquifer system. Although it is not implied in the schematic cross section, the upper dolostone unit and similar low-porosity rocks in this section of the Avon Park Formation dip eastward and become middle confining unit MCUI of Miller (1986) where these rocks become more deeply buried and are probably much less permeable than in north-central Florida. Deeper hydrogeologic units include the glauconite marker unit (previously described) and permeable zones in the basal part of the aquifer system.

Geologic Setting

The study area is underlain by a thick sequence of Cretaceous to Holocene unconsolidated and semiconsolidated layers of sand and clay, and poorly indurated to very dense layers of limestone and dolomite. The descriptions provided in this report focus on rock units ranging in age from Cretaceous through post-Miocene that compose the Floridan aquifer system and the overlying confining unit and surficial aquifer system (pl. 2). Also described are rocks and sediments that form the confining, semiconfining, and composite units within the system as well as those of the intermediate and surficial aquifer systems. Descriptions of other units are derived from published reports. The location and extent of rocks of various ages, compiled from State geologic maps, are shown in a generalized geologic map (fig. 9).

Relation of Stratigraphic and Hydrogeologic Units

Many different formation names have been used to describe the carbonate and clastic rocks that collectively form the Floridan aquifer system. To maintain consistency with previous USGS reports, stratigraphic nomenclature and age assignments conform to those described by Miller (1986) and Renken (1996). Detailed stratigraphic studies conducted by the State geological surveys and the USGS, including reports of Schmidt (1984); Scott (1990); Scott and Allmon (1992); Scott and others (2001) in Florida, and reports of Edwards (2001); Falls and Prowell (2001); Herrick (1961); Huddlestun (1988, 1993); Huddlestun and Hetrick (1985);

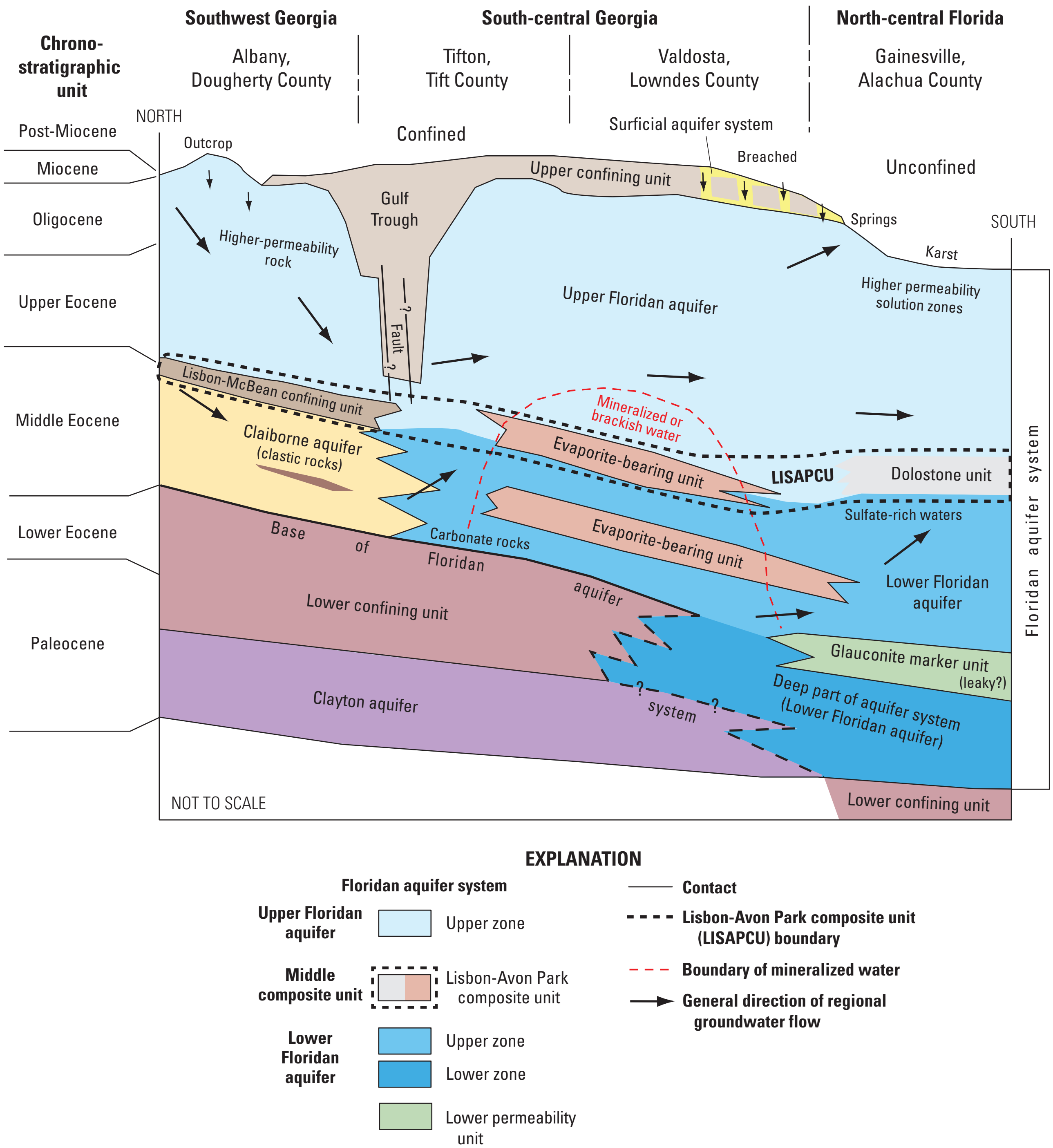


Figure 8. Schematic cross section showing transition of hydrogeologic units in southwestern and south-central Georgia and north-central Florida.

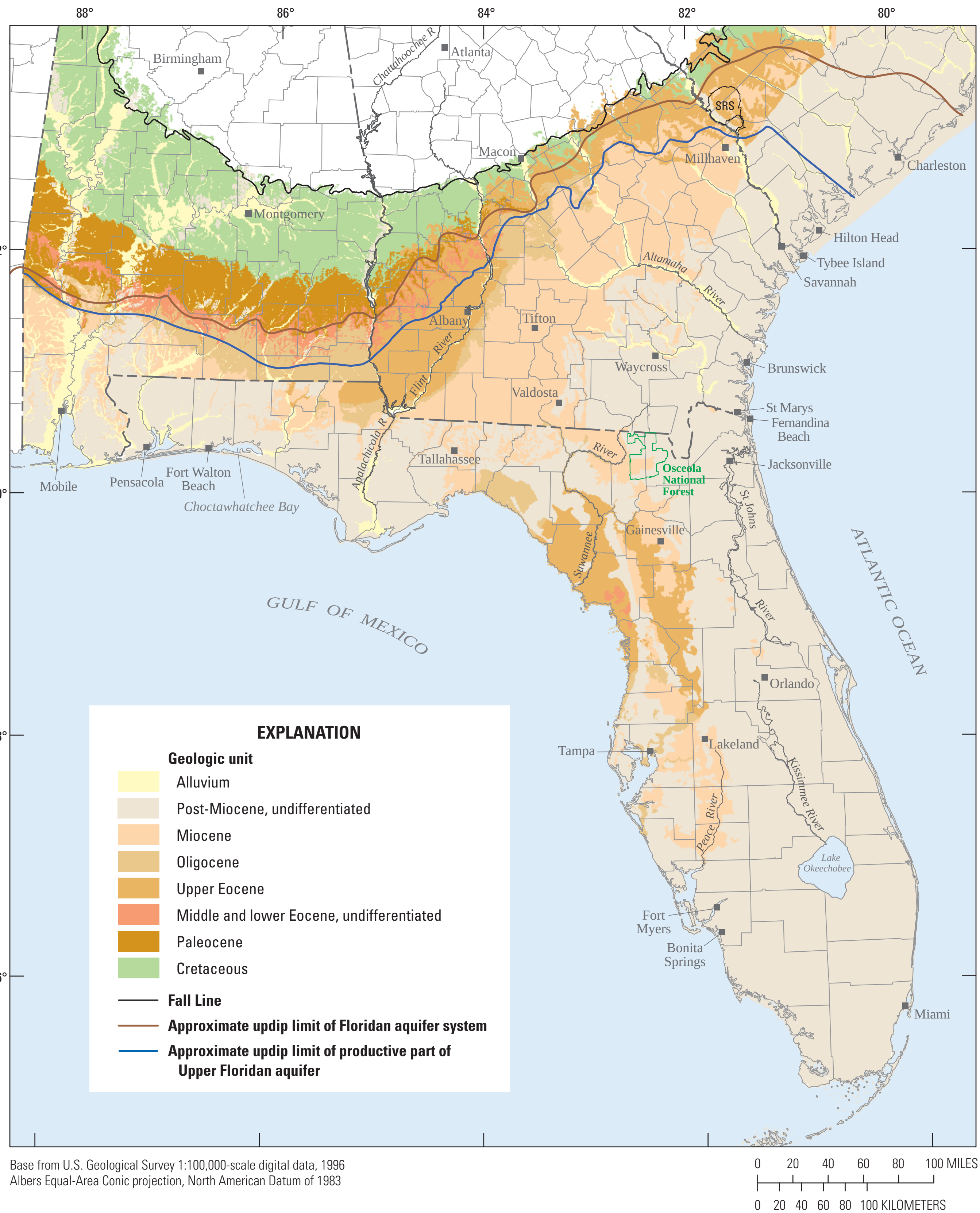


Figure 9. Generalized geologic map of the southeastern United States (compiled from Georgia Geologic Survey, 1976, Scott and others, 2001; Dickson and others, 2005; and Geological Survey of Alabama, 2006; SRS, Savannah River Site).

Weems and Edwards (2001) in Georgia also were consulted, but the aforementioned regional stratigraphy was primarily used to prepare the cross sections and descriptions.

A correlation chart of the Floridan aquifer system (pl. 2) shows the relation between the regionally correlated time-stratigraphic units and rock-stratigraphic units and the corresponding position of the aquifer system. The chart was modified from plate 2 of Miller (1986) and includes several additional columns that depict stratigraphic relations among the various regions of Florida. As mapped in the current revision, the aquifer system includes all or part of those formations that include the vertically continuous sequence of carbonate rocks in downdip areas of Georgia and Florida and the hydraulically connected clastic rocks and sediments that generally are present in updip areas of Alabama, Georgia, and South Carolina (pl. 2). The aquifer system is underlain by clastic, carbonate, or evaporitic-bearing rocks of relatively lower permeability that form a lower boundary. This boundary is within, or at the top of, various time-stratigraphic units, depending on the lithologic variation within the formations. The system is overlain by low-permeability clastic or carbonate rocks, except where it is unconfined or overlain by either a residuum or unconsolidated surficial materials.

A map showing the generalized surficial geology of time-stratigraphic rock units, compiled from State geologic maps, indicates that most of the time-stratigraphic rock units crop out along a southwest-to-northeast band that generally parallels the Fall Line (fig. 9). Older units are exposed near the Fall Line owing to the regional dip of the formations. One exception is along the western coast of the Florida peninsula where units of middle and lower Eocene through Miocene are exposed and rocks forming the permeable units of the aquifer system are near land surface. In such areas, water can more readily recharge the aquifers and there is strong interconnection between the aquifers and surface-water features.

Structure

Coastal Plain sediments and rocks in the southeastern United States have the general configuration of a wedge that slopes and thickens seaward from a thin edge in outcrop areas (fig. 3). Structures of subregional extent that affected Coastal Plain sedimentation are superimposed on this wedge (fig. 10). Florida's Peninsular arch was a positive structure continuously from the Jurassic until the Late Cretaceous and was intermittently active during the Cenozoic. The Peninsular arch is similar in shape to that of an anticline produced by compressional tectonics; however, the corresponding synclines are not present on either side of this feature. The Ocala "platform" parallel to, and southwest of, this arch is not a true uplift; this structure affects only middle Eocene or younger sediments and probably was formed by differential compaction (Miller, 1986). Sedimentation largely has been controlled by regional positive and negative structural features that have affected the accumulation of sediments in the area over long periods of geologic time (Miller, 1986).

Several major depositional centers have been active northeast, northwest, and south of the Peninsular arch since at least the Early Cretaceous. To the northeast, the Southeast Georgia embayment (fig. 10) is a shallow east- to northeast-plunging syncline that has slowly subsided during its depositional history. Inside the embayment, lower Cretaceous clastic sediments are overlain by Upper Cretaceous and Tertiary carbonate rocks, which in turn are overlain by younger carbonate and clastic deposits. Northwest of the Peninsular arch lies the Southwest Georgia embayment, also known as the Apalachicola embayment (Schmidt, 1984; Kellam and Gorday, 1990), where thick accumulations of mostly clastic rocks have been deposited since at least the Late Jurassic. In the westernmost part of the Florida panhandle and in southern Alabama, sediments thicken greatly westward into the Gulf Coastal Plain (Grubb, 1998) where carbonate rocks of the Floridan grade into fine-grained clastic rocks. South of the Peninsular arch, thick sequences of carbonate rocks have been deposited in the broad shallow South Florida basin.

Several relatively small structures are present along the west coast of Florida in the near-shore to offshore areas, including the Middle Ground arch, Tampa basin, Tampa-Sarasota arch, Charlotte high, and the Lee-Collier swell (Pollastro and Viger, 1998; fig. 10). The Tampa-Sarasota arch flanks and separates the South Florida basin from the Tampa basin (Reese and Richardson, 2008; fig. 11). In southeastern Florida, the Largo high is a gently sloping positive feature that may affect sedimentation in Miami-Dade County and, based on correlation, may extend farther north along eastern Broward and Palm Beach Counties.

The Gulf Trough is a narrow structural low that extends from southwestern Georgia into east-central Georgia and probably ends in Effingham County (Applied Coastal Research Laboratory, 2002). Various alternate interpretations of the Gulf Trough were presented by Patterson and Herrick (1971), who indicated it could either represent a buried submarine valley, graben complex, syncline, or buried solution valley. Miller (1986) proposed this feature comprised a series of both isolated and connected fault grabens. Kellam and Gorday (1990) assessed the nature of this feature and determined that its effect on groundwater flow was greatest in central and southwestern Georgia. Although this feature is relatively narrow, it has a substantial effect on the potentiometric surface of the Upper Floridan aquifer (see for example Bush and others, 1987; Kinnaman and Dixon, 2011).

Several local structural features in the northern coastal area also were described by Williams and Gill (2010). One important feature in this area is the Beaufort arch (fig. 10), which locally controls the position of the Upper Floridan aquifer in relation to potential saltwater intrusion in the Savannah-Hilton Head area (Falls and others, 2005b; Payne, 2010). Across the arch, the upper confining unit thins and paleochannels may have eroded through it, creating breaches where seawater can enter the Floridan aquifer system (Payne and others, 2005; Provost and others, 2006). This feature was originally named the "Beaufort High" by Heron and Johnson (1966) and subsequently called the Beaufort arch by Colquhoun and others (1969).

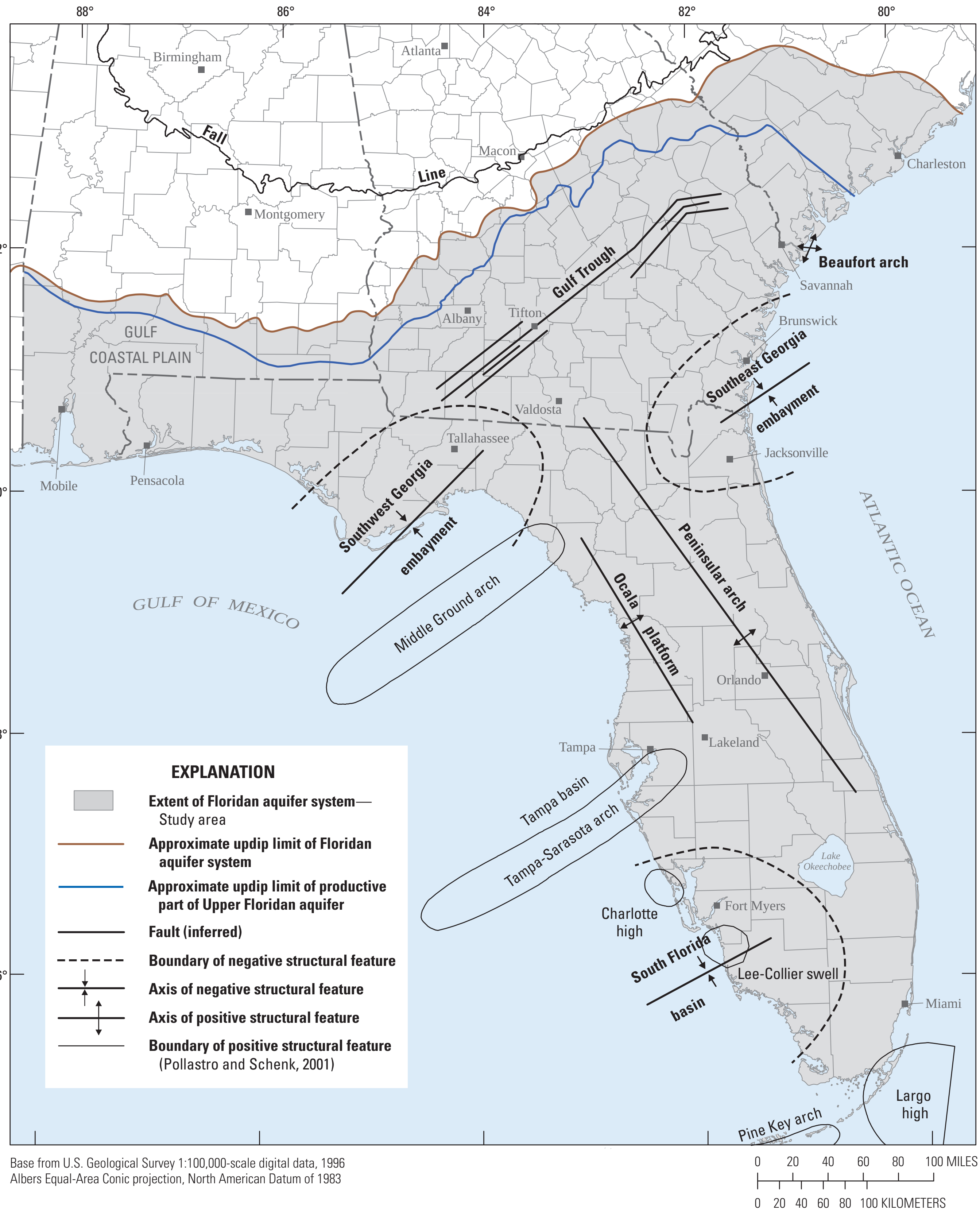


Figure 10. Major structural features influencing the Floridan aquifer system, southeastern United States (modified from Miller, 1986).

Stratigraphy

In a regional study, complex facies changes exist in all rock units within the study area. Many formation names have been assigned to both clastic units and the carbonate-rock units that are the principal focus of the framework revision. To avoid confusion, cumbersome terminology, and needless detailed explanation, the stratigraphic units described herein are time-rock units that include all or parts of several formations. Miller (1986) and Renken (1996) describe the various time-stratigraphic (chronostratigraphic) units in considerable detail and present a series of maps and cross sections that portray variations within the units. Miller's (1986) work describes the mostly carbonate rock section, whereas Renken (1996) focuses on clastic strata.

Cretaceous System: Gulfian Series

In the study area, rocks of the Gulfian Series (pl. 2) are mostly found in the subsurface. Although the Gulfian Series consists of five provincial stages, only the uppermost two, the Tayloran and Navarroan stages, compose either part of the Floridan aquifer system or part of its lower confining unit.

In the updip areas of Alabama, Georgia, and South Carolina, Tayloran strata in the shallow subsurface or in outcrop are clastic rocks, chalk, or low-permeability carbonate rocks and have been divided into several formations (pl. 2). In most of the subsurface of the eastern Gulf Coast, however, Tayloran rocks are unnamed. In southern Alabama, southern Georgia, and the Florida panhandle, Tayloran rocks are mostly massive calcareous clay; in peninsular Florida, they consist primarily of chalk. Tayloran strata compose part of the lower confining unit of the Floridan aquifer system where they underlie permeable Navarroan limestone in southeastern Georgia.

Navarroan rocks are divided into several named formations consisting of chalk and clastic rocks in outcrop areas and the shallow subsurface (pl. 2). The rocks are thin and discontinuous over much of the study area. These rocks are unnamed in the deeper subsurface, except for the Lawson Limestone in parts of Georgia and Florida (Applin and Applin, 1944, 1967). The Lawson is a light-colored, fossiliferous, pelletal, dolomitic limestone that locally is very porous in the Brunswick area of southeastern Georgia and adjacent areas of northeastern Florida. In areas where these rocks are hydraulically connected to overlying rocks of the Floridan aquifer system, parts of the Lawson Limestone may be considered to be part of the Floridan aquifer system. Elsewhere, Navarroan rocks are composed of sand, clay, and (or) chalk.

Tertiary System: Paleocene Series

Paleocene rocks in the study area can be categorized into three groups. The first group, which is the most important to this study, primarily consists of interbedded dolomite and anhydrite of the Cedar Keys Formation, which underlies part of southeastern Georgia and all of peninsular Florida. The second group, which is unnamed and located north and west of the first group, consists mostly of clay with a few beds of sand and sandy limestone. The final group, located in eastern Alabama and southwestern Georgia, consists of sand and minor sandy limestone of the Clayton Formation that were considered part of a regional clastic aquifer by Renken (1996).

Most of the Paleocene strata in eastern Alabama and the central to western coastal plain of Georgia have been assigned to the Clayton Formation. Updip, this formation consists of coarse-grained sand with a few beds of fossiliferous sandy limestone. In western Georgia, the uppermost part of the Clayton is a hard, sandy, fossiliferous limestone that constitutes an important aquifer (Clarke and others, 1984). The sand and limestone beds grade downdip into massive clays that locally form the base of the Floridan aquifer system. The limestone of the Clayton aquifer is not hydraulically connected to other Tertiary limestones of the Floridan aquifer system.

Interbedded dolomite and anhydrite, both being of lower permeability, compose the lower two-thirds of the Cedar Keys Formation of peninsular Florida and southeastern Georgia. This carbonate-evaporite sequence forms the base of the Floridan aquifer system. In contrast, the upper third of the formation consists of light-colored, coarse, crystalline dolomite of moderate to high porosity. Where present, this dolomite forms the lowermost part of the Floridan aquifer system (see pl. 2). In the Brunswick, Ga., area, the entire Cedar Keys Formation is permeable and may be part of the Floridan.

Tertiary System: Eocene Series

A thick, extensive sequence of Eocene strata underlies the entire study area. Where these strata consist of carbonate rocks, most are moderately to highly permeable and compose the majority of the Floridan aquifer system. Eocene rocks commonly are highly porous, showing much intergranular (primary) and dissolution (secondary) porosity. The upper parts of the Eocene section are especially porous and permeable. In downdip areas of the section, lower permeability beds compose confining units of subregional extent within the Floridan aquifer system. Upper and middle Eocene strata grade from carbonate rocks in downdip and mid-dip areas into clastic rocks in updip areas. In contrast, upper Eocene rocks are predominantly carbonate.

The carbonate-clastic rock transition in lower Eocene beds generally lies farther northward and westward than the similar transition in Paleocene strata. In middle Eocene rocks, this facies change is still farther to the west and north. Late Eocene beds commonly retain their carbonate character until they are truncated in outcrop and subcrop. This progression represents a general regional transgression of the sea that began in Paleocene time and lasted through late Eocene time. During deposition, marine carbonate sediments of the lower Tertiary sea extended progressively farther inland. An exception to this general transgression is in southwestern Georgia and eastern Alabama, where marine Eocene strata lie progressively farther southward and eastward as they become younger, in an offlap relationship.

Almost all the early Eocene carbonate rocks in the study area are part of the Oldsmar Formation of peninsular

Florida and southeastern Georgia. The Oldsmar is mostly light-colored, finely pelletal to micritic limestone containing thick to thin interbeds of gray, tan, or light-brown dolomite that is commonly vuggy. The lower Oldsmar contains more dolomite than the upper part, and, where gypsum and anhydrite are present in lower Oldsmar beds, these lower permeability evaporite units are part of the lower confining unit of the Floridan aquifer system. Oldsmar carbonate rocks show increasing amounts of clastic material and decreasing permeability as they grade updip from Georgia to South Carolina into sandy glauconitic limestone of the Fishburne Formation (Williams and Gill, 2010). The Fishburne is not considered part of the Floridan aquifer system; however, sands in the upper part of the Hatchetigbee Formation in southwestern Georgia are considered part of the Lisbon aquifer. Where hydraulically connected, the Lisbon aquifer is considered part of the Floridan aquifer system herein.

Middle Eocene carbonate rocks underlie the eastern part of the Florida panhandle, about half of the coastal plain of Georgia, and all of peninsular Florida. These marine rocks grade updip into clastic rocks that were deposited in marine to marginal marine environments. Almost all the middle Eocene carbonate rocks are assigned to the Avon Park Formation except those of the Santee Limestone in South Carolina.

The Avon Park Formation is a sequence of cream, tan, or brown, soft to indurated, pelletal to micritic limestone interbedded with cream to brown, crystalline dolomite that is commonly vuggy and fractured in some places. The middle part of the formation in much of southwestern Georgia and in eastern peninsular Florida is mostly lower permeability, micritic to finely pelletal limestone that forms an important and extensive confining unit within the Floridan aquifer system. In west-central peninsular Florida, the lower half of the Avon Park consists of lower permeability, dark-colored, gypsum-bearing limestone and dolomite that forms a composite unit within the Floridan aquifer system. Updip, in Alabama, the Florida panhandle, and western Georgia, the Avon Park grades into sands of the Tallahatta and Lisbon Formations (and local argillaceous limestone in the Lisbon). Together, these formations compose the Lisbon aquifer (Gillett and others, 2000). In turn, the argillaceous limestone grades into the Santee Limestone in South Carolina, which is included in the Floridan aquifer system. Sands of the Tallahatta and Huber Formations were included in the Gordon aquifer system (Brooks and others, 1985) and equivalent beds in southwestern Georgia were called the Claiborne aquifer (McFadden and Perriello, 1983). Like the Lisbon aquifer, the Gordon and Claiborne aquifers are considered part of the Floridan aquifer system in this report. Locally, sands of the Gosport Sand in Alabama and the McBean Formation in South Carolina are hydraulically connected to the carbonate rocks of the Floridan aquifer system and are considered part of it. Plate 2 shows the relations between these various middle Eocene formations.

Upper Eocene carbonate rocks are present throughout almost all of the study area, except locally within peninsular Florida where they have been eroded away. In the Florida panhandle and in Alabama, these rocks grade updip into clastic strata. The most extensive upper Eocene limestone unit in the Floridan aquifer is the Ocala Limestone. Puri (1953) considered the Ocala to be a group consisting of three formations; however, Miller (1986) was unable to consistently subdivide the Ocala and mapped it as a single formation.

The upper part of the Ocala Limestone consists of soft, white, porous coquina that is composed of bryozoan and echinoid fragments and large foraminifera, cemented loosely by limestone mud (micrite). The lower part of the Ocala is soft, fine-grained, micritic, fossiliferous limestone that is dolomitized in places and contains glauconite in southern Georgia. The Ocala is one of the most permeable units of the Floridan aquifer system. Locally, limestone in the lower part of the Cooper Formation in southeast Georgia is included in the Floridan, but this limestone is substantially less permeable than that of the Ocala. Sands of the Moodys Branch Formation in Alabama and the Florida panhandle, the Barnwell Group of Georgia and South Carolina, the Clinchfield and Tobacco Road Sands of Georgia, and part of the Cooper Formation in Georgia (pl. 2) are in hydraulic connection with limestones of the Floridan aquifer system and are considered part of the system in this report.

Tertiary System: Oligocene Series

Oligocene rocks underlie about two-thirds of the study area and are present in two large bodies. The larger of the two bodies extends seaward from outcrop areas over much of the coastal plain of Alabama and Georgia, and over a small part of South Carolina. The smaller body extends over approximately one-fourth of the Florida peninsula. Erosional remnants of Oligocene rocks between these bodies indicate that the Oligocene sea extended over a much larger area before rocks of this age were eroded away. The Oligocene rocks are carbonates except where they grade into clastic beds in southwestern Alabama, the western part of the Florida panhandle, and parts of northeast Georgia and southwest South Carolina. The oldest Oligocene carbonate rocks in the study area are those of the Bumpnose Formation and the overlying Marianna Formation of the Florida panhandle, southeastern Alabama and southwest Georgia (pl. 2). In outcrop, both the Bumpnose and the Marianna are soft, light-colored, fossiliferous limestones; both formations grade downdip into a thick sequence of unnamed interbedded limestone and dolomite. In southwestern Georgia, the Mariana is overlain by the Glendon Limestone, and both formations grade laterally into the Ochlockonee Formation. In some areas, the Bridgeboro Limestone overlies these units, all of which are considered to be part of the Floridan aquifer system (pl. 2).

The most extensive sequence of Oligocene rocks in the study area is the Suwannee Limestone (pl. 2). The Suwannee typically consists of cream to tan, crystalline limestone that contains abundant molluscan casts and molds and is commonly highly vuggy. This lithology represents the upper part of the Suwannee in the northern body of Oligocene rocks and the lower part of the formation in the southern body. The lower part of the Suwannee in the northern body is white to cream, micritic, pelletal limestone; in peninsular Florida, this lithology is common in the upper part of the Suwannee. In South Carolina, the age-equivalent formation of the Suwannee is a lower porosity fine- to medium-grained calcarenite (calcareous sand).

In much of the Florida panhandle and in southern Alabama, white, micritic to pelletal, fossiliferous hard limestone with beds of brown, fine- to medium-grained crystalline dolomite is part of the Chickasawhay Formation. The Chickasawhay grades eastward into unnamed Oligocene carbonate rocks that, in turn, grade northeastward into Suwannee Limestone. West of the Okaloosa-Walton County line, the Bucatunna Clay Member of the Byram Formation is a lower permeability silty to sandy clay that separates underlying and overlying permeable limestones of the Floridan aquifer system.

Tertiary System: Miocene Series

Miocene beds underlie most of the study area and are composed largely of clastic sediments. The beds are absent along a wide band in northwestern peninsular Florida and southwestern Georgia where they have been eroded away. Locally, basal Miocene beds form the uppermost part of the Floridan aquifer system.

The thickest and most extensive Miocene unit in the study area is the Hawthorn Group. The lithology of the Hawthorn varies greatly between areas, but mostly consists of phosphatic clay, silt, and sand that range in color from cream or gray to green to brown. An in-depth discussion of this formation is provided in Scott (1988, 1990) and is summarized here.

In parts of central and northern Florida, thick, extensive phosphate beds in the Hawthorn Group are mined for use in fertilizer. White to brown, lower permeability beds of limestone and dolomite are commonly found in the lower part of the Hawthorn. The entire formation forms a thick, generally clastic, highly variable sequence of lower permeability rock that, where present, is considered to be the upper confining unit of the Floridan aquifer system. In parts of Florida, permeable beds of the Hawthorn locally are included in the intermediate aquifer system. In Georgia, permeable Hawthorn beds locally were included in the Brunswick aquifer system (Clarke and others, 1990).

In the western Floridan panhandle, the Alum Bluff Group is composed of clays, sand, and shell beds. The Alum Bluff includes the Chipola Formation, Oak Grove Sand, and Coosawhatchie Formation (Braunstein and others, 1988). Also present in the westernmost part of the Floridan panhandle is the Pensacola Clay, consisting of upper and lower clay members and a middle sand member (Scott and others, 1991). The Pensacola Clay is composed mostly of carbonaceous silty and sandy clay (Marsh, 1966); where the unit is composed of low-permeability clay, it is included in the confining beds overlying the Floridan aquifer system. To the north, the Pensacola Clay grades into coarse sands, and to the east, it grades into the Alum Bluff Group (Clark and Schmidt, 1982).

Miocene carbonate rocks chiefly consist of sandy limestone of the Tampa Member of the Arcadia Formation and dolomite beds of the undifferentiated Arcadia Formation belonging to the Hawthorn Group. In southern Florida, carbonate rocks are present in the undifferentiated Arcadia Formation and its Nocatee and Tampa Members (Scott, 1988). Only the Tampa, Nocatee, and lower part of the Arcadia Formation are considered part of the Floridan aquifer system in southern Florida, whereas parts of the St. Marks and Chattahoochee Formations are locally included in the Floridan aquifer system in the Florida panhandle and in northern peninsular Florida (pl. 2). The Bruce Creek Limestone, a time equivalent of the Torreya Formation, is locally hydraulically connected to the Floridan aquifer system in central and western parts of the Florida panhandle and grades into finer grained sediments further east that are part of the Alum Bluff Group (Schmidt, 1984).

The Tampa Member of the Arcadia Formation is white to light-gray, fossiliferous, sandy to clayey limestone that locally contains chert and phosphate. The lithology of the Tampa closely resembles that of the Suwannee Limestone except for the sand, phosphate, and chert of the Tampa. This formation is located primarily in the southern and southwestern Florida peninsula. In the central and eastern parts of the Florida panhandle, local beds of Tampa lithology have been called the St. Marks Formation by some workers and the Tampa Limestone by others. This report follows Miller (1986), who assigned these local beds to the Tampa Member. Where present, the Tampa is the uppermost part of the Floridan aquifer system.

In southern Florida, Scott (1988) assigned the lower Hawthorn carbonate section to the Arcadia Formation. The undifferentiated Arcadia Formation is similar to the Tampa, consisting mostly of limestone and dolostone with varying amounts of clay, quartz sand, and phosphate grains (Scott, 1988). Calcareous clay beds are discontinuous in this formation. In contrast to the undifferentiated Arcadia Formation, the Nocatee Member is mostly a siliciclastic unit consisting of interbedded, phosphatic, quartz sand, clay, and carbonate rocks near the base of the Arcadia Formation in southwestern Florida.

Tertiary and Quaternary Systems: Post-Miocene Rocks and Sediments

Post-Miocene beds in the study area generally can be grouped into three units. From oldest to youngest, these are (1) Pliocene marginal marine to shallow marine sand, clay, and limestone; (2) Pleistocene sandy, locally shelly and carbonaceous marine terrace deposits; and (3) Holocene fluvial sand, gravel and (or) residuum. Collectively, the permeable beds of these three subdivisions are called the surficial aquifer system. Parts of this post-Miocene sequence have been given aquifer names in places where they have been tapped and yield large volumes of groundwater. These local to subregional aquifers include the sand and gravel aquifer in the western part of the Florida panhandle (Hayes and Barr, 1983) and the lower Tamiami aquifer (Shoemaker and Edwards, 2003), gray limestone aquifer (Reese and Cunningham, 2000), and Biscayne aquifer (Fish and Stewart, 1991) in southern Florida.

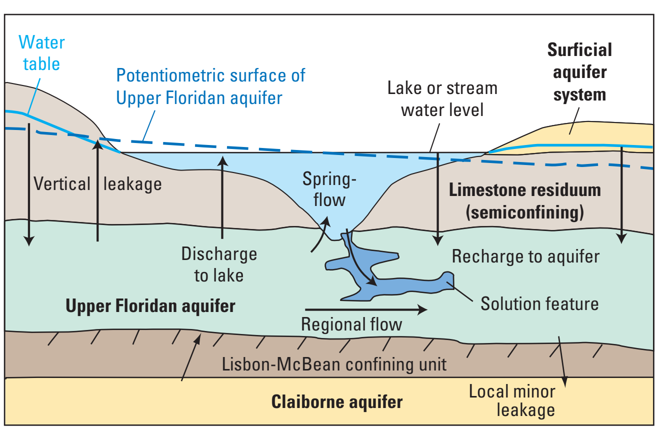
Karst Features of the Floridan Aquifer System

Karst features (springs, sinkholes, and sinking streams) are present over most of the extent of the Floridan aquifer system (Veni and others, 2001; Tobin and Weary, 2004) and are critical in controlling recharge and discharge. Dissolution of carbonate rocks and development of secondary porosity and karst features is a principal reason the Floridan aquifer system is a highly productive aquifer.

The development of solution zones, or cavities, is partly related to the degree of confinement of the Floridan aquifer system. Where the aquifer system is unconfined or thinly confined, movement of infiltrating water dissolves the rock, creating areas of generally increased transmissivity. Where the aquifer system is thickly confined, much less dissolution occurs near land surface and transmissivity tends to be lower. The development of dissolution features result in a transmissivity range that exceeds six orders of magnitude (Kuniansky and Bellino, 2012).

In a study of the Floridan aquifer system in southwestern Georgia, Torak and Painter (2006) describe karst features in exposed limestone of the Floridan aquifer system that are hydraulically connected to the principal rivers and lakes in that region, thereby creating a stream-lake-aquifer flow system (fig. 11). In such areas, the karst features along incised streams that flow over the limestone strongly connect surface-water features with the groundwater flow system. In localized areas, surface water recharges the aquifer where the level of the streambed is higher than the water-table surface of the aquifer, and in other areas, groundwater discharges into the stream either at distinct springs or along diffuse reaches of the streams.

Sinkholes are one of the most common karst features developed in the Floridan aquifer system. These features generally develop in areas where limestone (or dolomite) is at or near the land surface. For example in the Dougherty Plain of southwestern Georgia (fig. 1), limestone is thinly covered with surficial materials or weathered into a residuum. In these areas, numerous sinkholes have developed that connect the aquifer to surface-water drainage, thereby increasing recharge. Although the presence of sinkholes indicates karstification and commonly increased recharge rates, less-permeable cover materials may fill in the sinkholes and their associated conduits (Sinclair and Stewart, 1985; Wilson and Shock, 1996; Tihansky, 1999). Lindsey and others (2010) determined that carbonate aquifers with high sinkhole density had increased susceptibility to nitrate contamination from land-use activities.



NOT TO SCALE

Figure 11. Conceptual diagram of groundwater and surface-water flow in the interconnected stream-lake-aquifer flow system in southwestern Georgia (modified from Torak and Painter, 2006).

Additionally, collapse features resulting from dissolution also occur at depth and within confined parts of the system in southern Florida (Cunningham, 2013). Many circular lakes in central Florida are in confined parts of the Floridan aquifer system formed by cover subsidence, cover collapse and buried sinkholes structures (Kindinger and others 1994, 1999, and 2000).

Topographically closed depressions have been used by the FGS to indicate potential sinkhole development for aquifer vulnerability assessments (Arthur and others, 2007b). For the present study, the National Elevation Dataset (NED) was used to identify closed-basin depressions (fig. 12). Although highly regionalized, the frequency of closed depressions shown on the map in figure 12 provides an indicator of karst development and helps to delineate potential areas where the groundwater and surface-water systems may be strongly interconnected. To produce this map, a flow direction grid was first generated from the NED and used to delineate closed depressions meeting certain criteria. The depth of each depression was calculated by determining its minimum and maximum altitudes using the NED and then subtracting the minimum from the maximum. Closed depressions having a depth criterion of at least 10 ft were retained and then converted into polygon features. These features were then filtered to remove all polygons that encompassed areas less than 200,000 square feet (ft^2) and any polygons intersecting segments of primary streams. A 25-mi^2 grid was then intersected with the polygons to determine the number of closed depressions within each grid cell.

The geographic information system analysis of the NED data indicated that the greatest density of closed depressions (and potential sinkhole development) is in north-central Florida in the aquifer outcrop area (fig. 12). In east-central Florida, a relatively high density of topographic depressions also appears to be present, mostly where the Floridan aquifer system is thinly confined or unconfined. In areas of thin confinement, the overlying Hawthorn Group or undifferentiated post-Miocene sediments are breached by numerous sinkholes, increasing potential recharge to the aquifer in those areas (Spechler and Halford, 2001). Other areas having a high density of closed depressions include northwestern peninsular Florida, southwestern Georgia, and parts of the Florida panhandle. Because of the uncertainty inherent in identifying closed depressions by using the NED, not all closed depressions identified in this manner may represent actual karst features, and some karst features are buried and therefore are not detectable by this method.

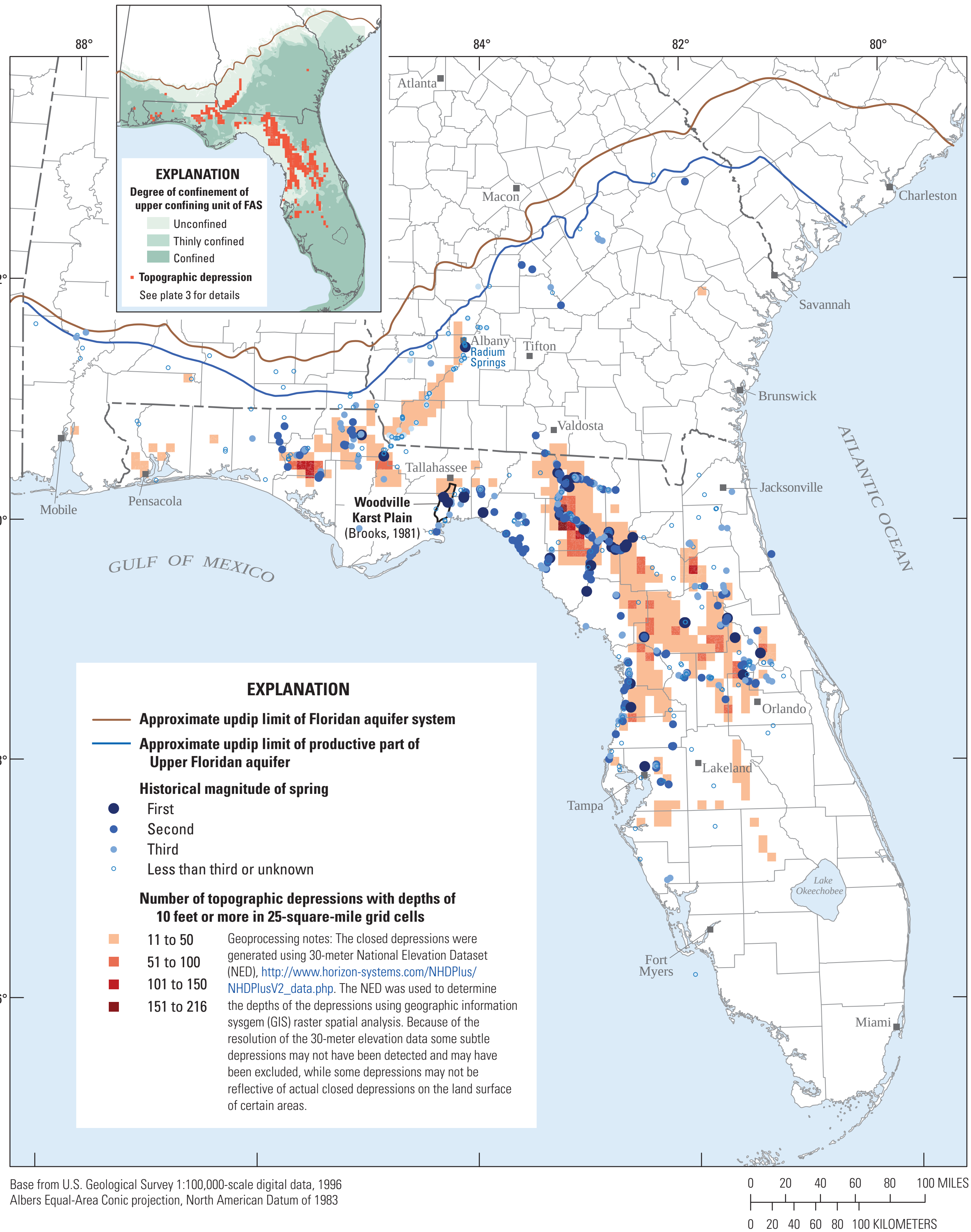


Figure 12. Frequency of closed depressions in relation to major springs of the Floridan aquifer system (FAS), southeastern United States (spring data from Chandler and Moore ,1987; Harrington and others, 2010; Stringfield, 1966; and U.S. Geological Survey, 2013).

Another major indicator of karstification and development of secondary porosity features is the presence of springs, especially first- and second-magnitude springs, which are defined as having historical discharges greater than 100 and 10 cubic feet per second (ft^3/s), respectively. Large-diameter, submerged, interconnected caves over 300 ft (100 meters) in diameter have been mapped in the Woodville Karst Plain (Brooks, 1981; fig. 12). Outside of Florida, the only historical first magnitude spring is Radium Springs in Albany, Ga., and the only historical high flowing third-magnitude spring is Bazemore Mill Spring in the southeast corner of Alabama near the border of Florida and Georgia.

In the subsurface, karst features, such as submerged caves, large vugs, bedding plane voids and vertical joints, have been observed using borehole cameras or acoustic and optical televiewers. In west-central Florida, shallow groundwater circulation and high recharge rates contribute to large-scale dissolution of the carbonate rocks of the Floridan aquifer system along joints, fractures, and bedding planes. Knochenmus and Robinson (1996) classified secondary porosity from four test wells in west-central Florida into vugs, cavities, and fractures, based on definitions proposed by Safko and Hickey (1992). In these wells, they observed zones of vuggy porosity, fracture porosity, and large interconnected vugs intersected by high-angle fractures. The distribution of secondary porosity features in these wells indicated dissolution commonly occurs at major lithologic contacts creating horizontal preferential flow zones at these contacts. They noted that the majority of water is produced from highly fractured and vuggy dolomitic units of the Avon Park Formation and concluded that the types of secondary porosity are different in limestone and dolomite sequences, possibly because of the differing responses of softer limestone and harder brittle dolostone to stress (Knochenmus and Robinson, 1996).

In northeastern Florida and southeastern Georgia, Williams and Spechler (2011) used acoustic televiewer (ATV) images, flowmeter logs, and borehole geophysical logs to identify and map the types and distribution of highly transmissive production zones in rocks of the Floridan aquifer system. The ATV images and flowmeter traverses also indicated that water in most wells is largely derived from systems of highly transmissive solution zones formed along bedding planes and major formational/lithologic contacts. These features were referred to as horizontal bedding-plane conduit systems and used to modify a conceptual model of how these systems may locally influence the movement of brackish and saline water in the Floridan aquifer system.

An example of a horizontal bedding-plane conduit system near the base of the Oldsmar Formation in Brunswick, Ga., is shown in figure 13. The ATV displays an oriented image of the borehole wall projected onto a flat plane. Cardinal directions are indicated at the top of the image. Horizontal or low-angle features intersecting the borehole, such as bedding planes, appear as horizontal lines across the image. Moderately to steeply dipping features are displayed as sinusoidal curves, with the lowest point on the curve indicating the dip azimuth.

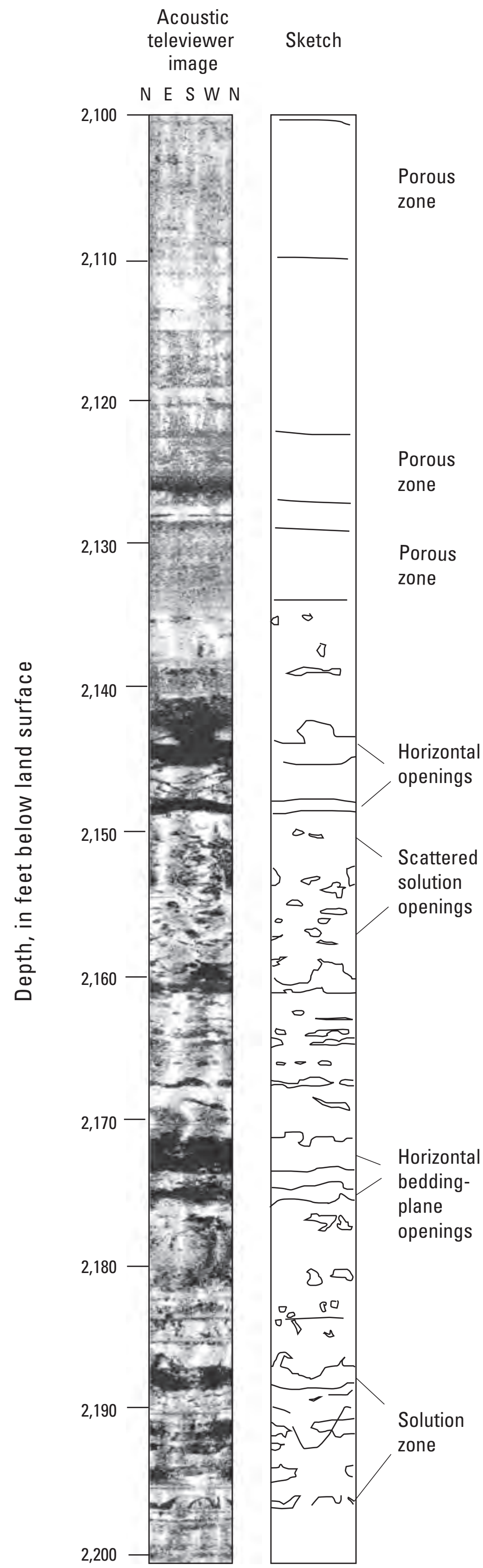


Figure 13. Acoustic televiewer image from 2,100 to 2,200 feet showing solution openings formed along bedding planes and in discrete zones near the base of the Oldsmar Formation in test well GA–GLY9, Brunswick, Georgia (well location shown on plate 1).

Numerous horizontal openings can be observed parallel to bedding planes and are notably visible within the ATV image interval shown in figure 13. The larger openings are approximately 1- to 2-ft wide and were first indicated during drilling by frequent drops in the drill bit. In well GA–GLY9 (pl. 1), this pattern of solution-riddled zones separated by confining beds repeats several times within the middle and lower part of the Avon Park Formation and underlying Oldsmar and Cedar Keys Formations. (Only a small part of the ATV image near the base of the Oldsmar Formation is shown in fig. 13.) The deepest and most cavernous of the solution intervals identified in this well is the Fernandina permeable zone (Miller, 1986).

Within areas where an aquifer consists of discrete horizontal openings separated by lower permeability rock, flow paths within the aquifer system can be greatly restricted vertically by local or regional confining units, except where these confining units are breached by collapse features or vertical fractures (fig. 14). Near major pumping centers, such as in the Jacksonville area in northeastern Florida, water probably moves preferentially along horizontal conduits toward discharging wells. The source of water moving into the transmissive conduits is either derived from upward migration along vertical fracture systems or from more diffuse leakage from adjacent porous rock units. Some trapped relict water in adjacent lower permeability units may locally contribute to the high chloride concentrations observed in some wells (Wait, 1962, 1965; Wait and Gregg, 1973).

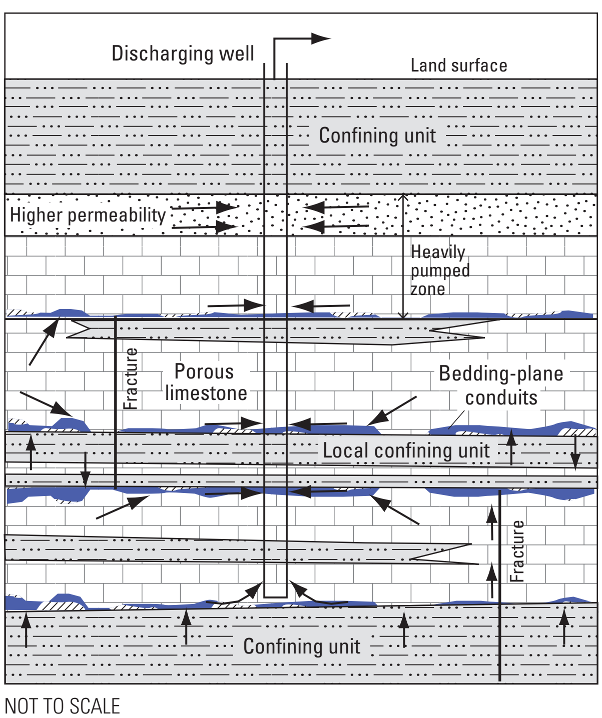


Figure 14. Conceptual model of well tapping horizontal conduit systems. Arrows indicate general direction of groundwater movement.

Geophysical-Log Correlation Marker Horizons

An important aspect of the revised hydrogeologic framework was to identify and use recognizable geophysical log markers or distinctive log patterns to help identify and map the major and minor hydrogeologic units of the Floridan aquifer system. Regionally, geophysical logs have been widely used to identify distinctive lithologic and formational units in the study area (Renken, 1996). These logs often are the only reliable information that can be obtained from a well to identify units, particularly in areas where drilling fluids are lost and drill cuttings are not available. Although a wide variety of logs are collected for various reasons, the gamma-ray, electric resistivity (including long and short normal, spherically focused, and lateral logs), and induction logs primarily are used because of their wide availability and the distinctive responses each provides across the rocks units being studied. Johnson (1984) identified gamma-ray and electric-log characteristics of nine formations in peninsular Florida, ranging from Paleocene to Pliocene, and many others have used geophysical markers (Wait, 1962; Wait and Gregg, 1973; Winston, 1977; Kwader, 1982; Clarke and others, 1990; Reese, 1994, 2000; Reese and Richardson, 2008). Although geophysical log markers were extensively used in this study, several were particularly important in helping to define and map specific hydrogeologic units:

- Gamma-ray markers A, B, C, and D observed in rocks of late Eocene to Miocene in the coastal region of Georgia and South Carolina were used to define several permeable beds in the upper confining unit and to identify the top of the Suwannee Limestone (or age-equivalent formations) and the Ocala Limestone that forms the most permeable part of the Upper Floridan aquifer.
- A gamma-ray pattern at the base of the Hawthorn Group delineating the lower Hawthorn marker unit in southern Florida was used to identify the top of the uppermost permeable zone in the Floridan aquifer system.
- A distinctive high electrical resistivity pattern across the first low-porosity, locally massive, dolostone unit in the Avon Park Formation in southeastern Georgia and peninsular Florida was used to remap permeable and less-permeable zones associated with this horizon.
- A subtle gamma-ray peak denoting the glauconite marker horizon in probable early Eocene rocks in central and southern Florida, and extended by way of correlation into north-central Florida, was used to define a semiconfining unit in the deeper part of the aquifer system. This peak is referred to hereafter as the "glauconite marker."
- Several distinctive gamma-ray and resistivity markers were used to map various basal units of the Floridan aquifer system in central and southern Florida.

In the coastal region of Georgia and South Carolina, gamma-ray markers have long been used to map permeable strata within the upper confining unit and to identify permeable formations near the top of the Floridan aquifer system. These include gamma-ray markers A through D of Clarke and others (1990), originally defined by McCollum and Counts (1964), Wait (1962), Wait and Gregg (1973), and shown in figure 15*A*. Gamma-ray marker C approximates the top of the Suwannee Limestone or age-equivalent Oligocene strata, and generally has been used to map the top of the Floridan aquifer system in the coastal regions of Georgia and South Carolina. Gamma-ray marker D, which approximates the top of the Ocala Limestone of late Eocene age, marks the first major permeable zone of the Floridan aquifer system (Williams and Gill, 2010). Although these gamma-ray markers have never been extended into northeastern Florida, similar gamma-ray patterns described by Johnson (1984), as well as other local markers, are locally used to define the top of the Floridan aquifer system (Davis and others, 2001). In southern Florida, Reese and Richardson (2008) describe a gamma-ray signature widely used to delineate permeable strata at the base of the Hawthorn Group, which is usually the uppermost permeable zone of the Upper Floridan aquifer. The signature includes two gamma-ray peaks separated by an interval of lower gamma radiation (fig. 15*B*). This marker has been used in southwestern Florida (Reese, 2000), Palm Beach County (Reese and Memberg, 2000), and Martin and St. Lucie Counties (Reese, 2004), and is reported to be persistent over much of southern Florida, ranging from 50 to 100 ft thick (Reese and Richardson, 2008).

In this study, a distinctive high-resistivity (low-porosity) interval near the top of the Avon Park Formation was first noted over a fairly extensive area of southeastern Georgia and northeastern Florida. This marker, informally designated the "Avon Park upper dolostone unit" (upper dolostone unit, hereafter), was first identified using logs from several test wells in Brunswick, Ga. (Jones and others, 2002; Falls and others, 2005a) and a test well in Waycross, Ga.

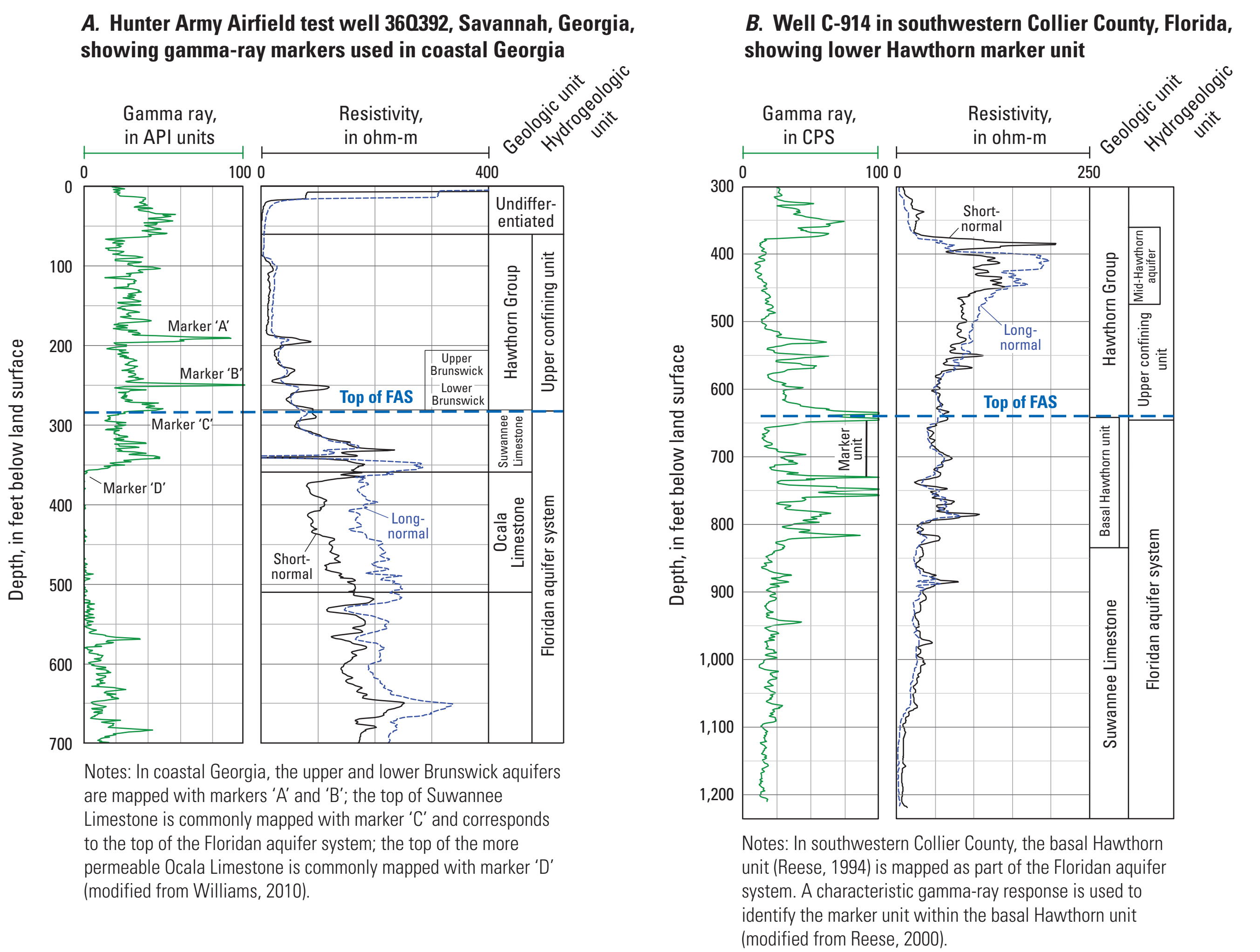


Figure 15. Geophysical marker horizons used for mapping hydrogeologic units in the Floridan aquifer system. [API, American Petroleum Institute; ohm-m, ohm-meter; CPS, counts per second; FAS, Floridan aquifer system; well locations shown on plate 1]

(Matthews and Krause, 1984), and then farther south as a less-pronounced resistivity response in a well at Fernandina Beach, Fla., (Brown, 1980) and in test wells in Jacksonville, Fla. (Brown and others, 1984, 1985). In correlation logs used by Miller (1986), this highly resistive low-porosity unit is mapped as middle confining unit MCUI, consisting of hard dolomitic limestone and dolostone and is identified by Johnson (1984) as a characteristic series of resistivity peaks near the top of the Avon Park Formation.

The upper dolostone unit, as defined in this study, is mapped largely on the basis of electrical resistivity, or resistivity contrasts, with underlying and overlying units. Sonic, neutron, and density logs can also be used to identify the sequence of beds of very low porosity (usually less than 10 percent) that are characteristic of this unit; however, these types of logs are far less common than electric logs. One of the better examples of the upper dolostone unit can be observed in a borehole geophysical log obtained from a USGS test well in Waycross, Ga. (GA–WA2, fig. 2). As shown in figure 16, formation resistivity is not necessarily uniform across this unit, but the overall resistivity response is relatively high compared to that of units above and below it. The top of the unit is commonly indicated by a distinctive massive dolostone bed ranging from 30 to 50 ft in thickness. Although the dolostone unit is obvious and clearly delineated in the spherically focused resistivity log used in this example, it is noted that such a prominent resistivity contrast may not be as apparent in long- and short-normal resistivity logs, which tend to smear out the resistivity across thin resistive beds.

The upper dolostone unit mostly is composed of dolostone, although dolomitic limestone and limestone also compose part of this interval locally and can be a dominant component in certain areas. In Alachua, Lake, Marion, and Polk Counties, Fla. (fig. 1), Johnson (1984) described this unit as a series of thin resistive zones interbedded with less resistive units and called it the false dolostone zone. In a test well in Alachua County, Fla. (A–0366, location shown on pl. 1), this unit is composed almost entirely of a moderate to pale yellowish-brown low-porosity limestone (Brooks, 2006).

One notable aspect of the upper dolostone unit, besides being an important correlation marker, is that it is considered to be semiconfining in the northern part of its extent and is included in the MCUI region of the LISAPCU (discussed later), but becomes part of the highly permeable APPZ (see relation shown in fig. 7). The configuration of this marker bed generally conforms to the dip of the rocks in the upper part of the Avon Park Formation (fig. 17). The upper dolostone unit may represent an extensive zone of dolomitization or a stratigraphic horizon that has a characteristically low porosity. Another possibility is that the upper dolostone unit may represent a series of disconnected dolomitized zones or low-porosity zones in the upper part of the Avon Park Formation. In either case, this interval seems to be correlative over a wide area and can be used reliably in conjunction with other markers to identify hydrogeologic units within the Floridan aquifer system.

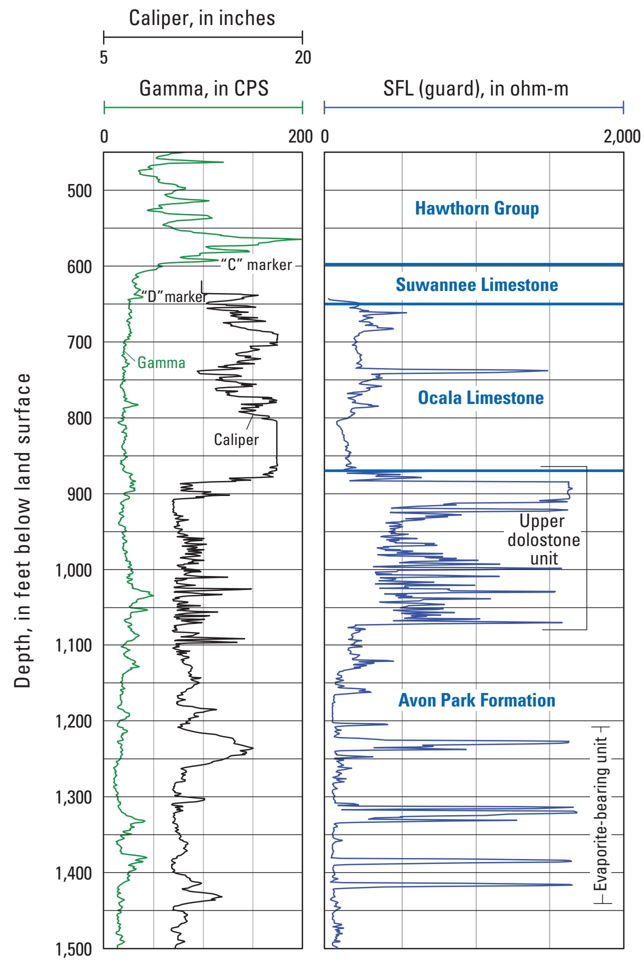


Figure 16. Borehole geophysical log characteristics of the upper dolostone unit of the Avon Park Formation in test well GA–WA2, Ware County, Georgia. [CPS, counts per second; SFL, spherically focused log (resistivity); ohm-m, ohm-meter; well location shown on plate 1]

Another glauconite geophysical log marker is present along Florida's southeastern coast in Brevard, Martin, St. Lucie, and Palm Beach Counties (fig. 1), where Duncan and others (1994a, b) noted the presence of a distinctive glauconitic interval located in the uppermost part of the Oldsmar Formation. They called this interval the glauconite marker bed and described its stratigraphic position as being slightly above the Boulder Zone. Fracturing and cavernous intervals were noticeably absent, and this sequence was believed to be part of the confining sequence overlying deep injection zones in the Boulder Zone that could be mapped using a distinct gamma-ray marker. Reese and Richardson (2008) extended this marker on the basis of gamma-ray log correlation and called it the glauconite marker horizon. They indicated that although there is some variation in the gamma-ray patterns between individual wells, a correlative pattern can be recognized by considering the entire section and taking into account local thinning and thickening as a result of erosion or non-deposition, faulting, or slight changes in lithology.

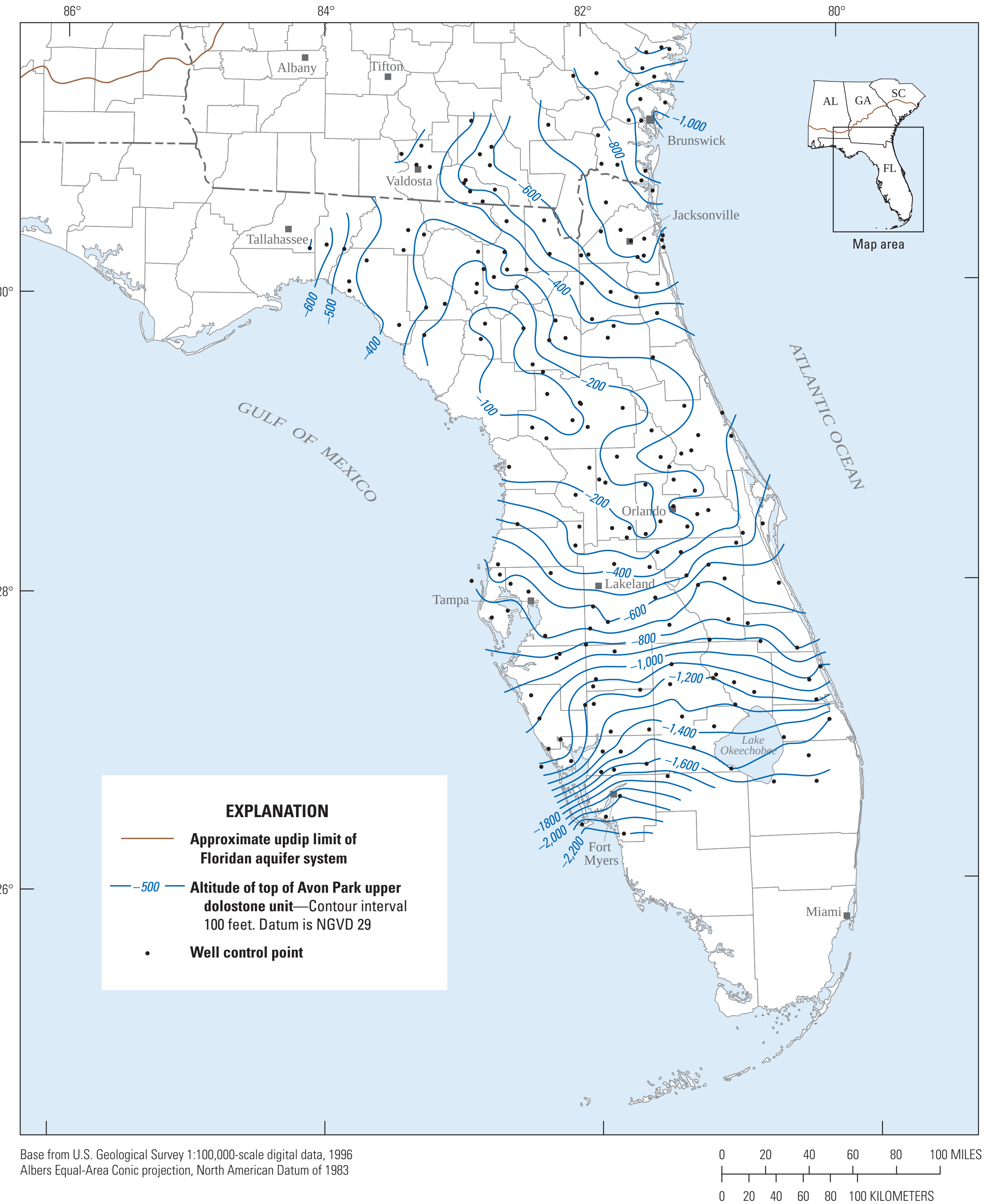


Figure 17. Altitude of the top of the upper dolostone unit in the Avon Park Formation, peninsular Florida, northeastern Florida, and southeastern Georgia.

One of the better examples showing the geophysical characteristics of the glauconite marker in the upper part of the Oldsmar Formation is present in logs obtained from Opal Knight Unit #19–2 (P679A) in De Soto County, Fla. (figs. 2 and 18, plate 1). This marker is the first gamma-ray peak, or bulge, below an interval of generally lower gamma radiation. The marker generally is coincident with the upper part of a low-resistivity interval, labeled the “glauconite marker unit” in figure 18. The glauconite marker unit is described later in this report and is a new unit defined in the hydrogeologic framework.

Using data points from previous reports and from mapping conducted during this study, the glauconite marker horizon of Reese and Richardson (2008) was extended much farther north than previously mapped. The revised and extended structural surface of this horizon is shown in figure 19. The data points used to construct this map were based on correlations made during this study between representative borehole geophysical log data collected in Brevard County, Fla., and data presented in Duncan and others (1994a, b). Because the glauconite marker is associated with a zone of low resistivity, the low-resistivity characteristic was also used in conjunction with the gamma-ray signatures. In north-central Florida, where fewer gamma-ray logs are available for correlation, the low resistivity characteristic of the interval is used in lieu of the gamma-ray log signatures.

A second gamma-ray marker, denoted as the “basal gamma-ray marker” in figure 18, is a local geophysical marker that is usually associated with a low-resistivity interval below a massive dolomitic interval. Like many of the gamma-ray markers in this area, it is not extensive enough to use as a regional marker but may be useful for local correlations. The extent of this marker, which was identified as part of this study, is not presently known, but it appears to be fairly persistent across south-central Florida.

A few additional geophysical log patterns were used to identify hydrogeologic units near or below the base of the Floridan aquifer system. The first pattern is characterized

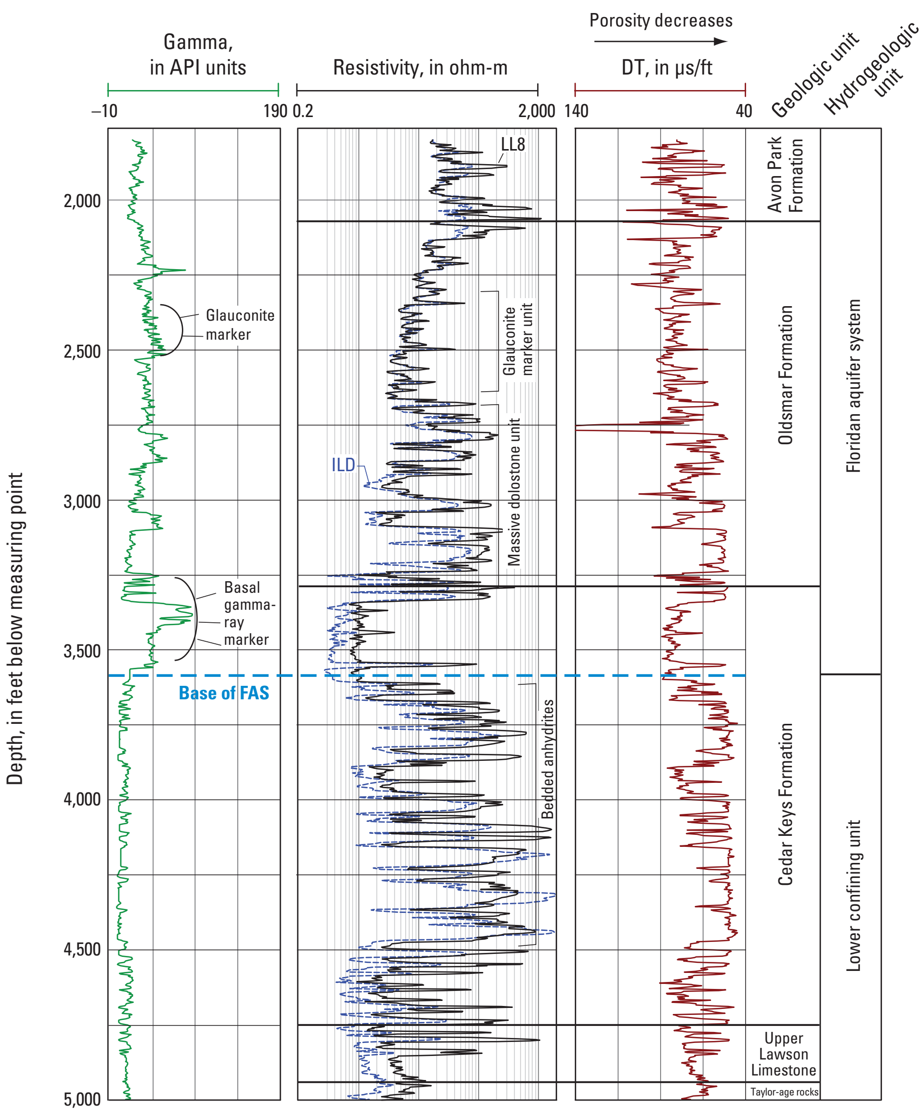


Figure 18. Gamma-ray and resistivity markers used to map basal units of the Floridan aquifer system from well P679A, Opal Knight Unit #19-2, De Soto County, Florida. [Measuring point altitude is 121 feet NGVD 29; API, American Petroleum Institute; ILD, induction log deep; LL8, laterolog 8; ohm-m, ohm-meter; DT, interval transit time; µs/ft, microseconds per foot; FAS, Floridan aquifer system; well location shown on plate 1]

Notes: In peninsular Florida, the base of the Floridan aquifer system is mapped on the top of a massive bedded anhydrite sequence in the Cedar Keys Formation. This unit has a distinctive resistivity pattern with extremely high and low resistivity peaks on the resistivity logs and very low porosity, as indicated by the interval transit time log (DT). Above the anhydrites, the basal part of the Floridan includes a characteristically low-resistivity unit (glauconite marker unit) and a massive dolostone unit (Oldsmar permeable zone). These two units are commonly marked by distinctive gamma-ray markers (see above). Glauconite marker is the subtle gamma-ray bulge whose top is at about 2,370 feet below the measuring point.

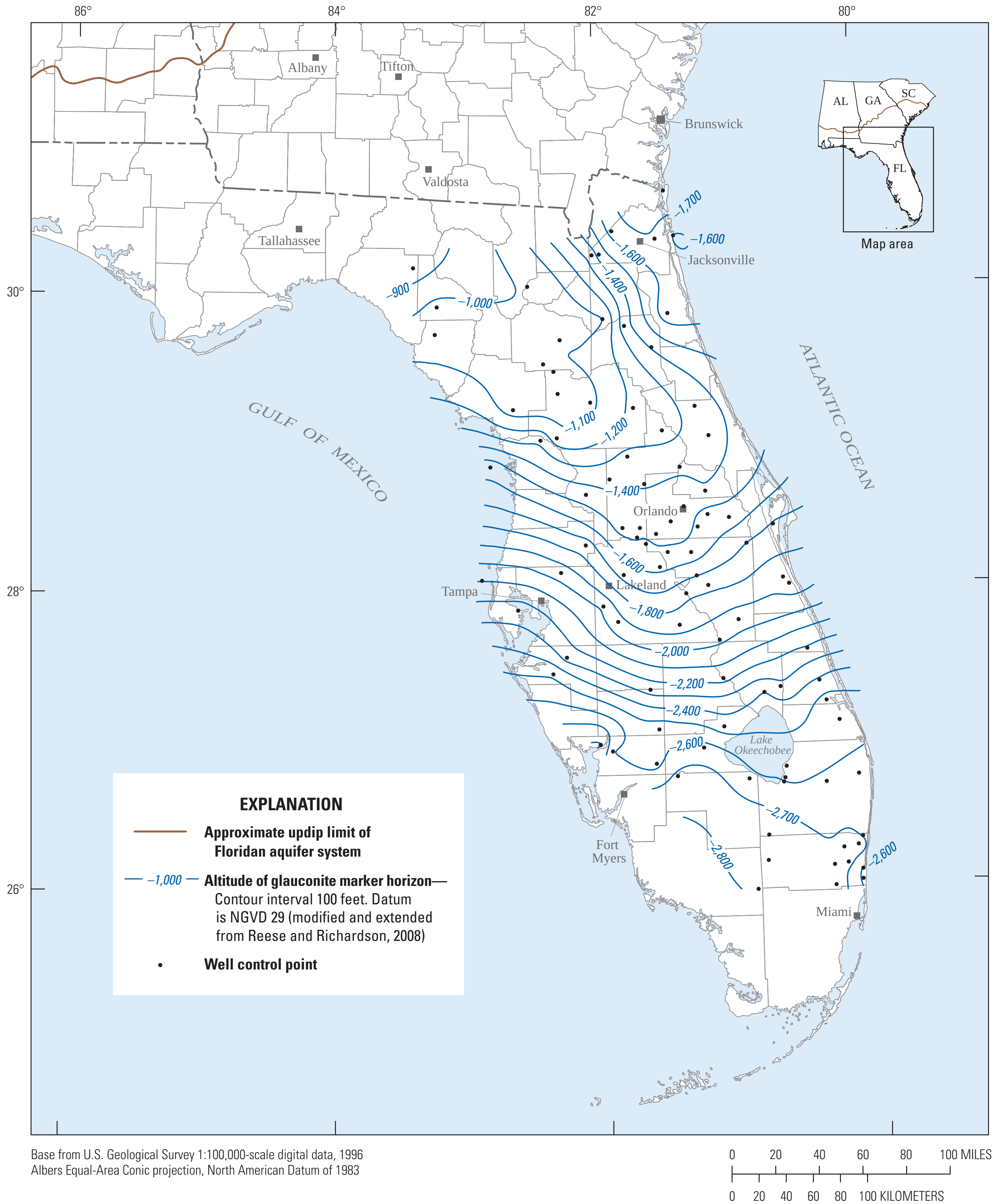


Figure 19. Altitude of the glauconite marker horizon, peninsular and northeastern Florida.

by very high resistivity zones with associated sharp low-resistivity zones that develop in thickly bedded sequences of limestone and dolostone, informally designated the "massive dolostone unit" (fig. 18). This unit is believed to be entirely within the Oldsmar Formation and is identified as the Delray Dolomite (Winston, 1995). High resistivity intervals represent low-porosity dolostone, whereas the low-resistivity intervals represent fractures, cavernous zones, or high-porosity limestone interbeds within the massive dolostone unit.

Just below the massive dolostone unit, a second log pattern is characterized by a relatively uniform low resistivity log response that appears to correspond to an interval in the upper part of the Cedar Keys Formation, previously named Cedar Keys "A" by Winston (1977, 1994; and, 1995). From drill cuttings and core samples, this interval has been described as a finely pelletal limestone and gypsiferous limestone of relatively high porosity and low permeability.

In peninsular Florida, the base of the Floridan aquifer system usually is mapped just above a massive bedded anhydrite sequence in the Cedar Keys Formation (Miller, 1986). This bedded anhydrite sequence produces a distinctive resistivity pattern shown in the logs presented in figure 18. The anhydrite section is identified by a sharp increase in resistivity and a decrease in the interval transit time log as a result of a substantial decrease in porosity.

Hydrogeologic Units

In this section, the top, bottom, and overall configuration of major and minor hydrogeologic and composite units are discussed. The two major groundwater flow systems in the study area are the surficial aquifer system and the Floridan aquifer system. These systems interact with each other to varying degrees and are separated over much of their extent by a lower permeability sequence of clastic sediments called the upper confining unit of the Floridan aquifer system. The upper confining unit also contains the intermediate aquifer system and Brunswick aquifer system, which locally interact with the Floridan and surficial aquifer systems. The Floridan is underlain everywhere by low-permeability rocks called the lower confining unit, which separates the Floridan aquifer system from older, deeper aquifers of the Southeastern Coastal Plain aquifer system.

Surficial Aquifer System

The uppermost hydrogeologic unit in the study area is the surficial aquifer (Miller, 1986) or, as identified in this report, the surficial aquifer system. The system includes all permeable material, other than the Floridan aquifer system outcrops, that contains water under mostly unconfined conditions (Miller, 1986). The surficial aquifer system consists mostly of sand and locally contains gravel and sandy limestone of Pliocene to Holocene age. Where these sediments are thick and highly permeable, they have been assigned to local aquifers, including the sand and gravel aquifer in the western Florida panhandle (Hayes and Barr, 1983) and the lower Tamiami (Shoemaker and Edwards, 2003), gray limestone aquifer (Reese and Cunningham, 2000), and Biscayne aquifers (Fish and Stewart, 1991) in southern Florida. With the exception of the gray limestone and Biscayne aquifers, the surficial aquifer system is composed of clastic material. The gray limestone and Biscayne aquifers are composed of carbonate rocks. The surficial aquifer system may be in direct contact with the Floridan aquifer system or separated from it by confining beds; in west-central Florida, the system overlies the intermediate aquifer system.

A map showing the aggregated thickness of the surficial materials above the upper confining unit or the intermediate aquifer system/intermediate confining unit was constructed using data from 4,610 wells (fig. 20). Thickness was determined from lithologic logs, geophysical logs, or a combination of both sources of information. The data include information from the Floridan Aquifer Vulnerability Assessment dataset (Arthur and others, 2007a) and from the hydrogeologic framework dataset of the SWFWMD (Arthur and others, 2008). In addition to these sources of information, a large number of control points were provided by Jeffery B. Davis (St. Johns River Water Management District, written commun., 2012), and additional data were obtained from the SFWMD database DBHYDRO.

Surficial deposits are thickest in the western Florida panhandle and coastal Alabama in the sand and gravel aquifer. In this region, sediment thickness increases dramatically westward into the Gulf Coastal Plain and may exceed 1,200 ft (figs. 10 and 20). Coarse-grained deposits of the sand and gravel aquifer are part of the Citronelle Formation, Miccosukee Formation, and undifferentiated sediments.

In the northern part of peninsular Florida, the surficial deposits are highly variable in thickness and may not form an aquifer system in all parts of that area. The Anastasia Formation and Cypresshead Formation, as well as limestone and shell beds that are equivalent to the Caloosahatchee and Fort Thompson Formations, are reported to form this surficial aquifer system (Scott and others, 1991).

In southern Florida, the surficial aquifer system includes rocks and sediments of the Tamiami, Fort Thompson, and Anastasia Formations, and the Key Largo and Miami Limestones. Reese (1994) reported that the surficial aquifer system extends from land surface to a depth of 160 to 350 ft in Broward County (Fish, 1988). To the south in the Miami-Dade County area, the Biscayne aquifer is included in the surficial aquifer system (Fish and Stewart, 1991) and is the primary source of freshwater. The thickness of the surficial aquifer system varies widely throughout southeastern Florida, but generally ranges from 100 to 200 ft in inland areas (fig. 20) and exceeds 300 ft along the coastline (Schroeder and others, 1954, 1958; Reese and Memberg, 2000; Reese and Wacker, 2009). In St. Lucie and Martin Counties, the surficial aquifer system consists of quartz sand, silt, clay, shell beds, coquina, calcareous sandstone, and sandy, shelly limestone (Reese, 2004).

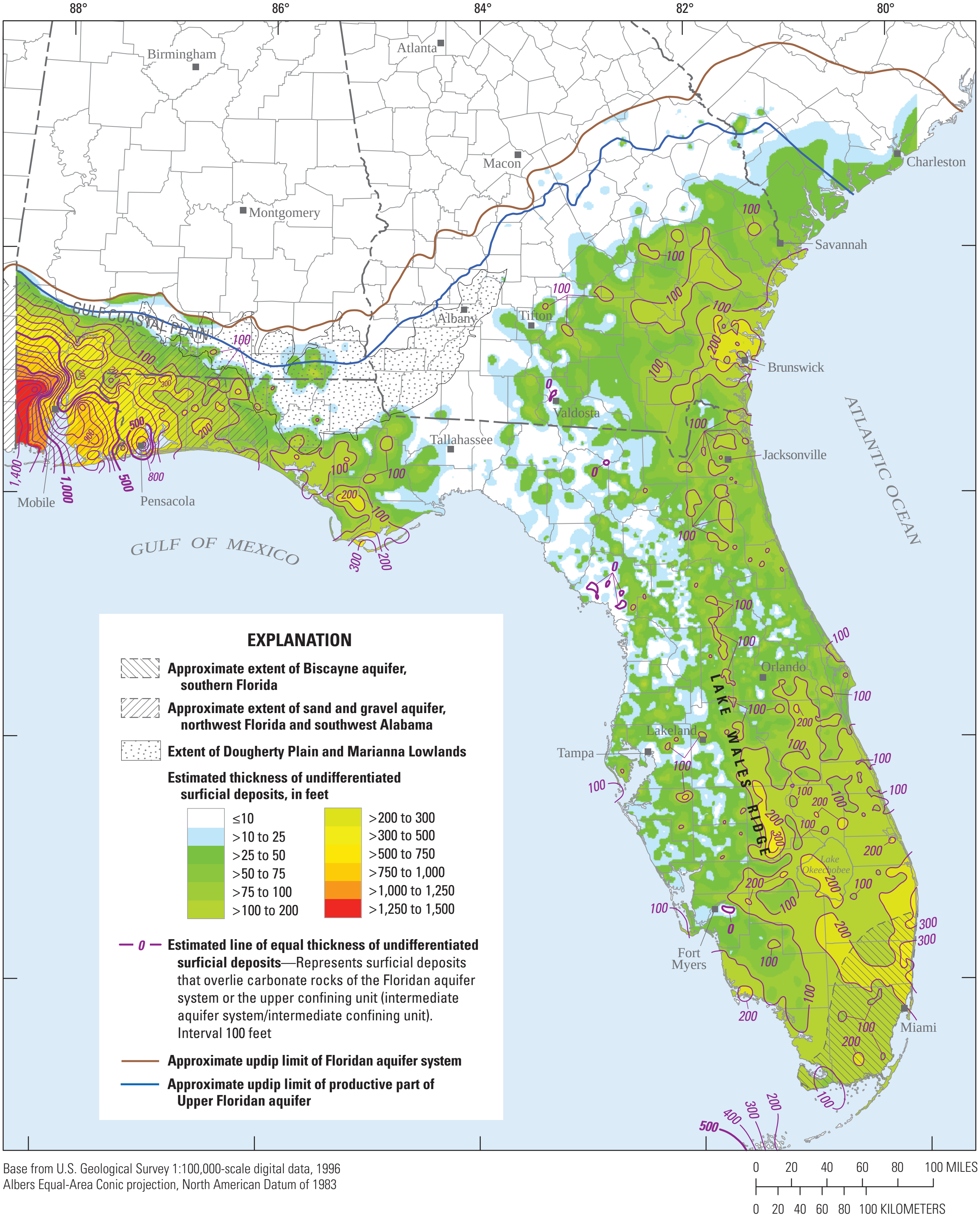


Figure 20. Estimated thickness of undifferentiated surficial deposits that may, in part, compose the surficial aquifer system, southeastern United States (see plate 3 for more detail).

In Highlands County of south-central Florida, as well as other recharge areas where surficial materials are thick, the surficial aquifer system is an important component of the groundwater flow system because it provides temporary storage of infiltrating water that eventually recharges underlying aquifers or discharges laterally to surface-water bodies (Spechler, 2010). The highest recharge rates were identified along Lake Wales Ridge (fig. 20), which is characterized by poorly developed stream drainage and closed depressions. Thick deposits along the ridge absorb most of the infiltrating rainfall that is not lost to evapotranspiration. Deposits of similar thickness and character are present in Polk County, Fla. (Spechler and Kroening, 2007).

In northeastern Florida and southeastern Georgia, the thickness of the surficial aquifer system is substantial and the system forms a receiving zone for diffuse (upward) discharge from the Floridan aquifer system in low-lying coastal areas. In northeastern Florida, the surficial aquifer system ranges from 10 to more than 100 ft (fig. 20) thick and is composed of two units: a water-table unit consisting of Holocene and Pleistocene sand deposits 25 to 50 ft thick and an underlying Pliocene or Miocene limestone unit about 5 to 40 ft thick (Phelps, 1994). Farther north along the coastal region of Georgia, the surficial aquifer system consists mostly of Pleistocene and Pliocene sands and clays and, in some areas, hydraulically connected Miocene sediments (Gill and others, 2011). In coastal Georgia, the surficial aquifer system consists of three zones—the shallow water-table zone and two deeper zones identified as the confined upper and confined lower water-bearing zones (Leeth, 1999). The areal extent of the confined units of the surficial aquifer system is generally not known.

In southwestern Alabama and the westernmost part of the Florida panhandle, the surficial aquifer system is thick and permeable, and serves as the primary source of water for Baldwin County, Washington County, and western Escambia County, Ala., and for Santa Rosa and Escambia Counties, Fla. (Miller, 1990). In this area, the aquifer system is called the sand and gravel aquifer (Miller, 1990) but locally is also known as the Miocene-Pliocene aquifer in Alabama. Because of declining water levels in the Floridan aquifer system, Hayes and Barr (1983) assessed the sand and gravel aquifer as an additional source of water supply in southern Okaloosa and Walton Counties, Fla. In the Florida panhandle, the sand and gravel aquifer is differentiated into the surficial water-table zone (unconfined) and the main producing zone (confined). The water-table zone is composed of fine- to medium-grained sand, whereas the main producing zone is mostly coarse sand and fine gravel. Where present, layers of clay, sandy clay, and clayey sand separate the water-table zone from the producing zone. Large-diameter wells in southwestern Okaloosa County reportedly yield 500 to 1,000 gal/min from this aquifer (Hayes and Barr, 1983).

Upper Confining Unit

The upper confining unit (also known as the intermediate aquifer system/intermediate confining unit in Florida) overlies and confines the Floridan aquifer system. The upper confining unit includes all low-permeability late and middle Miocene beds, where present, and locally includes low-permeability post-Miocene beds (Miller, 1986). The generalized thickness and extent of the upper confining unit is shown in figure 21 and a more detailed version of this map is presented on plate 3. Interbedded, locally phosphatic, sand, silt, and clay are the predominant clastic components of the upper confining unit. Locally, lower permeability early Miocene carbonate rocks are included in the upper confining unit. A residuum of limestone may locally form a semiconfining layer in the outcrop areas of the Upper Floridan aquifer, such as in southwestern Georgia, but generally is not considered part of the upper confining unit. The upper confining unit may be breached locally by sinkholes and other openings that connect the Floridan aquifer system to the surficial aquifer system or directly to land surface. Local aquifers are present in the upper confining unit where thick, permeable sand beds or sandy limestone beds are present, including the intermediate aquifer system of southwestern Florida (Knochenmus, 2006; Torres and others, 2001) and the Brunswick aquifer system of coastal Georgia (Clarke and others, 1990; Clarke, 2003).

An updated map showing the thickness and extent of the upper confining unit (pl. 3) was developed using data from 4,610 wells from the same sources of information listed previously for the surficial aquifer system. Three shaded regions on plate 3 serve to depict areas of relative degree of confinement: (1) confined areas more than 100 ft thick, (2) thinly confined areas less than 100 ft thick, and (3) unconfined areas where the upper confining unit is absent or very thin. The thickest parts of the upper confining unit are in Miami-Dade County in extreme southern Florida where the thickness exceeds 1,000 ft, and in the southern parts of Escambia County, Fla., and Mobile and Baldwin Counties, Ala., where the thickness exceeds 1,800 ft.

Although the thickness of the upper confining unit is used to depict the relative degree of confinement of the Floridan aquifer system in this and previous reports, the lithologic character of the beds that form this unit is the principal factor that determines its confining properties and the degree to which it restricts movement between the surficial and Floridan aquifer systems. Where the beds consist mostly of thick, low-permeability, plastic clays, leakage across the upper confining unit is negligible. Conversely where the beds consist of clayey sand, limestone, dolostone, and silty clay, higher leakage rates probably occur.

In northeastern Florida and southeastern Georgia, Brown (1984) estimated the upper confining unit to be about 400 ft thick, consisting entirely of sediments in the Hawthorn Group. Based on laboratory analysis of core samples from wells in Duval County, Fla., Franks and Phelps (1979) estimated

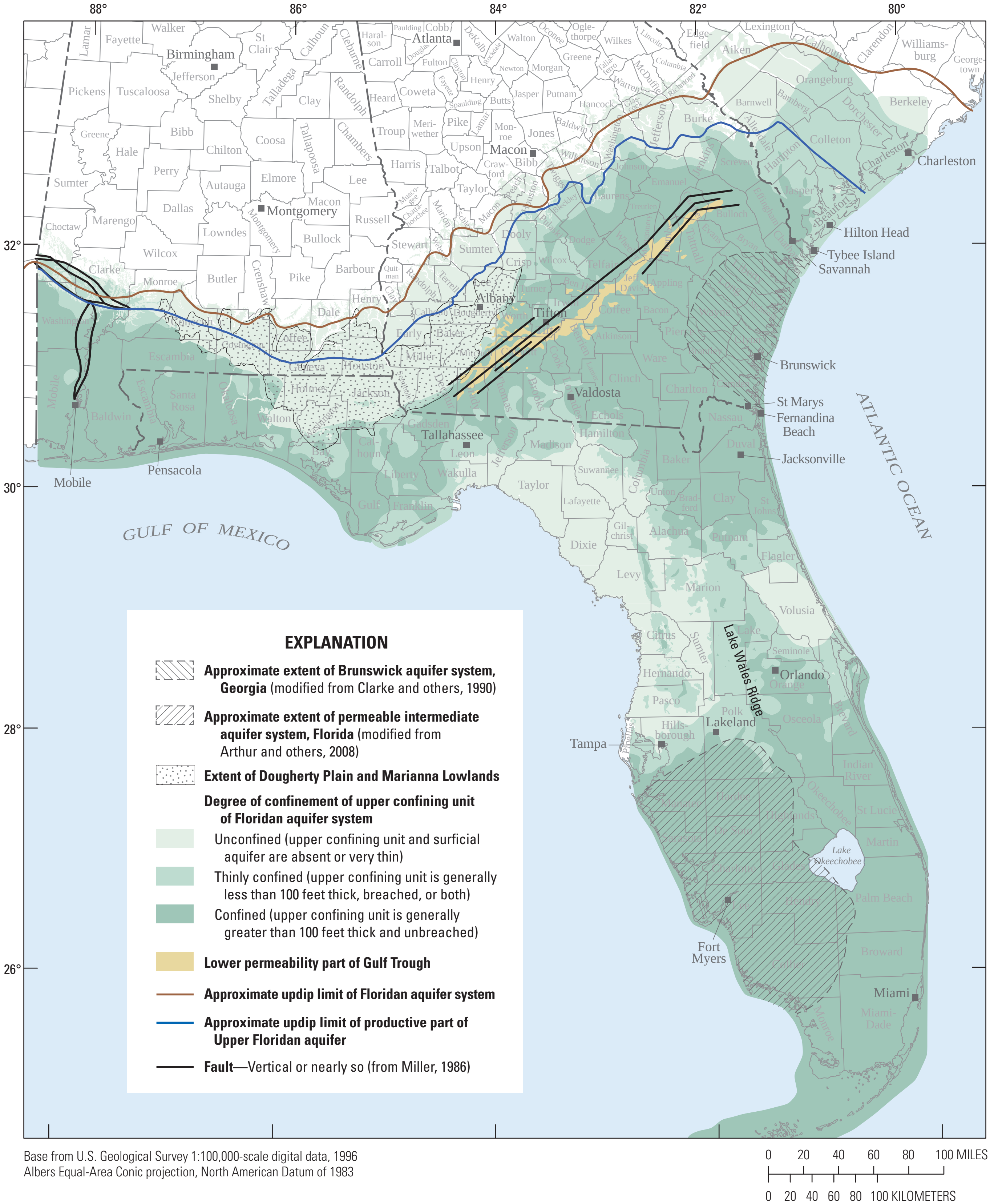


Figure 21. Relative degree of confinement of the upper confining unit of the Floridan aquifer system and extent of the intermediate and Brunswick aquifer systems (see plate 3 for more detail).

the hydraulic conductivity of the upper confining unit to be 1×10^{-3} foot per day (ft/d). A similar value was reported for this unit in the Osceola National Forest (Miller and others, 1978).

In areas where thick sections of the upper confining unit overlie the Floridan aquifer system, it is commonly believed that leakage across the upper confining unit is small. In a rare opportunity, however, the response of leakage across the unit (estimated to be 400 ft thick) to decreased pumpage from the Upper Floridan aquifer was observed in St. Mary's, Ga., in Camden County following the cessation of operations at a pulp and paper mill in October 2002 (Peck and others, 2005; fig. 21). As a result of a decrease in pumpage of 35.6 million gallons per day (Mgal/d), there was an observed recovery response in nearby confined surficial, upper Brunswick, and Upper and Lower Floridan aquifer monitoring wells over a period of 8 to 12 months (Peck and others, 2005). Average hydraulic head differences between the surficial and Brunswick aquifer wells before the plant shutdown was –3.81 ft, indicating a downward gradient between the surficial and Brunswick aquifers, compared to +11.43 ft after the shutdown, thus yielding a net hydraulic head increase of about 15 ft. The total apparent recovery response in the Brunswick well during the 12 months following the shutdown was estimated to be about 17.6 ft, indicating substantial leakage was occurring across the upper confining unit as a result of the local pumpage from the Floridan aquifer system.

At St. Mary's, Ga. (see fig. 21 for location), the upper confining unit consists mostly of greenish shelly phosphatic clay with beds of clayey limestone, pale olive phosphatic fine sand to light olive very fine sand, and clay with very fine sand and minor phosphate with a total thickness of approximately 400 ft (Falls and others, 2005a). Farther south, at Fernandina Beach, Fla., Brown (1980) described a similar sequence of the upper confining unit measuring approximately 300 to 400 ft thick and consisting of dark olive-green clay, dark olive-green sand and clay, dark gray phosphatic fine- to coarse-grained sand, dolomitic sand, and a basal dark olive-green dolomite. The grain size of the materials forming the upper confining unit appears to increase westward based on descriptions from a test well in Waycross, Ga. (GA–WA2, location shown in fig. 2). Matthews and Krause (1984) describe the upper part of the upper confining unit in the Hawthorn Group, 100 to 400 ft below land surface, as mostly a fine- to coarse-grained sand with beds of cream-colored limestone, greenish-blue clay, and minor phosphate. The lower part of the upper confining unit, 400 to 600 ft below land surface, consists of dark brown, sandy, shelly dolostone. Based on this description, the upper confining unit near the Waycross test well location seems to have a higher sand content than that described near the coast and may partly explain the leakage observed locally in this area.

Farther north along the Georgia coastline and in southeastern South Carolina, the upper confining unit ranges from 100 to 250 ft thick and consists almost entirely of olive-green phosphatic clay of the Hawthorn Group, which is highly confining in that area. Near the city of Savannah toward the coast, the upper confining unit thins over the Beaufort arch, and within several of the coastal waterways, the unit apparently has been eroded away beneath paleochannels, thus providing a potential flow path for movement of seawater into the Floridan aquifer system (Falls and others, 2005b).

In 2000, the USGS in cooperation with the Georgia Environmental Protection Division, drilled several wells in the offshore area from Hilton Head Island South Carolina and Tybee Island, Ga. (fig. 21), to assess the thickness and hydraulic properties of the upper confining unit (Falls and others, 2005b). Geophysical logs and core samples collected from the test wells located at various distances offshore and within coastal rivers documented a confining unit thickness of 17 to 32 ft at two sites located in paleochannels and a confining unit thickness of 17 ft at another site where no paleochannel was present. In one test boring, approximately 35 ft of fine-grained paleochannel fill sediments directly overlie Oligocene strata of the Upper Floridan aquifer (Falls and others, 2005b). The vertical hydraulic conductivity of core samples of upper confining unit material ranged from 6.5×10^{-3} to 2.3×10^{-4} ft/d and the conductivity of two core samples of fine-grained paleochannel fill were 4.5×10^{-4} and 5.4×10^{-4} ft/d. These results indicate the upper confining unit and paleochannel materials have similar hydraulic properties (Falls and others, 2005b).

In the western panhandle of Florida, the upper confining unit of the Floridan aquifer system locally is called the Pensacola Clay. The lithology is predominantly a gray to bluish-black and light brown carbonaceous or calcareous clay with some very fine to coarse-grained sand, gravel, and shell fragments (Maslia and Hayes, 1988). Trapp and others (1977) identified the lowest permeability sediments in the lower part of the Pensacola Clay and named this unit the "Pensacola confining unit." The unit is similar to the other parts of the upper confining unit and restricts the movement of water between the surficial aquifer system and the Floridan aquifer system, depending on the thickness and lithologic character of the sediments in this interval. The Pensacola confining unit also prevents saltwater in Choctawhatchee Bay (see fig. 9 for location) and other coastal lakes and rivers from moving downward into the Floridan aquifer system. On the basis of geophysical and lithologic logs, aquifer test data, and simulation results, the vertical hydraulic conductivity of the Pensacola Clay is estimated to range from 1×10^{-7} to 1×10^{-4} ft/d (Maslia and Hayes, 1988).

In peninsular Florida, the upper confining unit has been evaluated in several local subregional studies. In a ground-water flow simulation of east-central Florida, leakance coefficients ranging from 1×10^{-6} to 6×10^{-4} feet per day per foot ((ft/d)/ft) were derived for the upper confining unit (Tibbals, 1990, p. E38, fig. 30). Simulated leakage rates to and from the Upper Floridan aquifer through the upper confining unit ranged from 3 to 20 inches per year (in/yr) in parts of Lake, Polk, and Highlands Counties, and in the eastern and northern parts of Orange County, whereas lower leakage rates of 0 to 3 in/yr were obtained for parts of Osceola, Okeechobee, Flagler, Putnam, Volusia, and St. Johns Counties where the upper confining unit was thicker and finer grained.

In west-central Florida, Ryder (1985) divided the upper confining unit into an upper confining bed, the intermediate aquifer system, and a lower confining bed. In Hardee and De Soto Counties and west-central Manatee County and northwestern Sarasota County where the intermediate aquifer system is thickest (ranging from 100 to 200 ft), the uppermost confining bed ranges from 25 to 100 ft thick and the lowermost confining bed ranges from 100 to 200 ft thick. Leakance from a calibrated simulation ranged from 1.0×10^{-5} to 7.0×10^{-5} (ft/d)/ft for the upper bed and from 3.0×10^{-5} to 7.0×10^{-5} (ft/d)/ft for the lower confining bed (Ryder, 1985). Similar values were obtained in a more recent simulation of this area (Sepúlveda, 2002) with the exception of the high leakance (1.4×10^{-3} (ft/d)/ft) derived along the Peace River (see fig. 9 for location) and its tributaries in south-central Hardee County and the fairly high leakance (3.1×10^{-4} to 6.0×10^{-4} (ft/d)/ft) assigned along the Lake Wales Ridge in east-central Highlands and southwestern Polk Counties that accounted for increased leakage in that area.

In east-central Florida, including Lake, Seminole, Volusia, Flagler, and Putnam Counties, the upper confining unit generally is less than 100 ft thick. The thickness can vary greatly over short distances, however, such as in karst areas where the upper confining unit ranges from less than 10 to over 100 ft thick (pl. 3, fig. 21). The leakance of this unit also varies widely as a result of the thickness variation and the local presence of breached areas of the upper confining unit. Leakance values from aquifer tests are reported to range from 1.4×10^{-4} to 1×10^{-2} (ft/d)/ft in Seminole County, northeastern Polk County, and eastern Orange County (Spechler and Halford, 2001). In a local groundwater flow simulation constructed for this area, the vertical hydraulic conductivity of the upper confining unit was divided into four zones on the basis of the thickness of the confining unit (Spechler and Halford, 2001). The vertical hydraulic conductivity assigned to these zones ranged from a low of 0.001 ft/d where their thickness is greater than 100 ft to a high of 0.05 ft/d in karst areas where their thickness is less than 50 ft (Spechler and Halford, 2001). Subsequent simulations have derived similar leakance values for east-central Florida ranging from 3.0×10^{-4} to 1.0×10^{-3} (ft/d)/ft (Sepulveda, 2002). From south-central to southeastern Florida, permeable beds of the intermediate aquifer system grade into lower permeability sediments and become the intermediate confining unit (or, as identified in this report, the upper confining unit). In this area, the lithology of the upper confining unit includes fine-grained sediments, including clay, marl, micritic limestone, and silt, which provide substantial confinement.

Intermediate Aquifer System

The intermediate aquifer system is an important source of water in several counties in southwestern Florida where the underlying Floridan aquifer system is brackish or saline. In that area, permeable beds within the Hawthorn Group form this aquifer (Knochenmus, 2006; Miller, 1990). The approximate extent of the permeable beds of the intermediate aquifer system is shown in figure 21. In general, the aquifer system is composed of a complex assemblage of carbonate and siliciclastic sediments with abrupt contacts between facies, resulting in permeable zones that are only locally hydraulically connected. The permeable zones consist of indurated limestone and dolostone, and in some places, unconsolidated clastic material (Knochenmus, 2006).

Transmissivity in the intermediate aquifer system ranges from 1 to 40,000 square feet per day (ft^2/d), rarely exceeding 10,000 ft^2/d, and generally is 2 to 3 orders of magnitude lower than that of the Floridan aquifer system (Knochenmus, 2006). Leakance between the intermediate aquifer system and the Upper Floridan aquifer was estimated to range from 1.1×10^{-6} to 6.0×10^{-3} (ft/d)/ft (Knochenmus, 2006). Data from the lowermost permeable zone (zone 3 of Knochenmus [2006]) indicates this part of the intermediate aquifer system is moderately well connected to the Floridan aquifer system, whereas the upper zone in the intermediate aquifer system generally is hydraulically separated (Ron Basso, Southwest Florida Water Management District, written commun., 2013). Near the Tampa, Fla., area, the intermediate aquifer system/intermediate confining unit has been breached by sinkholes, and groundwater withdrawals from the Upper Floridan aquifer have resulted in lowered water levels in some lakes and wetlands near major pumping centers (Lee and others, 2009).

Brunswick Aquifer System

Similar to the intermediate aquifer system in Florida, several permeable beds within the Hawthorn Group in Georgia form the upper and lower Brunswick aquifers (Clarke and others, 1990). These two aquifers generally consist of poorly sorted fine- to coarse-grained phosphatic, slightly dolomitic sand but locally the lower Brunswick is a carbonate aquifer. The upper Brunswick aquifer is mapped between geophysical markers A and B and the lower Brunswick aquifer is mapped between geophysical markers B and C (fig. 15*A*). Clarke and others (1990) identified the lower Brunswick aquifer entirely within Miocene sediments and indicated that it is absent in the Savannah, Ga., area because sediments either had been eroded away or were never deposited. Later studies by Weems and Edwards (2001) determined that sediments equivalent to those in the lower Brunswick aquifer are present in the northern coastal region of Georgia and identified them as part of the Oligocene-Miocene Tiger Leap Member (Williams and Gill, 2010).

The upper Brunswick aquifer has a reported transmissivity ranging from 15 to 3,500 ft^2/d and the lower Brunswick aquifer has reported transmissivity ranging from 25 to 4,700 ft^2/d (Clarke, 2003). The higher transmissivity values correspond to thicker, more permeable sand and carbonate beds in the Hawthorn Group in the Southeast Georgia embayment in the vicinity of Glynn and Camden Counties, Ga. Along and outside the margins of the Southeast Georgia embayment, permeable beds of the Brunswick aquifer system are discontinuous and, accordingly, the upper confining unit includes a higher percentage of fine-grained sediments (Payne and others, 2005).

Floridan Aquifer System

The Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama, consists of a relatively thick sequence of mostly Tertiary-age predominantly carbonate rocks whose permeability generally is several orders of magnitude greater than that of rocks that bound the system above and below (Miller, 1986). Over the majority of its extent, the aquifer system consists of a vertically continuous sequence of limestone and dolostone that is interconnected to varying degrees vertically and horizontally, except for the extreme updip part of the system where it thins and grades into stratigraphically equivalent clastic units of the Southeastern Coastal Plain aquifer system (Renken, 1996). The top and base of the aquifer system are shown on plates 4 and 5, respectively, and the thickness of the aquifer system, defined as all rocks between the upper and lower confining units, is shown on plate 6. Hydrogeologic sections *A–A′* through *Q–Q′* (pls. 7–23) show variations in the depth and thickness of the aquifer system, major aquifers, and mapped zones within the major aquifers.

Extent of System

In updip areas, Miller (1986) defined the extent of the Floridan aquifer system where its thickness was less than 100 ft and the clastic component made up more than 50 percent of the rock column. In this revision, the updip limit of the aquifer system is extended slightly northward to include equivalent updip clastic aquifers of the Southeastern Coastal Plain aquifer system (Renken, 1996) that are hydraulically connected to downdip carbonate units of the Lower Floridan aquifer of the Floridan aquifer system of Miller (1986; figs. 1, 3, and 9). In updip areas of Georgia and Alabama, the Pearl River aquifer of the Southeastern Coastal Plain aquifer system (Renken, 1996) grades laterally into the Lower Floridan aquifer of the Floridan aquifer system (Miller, 1986). In these areas, although the upper part of the aquifer system (non-productive part of the Upper Floridan aquifer) is highly dissected by streams flowing across the outcrop, these overlying rocks control the vertical downward recharge into underlying clastic units that laterally grade into the carbonate rocks of the Lower Floridan aquifer. In South Carolina, Miller (1986) showed that rocks composing the Upper Floridan aquifer grade into lower permeability clastic rocks by means of a facies change in that area. This change is approximated by the linear boundary paralleling the Allendale and Bamberg County line in South Carolina, shown on plate 4, which was confirmed with data from additional wells in a study of the northern coastal region of the system (Williams and Gill, 2010). Although the Upper Floridan aquifer is not used as a source of water supply northeast of this boundary, this area serves as the subcrop for the Lower Floridan aquifer where recharge occurs. Thus, the approximate updip limit of the productive part of the Upper Floridan aquifer (fig. 1) indicates where the Floridan aquifer transitions to predominantly clastic rocks from carbonate rocks and is closer to the extent of the Floridan aquifer system defined by Miller (1986), but is based on well yields and lithologic logs.

Permeable carbonate rocks of the aquifer system also have been shown to extend into the offshore areas beneath the Atlantic Ocean (Falls and others, 2005b; Johnston and others, 1982). Although important to the overall groundwater flow system, these offshore areas are neither discussed in detail nor mapped because only limited data are available. Where possible, tops of some hydrogeologic units were identified using offshore wells.

Top of System

The top of the Floridan aquifer system is marked by the start of a vertically continuous sequence of carbonate rocks located beneath either the upper confining unit or below the surficial aquifer system. Although high permeability is the principal factor that was established by Miller (1986) to delineate the top of the aquifer system, in practice, either a distinct change in water level in the drilling annulus or an increase in artesian flow is used to identify the top of permeable strata. By using permeability as the primary factor, lower permeability carbonate rocks at the top of the system commonly are excluded, even though these rocks may have some hydraulic connection to the aquifer system.

Because no single formation or time-stratigraphic unit marks the top of the Floridan aquifer system, local or regional variations in permeability and connectivity are used to define which carbonate units are included or excluded from the Floridan aquifer system. The approximate extents of the tops of various time-stratigraphic units that generally are known to compose the top of the system are depicted in figure 22. In any given area, however, one or several anomalous wells may be isolated in a disconnected or poorly connected carbonate unit that may not be representative of the regional aquifer system.

Over a large part of the Floridan aquifer system, the top is marked by Oligocene rocks (Suwannee Limestone or equivalent) where such rocks are permeable and in hydraulic connection with the main part of the system. In other areas, late Eocene (or, locally, middle Eocene) rocks mark the top of the system. In the updip areas of South Carolina, calcareous clastic rocks form the top of the aquifer system and generally consist of fossiliferous, argillaceous, glauconitic, and calcareous clays of lower permeability that are part of one or more formations in the Barnwell Group (pl. 2). In the outcrop area in the extreme updip part of the Floridan, rocks in the lower part of the middle Eocene (Santee Limestone in South Carolina or Tallahatta Formation in Alabama and Georgia) form the top of the aquifer system, and in this area the transmissive part of the system is the Lower Floridan aquifer.

Several major structural features affect the configuration of the top surface of the Floridan aquifer system. This influence is evident, for example, in southeastern Georgia where the aquifer slopes seaward into the Southeast Georgia embayment and subsidence has occurred throughout the depositional history of the area (compare pl. 4 and figs. 10 and 22). Similarly, the top of the aquifer system is warped downward into the Southwest Georgia embayment (also called the Apalachicola embayment) in the area of

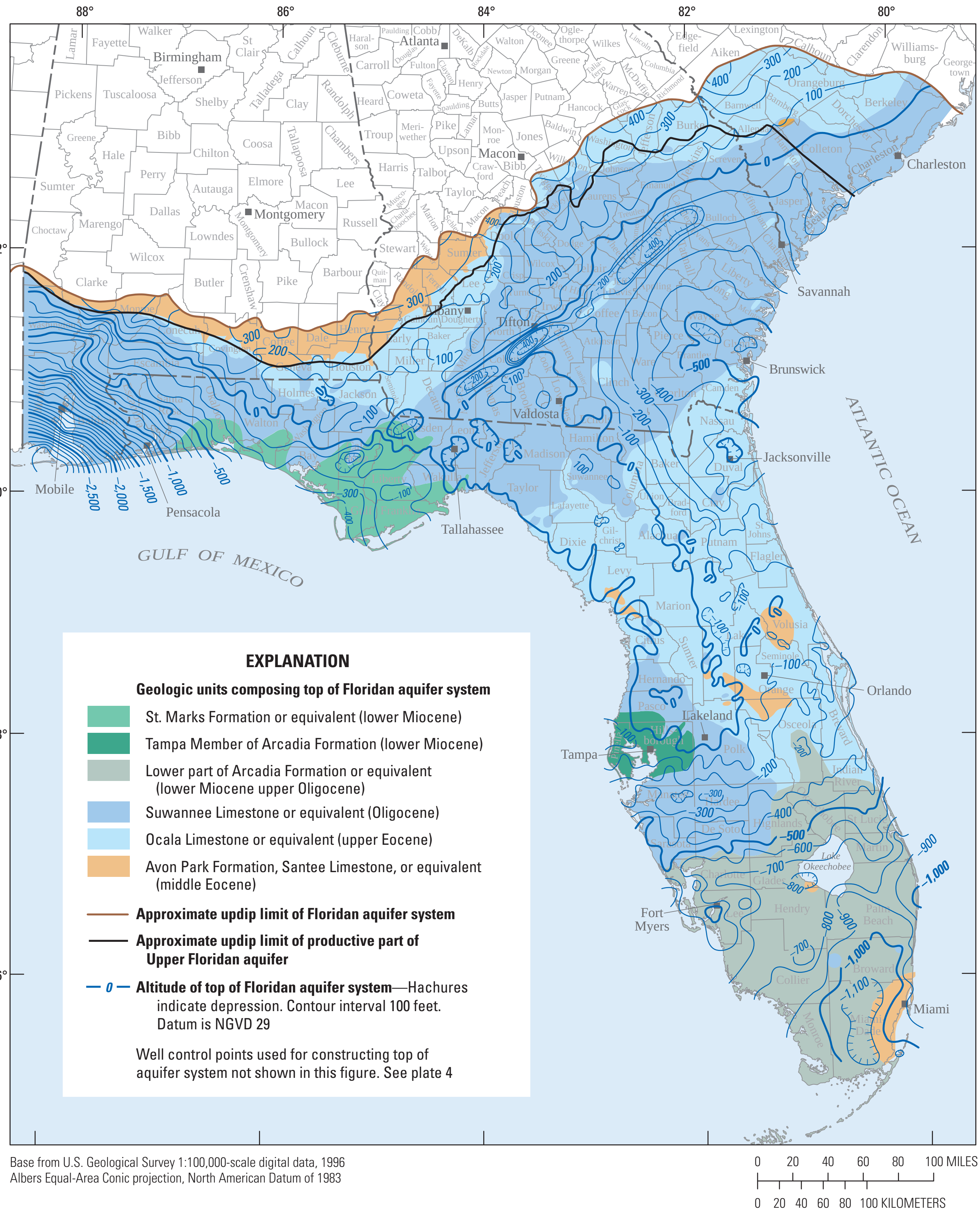


Figure 22. Generalized altitude of the top of the Floridan aquifer system, southeastern United States (see plate 4 for more detail).

Bay, Gulf, and Franklin Counties, Fla., and has a much steeper slope extending into the western Florida panhandle as influenced by the Gulf Coastal Plain (fig. 10).

In Georgia, the Gulf Trough forms a narrow, distinct structural low at the top of the Floridan aquifer system (figs. 10 and 22). This feature extends southwest to northeast along the central part of the Georgia coastal plain and interrupts the gentle southward slope of the Floridan aquifer system. As indicated previously, this structural low in the Gulf Trough could be the result of erosion inside the trough and deposition of thicker, possible Miocene sediments or, as proposed by Miller (1986), may be the result of down-dropped grabens in that area.

The top of the Floridan aquifer system has been subjected to extensive karstification across the broad, northwest-trending Ocala uplift or Ocala “platform” in north-central Florida and along the western coast of the peninsula near Dixie and Levy Counties, and extending into parts of west-central Florida (fig. 10, pl. 4). Across the Ocala platform, the upper confining unit overlying the limestone of the aquifer has been partly or completely removed resulting in greater karst development at the top of the aquifer system. Similarly, partial or complete removal of the upper confining unit across the Peninsular arch in east-central and parts of north-central Florida (fig. 6, pl. 3) has resulted in a highly irregular surface containing localized depressions and peaks in the top of the aquifer system that are indicative of karstification. Much of the irregular detail on the karst surface may not be visible in figure 22 or plate 4 because of the wide spacing of well control points in relation to individual karst features and the relatively large contour interval used on these maps. Farther south, the top of the Floridan aquifer system becomes deeply buried beneath a thick sequence of Miocene and post-Miocene sediments.

In the coastal area near the Georgia and South Carolina state line, the Beaufort arch (fig. 10) locally influences the altitude of the top of the Floridan aquifer system. Across the arch, the top of the Floridan aquifer system is brought near the land surface where paleochannels have caused breaches in the confining unit where seawater can enter the Floridan aquifer system (Payne and others, 2005; Provost and others, 2006).

Base of System

The base of the Floridan aquifer system is marked by the lower confining unit, consisting of predominantly low-permeability late Paleocene to middle Eocene rocks. A map of the altitude of the base of the aquifer system was constructed using data from 686 wells and is shown in figure 23 and plate 5. Control points used to construct the map primarily are located along cross-section lines and at deep oil-test and injection wells where the base was penetrated (pl. 1). In areas of sparse well control, however, the position of the base was estimated below the exploration depth of some wells by considering the general dip of the basal units along the cross sections.

In the northern coastal region of Georgia and South Carolina, the base of the Floridan aquifer system is formed by low-permeability middle Eocene marl (fig. 23). The marl forms the base of the aquifer system as far south as Glynn County, Ga., where it was identified in a test boring on St. Simons Island (Falls and others, 2005a; fig. 23). In southeastern Georgia, and parts of extreme northeastern Florida, the base is formed by evaporite-bearing rocks near the top of the Cedar Keys Formation. South of Brunswick, Ga., the base of the system drops several hundred feet into late Cretaceous rocks consisting of soft, friable, possibly Tayloran age, limestone with the permeable, late Cretaceous, Navarroan age Lawson Limestone above included as part of the Lower Floridan aquifer (Miller, 1986). In southwestern Georgia and southeastern Alabama, the base is marked by thick, plastic, clay beds of very low permeability within the upper Paleocene or lower Eocene Wilcox Group. In Georgia, the base is identified as the Wilcox confining zone, which separates the overlying Lower Floridan and Claiborne aquifers from the underlying Clayton aquifer (Clarke and others, 1984).

In the panhandle of Florida, the base of the system is marked by lower to middle Eocene rocks. In that area, the rocks grade from sandy limestone in the eastern panhandle to argillaceous limestone, sandy limestone, and clay in the western panhandle where they become part of the lower confining unit. In the Fort Walton Beach area (fig. 23), argillaceous beds that are age-equivalent to the Ocala Limestone are locally part of the lower confining unit. This unit includes light-gray calcareous shale and siltstone interbedded with gray limestone, very fine to coarse sand, and minor amounts of gray and brown clay (Marsh, 1966).

In north-central, central, and southern Florida, the base of the Floridan aquifer system is marked at the top of a distinctive massively bedded anhydrite sequence within the middle two-thirds of the Cedar Keys Formation (fig. 18). In these areas, a characteristic resistivity pattern on the logs is indicative of the bedded anhydrite sequence (fig. 18). This resistivity pattern is coincident with the base as mapped by Miller (1986), although he also recognized that evaporite-bearing rocks (not massively bedded) in the upper part of the Cedar Keys Formation may locally be part of the lower confining unit. At a test well in south-central Orange County, Fla., McGurk and Sego (1999) identified a lower permeability evaporitic interval at the top of the Cedar Keys Formation approximately 500 ft higher than previously mapped by Miller (1986). O’Reilly and others (2002) revised the base of the Floridan aquifer system in that area to include this shallower evaporite interval. Although the hydraulic properties of this interval are not well known, a distinctive low-resistivity signature can be used to identify and map the unit over its known extent, as in wells P31 and P237 in cross section *L–L'* (pl. 18) and well P679A in cross section *K–K'* (pl. 17, fig. 18). Using this geophysical log signature, the top of this marker interval was mapped as shown in figure 24; the map represents the altitude of the top of an interval of low-resistivity rocks and delineates the base of the Oldsmar permeable zone described later. In southeastern Georgia, the evaporitic rocks in the upper part of the Cedar Keys Formation may be hydraulically connected to the main body of the aquifer system, and the base of the aquifer system is lower as portrayed on plate 5.

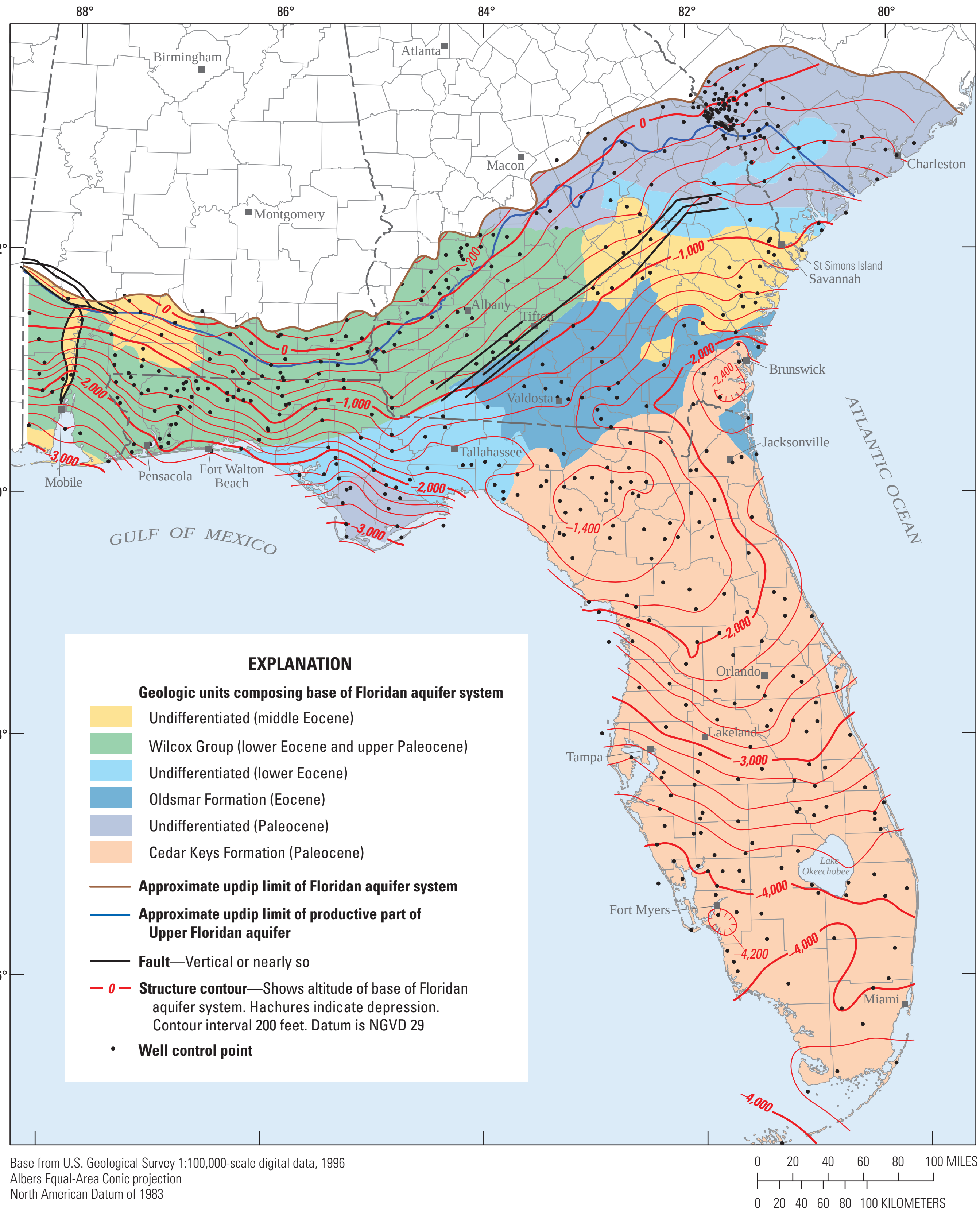


Figure 23. Generalized altitude of the base of the Floridan aquifer system, southeastern United States (see plate 5 for more detail).

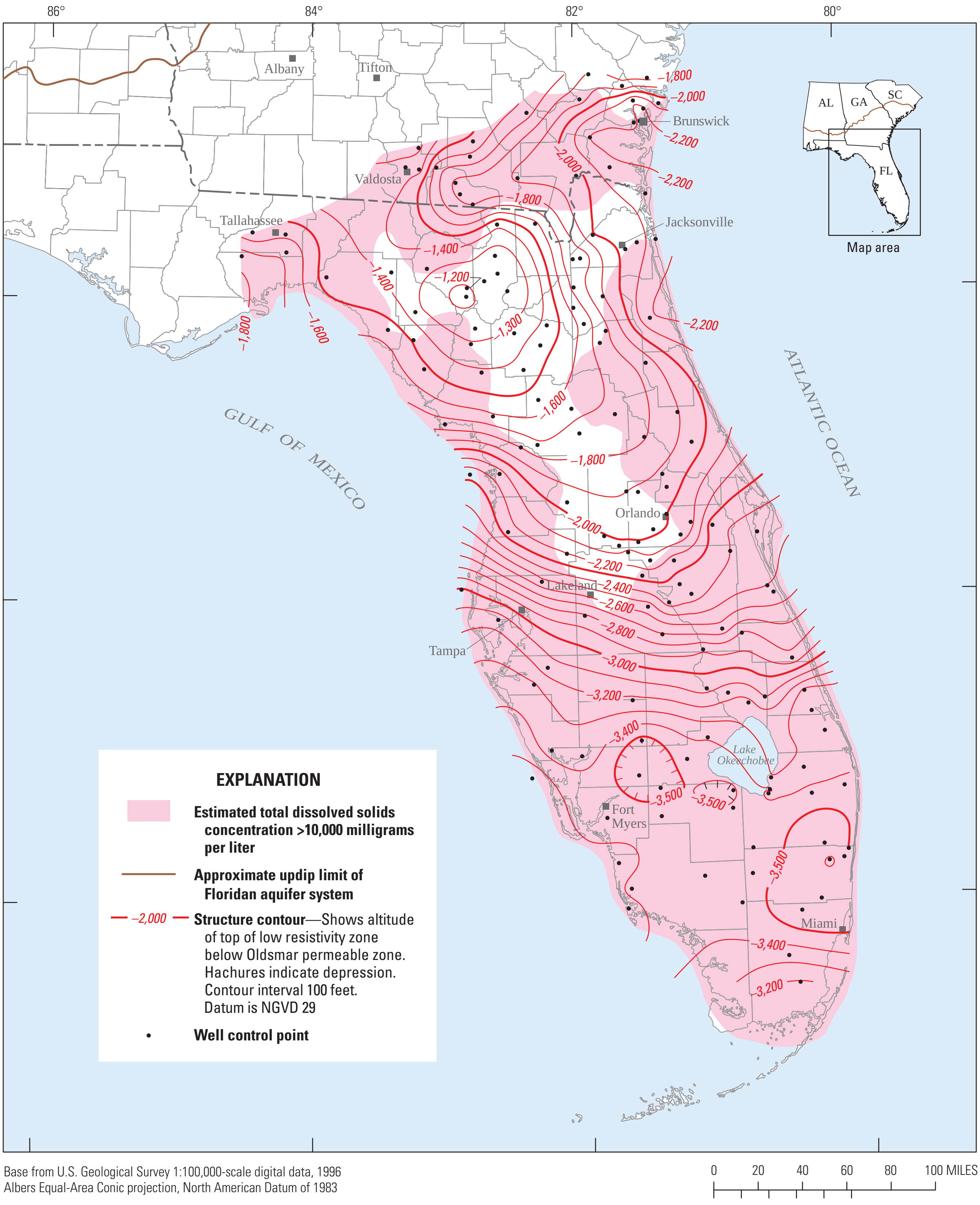


Figure 24. Altitude of the top of the low-resistivity interval below the Oldsmar permeable zone and estimated total dissolved solids concentration for peninsular Florida and southeastern Georgia.

Thickness of Aquifer System

The thickness of the Floridan aquifer system ranges from pinching out in the updip areas in Alabama, Georgia, and South Carolina, where it is highly dissected by streams, to greater than 3,700 ft in southwestern Florida (fig. 25, pl. 6). Thinning occurs in north-central Florida across the Peninsular arch, where the Floridan is about 1,400 ft thick. Slightly thicker deposits accumulated in the Southeast Georgia embayment where the aquifer system thickness exceeds 2,000 ft. Similarly thick deposits also accumulated in the Southwest Georgia embayment, west of the northern part of the Peninsular arch (fig. 10). The thickest part of the aquifer system extends from Tampa to Fort Myers in southwestern Florida (fig. 25, pl. 6). In that area, aquifer system thickness in several wells exceeds 3,600 ft and is probably associated with the accumulation of sediments in the South Florida basin. In southern Florida, in the area of Martin and Palm Beach Counties, Miller (1986) mapped a slightly thicker zone in the aquifer system that did not appear to be associated with any known structural feature. During development of the updated map, however, this thicker zone was not found to be present.

The aquifer system thickness maps shown on plate 6 and in figure 25 differ slightly from the previous thickness map of Miller (1986), mostly in the updip part of the system where hydraulically connected clastic aquifers are now included in the aquifer system. This inclusion generally results in greater aquifer system thickness in the updip areas of the aquifer system than previously mapped. Karstification across the top surface of the aquifer system causes local thinning to occur, and, local thickness of the system may vary slightly from what is shown on plate 6.

In the western Florida panhandle, Miller (1986) noted that the Floridan aquifer system does not thicken seaward as would be expected (fig. 25). Miller (1986) reasoned that this lack of seaward thickening was the result of increased clastic input to the system, precluding the accumulation of carbonate rocks while the aquifer was being formed.

At the time of Miller's work (1986), a graben system was proposed along the Gulf Trough structural feature (fig. 10). As a result, Miller (1986) interpreted thickening and thinning of the aquifer across fault grabens. For the updated map, however, the thickness was contoured without considering fault control. Similarly, the effects of other faults, many of which were proposed at the time of the Miller (1986) framework, were not used as control for calculating aquifer system thickness because either the offset or lateral extent of each fault was not great enough for the fault to be deemed sufficiently important to represent in the regional framework. Accordingly, local variations in the thickness of the Floridan aquifer system may exist near known faults, but are not accounted for on plate 6.

Upper Floridan Aquifer

The Upper Floridan aquifer includes the uppermost or shallowest permeable zones in the Floridan aquifer system. In the northern half of the study area, this aquifer behaves as a single hydrogeologic unit and is undifferentiated. In the southern half of the study area, including most of central and southern Florida, the Upper Floridan aquifer is thick and can be differentiated into three distinct zones, namely the uppermost permeable zone, the OCAPLPZ, and the APPZ.

The base of the Upper Floridan aquifer is marked by two composite units and one confining unit in the middle part of the Floridan aquifer system: the LISAPCU or the MAPCU, and the BCCU. In updip areas, the base of the Upper Floridan is either coincident with the top of the confining units above the Claiborne, Lisbon, or Gordon aquifers, or it lies above any clay bed that marks the boundary between mostly carbonate and mostly clastic units or previously mapped numbered MCUs of Miller (1986). If one or more evaporite units are present, such as middle confining unit MCUIII near Valdosta in south-central Georgia (see location in fig. 9) (Miller, 1986) or MCUII in southwestern Florida (Miller, 1986), the base of the Upper Floridan aquifer is coincident with the top of the evaporite unit. In regions where no distinct lower permeability unit is known to be present, the base of the Upper Floridan is extrapolated along a horizon that allows for a stratigraphic grouping of permeable rock into the upper or lower parts of the aquifer system. In southeastern Alabama, northern Florida, Georgia, and South Carolina, the stratigraphic units are grouped into the LISAPCU. In peninsular Florida, this horizon is coincident with one or more evaporite-bearing or non-evaporite-bearing units of the MAPCU. In the panhandle of Florida and southwest Alabama, the base is coincident with the top of the BCCU.

Undifferentiated Upper Floridan Aquifer—Over most of the northern half of the Floridan aquifer system, including most parts of Georgia, Alabama, and South Carolina, the Upper Floridan aquifer is thin and individual permeable zones generally are treated as a single hydraulic unit. In the extreme updip areas beyond the northern extent of the aquifer, as defined by Miller (1986), the Upper Floridan aquifer consists of Eocene to post-Eocene clastic sediments known as the Upper Three Runs aquifer (Aadland and others, 1995) or the Jacksonian aquifer (Vincent, 1982). Farther downdip, in Georgia, South Carolina, Alabama, and north-central Florida, the rocks that form the Upper Floridan aquifer grade fully into permeable carbonate rocks. Here, the Upper Floridan aquifer consists mostly of Oligocene Suwannee Limestone (if present) and late-Eocene Ocala Limestone. Along the axis of the Peninsular arch in Florida, highly permeable rocks in the upper part of the middle-Eocene Avon Park Formation are close to land surface and these rocks, in combination with overlying hydraulically connected units, form the permeable part of the aquifer system.

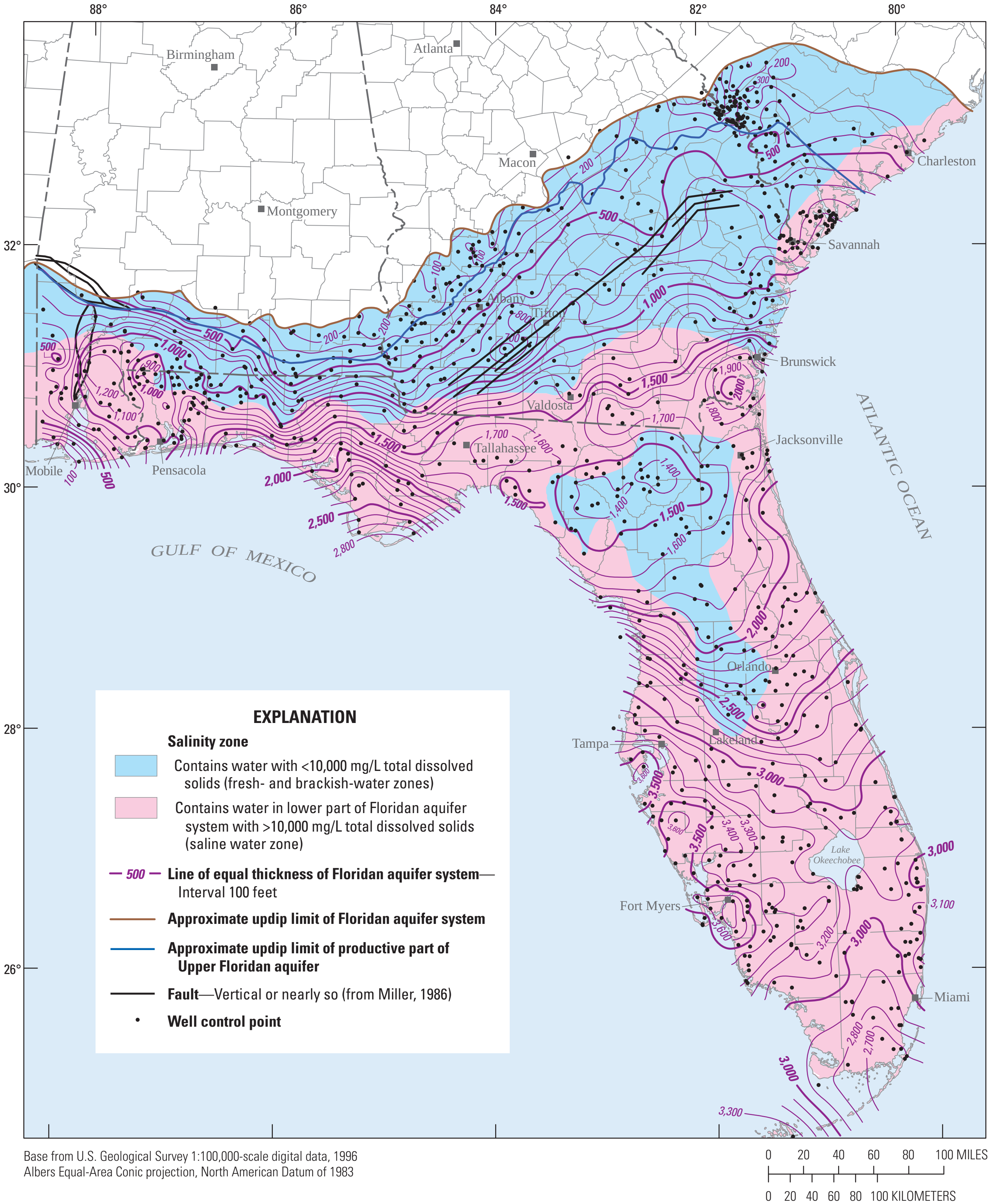


Figure 25. Thickness of the Floridan aquifer system, southeastern United States (see plate 6 for more detail; mg/L, milligrams per liter).

Uppermost Permeable Zone, Central and Southern Florida—The uppermost permeable zone of the Floridan aquifer system includes all of the permeable zones between the top of the Floridan (fig. 22, pl. 4) and the top of the OCAPLPZ. This uppermost permeable zone is equivalent to the Upper Floridan aquifer of Reese and Richardson (2008) and upper Floridan layer used for a regional flow simulation (U.S. Army Corps of Engineers, 2011).

Depending on local permeability variations, the uppermost permeable zone may include one or more flow zones that contribute most of the flow to wells that tap them. Local designations of these zones usually are taken from the primary rock-stratigraphic unit in which they are contained. In west-central and southwestern Florida, for example, the permeable Suwannee Limestone is called the Suwannee permeable zone (Hutchinson, 1992). In a synthesis of hydrogeologic data in southern Florida, Reese and Richardson (2008) noted the differences in stratigraphic position of the various zones and their hydrogeologic association in central and southern Florida, summarized in table 2.

Numerous reports describe the stratigraphic position and hydraulic properties of the uppermost permeable zone in the SWFWMD (Clayton and McQuown, 1994; Gates, 2000; Mallams and Lee, 2006; LaRoche, 2007; Horstman, 2011) and the SFWMD (Bennett, 2001, 2002, 2003; Bennett and Rectenwald, 2002). The characteristics of the uppermost permeable zone at several test sites are presented in table 3. Generally, the uppermost zone consists of a single productive interval or several intervals of higher permeability separated by thicker lower permeability units. Each of the higher and lower permeability intervals may be represented by different rock-stratigraphic units that are influenced by lateral lithologic and textural changes. In southern Florida, Reese and Richardson (2008) indicate that most of the productive capacity is commonly derived from one or two productive intervals, each typically less than 20 ft thick. Increased permeability in the uppermost permeable zone commonly is associated with vuggy or cavernous openings developed along major formational contacts at the top of the Suwannee Limestone, Ocala Limestone, or Avon Park Formation.

The subdivision of distinctly different permeability zones within the Upper Floridan aquifer is based on permeability contrasts. In the SWFWMD where this uppermost zone has been extensively studied, the boundaries usually are based on (1) data obtained through hydraulic testing, such as hydraulic conductivity profiles (from packer slug tests) that can be used to estimate where the permeable zone is positioned, or (2) lithologic descriptions, core analysis, flowmeter surveys, and geophysical logs.

Borehole geophysical logs are used in combination with hydraulic testing to distinguish the top and bottom of the uppermost permeable zone (Suwannee permeable zone) from underlying and overlying units, as shown in figure 26 for a test well in the SWFWMD. This well, ROMP39–Oak Knoll (ROMP39, location shown on pl. 1), is located in north-central Manatee County where the uppermost permeable zone consists of the Tampa Member of the Arcadia Formation (approximately 100 ft thick) and the Suwannee Limestone

Table 2. Relation of stratigraphic and hydrogeologic units of the uppermost permeable zone of the Floridan aquifer system in central and southern Florida.

[Modified from Reese and Richardson (2008); (?), uncertain formation designation for hydrogeologic unit]

Area	Stratigraphic unit	Hydrogeologic unit
West-central Florida	Tampa member of Arcadia Formation Suwannee Limestone Upper part of Ocala Limestone	Suwannee permeable zone
Southwestern Florida north of Lee and Hendry Counties	Basal part of Arcadia Formation Suwannee Limestone	Lower Arcadia zone (PZ3) of the intermediate aquifer system (Torres and others, 2001) Suwannee Limestone part of the Upper Floridan aquifer
Southwestern Florida including Lee, Hendry, and Collier Counties	Lower part of Arcadia Formation Suwannee Limestone	Well-developed lower Hawthorn producing zone and thick well-developed Suwannee Limestone; both zones are hydraulically part of Upper Floridan aquifer (Reese, 2000)
Southeastern Florida	Arcadia Formation (?) Suwannee Limestone (?) Avon Park Formation	Thinner Suwannee Limestone (Bennett and others, 2001) with permeable zone extending down into Avon Park Formation, or an alternate interpretation is a well-developed basal Hawthorn unit and absent Suwannee Limestone (Reese and Memberg, 2000)
East-central Florida	Ocala Limestone	Zone “A” (O’Reilly and others, 2002) forms uppermost zone of Upper Floridan aquifer

Table 3. Characteristics of the uppermost permeable zone of the Upper Floridan aquifer at selected test sites.

[ft, foot; APT, aquifer performance test; gal/min, gallon per minute; T, transmissivity; ft²/d, foot squared per day; S, storativity; SFWMD, South Florida Water Management District; WWTP, wastewater treatment plant; SWFWMD, Southwest Florida Water Management District]

Test site	Well identifier	Depth below land surface (ft)	Thickness (ft)	Hydrogeologic zones and lithology
Collier County, Fla., near Naples	I75-TW	690–1,318	628	Three subzones identified: (1) Highly permeable zone from 690 to 780 ft is identified in the basal Hawthorn Groupt and upper part of Suwannee Limestone. This zone consists of well indurated mudstones and wackestones, dolostone, and packstone. (2) Low-permeability zone from 780 to 905 ft identified in Suwannee Limestone. This zone consists of well indurated mudstones and wackestones. (3) High permeability zone from 905 to 1,050 ft in Suwannee Limestone. This zone consists of moderately indurated packstones
Collier County, Fla., Big Cypress	BICY-TW	820–1,200	380	A permeable zone is identified in the basal Hawthorn Group and upper part of Suwannee Limestone from 820 to 1,000 ft (brackish water). This zone consists mostly of yellowish gray, moderately indurated, sandy phosphatic packstone. Flowmeter logs suggest there is a productive horizon between 1,000 and 1,100 ft but was considered too salty for testing
Collier County, Fla., Immokalee Water & Sewer District WWTP	IWSD-TW	770–1,150	380	Three subzones identified: (1) Highly permeable zone from 773 to 910 ft in the basal Hawthorn Group and upper part of Suwannee Limestone. This zones consists of light gray, moderately indurated wackestones. (2) Low-permability zone from 910 to 1,052 ft in Suwannee Limestone consists of poorly to moderately indurated sandy mudstones and wackestones. (3) High permeability zone from 1,052 to 1,150 ft in Suwannee Limestone. This zone consists of well indurated grainstones
Hardee County, Fla., Bee Branch	ROMP43	298–518	220	The permeable section is the Suwannee Limestone consisting of yellowish gray, poorly indurated, wackestones, packstones, and grainstones with highly variable induration and a thin interval of fractured dolostone.
Highlands County, Fla., Kuhlman	ROMP28	479–710	231	The permeable section is formed in the upper part of the Suwannee Limestone consisting of very light orange, variable indurated, fossiliferous limestone. The lower part of this section is a slightly dolomitic calcarenite with a calcilutite matrix
Highlands County, Fla., Hicora	ROMP14	645–900	255	The permeable section is formed in the Suwannee Limestone and possibly upper part of Ocala Limestone consisting of very light orange to yellowish gray, very fine to rarely coarse grained, poorly-to-occasionally well indurated, chalky, calcarenite
Polk County, Fla., Progress Energy Well Site	ROMP45.5	290–450	160	The permeable section is formed in the Suwannee Limestone consisting of white to yellowish gray, poorly to moderately indurated, fossiliferous, mudstone to wackstone with beds of packstone.
Manatee County, Fla., Oak Knoll	ROMP39	388– 660	272	Permeable zones are developed in the undifferentiated Arcadia Formation and Tampa member of Arcadia Formation (380–513 ft) consisting of sandy dolostones and limestones and calcareous sandstones and Suwannee Limestone (513–717 ft) consisting of very light orange to yellowish gray, to fine grained, fossiliferous calcarenite
Orange County, Fla., Reedy Creek	ORF-60	80–250	170	Permeable zones are formed in the Avon Park Formation consisting of tan and cream, poorly to moderately indurated, packstones and grainstones. The upper part of this unit has phosphatic limestone intervals. A mudstone marks the base of this unit
Osceola County, Fla., Intercession City	OSF-97	86–285	199	Permeable zones are formed in the Avon Park Formation consisting of yellowish gray to light orange, moderately indurated, packstones and wackestones. Low permeable mudstones interbedded with bluish gray clay and dense dolostone marks the base of this unit
Duval County, Fla., Community Hall	M505	450–710	260	Permeable zones formed entirely in the Ocala Limestone. A lower permeability semiconfining unit forms the base of this unit
Chatham County, Ga., Hunter Army Airfield	36Q330	294–556	262	Permeable zones are formed in Ocala Limestone consisting of light gray to very pale brown calcarenite. Optical televiewer log indicates porous beds with vuggy and moldic porosity. A white, chalky, slightly dolomitic limestone forms the forms base of this unit

Table 3. Characteristics of the uppermost permeable zone of the Upper Floridan aquifer at selected test sites.—Continued

[ft, foot; APT, aquifer performance test; gal/min, gallon per minute; T, transmissivity; ft^2/d, foot squared per day; S, storativity; SFWMD, South Florida Water Management District; WWTP, wastewater treatment plant; SWFWMD, Southwest Florida Water Management District]

Well identifier	Hydraulic Properties	Notes
I75-TW	APT in the upper subzone using a well open from 690 to 780 ft pumping 1,472 gal/min caused 10 ft of drawdown in observation well 283 ft away; T estimated to be about 16,000 ft^2/d and S estimated to be 1.7×10^{-5} (leaky response). APT in the lower zone using a well open from 890 to 1050 ft and pumping 743 gal/min caused approximately 11 ft of drawdown in observation well 283 ft away; T estimated to be about 7,000 ft^2/d and S estimated to be 2.3×10^{-5} (leaky response)	SFWMD report WS-7 (Bennett, 2001; Bennett and others, 2001)
BICY-TW	APT using a well open from 840 to 1,010 ft (Hawthorn producing zone) pumping 820 gal/min caused 8.8 ft of drawdown in observation well 330 ft away. T estimated to be about 11,000 ft^2/d and S estimated to be 5×10^{-6} (leaky response)	SFWMD report WS-18 (Bennett, 2004)
IWSD-TW	APT using a well open from 1,050 to 1,160 ft pumping 1,100 gal/min caused about 3 ft of drawdown in observation well 240 ft away. T estimated to be about 36,000 ft^2/d and S estimated to be 1×10^{-2}	SFWMD report WS-14 (Bennett, 2002)
ROMP43	APT using a well open from 310 to 464 ft pumping 364 gal/min caused about 4 ft of drawdown in observation well 187 ft away; T estimated to be about 13,000 ft^2/d and S estimated to be 2×10^{-5}	SWFWMD Bee Branch Report (LaRoche, 2007)
ROMP28	APT using a well open from 485 to 600 ft pumping 150 gal/min yielded an estimated T of 333 ft^2/d and estimated S of 1.9×10^{-4}. Note: the uppermost permeable zone in this well has a much lower transmissivity than elsewhere in central Florida	SWFWMD ROMP28 Kuhlman Report (DeWitt, 1998)
ROMP14	APT using a well with an open interval from 650 to 730 ft pumping 386 gal/min caused a drawdown of 29.5 ft and 2.4 ft at observation wells 100 and 500 ft away, respectively. The average T from several methods was 6,570 ft^2/d and estimated S of 9.9×10^{-4}.	SWFWMD ROMP14 Hicora Report (Clayton, 1998)
ROMP45.5	APT using a well open from 290 to 392 ft pumping 393 gal/min caused a drawdown of 1.1 ft at an observation well 185 ft away. T estimated to be about 26,000 ft^2/d and S estimated to be of 3×10^{-5}	SWFWMD ROMP45.5 Progress Energy Report (Horstman, 2011)
ROMP39	APT using a well open from 520 to 714 ft pumping 762 gal/min caused a drawdown of 9 ft at an observation well 138 ft away. T estimated to be about 12,000 ft^2/d and S estimated to be of 1.6×10^{-4}	SWFWMD ROMP39 Oak Knoll Report (Clayton and McQuown, 1994)
ORF-60	Moderate production capacity estimated by Bennett and Rectenwald but interval was not tested	SFWMD report WS-20 (Bennett and Rectenwald, 2004)
OSF-97	APT of upper permeable zone with well open from 110 to 260 ft produced an estimated T of 15,500 ft^2/d and estimated S of 2.2×10^{-5}	SFWMD report WS-23 (Bennett and Rectenwald, 2003)
M505	An aquifer system simulation developed using data from a well open from 482 to 1,100 ft (across the Upper an Lower Floridan aquifers) produced an estimated T of 9,880 ft^2/d and S of 7.3×10^{-6} for the Upper Floridan aquifer (450–710 ft)	Report on simulation of aquifer test (Sepulveda, 2006)
36Q330	APT of the Upper Floridan aquifer with a well open from 295 to 425 ft produced an estimated T of 40,000 ft^2/d and estimated S of 2.0×10^{-4}. Leaky response indicated on drawdown curves of pumping and observation wells	Report on hydraulic testing at Hunter Army Airfield (Williams, 2010)

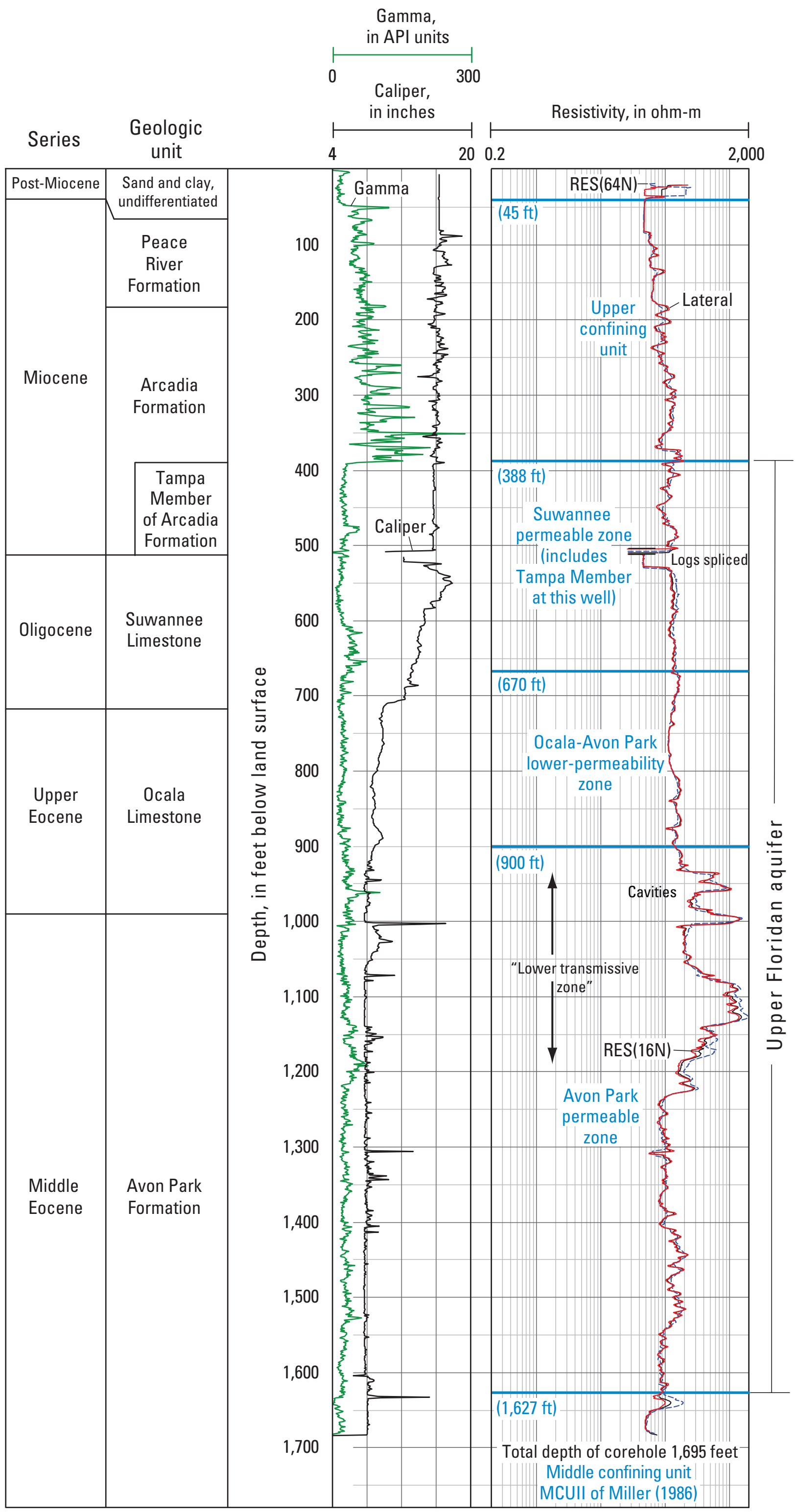


Figure 26. Borehole geophysical logs characteristics of the uppermost permeable zone (Suwannee permeable zone), Ocala-Avon Park lower permeability zone, and Avon Park permeable zone at Southwest Florida Water Management District test well ROMP39, Manatee County, Florida. [Formation depths from Florida Geological Survey, Tallahassee; geophysical logs provided by Southwest Water Management District, Brooksville, Florida; API, American Petroleum Institute; ohm-m, ohm-meter; ft, foot; RES(64N), long normal resistivity, RES(16N), short normal resistivity]

(approximately 200 ft thick). At ROMP39, the top of the uppermost permeable zone can be distinguished by a sharp decrease in gamma radiation with increasing depth and gauge hole (as indicated by caliper logs) representing the Tampa Member. Just below this boundary, the borehole is slightly enlarged where friable limestone of the Suwannee Limestone has been removed by drilling. Lower permeability rocks of the underlying Ocala Limestone are distinguished from the uppermost permeable zone by their slightly lower resistivity, very low gamma radiation, and a gauge hole indicative of the moderately indurated fine-grained limestones. The combined permeable section is about 280 ft thick and forms the Suwannee permeable zone. At the time this well was drilled, this unit was called the “upper transmissive zone” by Clayton and McQuown (1994).

Because the uppermost permeable zone is mapped based on permeability contrasts within the zone, the top and base of this unit may not always be coincident with the same formation contact, as shown for several of the wells listed in table 3. In the three examples given for Collier County, the uppermost permeable zone includes rocks in the basal Hawthorn Group and the Suwannee Limestone. At other sites, such as in Highlands and Polk Counties, the uppermost permeable zone is mapped almost entirely within the Suwannee Limestone but may include the uppermost few tens of feet of the Ocala Limestone in some areas.

Ocala-Avon Park Lower Permeability Zone, Central and Southern Florida—The OCAPLPZ forms a subregional leaky zone within the Upper Floridan aquifer that directly underlies the uppermost permeable zone. The OCAPLPZ includes fine-grained less-permeable carbonate rocks mostly within the Ocala Limestone in southwestern Florida, where it has been called the lower Suwannee-Ocala semiconfining unit (Hutchinson, 1992), the Ocala semi-confiner (Clayton and McQuown, 1994) and the Ocala low-permeability zone (LaRoche, 2007). The OCAPLPZ also includes relatively less-permeable carbonate rocks in the upper part of the Avon Park Formation in southeastern Florida within MCUI of Miller (1986) and the “semiconfining unit” of Lukasiewicz (1992). Reese and Richardson (2008) mapped the OCAPLPZ as a leaky unit above the APPZ and called it “MC1” in southern Florida. It should be noted that the term “lower permeability” used herein for the OCAPLPZ is not entrenched in the literature; however, the carbonates of the OCAPLPZ are not low permeability (hydraulic conductivity less than 10^{-3} ft/d), but several orders of magnitude less permeable than the cavernous or preferential flow zones within the Upper Floridan aquifer.

Reese and Richardson (2008) were the first to identify and map a continuous less permeable zone across southern Florida, and this report generally follows their work, updating the extent and position of this unit using data mostly from the SWFWMD ROMP network and from various test sites from the SFWMD. Lithologies characteristic of this unit include micritic limestone, dolomitic limestone, and dolostone that generally act as a leaky semiconfining unit overlying more permeable rocks of the APPZ. Because many of the wells that penetrate the boundary had insufficient data for a reliable determination, Reese and Richardson (2008) mapped the top of this less-permeable zone based on widely scattered data points and used the formation contact of the Ocala Limestone to represent this boundary in the area of the SWFWMD.

In the present study, a similar criterion was used in mapping the OCAPLPZ, although more emphasis was placed on using borehole geophysical logs to position this unit between the uppermost permeable zone and the APPZ. While the geophysical log characteristics of the OCAPLPZ are not especially distinctive, as shown on the logs from ROMP39 (fig. 26), this unit generally can be mapped on a subtle low-resistivity interval that extends down to the top of the first cavernous dolostone near the base of the Ocala Limestone or the uppermost part of the Avon Park Formation. Although this geophysical log pattern is subtle, it can be used reliably for mapping this unit over its extent (for example, in wells ROMP102.5 and P743 in cross section *J–J'* on pl. 16).

A good example of the geophysical log characteristics of the OCAPLPZ is shown in figure 27 for two test wells in Glades County, Fla. One of the wells (BREX–1, pl. 1) was drilled to investigate the potential of using the Upper Floridan aquifer for aquifer storage and recovery (Missimer Groundwater Science, 2007). In the cross section shown in figure 27, the nuclear magnetic resonance (NMR) derived hydraulic conductivity log (shown as the KSDR curve on the right side of BREX–1), helps to identify the OCAPLPZ. Because this type of log is not commonly collected, the position of the OCAPLPZ is mapped by identifying the typical low-resistivity saddle on the resistivity curve located between more resistive rocks above and below. This log pattern also is coupled with the gamma-ray and caliper logs to help position the OCAPLPZ within the stratigraphic interval.

In addition to geophysical log data, differences in water quality may also help define the position of the OCAPLPZ within the Upper Floridan aquifer. At the two test sites shown in figure 27, there were distinctive differences in water quality above and below the OCAPLPZ. At BREX–1, water samples collected from the uppermost permeable zone above the OCAPLPZ had a chloride concentration of 1,700 mg/L, compared to 655 mg/L for water samples collected beneath the OCAPLPZ from the APPZ.

In central Florida, rocks within the Ocala Limestone become more permeable throughout its vertical extent; therefore, the OCAPLPZ does not extend north past a line from Hernando to Volusia Counties (fig. 28). The top of this zone dips gently to the south, closely resembling the top of the Ocala Limestone in southwestern Florida and the top of the Avon Park Formation in southeastern Florida. The configuration of the surface resembles a broad plunging anticline developed along the Highlands-Okeechobee County boundary and parallel to, but southwest of, the axis of the Peninsular arch (figs. 10 and 28).

Hydraulic head differences across the OCAPLPZ, as determined at well clusters, vary from less than 1 ft to as much as 15 ft (fig. 28). These differences were determined

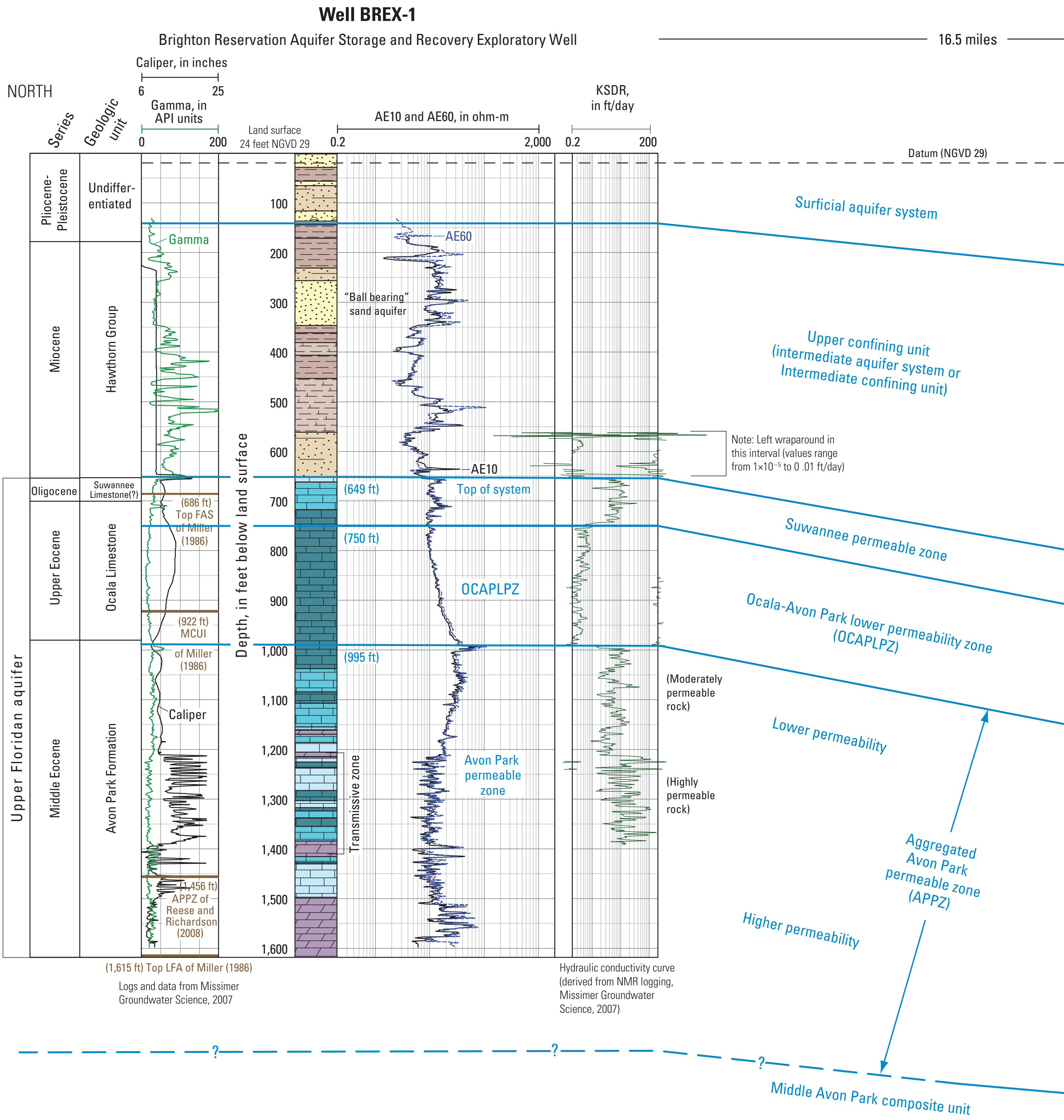
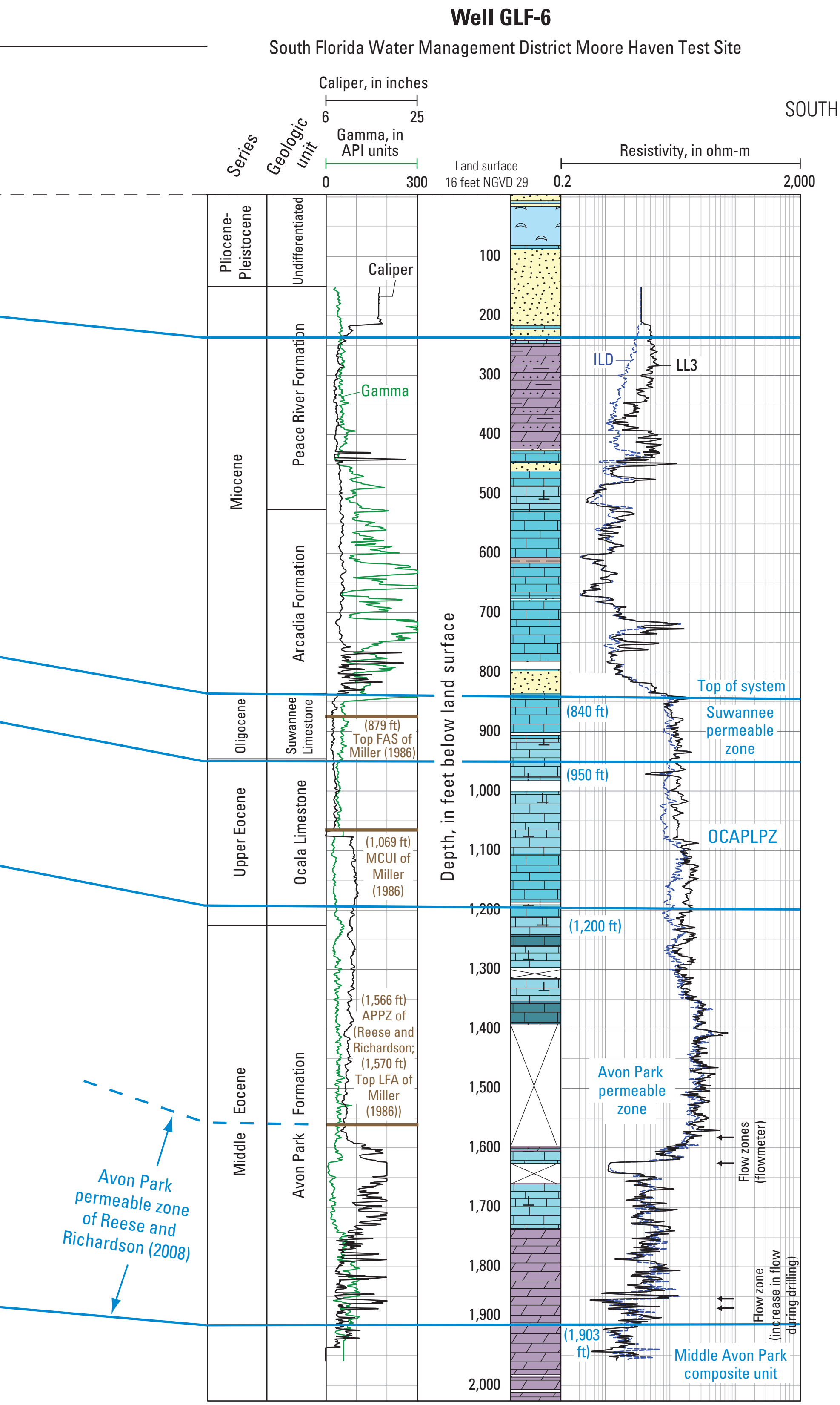


Figure 27. Cross section showing the relation of the Ocala-Avon Park lower permeability zone to overlying and underlying permeable zones of the Upper Floridan aquifer in Glades County, Florida. (see plate 1 for well locations).



Logs and data obtained from South Florida Water Management District DBHYDRO System
Modified from Bennett and Rectenwald, 2002

EXPLANATION

Lithology

- Limestone
- Calcarenite
- Calcilutite
- Chalk
- Coquina
- Dolostone
- Dolomitic limestone
- Silt-sized dolostone
- Grainstone
- Packstone
- Mudstone
- Sand
- Silt
- Clay
- Clayey sand
- No sample

Additional symbology

- Chalk or chalky
- Sandy
- Clayey
- Shells or shelly
- Calcareous

Abbreviations

AE10	shallow array induction
AE60	deep array induction
API	American Petroleum Institute
APPZ	Avon Park permeable zone
CAL	caliper
FAS	Floridan aquifer system
ft	foot
ft/day	foot per day
GR	gamma ray
ILD	induction log deep
LFA	Lower Floridan aquifer
LL3	laterolog 3
KSDR	hydraulic conductivity derived curve from nuclear magnetic resonance log
NMR	nuclear magnetic resonance logging
OCAPLPZ	Ocala-Avon Park lower permeability zone
ohm-m	ohm-meter

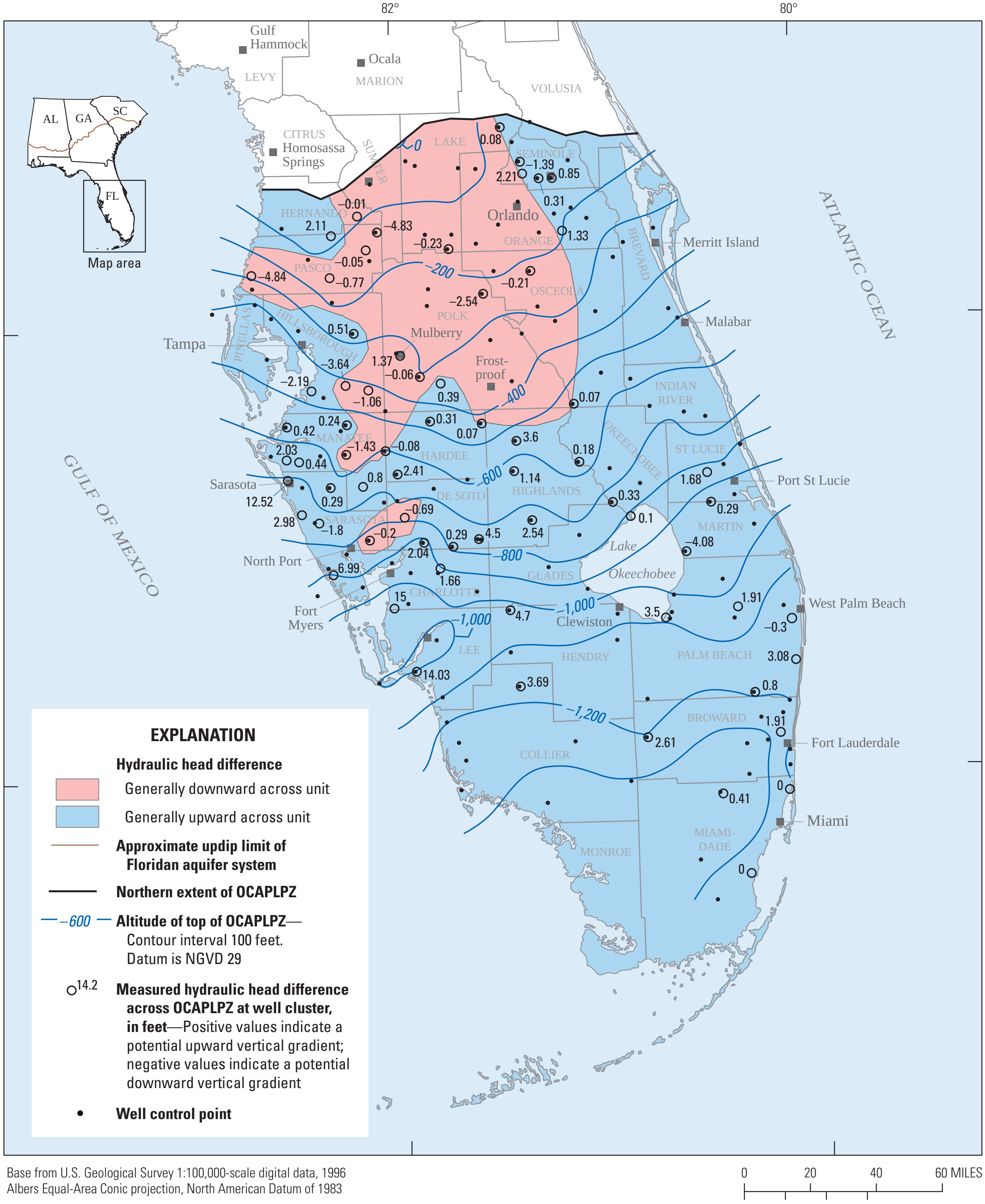


Figure 28. Altitude of the top and hydraulic head difference across the Ocala-Avon Park lower permeability zone (OCAPLPZ) in central and southern Florida.

by subtracting the average daily water-level altitude of wells tapping the uppermost permeable zone from the average daily water-level altitude of wells tapping the APPZ. Although the difference in average daily values varies somewhat over time, it provides a general sense of the hydraulic head difference across the OCAPLPZ. Because of salinity increases in southern Florida and along some of the coastal areas, water levels in some of the wells had to be corrected to an equivalent freshwater hydraulic head for comparative purposes. Wells containing water with TDS concentrations greater than about 17,000 mg/L (half that of seawater) were not used for comparing hydraulic head differences across the OCAPLPZ.

Vertical hydraulic gradients across the OCAPLPZ generally are downward near its northern extent in inland central Florida and are upward along the surrounding coasts and in southern Florida (fig. 28). In central Florida, water moves from the uppermost permeable zone downward through the OCAPLPZ and into the APPZ. Elsewhere, the vertical hydraulic gradients across the OCAPLPZ are generally upward (fig. 28). Over 90 percent of the well cluster sites used for vertical hydraulic head difference evaluations had calculated head differences of less than 5 ft and 60 percent had hydraulic head differences of less than 1 ft over the period of record, indicating that the OCAPLPZ may have a relatively small effect on restricting the movement of water between the overlying and underlying permeable zones. Hydraulic head differences near the northern extent of the OCAPLPZ are negligible (fig. 28).

The leaky nature of the OCAPLPZ has been documented in a number of aquifer tests conducted at test well sites of the SWFWMD. At these sites, the aquifer tests were designed using multiple wells with open intervals in successively deeper hydrogeologic units to determine hydraulic properties and leakage between the units. In numerical simulations of the aquifer tests, Yobbi and Halford (2008) derived the leakance and vertical hydraulic conductivity of what they called the Ocala Limestone unit (table 4), which is correlated to the OCAPLPZ described herein. Based on the assigned thicknesses, the vertical hydraulic conductivity of this unit was determined to range from 0.14 to 5.2 ft/d.

The hydraulic conductivity of the OCAPLPZ probably varies much more than suggested by the aquifer tests described previously, which were mostly completed in west-central Florida. Average values of hydraulic conductivity compiled from packer tests conducted within the OCAPLPZ range from 0.01 to 55 ft/d (table 5). The highest values are from tests conducted in Miami-Dade, Lee, Broward, and Hardee Counties in southeastern Florida, whereas the lowest values are from tests in southwestern and south-central Florida in Collier, Highlands, and DeSoto Counties (table 5). Because the packer tests measure horizontal hydraulic conductivity within a relatively short interval along a hole, the values obtained are more likely to reflect small-scale heterogeneity compared to vertical hydraulic properties derived from simulations or field aquifer tests.

Table 4. Summary of estimated hydraulic properties for the Ocala-Avon Park lower permeability zone (Ocala Limestone unit) in southwestern Florida determined from simulation of aquifer tests.

[Latitude/longitude referenced to NAD 83; altitude referenced to NGVD 29; ft, foot; ft/d, foot per day; (ft/d)/ft, foot per day per foot]

Well name	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (ft)	[1]Vertical hydraulic conductivity (ft/d)	[1,2]Leakance [(ft/d)/ft]	[1]Specific storage (10^{-6}/ft)
ROMP5	Charlotte	26.95	–81.81	41	0.14	0.002	0.3
ROMP9	Charlotte	27.08	–82.15	25	4.5	0.016	1.6
ROMP12	De Soto	27.04	–81.74	41	2.2	0.010	1.1
ROMP13	De Soto	27.07	–81.62	62	0.55	0.002	4.7
ROMP14	Highlands	27.15	–81.35	145	2.3	0.008	210
ROMP20	Sarasota	27.19	–82.48	19	0.34	0.001	11.7
ROMP22	Sarasota	27.31	–82.34	35	5.2	0.017	0.6
ROMP25	Hardee	27.37	–82.01	85	0.29	0.001	0.1
ROMP28	Highlands	27.37	–81.44	84	0.95	0.004	0.1
ROMP39	Manatee	27.59	–82.25	125	0.019	0.000	4.1
ROMP TR 4-1	Sarasota	27.06	–82.44	10	1.3	0.006	0.2
ROMP TR 9-2	Hillsborough	27.77	–82.39	12	0.18	0.001	0.1

[1]Table 4 from Yobbi and Halford (2008).

[2]Equals vertical hydraulic conductivity divided by thickness of unit.

Table 5. Hydraulic conductivity of the Ocala-Avon Park lower permeability zone in peninsular Florida determined from packer tests.

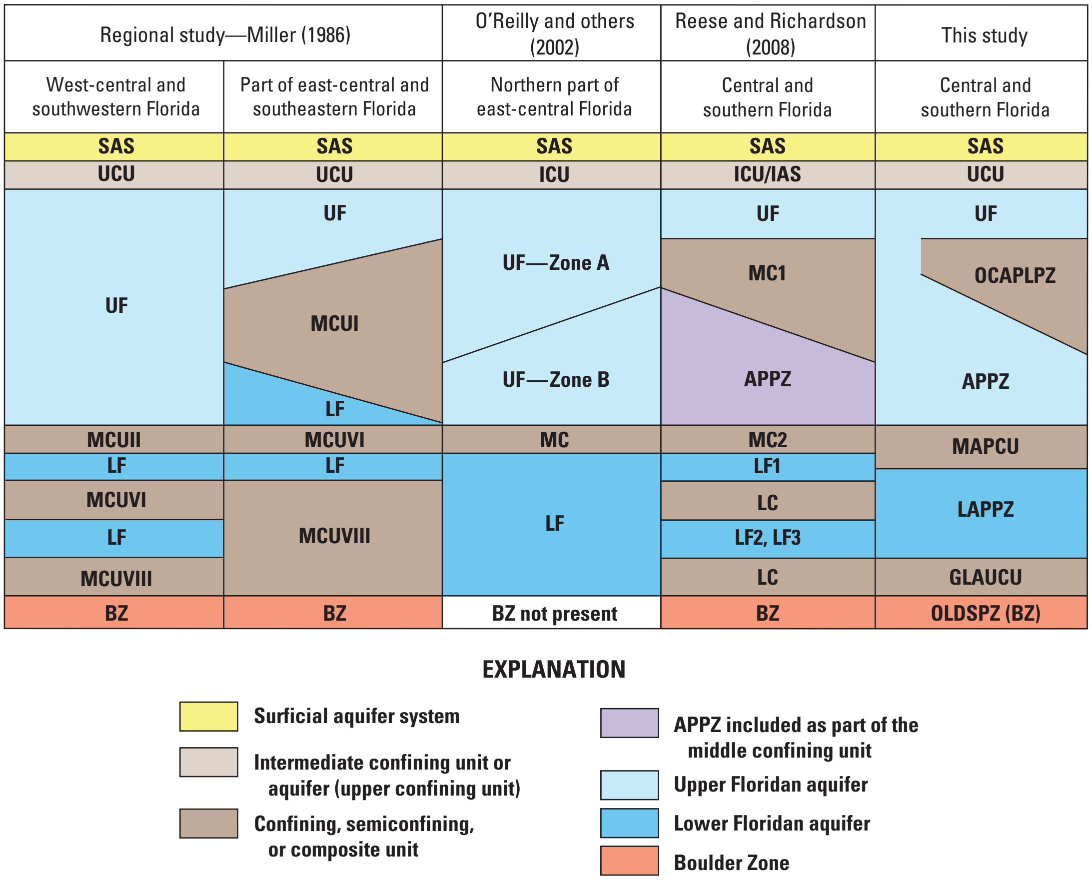
[ft/d, foot per day; ft, foot; average thickness is the average thickness of the unit tested or average length of the isolated test zone; data from reports of the Southwest Florida Water Management District and from the South Florida Water Management District DBHYDRO database, values rounded to two significant digits]

County	Hydraulic conductivity (ft/d)				Count	Average thickness (ft)
	Minimum	Maximum	Average	Median		
Broward	0.94	4.9	2.7	2.1	3	30
Charlotte	0.19	0.52	0.36	0.36	2	12
Collier	0.011	0.23	0.076	0.018	7	43
De Soto	0.012	0.012	0.012	0.012	1	53
Hardee	0.032	4.7	0.84	0.1	7	41
Highlands	0.011	0.95	0.18	0.013	6	56
Lee	0.007	45	2.4	0.064	25	46
Manatee	0.013	0.72	0.35	0.4	6	64
Miami-Dade	3	120	55	52	6	40
Pasco	0.1	0.1	0.1	0.1	2	30
Pinellas	0.5	1.2	0.85	0.85	4	7
Sarasota	0.044	0.25	0.15	0.15	4	60

Avon Park Permeable Zone, Central and Southern Florida—The APPZ lies within the Upper Floridan aquifer between the OCAPLPZ and the MAPCU and typically consists of thick beds of permeable, fractured, cavernous dolostone with interbedded lower permeability limestone, dolomitic limestone, and dolostone. A revision to the definition of the APPZ of Reese and Richardson (2008) to include less-permeable rocks along with the highly transmissive zones is designated the "aggregated Avon Park permeable zone," herein and was necessary to allow multiple permeable zones to be grouped into a single unit. Characteristics of the aggregated Avon Park permeable zone at selected wells are summarized in table 6.

Previous definitions of the Avon Park Permeable Zone—Various workers have identified the APPZ using differing terminology and have included it in either the Upper or Lower Floridan aquifers or within the middle confining unit (fig. 29). These discrepancies in terminology exist because the APPZ is a relatively thick, non-homogeneous unit whose position varies areally across a wide stratigraphic interval of the Avon Park Formation. The APPZ was first mapped in west-central Florida, where it is tapped by many high-capacity water-supply wells, and was called the highly permeable dolomite zone by Wolansky and others (1980). In southwestern Florida, the APPZ was called the Avon Park highly permeable zone where it was used for deep-well injection (Hutchinson, 1992). In east-central Florida, McGurk and Presley (2002) mapped the APPZ as the dolostone zone, and it has been identified as zone B of the Upper Floridan aquifer by others (O'Reilly and others, 2002; Spechler and Halford, 2001).

Southward, the APPZ gradually begins to interfinger with less-permeable rock and eventually becomes part of what was previously mapped as the Lower Floridan aquifer (see cross sections *L–L'* and *M–M'* on pls. 18 and 19, for example). This transition has caused considerable problems in nomenclature and inconsistencies in stratigraphic positioning of hydrogeologic units at a regional scale. In the updip areas, these zones were mapped as part of the Upper Floridan aquifer, whereas in the downdip areas they were mapped as part of the Lower Floridan aquifer. Because of the large amount of fine-grained, less-permeable rocks in southern Florida, the SFWMD identified the APPZ as a productive horizon in a middle confining unit and called it the middle Floridan aquifer (Bennett and Rectenwald, 2003; Lukasiewicz, 2003a,b; Bennett and Rectenwald, 2004). Reese and Richardson (2008) renamed this unit the "Avon Park permeable zone," bounded by overlying and underlying semiconfining units they respectively called MC1 and MC2 (fig. 29).



APPZ	Avon Park permeable zone
BZ	Boulder Zone
GLAUCU	Glauconite marker unit
IAS	Intermediate aquifer system
ICU	Intermediate confining unit
LAPPZ	Lower Avon Park permeable zone
LC	Confining unit inside Lower Floridan aquifer
LF	Lower Floridan aquifer
LF1, LF2, LF3	Permeable zones inside Lower Floridan aquifer (Reese and Richardson, 2008)
MAPCU	Middle Avon Park composite unit
MC, MC1, MC2	Middle confining unit designations (Reese and Richardson, 2008)
MCUI, MCUII, MCUVI, MCUVIII	Middle confining units (Miller, 1986)
OCAPLPZ	Ocala-Avon Park lower permeability zone
OLDSPZ	Oldsmar permeable zone
SAS	Surficial aquifer system
UCU	Upper confining unit
UF	Upper Floridan aquifer

Figure 29. Schematic comparison of hydrogeologic nomenclature used in this study with previous studies (modified from Reese and Richardson, 2008).

Table 6. Characteristics of the aggregated Avon Park permeable zone at selected test sites.

[ft, foot; (gal/min)/ft, gallon per minute per foot; SFWMD, South Florida Water Management District; WWTP, wastewater treatment plant; APT, aquifer performance test; T, transmissivity; S, storage coefficient (dimensionless); ft^2/d, foot squared per day; gal/min, gallon per minute; SWFWMD, Southwest Florida Water Management District; mg/L, milligrams per liter]

Test site	Well identifier	Depth (ft)	Thickness (ft)	Hydrogeologic zones and lithology
Collier County, Fla., near Naples	I75-TW	1,688–2,278	590	Permeable zone consists of brown, moderately to well indurated, packstones and grainstones interbedded with minor dolostone in the upper part of the Avon Park Formation.
Collier County, Fla., Big Cypress	BICY-TW	1,787–2,276	489	Permeable zone consists of tan to yellowish gray, moderately indurated, wackestones and grainstones in the upper part of Avon Park Formation. Uniform lithology indicated by dual-porosity log with photo-electric factor curve.
Collier County, Fla., Immokalee Water & Sewer District WWTP	IWSD-TW	1,711–2,151	440	Inflection on fluid logs indicate a distinct flow zone in the upper part of the Avon Park Formation from 1,730 to 1,850 ft consisting of very light orange and grayish brown packstone.
Hardee County, Fla., Bee Branch	ROMP43	708–1,576	868	Two permeable intervals identified in this unit. (1) Upper permeable interval from 709 to 745 ft consists of moldic dolomitic packstones. This is underlain by a lower-permeability interval from 745 to 1,066 ft consisting of yellowish-gray poorly indurated mudstones, packstones, and grainstones. (2) A lower highly fractured and permeable interval from 1,066 to 1,210 ft consists of sucrosic and porous dolostone. All intervals are in the Avon Park Formation.
Highlands County, Fla., Kuhlman	ROMP28	925–1,720	795	Permeable section starts at top of Avon Park Formation. An upper interval from 925 to 1,289 ft consists of light orange limestone; is probably moderately permeable and a lower interval from 1,289 to 1,670 ft consists of grayish brown to orange fractured crystalline dolostone interbedded with sucrosic dolostone that is highly permeable.
Highlands County, Fla., Hicora	ROMP14	1,090–1,910	820	Permeable section starts about 200 ft below top of Avon Park Formation. An upper interval from 1,200 to 1,450 ft consists of brown dolostone interbedded with thin beds of pale orange to yellowish gray dolomitic limestone. A lower interval from 1,450 to 1,780 ft is the “high T zone” consisting of fractured and cavernous dolostone.
Polk County, Fla., Progress Energy	ROMP45.5	640–1,470	830	Permeable section starts about 100 ft below top of Avon Park Formation. An upper highly-permeable section is identified in the interval from 730 to 912 ft consists of dark yellowish brown, well indurated, slightly fossiliferous, vuggy and fractured, crystalline dolostone. A lower moderately permeable interval from 900 to 1,200 ft had estimated hydraulic conductivity ranging from 8 to 23 ft/d and averaging 8 ft/d from slug tests.
Manatee County, Fla., Oak Knoll	ROMP39	900–1,627	727	An upper highly permeable interval from 965 to 1,145 ft in the upper part of the Avon Park Formation consists of fractured dolostone and a thick bed of porous calcarenite. Cavities were identified between 969 and 983 ft in this interval. A deeper interval from 1,145 to 1,600 ft may also be permeable but water quality degrades with depth. Evaporitic rocks form the base of this unit.
Orange County, Fla., Reedy Creek	ORF-60	270–890	620	A majority of the production is from an interval from 310 to 425 ft consisting of cream-colored grainstone and vuggy tan to dark brown dolostone with minor mudstone. Smaller less productive zones are in the interval from 425 to 740 ft based on deflections on the flowmeter log and fluid logs and consists of poorly to moderately indurated, vuggy, packstones and grainstones. A well indurated wackestone forms the base of this unit.

Table 6. Characteristics of the aggregated Avon Park permeable zone at selected test sites.—Continued

[ft, foot; (gal/min)/ft, gallon per minute per foot; SFWMD, South Florida Water Management District; WWTP, wastewater treatment plant; APT, aquifer performance test; T, transmissivity; S, storage coefficient (dimensionless); ft^2/d, foot squared per day; gal/min, gallon per minute; SWFWMD, Southwest Florida Water Management District; mg/L, milligrams per liter]

Well identifier	Hydraulic Properties	Notes
I75-TW	No distinct flowzone were identified on the flowmeter survey. Specific capacity from a packer test interval from 1,851 to 1,901 ft was 13.49 (gal/min)/ft.	From SFWMD report WS-7 (Bennett, 2001)
BICY-TW	Minor production identified from 1,550 to 1,785 ft, however the flowmeter survey was of limited use because of enlarged hole. Specific capacity from packer test interval 1,790 to 1,910 ft was 3 (gal/min)/ft.	From SFWMD report WS-18 (Bennett, 2004)
IWSD-TW	Packer tests were not performed because of poor hole conditions.	From SFWMD report WS-14 (Bennett, 2002)
ROMP43	APT using a well open from 720 to 1,210 ft pumping 1,277 gal/min caused about 0.4 ft of drawdown in observation well 155 ft away. T estimated to be about 350,000 ft^2/d and S estimated to be 1×10^{-3}.	From SWFWMD Bee Branch Report (LaRoche, 2007)
ROMP28	APT using a well open from 960 to 1,642 ft pumping 1,300 gal/min. T estimated to be about 59,600 ft^2/d and S was not estimated.	From SWFWMD ROMP28 Kuhlman Report (DeWitt, 1998)
ROMP14	APT using a well open from 1,003 to 1,670 ft pumping 1,670 gal/min did not produce any noticeable drawdown in observation well 451 ft away. T estimated to be about 7,600 ft^2/d and S estimated to be 2.2×10^{-5}.	From SWFWMD ROMP14 Hicora Report (Clayton, 1998)
ROMP45.5	APT using a well open from 555 to 915 ft pumping 3,053 gal/min had a maximum drawdown of 10 ft in the pumping well but did not produce any noticeable drawdown in an observation well 160 ft away. T was not estimated.	From SWFWMD ROMP45.5 Progress Energy Report (Horstman, 2011)
ROMP39	No APT was conducted at this site but Clayton and McQuown (1994) report that a similar interval in ROMP22 located about 18 miles to the southwest of this site had an estimated T of 247,000 ft^2/d.	From SWFWMD ROMP39 Oak Knoll Report (Clayton and McQuown, 1994)
ORF-60	A series of step tests performed on this interval indicates a specific capacity of 235 (gal/min)/ft while pumping 2,610 gal/min.	From SFWMD report WS-20 (Bennett and Rectenwald, 2004)

Table 6. Characteristics of the aggregated Avon Park permeable zone at selected test sites.—Continued

[ft, foot; (gal/min)/ft, gallon per minute per foot; SFWMD, South Florida Water Management District; WWTP, wastewater treatment plant; APT, aquifer performance test; T, transmissivity; S, storage coefficient (dimensionless); ft^2/d, foot squared per day; gal/min, gallon per minute; SWFWMD, Southwest Florida Water Management District; mg/L, milligrams per liter]

Test site	Well identifier	Depth (ft)	Thickness (ft)	Hydrogeologic zones and lithology
Osceola County, Fla., Intercession City	OSF-97	390–1,030	640	A fractured and cavernous dolostone unit from 400 to 570 ft is the main producing interval at this well. This is underlain by grayish brown to grayish orange, moderately indurated, vuggy, packstones and grainstones with thin beds of dolostone that is relatively less permeable. Evaporitic rocks form the base of this unit.
Glades County Fla., Brighton Reservation	BREX-1	995–total well depth at 1,618	ND	The upper part of this unit consists of yellowish gray, moderately indurated mudstones, packstones, and wackestones from 1,000 to 1,200 ft. These rocks are of relatively lower permeability based on specific capacity testing. This is underlain by a fractured dolostone of very high-permeability from 1,200 to 1,210 ft. The remainder of the unit beneath the highly permeable zone may also be productive but flow in this well is dominated by the 1,200 ft zone.
Glades County, Fla., Moore Haven	GLF-6	1,200–1,903	703	Well indurated mudstones and wackestones in the interval from 1,110 to 1,600 ft is lower permeability and may be locally confining. Top of zone is estimated to start about 1,200 ft. A cavernous dolomitic limestone and dolostone interval from 1,600 to 1,740 ft is permeable. Lost circulation at top of this zone.
De Soto County, Fla., Fort Odgen	ROMP16.5	1,140–1,830	690	A moderately permeable zone is present in the interval from 1,140 to 1,250 ft consisting of light orange to yellowish gray dolostone and a highly permeable fractured dolostone interval from 1,540 to 1,814 ft.
Hillsborough County, Fla., Sun City Center	ROMP50	730–1,394	664	Production is associated with a massive highly-resistive dolostone interval between 730 and about 900 ft at the top of the Avon Park Formation. Also, inflections on fluid logs indicate apparent flow zones between 1,300 and 1,400 ft. The deeper zone is about 100 ft above evaporitic rocks of the underlying confining unit.
Hendry County, Fla., Labelle	LAB-TW	1,409–2,029	620	Based on flowmeter survey this unit includes an upper productive interval from 1,409 to 1,650 ft consists of very light orange, poorly to moderately indurated, packstones and wackestones. A middle productive interval consists of very light orange to dark yellowish brown dolostone with a cavernous interval at 1,700 ft. While drilling through this zone there was a loss of mud circulation and 4-ft rod drop. Dolostones extend down to about 1,900 ft. A lower interval from 1,900 to 2,030 ft consists of light orange wackestones and packstones of relatively lower apparent permeability that is either non-productive or low production as indicated by inflections on fluid logs.
Hillsborough County, Fla., Thomas Grassing, Inc.	FL-HIL2	517–1,072	555	Permeable interval probably near top of Avon Park Formation based on other wells in area. Gage hole between 450 and 600 ft on caliper log could be a local confining unit.
Palm Beach County, Fla., South Bay	PBF-7	1,250–2,170	920	Upper and lower producing intervals were identified at this site. The upper producing interval from 1,200 to 1,400 ft consists mostly of grayish orange, well indurated packstones and grainstones. The lower producing interval from 1,900 to 2,170 ft consists of brown crystalline dolostone, which has been previously identified as the “upper dolostone unit” of Meyer (1989) and the “dolomite unit” of Reese and Memberg (2000).
Sarasota County, Fla., Englewood	Englewood-IW-1	1,050–1,909	859	Two distinct flow zones are indicated from the flowmeter survey. An upper zone is identified from 1,050 to 1,150 ft that produces water from within the upper dolostone unit of the Avon Park Formation. The lower zone from 1,550 to 1,600 ft produces water from an interbedded limestone and dolostone sequence above a underlying massive dolostone interval.

Table 6. Characteristics of the aggregated Avon Park permeable zone at selected test sites.—Continued

[ft, foot; (gal/min)/ft, gallon per minute per foot; SFWMD, South Florida Water Management District; WWTP, wastewater treatment plant; APT, aquifer performance test; T, transmissivity; S, storage coefficient (dimensionless); ft^2/d, foot squared per day; gal/min, gallon per minute; SWFWMD, Southwest Florida Water Management District; mg/L, milligrams per liter]

Well identifier	Hydraulic Properties	Notes
OSF-97	APT with a well open from 310 to 680 ft produced an estimated T of 69,000 ft^2/d and estimated S of 1.2×10^{-5}.	From SFWMD report WS-23 (Bennett and Rectenwald, 2003)
BREX-1	APT of the well after penetrating a fracture interval from 1,200 to 1,210 ft (open from 640 to 1,216 ft) had an artesian flow of 1,000 gal/min. The T was estimated to be 11,200 ft^2/d based on specific capacity. This is a slightly brackish-water zone with chloride of 750 to 900 mg/L.	Brighton Reservation ASR exploratory well program (Missimer Groundwater Science, 2007)
GLF-6	Testing of this interval indicates a specific capacity of 175 (gal/min)/ft. This is a brackish-water zone with total dissolved solids concentration of 9,500 mg/L.	SFWMD Moore Haven Site preliminary report (Bennett, 2002)
ROMP16.5	APT with a well open from 715 to 1,537 ft had an estimated T of 3,566 ft^2/d and an estimated S of 7.9×10^{-4}.	From SWFWMD Ft. Odgen Phase II report (Gates, 2001)
ROMP50	No APTs were conducted in this interval.	
LAB-TW	APT was conducted by CH2M Hill on a modified LAB-PW with the well open from 1,658 to 1,758 ft. This test gave an estimated T of about 560,000 ft^2/d and an estimated S of 6.6×10^{-4}.	CH2M Hill engineering report on the modification and testing of LAB-PW, May 2007; SFWMD LaBelle Technical Report WS-15 (Bennett, 2003)
FL-HIL2	Two distinct producing intervals were identified: (1) 650 to 750 ft immediately below low-porosity unit at top of Avon Park formation; (2) 900 to 1,000 ft just above the evaporite bearing rocks of the underlying confining unit.	Logs from files of the USGS, Tampa office
PBF-7	APT of well open from 1,202 to 1,447 ft pumping 1,550 gal/min had a drawdown of 12.2 ft in an observation well 398 ft away. T estimated to be 9,600 ft^2/d and S estimated to be 2.9×10^{-4}. APT of well open from 1,960 to 2,040 ft pumping 1,030 gal/min had a drawdown of 1.1 ft in an observation well 398 ft away. T estimated to be 68,000 ft^2/d and S estimated to be 2.6×10^{-5}.	SFWMD Report WS-2 (Lukasiewicz and others, 2001)
Englewood-IW-1	APT of the well open from 1,040 to 18,00 ft pumping 1,000 gal/min produced a drawdown of 0.2 ft in a nearby observation well. T estimated to be 78,600 ft^2/d and S estimated to be 7×10^{-7}. This an injection well test in the saline water zone.	Consulting report for Englewood reverse osmosis injection well (CH2M Hill, 1986)

Revised Definition of the Avon Park Permeable Zone—To maintain consistency with a two-aquifer system, the APPZ is redefined here to include all highly permeable fractured and cavernous rocks, as well as moderately permeable rocks that lie between the OCAPLPZ and the MAPCU (for example, see fig. 27). Although this definition helps to clarify the position of the APPZ in the regional aquifer system, it also is recognized that in southern Florida, the APPZ is more isolated by thicker lower permeability rocks than elsewhere in the system and locally may act as a distinct aquifer within the system.

The APPZ is mapped using several distinguishing characteristics (Reese and Richardson, 2008):

- in-gauge hole (hole similar to drill-bit size) or nearly in-gauge hole diameter with numerous caliper excursions as typically seen on caliper logs;
- high electrical resistivity rapidly changing to anomalously low resistivity in fractured zones;
- erratic low and high porosity curve spikes, including anomalously high sonic-log transit time caused by cycle skipping;
- slight increases in gamma-ray log activity associated with dolostone; and
- spontaneous-potential curve activity.

Lithologic, geophysical, and hydraulic characteristics of the APPZ are illustrated on the cross section for test wells BREX–1 and GLF–6 in Glades County, Fla. (fig. 27). In BREX–1, the NMR-derived hydraulic conductivity log indicates the presence of about 200 ft of moderately permeable rock above the highly transmissive part of the APPZ. This relation can be extended to GLF–6 by correlating the NMR log with other logs (fig. 27). Accordingly, the top of the aggregated APPZ is picked several hundred feet higher in this area than previously mapped. The resulting structural surface of the aggregated permeable zone is shown in figure 30. A map showing the altitude of the highly permeable part of the aggregated APPZ is provided in Reese and Richardson (2008).

Borehole geophysical logs and flowmeter data indicate that in some areas, the APPZ may consist of several permeable zones at different levels within the APPZ instead of a single permeable zone (table 6). Heterogeneity within the aggregated APPZ, and within the entire Upper Floridan aquifer, has been a topic of study at several municipal well fields in west-central Florida (Knochenmus and Robinson, 1996; Tihansky, 2005). At these well fields, fracture systems and cavernous zones create preferential flow paths along which poor-quality water can encroach upon major pumping centers, either vertically along fractures or laterally along contact zones. Dissolution along fractures and bedding planes creates extremely permeable zones (Knochenmus and Robinson, 1996).

The numerous flowmeter and fluid logs examined during this study indicate that many high-capacity wells in the region produce water from more than one higher permeability interval within the APPZ, some of which are listed in table 6 (Williams and others, 2013). At well ROMP45.5 for example, the upper and lower producing zones described for the APPZ (Horstman, 2011) are similar to those observed in well FL–HIL2, whereas farther east, the lower producing zone appears to grade into less permeable limestone of the MAPCU at wells ROMP74X (Gates, 2006), OSF–97 (Bennett and Rectenwald, 2003), and ORF–60 (Bennett and Rectenwald, 2004).

Observations from rock cores and ATV logs indicate that fractures commonly terminate at upper and lower contacts of major lithologic units, potentially enhancing the development of transmissive zones at major lithologic contacts. In west-central Florida, such development appears to have occurred along two main dolomitic intervals in the Avon Park Formation. One cluster of transmissive zones is associated with the upper dolostone unit (fig. 17), and a second zone is associated with a deeper dolomitic interval located a few tens of feet above the top of the MAPCU. Although both the shallow and deeper permeable zones are known to produce large quantities of water to wells that tap these zones, neither zone is continuous across the area (Knochenmus and Robinson, 1996).

One area where the aggregated Avon Park permeable zone is particularly well developed is in northern Hillsborough County, Fla. An example, of a geophysical log collected in this area from test well FL–HIL2, is shown in figure 31. At this well, Miller (1986) mapped a very thick, undifferentiated Upper Floridan aquifer starting at about 40 ft below land surface and extending down to the top of middle confining unit MCUII at a depth of 1,050 ft. In the current study, this interval is now differentiated into several distinct zones, including the uppermost permeable zone, OCAPLPZ, and the aggregated APPZ. Because of the lack of flowmeter data at this well, the APPZ is distinguished from the overlying OCAPLPZ and uppermost permeable zone on the basis of geophysical characteristics, including high formation resistivity, caliper excursions, and the wide variation in estimated porosity exhibited in the neutron porosity log. The base of the APPZ is coincident with the MCUII region of the MAPCU, and identified by a decrease in formation resistivity and an in-gauge hole as indicated on the caliper log. The decrease in resistivity, in the underlying confining unit at FL–HIL2, may be caused by the presence of organic-rich clayey and evaporitic carbonate rocks that have low electrical resistivity. The relatively low formation resistivity of below 10 ohm-meters may indicate the presence of brackish or saline water in the underlying confining unit and marks the base of the freshwater flow system.

The extent of the aggregated APPZ, both laterally and vertically, is associated with the presence of thick, fractured dolostone intervals; conversely, the APPZ tends to be less fractured and productive where dolomitization is less pervasive. From west-central and east-central Florida toward extreme southern Florida, the number and thickness of dolostone units

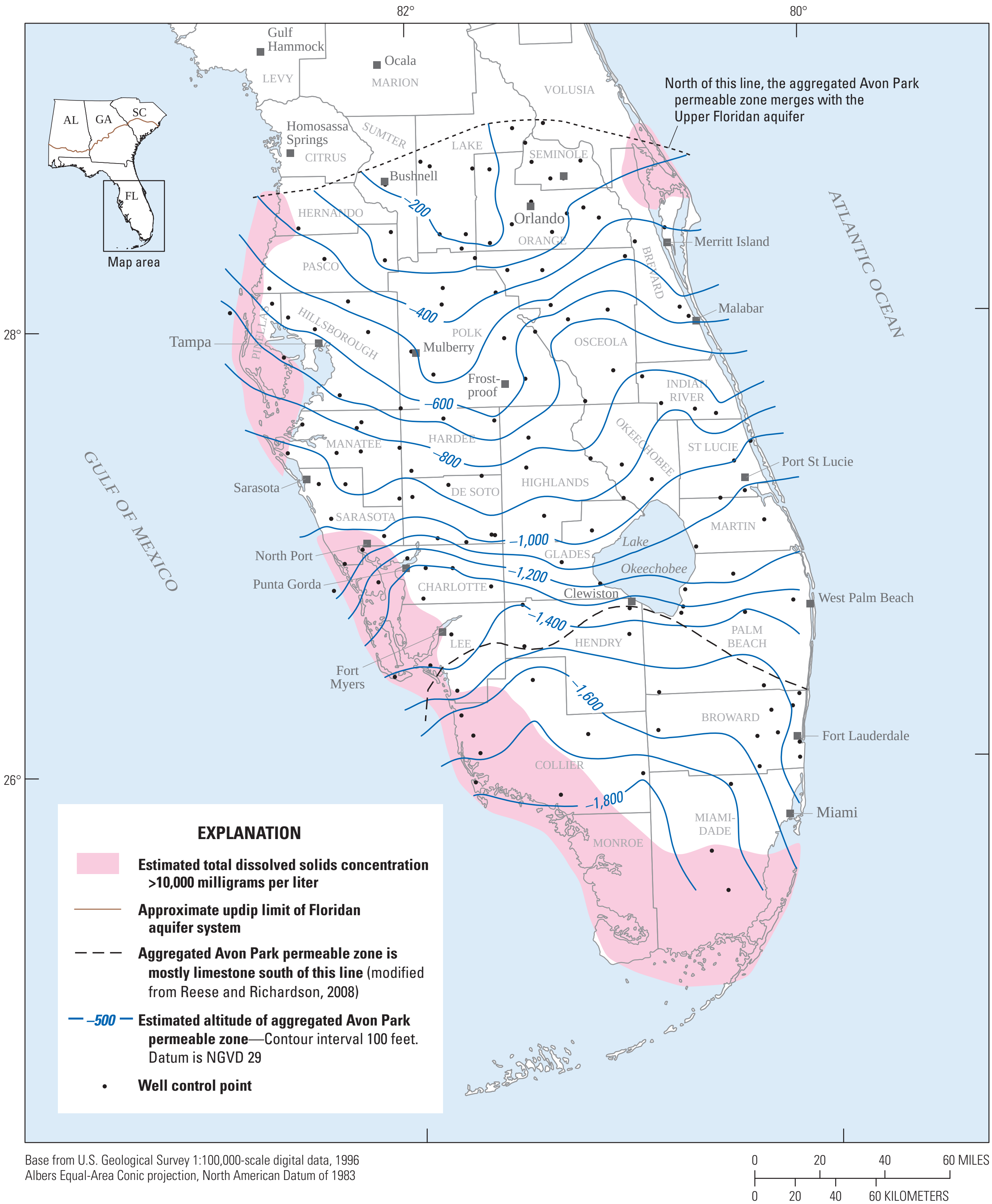


Figure 30. Altitude of the top of the aggregated Avon Park permeable zone and estimated total dissolved solids concentration in central and southern Florida.

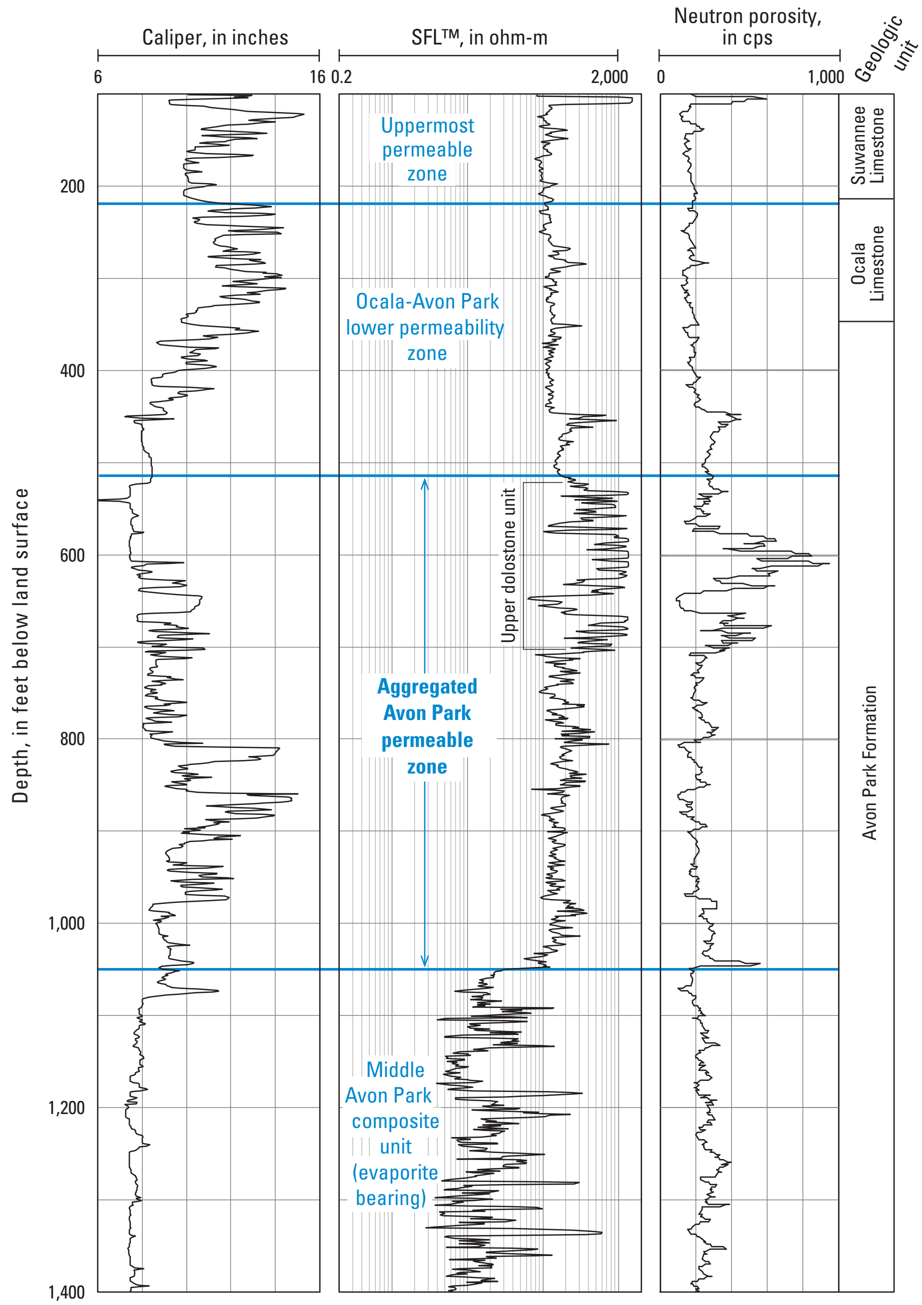


Figure 31. Borehole geophysical log characteristics of the aggregated Avon Park permeable zone in test well FL–HIL2, Hillsborough County, Florida. [SFL, spherically focused log (resistivity); ohm-m, ohm-meter; cps, counts per second; well location shown on plate 1]

gradually decrease within the stratigraphic interval mapped as the aggregated APPZ. Coincident with this transition, Reese and Richardson (2008) showed that the APPZ becomes less transmissive as it grades into limestone; the extent of this limestone is shown in figure 30.

The configuration of the top and base of the aggregated APPZ generally conforms to the overall dip of the litho-stratigraphic units of central and southern Florida (fig. 30). At its northern extent, the altitude of the aggregated APPZ is about –200 to –400 ft. Farther south, the unit dips gently into southern Florida where its altitude ranges from –1,300 to –1,600 ft. From central to southern Florida, salinity in this zone transitions from slightly brackish to brackish, with TDS concentrations generally ranging from 3,000 to 5,000 mg/L (Reese and Memberg, 2000; Reese, 1994, 2000, 2002; Reese and Richardson, 2008). The aggregated APPZ contains water with a TDS concentration greater than 10,000 mg/L in a small coastal area from Hernando to Manatee Counties, and along the coastal areas of Sarasota, Charlotte, and Lee Counties where used for deep-well injection (fig. 30). Saline water may be present in this zone along the coastline in northern Brevard and Southern Volusia Counties and in coastal and southern Miami-Dade County.

Thickness—The Upper Floridan aquifer ranges in thickness from only a few feet in the updip outcrop areas of Alabama and Georgia to more than 1,700 ft in southwestern Florida (fig. 32). Where the base of the Upper Floridan aquifer is mapped on the top of the LISAPCU, the shallower composite unit or BCCU, the aquifer is less than 500 ft thick; where the base is mapped on the top of the MAPCU, the deeper composite unit, the aquifer is greater than 500 ft thick. Shaded areas depicting the individual units that make up the two composite units and the transitional area selected as the base of the Upper Floridan aquifer are shown in figure 32 and discussed in more detail later. The total thickness of the Upper Floridan aquifer includes highly and less-permeable zones within the aquifer.

Middle Composite and Confining Units

Miller (1986) mapped seven middle confining (or semi-confining) units (MCUI–VII) of subregional extent. These MCUs were used to divide the Floridan aquifer system into the Upper and Lower Floridan aquifers (Miller, 1986). Where there was no semiconfining unit, the system was previously mapped as one aquifer and named the Upper Floridan aquifer for the entire system (Miller, 1986). In this revision, these numbered middle confining units have either been reassigned to two composite units that divide the system into the Upper or Lower Floridan aquifers, reassigned to an aquifer or zone, abandoned altogether, or renamed. Middle confining units MCU1, MCUII, MCUIII, and MCUVI have been reassigned. Middle confining units MCUIV and MCUVII have been abandoned and MCUV has been renamed the BCCU.

The two composite units are the LISAPCU and the MAPCU. The LISAPCU consists mostly of fine-grained carbonate rocks previously mapped as middle confining unit MCUI of Miller (1986) in the uppermost part of the Avon Park Formation and lower permeability clastic confining beds in the updip part of the aquifer system belonging to the Lisbon Formation or equivalent middle Eocene strata. The MAPCU consists of evaporite-bearing rocks of middle confining unit MCUII of Miller (1986) and stratigraphically equivalent non-evaporite-bearing carbonate units that may be semiconfining or part of a transmissive system in the middle part of the Avon Park Formation. The BCCU, which includes a clay facies represented by the Bucatunna Clay Member of the Byram Formation and a clayey sand and marl facies represented by unnamed Oligocene rocks, is a disconnected confining unit in the predominantly clastic sediments in the southern part of the western panhandle of Florida adjacent or overlying the LISAPCU (fig. 32).

The composite units are defined on the basis of regional litho-stratigraphy of the relatively less-permeable units that may restrict flow within the middle part of the system. The two composite units and the BCCU overlap each other; however, no unit extends throughout the entire system. Regional variations in relative permeability of the composite units are delineated along with indication of the individual confining units that make up each composite unit. In some regions the hydraulic properties may be well known, whereas in other regions they may be inferred through geologic assessment of the materials that constitute the unit.

Lisbon-Avon Park Composite Unit, Northern Florida and Southern Georgia, Alabama, and South Carolina—The LISAPCU consists of several different subregionally extensive confining, semiconfining, and leaky units in the northern half of the study area (table 7, fig. 33). Collectively, these units separate the highly transmissive Upper Floridan aquifer from the deeper, commonly less-transmissive Lower Floridan aquifer.

The LISAPCU is divided into regions on the basis of its relative degree of confinement or "leakiness," estimated from hydraulic head differences across the unit, hydraulic head responses to pumping, or from previous investigations that estimated the hydraulic properties of the unit. The regions composing this unit ordered from generally lower to higher leakiness, include the

- *Lisbon confining unit-Lisbon aquifer region* in southeastern Alabama—generally confining, although properties vary locally, and consisting of sand and clay at the top of rocks of middle Eocene age; in western panhandle—tightly confining Bucatunna Clay consisting of clay and marl of Oligocene age overlies LISAPCU;
- *Claiborne confining unit-Claiborne aquifer region* in southwestern Georgia—generally confining although properties vary locally, and consisting of sand and clay of the Lisbon confining unit;

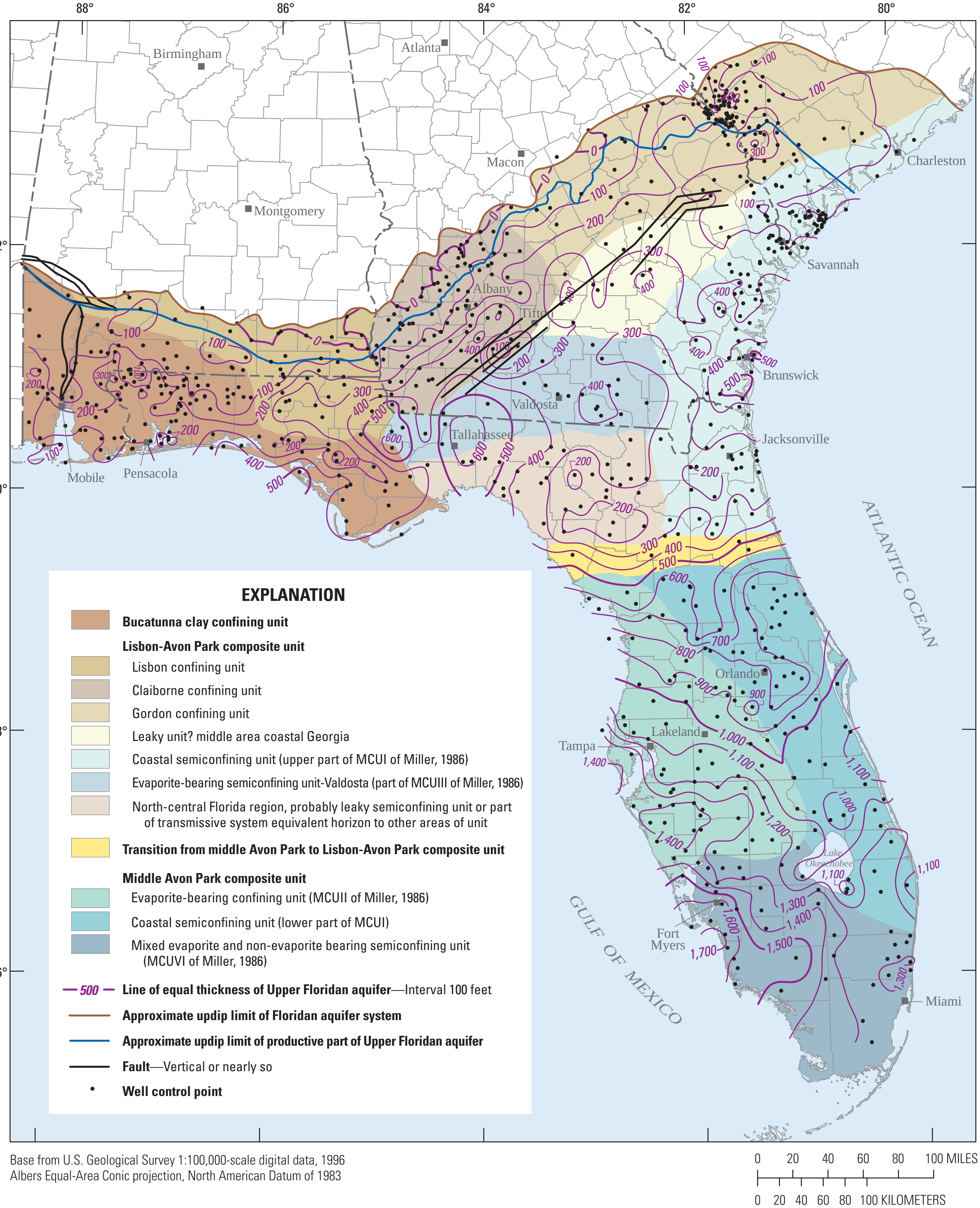


Figure 32. Thickness of the Upper Floridan aquifer and underlying units, southeastern United States.

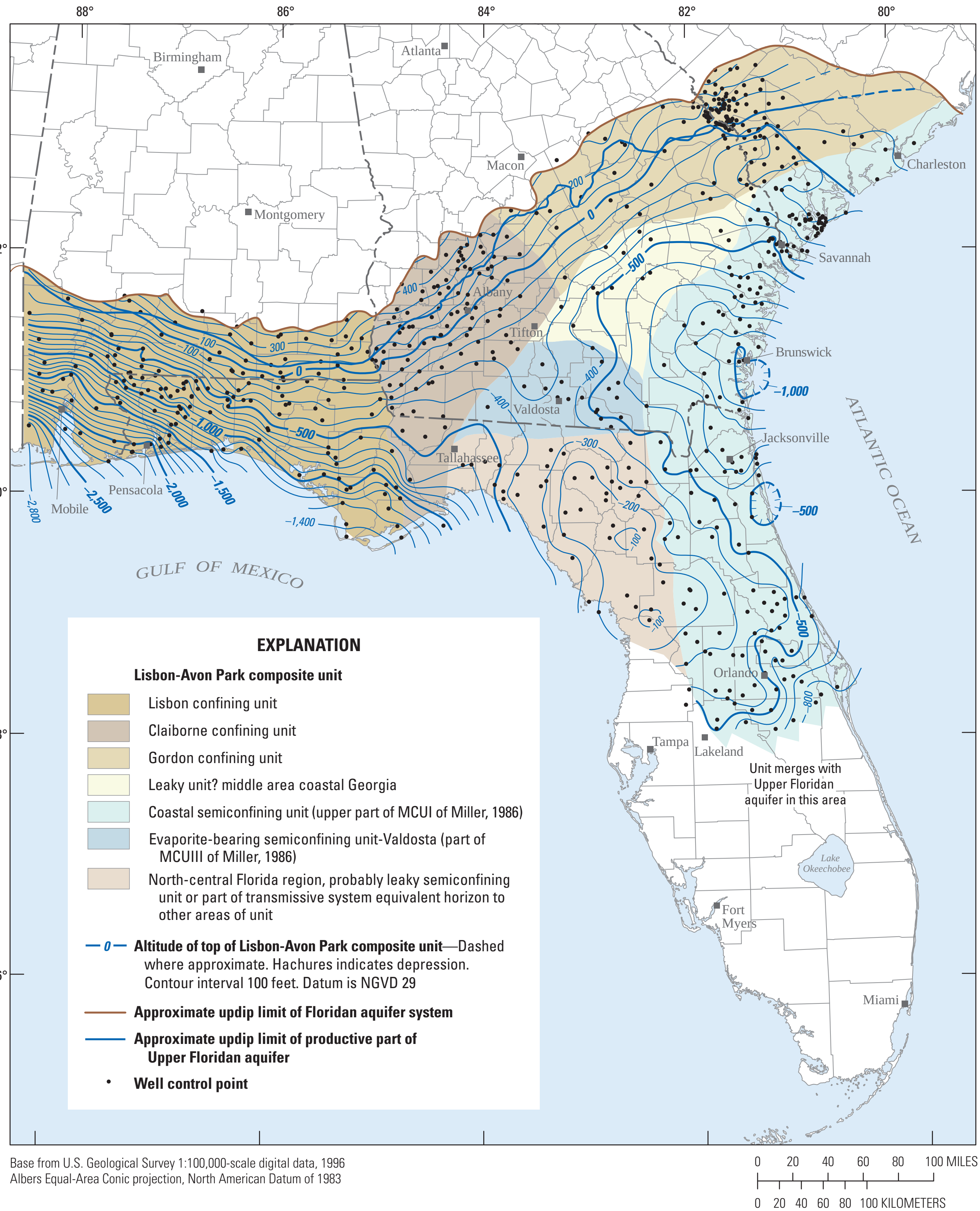


Figure 33. Altitude of the top of the Lisbon-Avon Park composite unit, southeastern United States.

Table 7. Subregional characteristics of the Lisbon-Avon Park composite unit.

[Regions refer to those shown in figure 33]

Area	Equivalent hydrogeologic unit	Stratigraphic unit	Lithology	Identifying characteristics	Water-bearing properties
Lisbon aquifer region, Alabama	Lisbon-McBean confining unit (Barker and Pernick, 1994)	Yazoo Clay	Clay, sand, argillaceous limestone	Low resistivity response on electric logs, lithology.	Mostly confining, may vary laterally depending on lithology.
Claiborne aquifer region, southwestern Georgia	Lisbon confining unit (Clarke and others, 1984)	Consists of the upper part of Lisbon Formation	Sand and argillaceous limestone	Medium-to-low resistivity response, glauconite common	Variable confining, hydraulic head differences of 5 to more than 30 feet.
Gordon aquifer region, east-central Georgia	Gordon confining unit (Brooks and others, 1985; Falls and others, 1997)	McBean Formation	Mostly clay or clayey sand	Low-resistivity response, lithology.	Confining to semiconfining, hydraulic head differences range from less than 5 to more than 50 feet.
Coastal region semiconfining unit, Georgia, South Carolina, Florida	Middle confining unit MCUI (Miller, 1986)	Consists of the upper part of Avon Park Formation in Georgia and Florida; part of Santee Limestone in South Carolina	Limestone, dolomitic limestone, dolostone	High resistivity response on electric logs across low-porosity dolostone intervals and uniform resistivity response with large washed out intervals in softer poorly indurated limestone intervals.	Mostly acts as a leaky semiconfining unit; hydraulic head differences range from less than 1 foot to greater than 5 feet.
North-central Florida region dolomite zone	Previously mapped as part of Upper Floridan aquifer	Consists of dolomitized intervals in the upper part of the Avon Park Formation	Dolostone and some limestone	Distinct high resistivity response across low-porosity dolostones at top of Avon Park Formation.	Based on lithology it may act as a leaky semiconfining unit similar to the coastal region or could be part of transmissive system if fractured and solutioned. Head differences across this unit are unknown.
Central Georgia coastal region	Previously mapped as part of Upper Floridan aquifer	Consists of dolomitized intervals in the upper part of the Avon Park Formation	Limestone and dolomitic limestone	Distinct high resistivity response across dolomitic limestone.	Based on lithology may act as a leaky semiconfining unit similar to the coastal region or could be part of transmissive system if fractured and solutioned. Hydraulic head differences unknown.
Valdosta region, central area along Georgia-Florida State line	Middle confining unit MCUIII (Miller, 1986)	Consists of low-permeability carbonate rocks in the Avon Park Formation	Limestone and dolomitic limestone with gypsum	Very high resistivity response (low porosity) across beds of limestone and dolomitic limestone; intergranular gypsum common in this unit.	Probably acts as a leaky semiconfining unit, hydraulic head differences less than 5 feet based on packer testing.

- *Gordon confining unit-Gordon aquifer region* in east-central Georgia and southeastern South Carolina—generally confining although properties vary locally, and consisting of sand, silt, and clay of the Gordon confining unit;
- *Valdosta region* in south-central Georgia—semiconfining and consisting of evaporite-bearing carbonate rocks previously mapped as the upper part of middle confining units MCUIII and MCUVII by Miller (1986);
- *Coastal semiconfining unit* extending from South Carolina to east-central Florida—semiconfining to leaky and consisting of less-permeable carbonate rocks previously mapped as middle confining unit MCUI by Miller (1986);
- *North-Central Florida region*—probably a leaky semiconfining unit or part of the transmissive aquifer system lying at a similar stratigraphic interval to adjacent regions, and consisting of a dolomite zone at the top of the Avon Park Formation; and the
- *Central Georgia coastal region*—possibly leaky or part of the transmissive aquifer system lying at a similar stratigraphic interval to adjacent regions and consisting of limestone and dolomite at the top of the Avon Park Formation.

In the *Lisbon confining unit-Lisbon aquifer* and *Claiborne confining unit-Claiborne aquifer regions*, the LISAPCU overlies and confines the Lisbon and Claiborne aquifers (figs. 33 and 34, pls. 7–11). Within these regions, lower permeability clastic units separate the highly permeable Upper Floridan aquifer from less permeable clastic or carbonate-clastic aquifers beneath it. Over most of its extent, the composite unit in the Lisbon and Claiborne aquifer regions generally consists of sands, silts, and clays of relatively lower permeability that restrict the movement of water between the overlying and underlying aquifers. In southwestern Georgia, the composite unit grades into hard, sandy, clayey limestone of distinctly lower permeability than that of the overlying Ocala Limestone (Watson, 1981), and was identified by Clarke and others (1984) as the Lisbon confining zone. The composite unit also has been identified by Faye and Mayer (1997) as the Lisbon-McBean confining unit. Where lower permeability rocks are absent, the carbonate rocks of the Upper Floridan aquifer may directly overlie clastic rocks of the Lisbon and Claiborne aquifers; in these areas, the Upper and Lower Floridan aquifers may be hydraulically connected.

Farther east, in the *Gordon confining unit-Gordon aquifer region*, the Gordon aquifer is overlain by the Gordon confining unit (fig. 33, pls. 11 and 12), which separates the overlying and generally more permeable Upper Floridan aquifer from the underlying Gordon aquifer. As shown on cross section *F–F'* (fig. 35, pl. 12), the Gordon confining unit extends southward toward the Gulf Trough where it eventually grades into carbonate rocks of the Floridan aquifer system. The Gordon confining unit derives its name from the Gordon aquifer of Brooks and others (1985) where it was first established in east-central Georgia. The Gordon aquifer, as mapped herein, is equivalent to the Gordon aquifer defined in Georgia by Brooks and others (1985) and is roughly equivalent to the Gordon aquifer described and mapped in South Carolina by Aadland and others (1995) and Gellici and Lautier (2010). Falls and others (1997) correlated the Gordon confining unit to a fine-grained limestone unit of the Tinker-Santee unit in South Carolina and to the Lisbon and McBean Formations in Georgia. In these areas, the Gordon confining unit generally consists of clay and marl in the lower part of these formations (Clarke and West, 1998). The McBean also has been described as a sandy, fine-grained limestone (Clarke and others, 1994), a sandy marl in Burke County, Ga., (Leeth and others, 1996), and as a thin marl unit at a test well in Screven County, Ga. (Clarke and others, 1996). This unit correlates to the “green” clay confining unit at the Savannah River site (Fallaw and Price, 1995).

Hydraulic head differences across the Gordon confining unit vary widely depending on the location of individual wells with respect to incised streams and whether these wells are located in recharge or discharge areas. Using water-level data from selected wells in South Carolina and from other monitoring wells in eastern Georgia, Clarke and West (1998) evaluated vertical hydraulic head gradients between the major aquifers. As part of this analysis, hydraulic head differences were determined between the Gordon aquifer, which is the clastic equivalent of the Lower Floridan aquifer, and the Upper Three Runs aquifer, which is the clastic equivalent of the Upper Floridan aquifer. The water-level differences between the two aquifers ranged from less than 5 ft to greater than 50 ft in the wells analyzed. Hydraulic head gradients between the aquifers generally were downward in the inter-stream areas and generally upward near major streams or within the Savannah River alluvial valley. Gellici and Lautier (2010) reported hydraulic head differences of 40 to 50 ft in core holes completed in Allendale and Orangeburg Counties, South Carolina.

River incision associated with the Savannah River alluvial valley greatly influences the configuration of the potentiometric surface, groundwater-flow direction, and stream-aquifer relations. Clarke and West (1998) mapped and described the influence of the alluvial valley on groundwater flow in this area.

The horizontal hydraulic conductivity of core samples of the Gordon confining unit were reported to range from 1.2×10^{-4} to 2.0×10^{-4} ft/d (Aadland and others, 1995). A similar value of 3.34×10^{-4} for the vertical hydraulic conductivity was reported for a core sample collected from a yellow-green calcareous sandy clay within the confining unit (Leeth and others, 1996). Because of the relative lack of quantitative data for the hydraulic conductivity of the confining unit, Barker and Pernik (1994) initially assigned a hydraulic conductivity value of 8.6×10^{-6} ft/d to this unit and leakance, derived from simulation, of 8.6×10^{-5} (ft/d)/ft to 8.6×10^{-4} (ft/d)/ft.

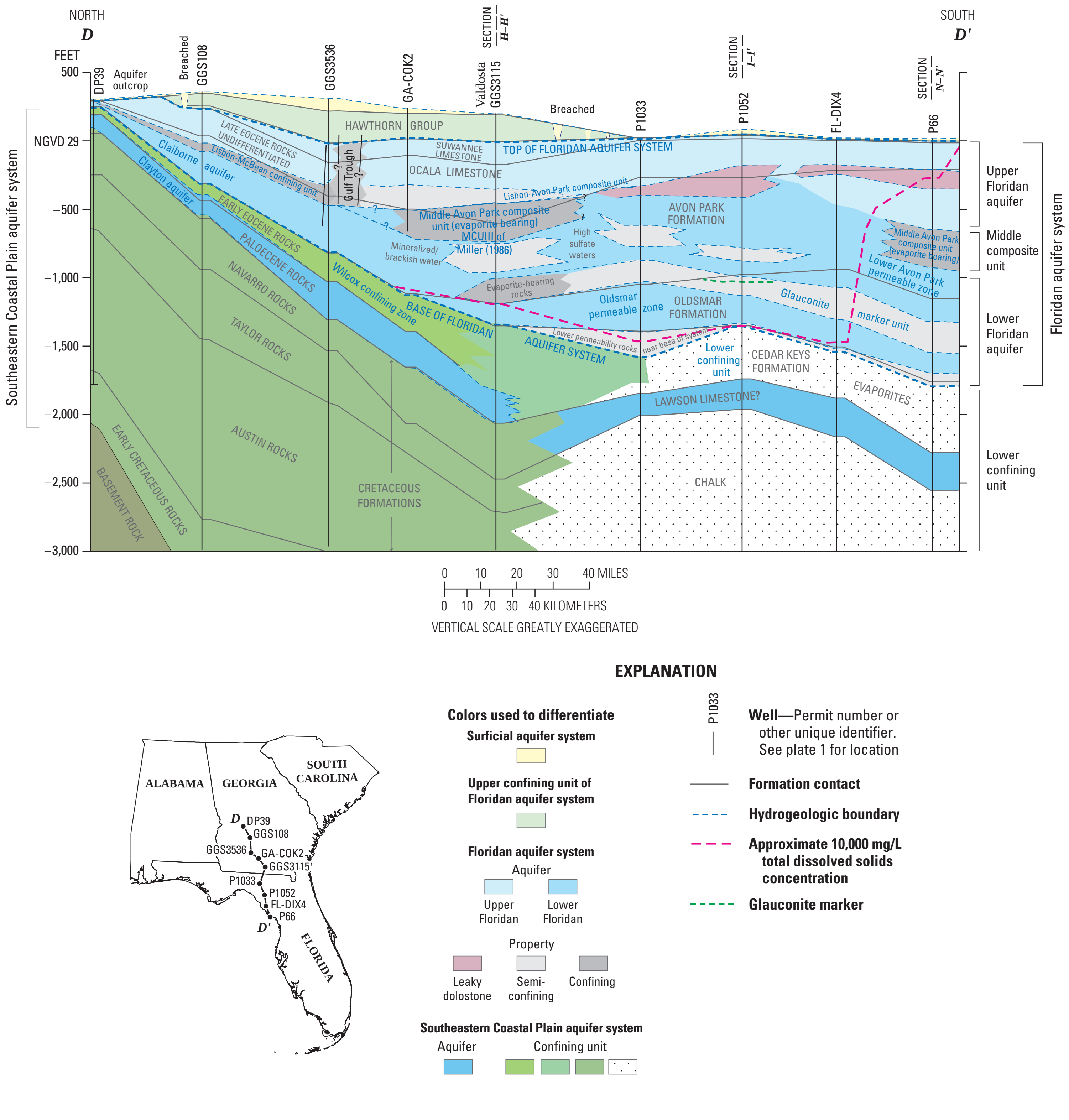


Figure 34. Generalized hydrogeologic cross section *D–D'* from Macon County, Georgia, to Levy County, Florida (see plate 10 for more detail).

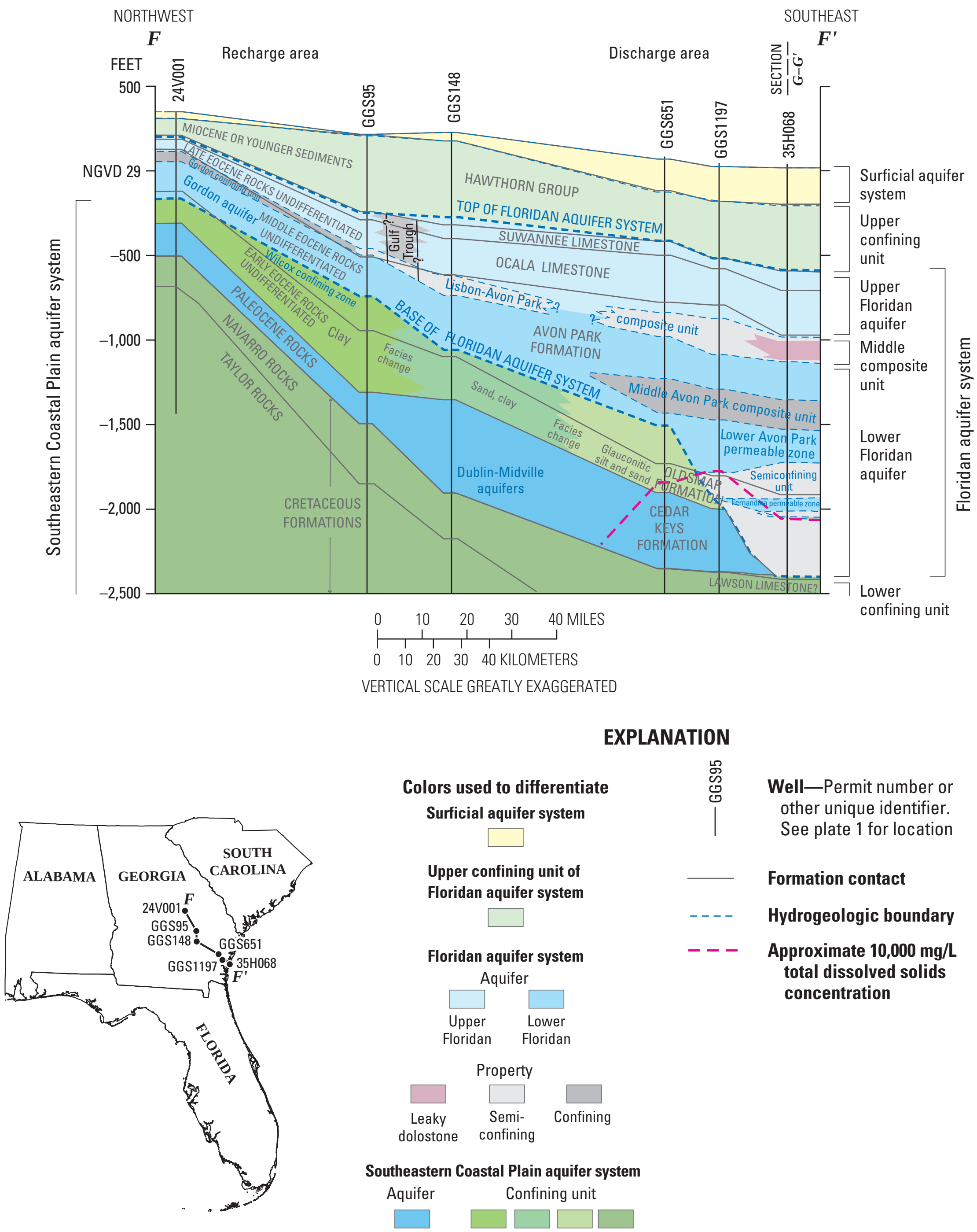


Figure 35. Generalized hydrogeologic cross section *F–F′* from Johnson County, Georgia, to Glynn County, Georgia (see plate 12 for more detail).

Downdip in the Valdosta region (fig. 33), the composite units of the Floridan aquifer system consists of lower permeability, dense, fossiliferous, gypsiferous, dolomitic limestone that lies in the lower and middle part of the Avon Park Formation (Miller, 1986). Also included in this region is a narrow, northeast-trending strip of micritic to finely crystalline limestone that contains lenses, pods, beds, and intergranular gypsum that was mapped as part of MCUVII (Miller, 1986). Water-quality data, lithologic descriptions, and geophysical logs were used by Miller (1986) to map the extent of an irregular and relatively thick middle confining unit, MCUIII, considered herein to be a "lumped unit" encompassing nearly the entire thickness of the Avon Park Formation and upper part of the Oldsmar Formation or early Eocene equivalent rocks. A lack of well control south of Valdosta, particularly in Hamilton, Madison, Suwannee, and Columbia Counties, Fla., required Miller to extend this unit primarily on the basis of a characteristic geophysical log pattern observed in other wells in the region and from sparse well cuttings available from scattered wells in that area. Because of the thickness and stratigraphic position of these lower permeability rocks, the middle confining unit MCUIII is reassigned into two distinct units herein. The upper unit is included in the LISAPCU and the lower unit is included in the MAPCU. Although these units are now mapped on the basis of stratigraphic position, the top and base of each are indicated by characteristic lithologic and geophysical log patterns.

- Upper unit—characterized by massively bedded, low-porosity, gypsiferous dolostone at the top of the Avon Park Formation and by relatively high resistivity on electric logs and low porosity on neutron, density, or sonic porosity logs.

- Lower unit—characterized by a thinly bedded sequence of soft limestone interbedded with tight, low-porosity, highly gypsiferous beds. The limestone and gypsiferous beds are respectively associated with low and high resistivity response on electric logs, creating a distinctive "spiky" pattern commonly referred to as the "gyp-pattern."

The relation of the evaporite-bearing semiconfining unit in the Valdosta region to the overlying and underlying units is depicted on cross section *D–D′* (pl. 10, fig. 34). The plate shows the full detail in the cross section with borehole geophysical and lithologic logs where these were available and notes placed along the section to clarify areas of uncertainty. In the middle of this cross section (pl. 10), the lithologic log for L.P. Shelton No. 1–A Hunt Petroleum well (GGS3115, fig. 2) shows the position of the evaporite-bearing units in the Valdosta region. The gypsiferous interval in GGS3115 was correlated to a corresponding interval in a USGS test well (not shown) drilled to a depth of about 1,000 ft (Krause, 1979). Updip from GGS3115, the rocks generally thin toward the outcrop area and are disrupted by the Gulf Trough. Because of its higher permeability, relative to other parts of the Floridan aquifer system, the Upper Floridan aquifer dominates the flow system updip from the Gulf Trough. As water approaches the Gulf Trough, however, it either moves below, around, or passes slowly through the materials in the Gulf Trough. South of the Gulf Trough, groundwater flow is once again dominated by highly transmissive rocks of the Upper Floridan (fig. 34).

Along the Atlantic coastal region, an extensive band of lower permeability carbonate rock extends from southeastern South Carolina to east-central Florida (table 7, fig. 33). This lower permeability unit was first mapped as middle confining unit MCUI (Miller, 1986) and was identified as the leakiest of all the middle confining units in the Floridan aquifer system. Because of the lack of distinguishing characteristics and its leaky nature, this unit is commonly referred to simply as the "semiconfining unit," and is mapped on the basis of flowmeter logs (O'Reilly and others, 2002; Williams, 2010; Williams and Gill, 2010). In this report, this unit is referred to as the MCUI region of the LISAPCU.

In the northern coastal region of Georgia and South Carolina, the semiconfining unit of the MCUI region separates the Upper and Lower Floridan aquifers (Williams and Gill, 2010). In this area, the semiconfining unit consists of a soft micritic limestone and fine-grained dolomitic limestone, grading laterally from calcareous sand and clay in northeastern Georgia into sandy clay in South Carolina (Miller, 1986). The strata that compose the semiconfining unit include the lower part of the Ocala Limestone in Beaufort and Jasper Counties, South Carolina, and the upper to middle parts of the Avon Park Formation elsewhere (Williams and Gill [2010]; pls. 2 and 3, fig. 19). The lithology of the semiconfining unit is similar to that of the overlying and underlying units, with the exception of its relatively less developed secondary porosity. Minor variations in hydraulic head and water quality exist across this lower permeability unit that, together with the flowmeter data, confirm it is semiconfining to leaky (Miller, 1986). Hydraulic head differences across the semiconfining unit in the northern coastal region of Georgia and South Carolina are reported to be relatively small, usually less than a few feet at most well cluster sites (Williams and Gill, 2010).

The relation of the semiconfining unit in the MCUI region to the overlying and underlying units is depicted in cross section *G–G′* (pl. 13) and also shown on a reduced version of that plate in figure 36. In southernmost South Carolina, figure 36 indicates the Upper Floridan aquifer consists entirely of a thin permeable zone near the top of the Ocala Limestone. As mentioned previously, the lower part of the Ocala Limestone in this area is fine grained and included in the semiconfining unit. The Upper Floridan aquifer is thinner but much more transmissive than the Lower Floridan aquifer in this area. At a recent test-drilling site near Savannah, Ga., hydraulic testing and simulation results indicated the Upper Floridan aquifer transmissivity was about 40,000 ft^2/d, whereas the Lower Floridan aquifer transmissivity was estimated to be about 10,000 ft^2/d (Williams, 2010; Clarke and others, 2011).

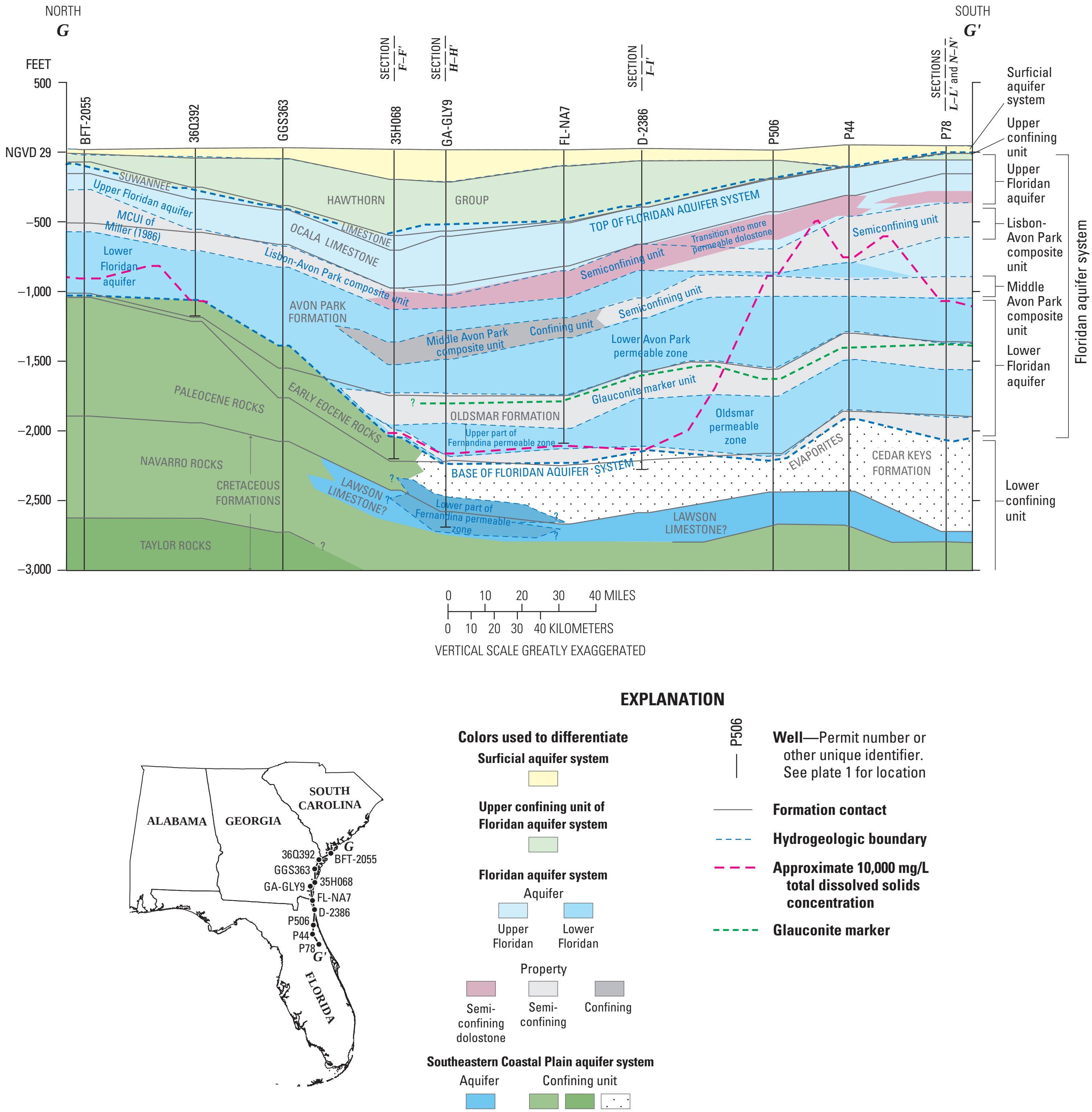


Figure 36. Generalized hydrogeologic cross section *G–G′* from Beaufort County, S.C., to Volusia County, Fla. (see plate 13 for more detail).

The thickness and hydraulic conductivity of the semiconfining unit controls the rate of leakage between the Upper and Lower Floridan aquifers in the MCUI region. Although this unit has been tapped by numerous test wells (mostly those for oil and gas), few aquifer hydraulic tests have been conducted. In the northern coastal region of Georgia, simulated vertical hydraulic conductivity of the semiconfining unit range from 0.0064 to 0.047 ft/d (Williams and Gill, 2010; Clarke and others, 2011). Packer testing at one of these sites indicated horizontal hydraulic conductivities ranged from 0.16 to 3.09 ft/d and averaged 1 ft/d for four tests. From these values, the vertical hydraulic conductivity was estimated to range from 0.02 to 0.36 ft/d on the basis of a horizontal-to-vertical hydraulic conductivity ratio of 8.5:1, which is in fairly good agreement with onsite testing and simulation (Clarke and others, 2010).

Brown (1984) estimated the vertical hydraulic conductivity of the semiconfining unit to be 0.001 ft/d for northeastern Florida and southeastern Georgia on the basis of reported vertical hydraulic conductivity values from core samples collected from hard dolomitic limestone of the Avon Park Formation (Pride and others, 1966). Using a thickness of 200 ft and a vertical hydraulic conductivity of 0.001 ft/d, a leakance of 5.0×10^{-6} (ft/d)/ft was estimated. The hydraulic properties used by Brown (1984) are much lower than an estimate of horizontal hydraulic conductivity derived from a simulation constructed by Sepulveda (2006) to simulate leakage through the semiconfining unit using data collected during an aquifer performance test of Upper and Lower Floridan aquifer wells in southwestern Duval County, Fla. The simulated horizontal hydraulic conductivity of the semiconfining unit was estimated to be 0.12 ft/d and the thickness of the semiconfining unit was estimated to be 165 ft (Sepúlveda, 2006). A vertical hydraulic conductivity value could not be determined from the simulation (Nicasio Sepúlveda, U.S. Geological Survey, written commun., 2013).

In east-central Florida, McGurk and Presley (2002) described the semiconfining unit as consisting of soft micritic limestone and dense dolomitic limestone with very little secondary porosity development, as compared to the overlying and underlying permeable zones. They excluded a fractured dolostone unit at the top of the Avon Park Formation that was previously included in MCUI as defined by Miller (1986) and used in regional and subregional simulation (Bush and Johnston, 1988; Tibbals, 1990). Spechler and Halford (2001) estimated the vertical hydraulic conductivity of the semiconfining unit to range from 0.004 to 0.6 ft/d on the basis of reported leakance coefficients from aquifer performance tests.

In the north-central Florida region (fig. 33), in a stratigraphically equivalent position to the semiconfining unit within the LISAPCU, a hard, low-porosity dolostone was mapped on the basis of lithology and resistivity log patterns and is labeled as the "upper dolostone unit" on plate 15. From lithologic logs, this interval appears to consist mostly of thick, massive dolostone similar to that of the semiconfining unit in the coastal region farther east; limestone also may be a large component of this interval. Because of a lack of well testing data, however, the hydraulic properties of the dolostone unit are presently unknown for this region. On the basis of lithology, the dolostone unit could be a leaky unit similar to the coastal region semiconfining unit or it could be a transmissive unit similar to the equivalent rock-stratigraphic horizon of the APPZ in central and southern Florida. Because of this uncertainty, this dolostone unit is identified on the maps and cross sections as "probably leaky semiconfining unit or part of permeable system equivalent horizon to other areas of unit." It should be stressed that although an equivalent stratigraphic horizon is mapped and included in the composite unit, it is not implied that this unit comprises lower permeability strata throughout this region and may actually represent rock that has hydraulic properties similar to those of the overlying and underlying aquifers.

Middle Avon Park Composite Unit, Central and Southern Florida—The MAPCU consists of lower permeability rocks in both evaporitic and non-evaporitic facies within the middle (or approximate middle) part of the Avon Park Formation (table 8, figs. 37 and 38). Because its permeability is generally lower than that of other less-permeable zones within the Floridan aquifer system, the MAPCU is considered the principal confining to semiconfining unit in peninsular Florida (fig. 38).

From generally lower to higher leakiness, the regions of the MAPCU include (fig. 38)

- A non-leaky evaporite-bearing confining unit—located in west-central and southwestern Florida, composed of lower permeability gypsiferous dolostone, gypsum, anhydrite, limestone, and organic-rich clays in the middle part of the Avon Park Formation, and previously mapped as middle confining unit MCUII by Miller (1986).

- A leaky to non-leaky(?), mixed evaporite- and non-evaporite-bearing semiconfining unit—located in south-central and southern Florida, composed of relatively lower permeability, mostly non-vuggy, locally gypsiferous limestone, dolomitic limestone, and dolostone in the middle part of the Avon Park Formation, and previously mapped as the southern part of middle confining unit MCUII and (or) MCUVI by Miller (1986).

- A leaky evaporite-bearing semiconfining unit—located in southern Georgia in the Valdosta region and northern Florida, composed of lower permeability gypsiferous limestone and minor dolomitic limestone in the middle part of the Avon Park Formation, and previously mapped as middle confining unit MCUIII by Miller (1986).

Table 8. Subregional characteristics of the middle Avon Park composite unit.

[Regions refer to those shown in figure 38]

Area	Equivalent hydrogeologic unit	Stratigraphic unit	Lithology	Identifying characteristics	Water-bearing properties
West-central Florida region	Middle confining unit MCUII (Miller, 1986)	Middle part of Avon Park Formation	Gypsiferous limestone and dolostone, dolomitic limestone, pods and layers of gypsum and anhydrite, carbonaceous clay	(1) Low resistivity with thin sharp resistivity "spikes" representing lower porosity beds of gypsum, anhydrite or dense dolostone or limestone intervals. (2) Overall low porosity with sharp increases in porosity (thin clay, peat, or fine-grained carbonate interbeds). (3) In-gage borehole with few caliper peaks indicating low fracture and vuggy porosity; although fractures and vuggy intervals are not uncommon in this unit. (4) Sharp thin gamma-ray spikes usually associated with carbonaceous or peaty intervals.	Non-leaky confining unit. Mineralized water in this unit suggests poor connection with freshwater in the overlying Upper Floridan aquifer. Hydraulic head differences exceed 30 feet in some areas.
East-central Florida region	Lower part of middle confining unit MCUI (Miller, 1986)	Middle part of Avon Park Formation	Soft, poorly indurated, limestone with beds of dolostone; overall a massive unit that lacks secondary porosity	Unit has a fairly uniform resistivity response (and generally high porosity); enlarged or washed out borehole commonly occurs in poorly indurated limestone that characterizes this unit.	Semiconfining unit. Hydraulic head differences can range from less than one foot to greater than 10 feet; water-quality changes across the unit suggests it is may be confining in some areas.
South Florida region	Consists mostly of middle confining unit MCUVI (Miller, 1986)	Middle part of Avon Park Formation	Heterogenous carbonate rock unit (1) locally gypsiferous limestone and dolostone beds, (2) low-porosity dolostone, (3) non-evaporitic carbonate rocks of relatively low permeability	Identified by a distinctive high-to-low resistivity log pattern owing to the thinly to thickly bedded carbonate rocks in this unit; also generally has a distinctively lower porosity than rocks above and below.	May be a confining unit in the evaporitic facies and semiconfining in non-evaporitic facies. Hydraulic head differences across the unit are not generally known. At a limited number of wells hydraulic head differences of greater than 5 feet have been observed.
Valdosta region	Middle confining unit MCUIII (Miller, 1986)	Middle part of Avon Park Formation	Limestone and dolomitic limestone with intergranular gypsum, rare thin pods and layers of gypsum	Thin highly resistive beds of very low porosity in an overall low-resistivity unit gives a "ratty" response on electric logs. Intergranular gypsum, pods, and rare layers of gypsum distinguish this unit from units above and below.	May be a leaky semiconfining unit. Hydraulic head differences less than 5 feet based on packer testing.

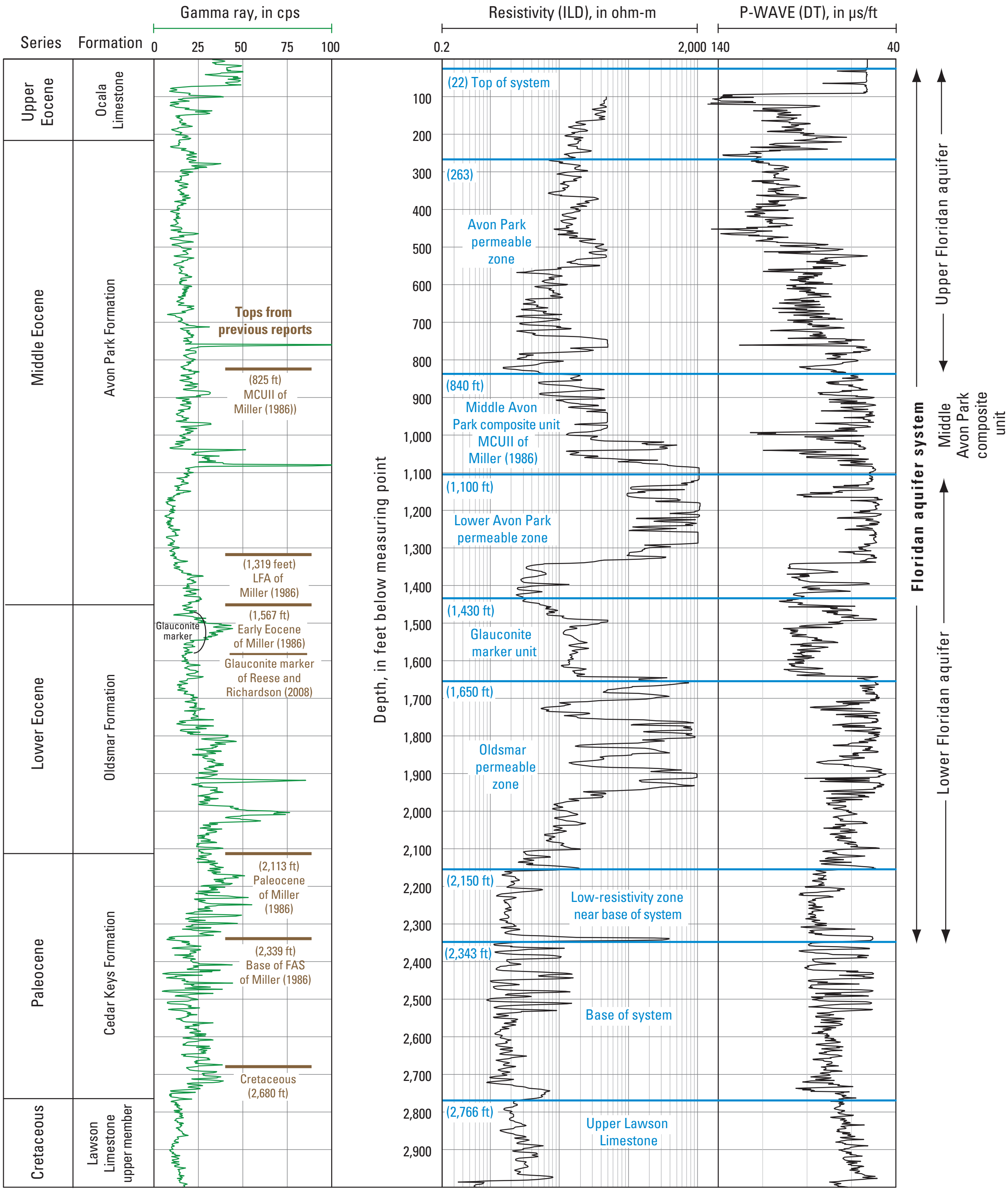


Figure 37. Borehole geophysical log characteristics of the middle Avon Park composite unit and other hydrogeologic units at well P350, the Mobile Oil Company #1 Garby, Citrus County, Florida. [Measuring point is 13 feet NGVD 29; cps, counts per second; ft, foot; ILD, induction log deep; ohm-m, ohm-meter; P-WAVE sonic log (DT), interval transit time; µs/ft, microseconds per foot; MCU, middle confining unit; LFA, Lower Floridan aquifer; FAS, Floridan aquifer system; well location shown on plate 1]

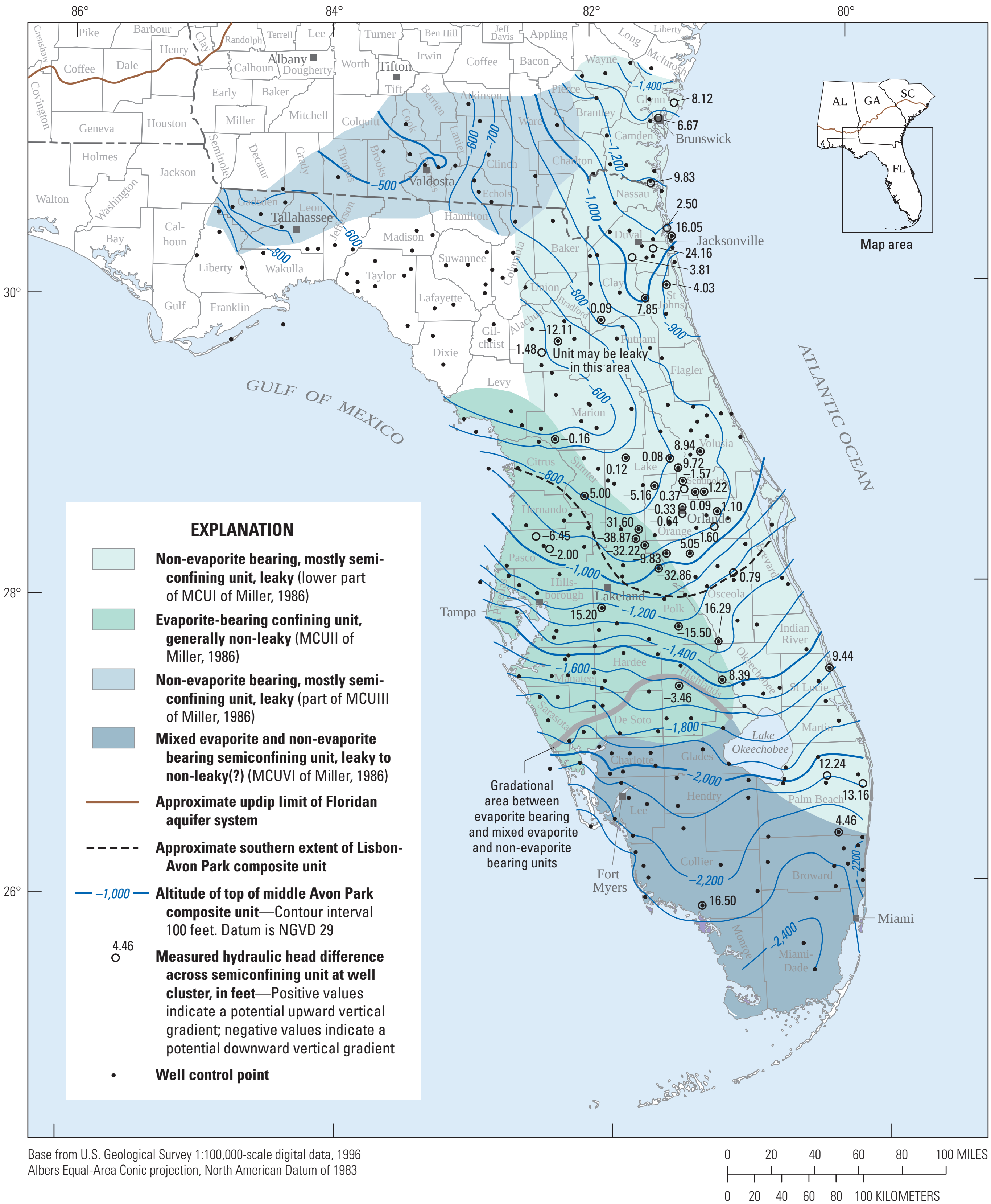


Figure 38. Altitude of the top and estimated properties of the middle Avon Park composite unit, peninsular and northeastern Florida and southeastern Georgia.

- A leaky, non-evaporite-bearing semiconfining unit—located in east-central to northeastern Florida and southeastern Georgia, composed of lower to moderately permeable, non-vuggy limestone, dolomitic limestone, and locally argillaceous limestone in the middle part of the Avon Park Formation, and previously mapped as the lower part of middle confining unit MCUI by Miller (1986).

Geophysical log characteristics of the MCUII evaporite-bearing region of the MAPCU in west-central Florida are shown in a log from Mobile Oil Company #1 Garby (well P350) located on the coastline of the Gulf of Mexico in Citrus County, Fla. (fig. 37, pl. 1). In this well, the evaporite-bearing unit is marked by a sharp decrease in sonic log interval transit time, indicating a decrease in porosity, coupled with an erratic high- and low-resistivity pattern indicating thinly bedded strata. Gamma-ray peaks also can be used to identify the unit, although these can be present anywhere within the confining unit, or can be absent. If present, the gamma-ray peaks are usually thin and sharp, possibly representing organic-rich intervals. The base of the unit is usually picked at the top of a very highly resistive (low-porosity) interval that typically contains thin permeable zones marked by sharp increases in interval transit time on the sonic log and (or) by abrupt borehole enlargements in caliper logs. No caliper logs were available for well P350.

The relation of the various subunits of the MAPCU to the overlying and underlying aquifers is shown in the southern grouping of cross sections *J–J'* through *Q–Q'* (pls. 16–23). Reduced versions of cross sections *K–K'*, *O–O'*, and *P–P'* are provided in figures 39–41 for discussion purposes. Lithologic, geophysical, and water-bearing properties of the MAPCU and its subunits are summarized in table 8. The altitude and configuration of the evaporite-bearing region of the MAPCU (fig. 38) are nearly identical to that previously mapped as middle confining unit MCUII by Miller (1986). In central Florida, the extent of this evaporite-bearing unit has been refined using more recent test drilling in west-central Polk County (Gates, 2006), southwestern Orange County (Bennett and Rectenwald, 2004), northwestern Osceola County (Bennett and Rectenwald, 2003), Lake County (Fredericks, 2011) and in Marion County (Janosik, 2011; LaRoche, 2012).

The non-evaporite-bearing semiconfining unit (fig. 38) lies at an altitude of about –800 to –900 ft in western Orange County in wells P574 and ORF–60 (fig. 39, pl. 17). In this area, flowmeter data and geophysical logs collected from wells in the Orlando vicinity indicate that this unit is characterized by a relatively uniform, non-producing interval composed mostly of limestone. Farther south in central Florida, the non-evaporitic unit grades into evaporitic facies of the evaporite-bearing confining unit (fig. 38), as indicated between wells ORF-60 and OSF-97 in section *K–K'* (fig. 39). From south-central to southern Florida, this unit grades into the mixed evaporite- and non-evaporite-bearing semiconfining unit (fig. 38) between wells P609 and P373 (fig. 39), which roughly correlates to middle confining unit MCUVI of Miller (1986), and is discussed in more detail later. As shown in figures 40 and 41 and plates 21–23, the evaporitic facies is dominant in the MAPCU on the western side of the central Florida peninsula. To the east, these rocks grade into a fine-grained micritic limestone facies and form a non-evaporitic semiconfining unit. In south-central Georgia, the rocks that compose the evaporite-bearing semiconfining unit (fig. 38) were considered to be part of a leaky semiconfining unit that includes middle confining unit MCUIII of (Miller, 1986), or part of the deeper sluggish flow system beneath the Upper Floridan aquifer.

Because of variations in lithology and the presence or absence of pore-filling evaporites, hydraulic properties vary widely within the MAPCU, even within a given region (table 9). In general, the hydraulic conductivity of the composite unit is usually more than one order of magnitude lower in counties underlain by the evaporitic facies of middle confining unit MCUII than in counties underlain by the non-evaporitic facies. For example, the hydraulic conductivity of the evaporitic facies in Pasco County in west-central Florida averages 0.48 ft/d and has a median of 0.015 ft/d, as indicated by results from four packer tests. Conversely, the non-evaporitic facies in Broward County in southeastern Florida has an average hydraulic conductivity of 4.6 ft/d and a median of 0.5 ft/d, as indicated by results from 16 packer tests (table 9). The number of tests conducted in each county is relatively low, and test results typically consist of data from a single well or only a few scattered wells; therefore, the regional representation of the values is uncertain. Counties underlain by both evaporitic and non-evaporitic portions of the confining unit have a wide variation in hydraulic properties as indicated in table 9.

The MAPCU has some of the lowest reported hydraulic conductivity values; far less than the OCAPLPZ and the glauconite marker unit in central and southern Florida. Figure 42 shows the range of horizontal hydraulic conductivity values determined from packer tests and core analysis of the three less-permeable units or zones. From the packer test results alone, the overall range and median horizontal hydraulic conductivity of the MAPCU for evaporitic and non-evaporitic facies appear to be similar to those of the OCAPLPZ; however, as indicated in table 9, the evaporitic part of the MAPCU has much lower hydraulic conductivity than the non-evaporitic parts in most counties. These findings also are reflected by core analysis of samples collected from the MAPCU, which have a median value that is one order of magnitude lower than that of the OCAPLPZ (fig. 42). The median core-derived hydraulic conductivity of the MAPCU is also much lower than that of the glauconite marker unit. Collectively, the results of packer tests and core analysis indicate that the interquartile range in hydraulic conductivity of the MAPCU is over four orders of magnitude, which is the result of the heterogeneous nature of the rocks that compose this unit. This interquartile range is more than twice that of the overlying OCAPLPZ, whose lithology is more uniform (fig. 42).

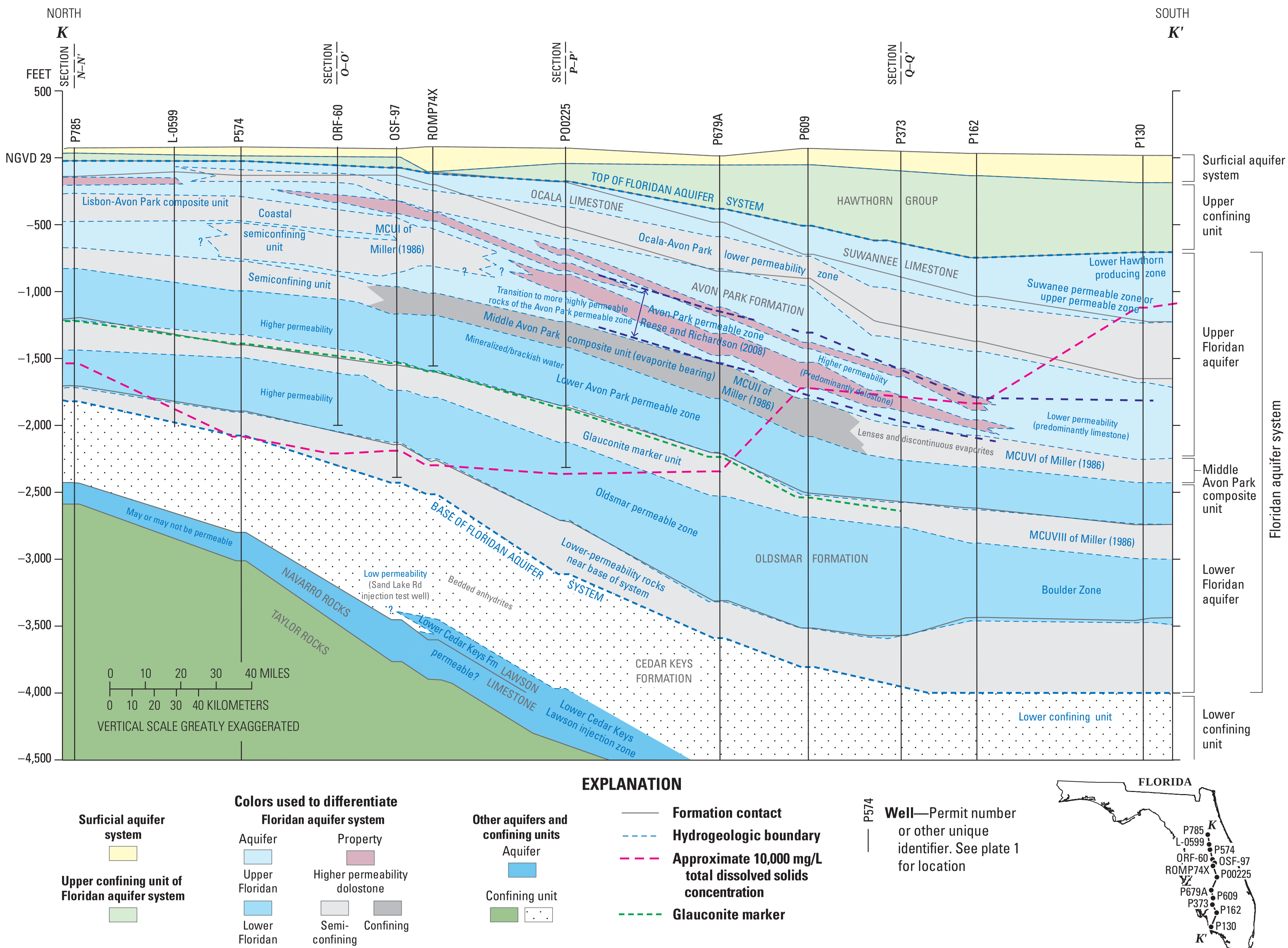


Figure 39. Generalized hydrogeologic cross section *K–K'* from Marion County, Florida, to Collier County, Florida (see plate 17 for more detail).

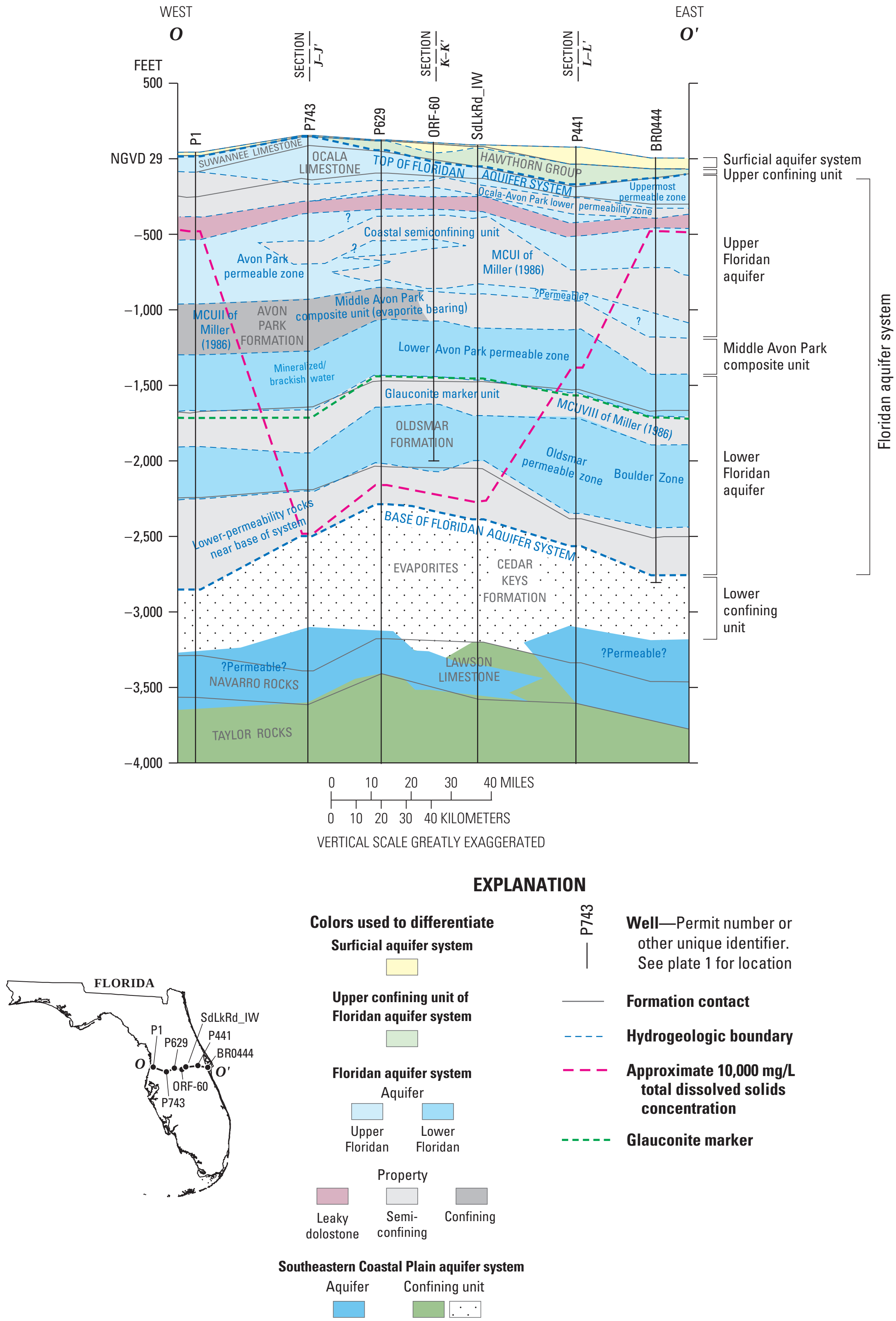


Figure 40. Generalized hydrogeologic cross section *O–O′* from Hernando County, Florida, to Brevard County, Florida (see plate 21 for more detail).

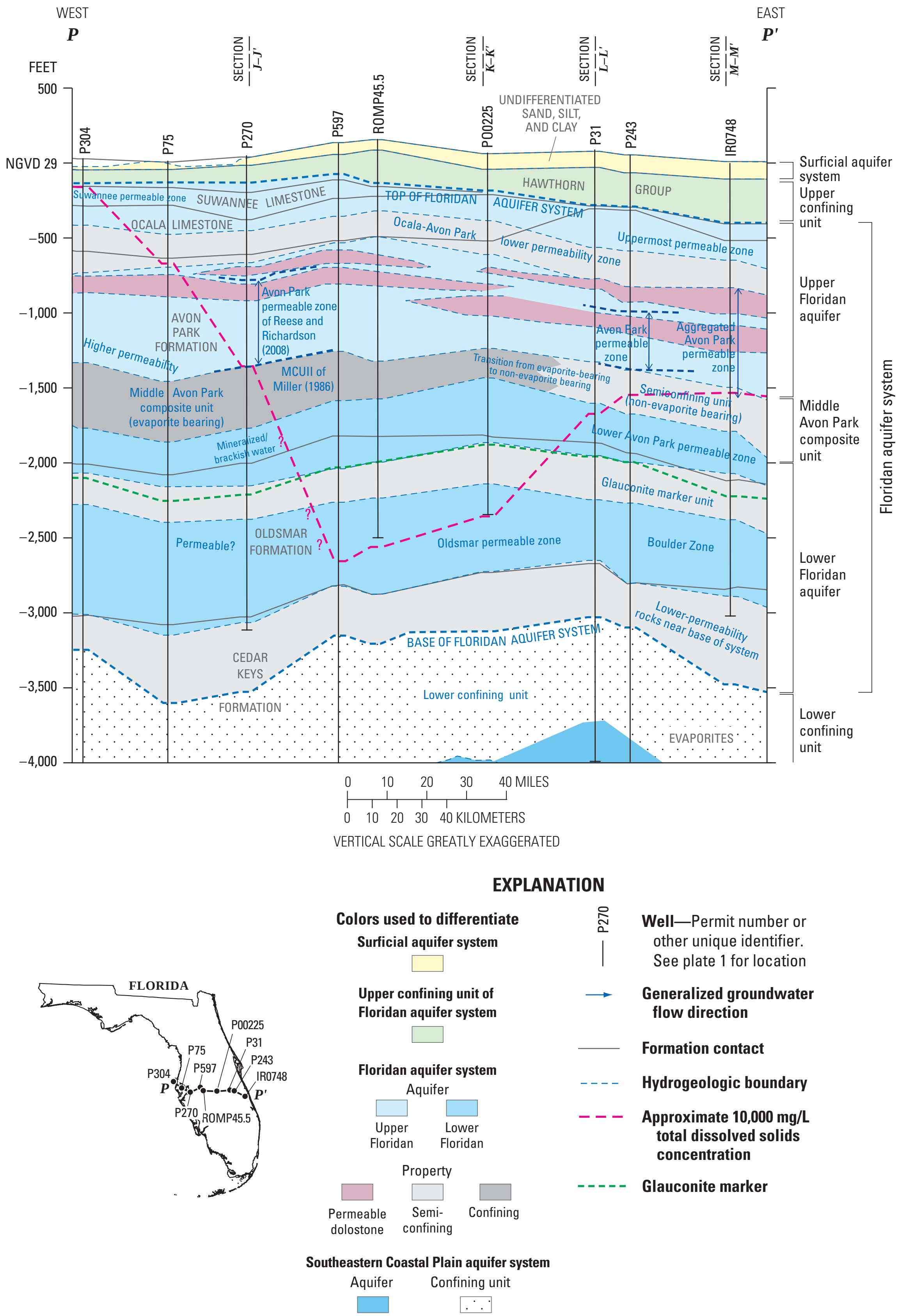


Figure 41. Generalized hydrogeologic cross section *P–P′* from offshore Pinellas County, Florida, to Indian River County, Florida (see plate 22 for more detail).

Table 9. Hydraulic conductivity of the middle Avon Park composite unit in peninsular Florida determined from packer tests.

[ft/day, foot per day; ft, foot; average thickness, average test interval length is the average open interval from packer tests; data compiled from South Florida Water Management District DBHYDRO database and reports of the Southwest Florida Water Management District]

County	Minimum (ft/day)	Maximum (ft/day)	Average (ft/day)	Median (ft/day)	Count	Average test interval length (ft)
Brevard[1]	0.11	70	18	0.88	4	13
Broward[1]	0.02	29	4.6	0.52	16	26
Collier[2]	0.01	2.1	0.96	0.73	3	37
De Soto[3]	0.02	0.02	0.02	0.02	2	77
Hardee[3]	0.05	3.00	1.50	1.50	2	41
Hendry[2]	0.16	0.20	0.18	0.18	2	30
Highlands[3]	0.00	21	4.4	0.14	5	60
Lee[2]	0.02	4.8	1.6	0.07	3	25
Manatee[3]	0.01	0.01	0.01	0.01	1	40
Marion[3]	0.01	0.20	0.11	0.11	2	32
Miami-Dade[1]	1.5	2.7	2.2	2.3	3	40
Okeechobee[4]	0.49	18	11	14	3	24
Palm Beach[1]	0.01	0.15	0.09	0.10	3	20
Pasco[3]	0.01	0.15	0.05	0.02	4	34
St Lucie[1]	0.22	0.76	0.49	0.49	2	31

[1]Tests are representative of non-evaporitic part of composite unit.

[2]Tests are representative of mixed evaporitic and non-evaporitic units.

[3]Tests are representative of evaporitic part of composite unit.

[4]Tests representative of evaporitic and non-evaporitic units.

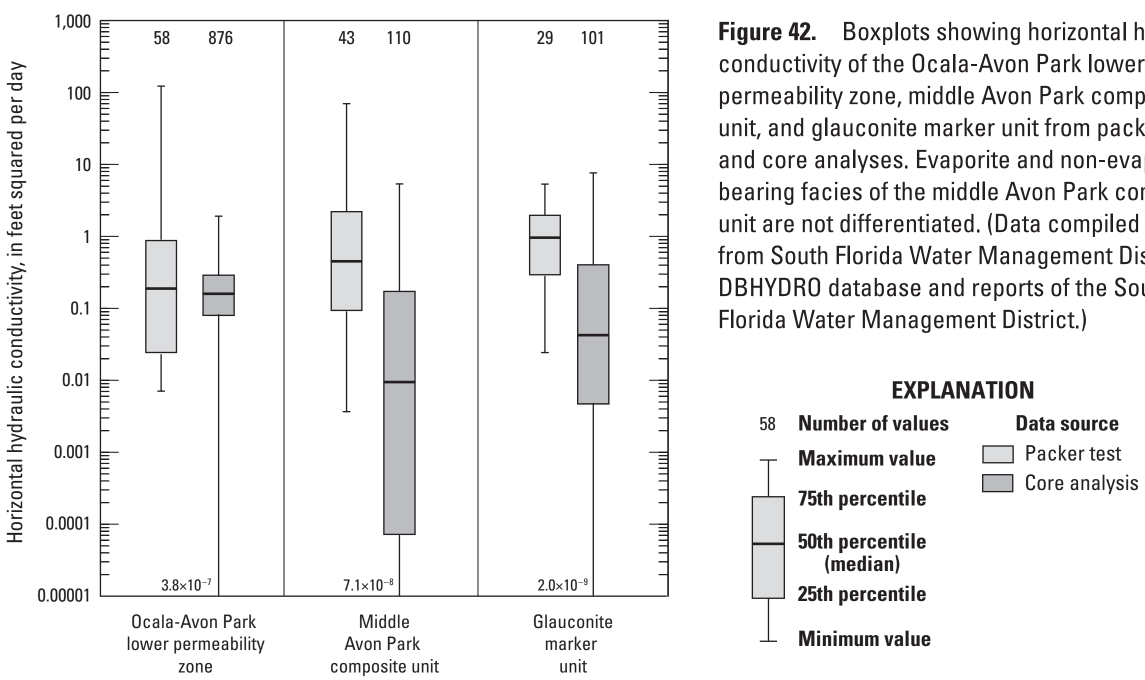


Figure 42. Boxplots showing horizontal hydraulic conductivity of the Ocala-Avon Park lower permeability zone, middle Avon Park composite unit, and glauconite marker unit from packer tests and core analyses. Evaporite and non-evaporite bearing facies of the middle Avon Park composite unit are not differentiated. (Data compiled from South Florida Water Management District DBHYDRO database and reports of the Southwest Florida Water Management District.)

Bucatunna Clay Confining Unit, Western Florida Panhandle—In the western part of the Florida panhandle and in the contiguous part of Alabama, this unit is formed by dark-gray, calcareous, soft sandy clay of the Bucatunna Clay Member of the Oligocene Byram Formation and by Oligocene clayey sand and marl (fig. 43). The BCCU overlies the LISAPCU (cross sections *A–A′* and *B–B′* on pls. 7 and 8). The BCCU (previously MCUV of Miller, 1986) has two distinct regions. The most confining part of this unit is formed by the Bucatunna Clay Member, which extends as far eastward as south Walton County, Fla., where test drilling indicates the unit to be absent or very thin (Tony Countryman, Northwest Florida Water Management District, written commun., 2013). The water resource program of the Northwest Florida Water Management District has historically used the easternmost extent of the highly confining Bucatunna Clay Member to define the separation between the Upper and Lower Floridan aquifers. This unit separates the two aquifers, except possibly along its updip extent where the unit thins and grades into the main body of the Floridan aquifer system. Maslia and Hayes (1988) indicated that in the coastal areas of Fort Walton Beach, Fla., water levels in the Lower Floridan aquifer were approximately 5 ft above sea level, compared to 50 ft below sea level in the Upper Floridan aquifer where groundwater

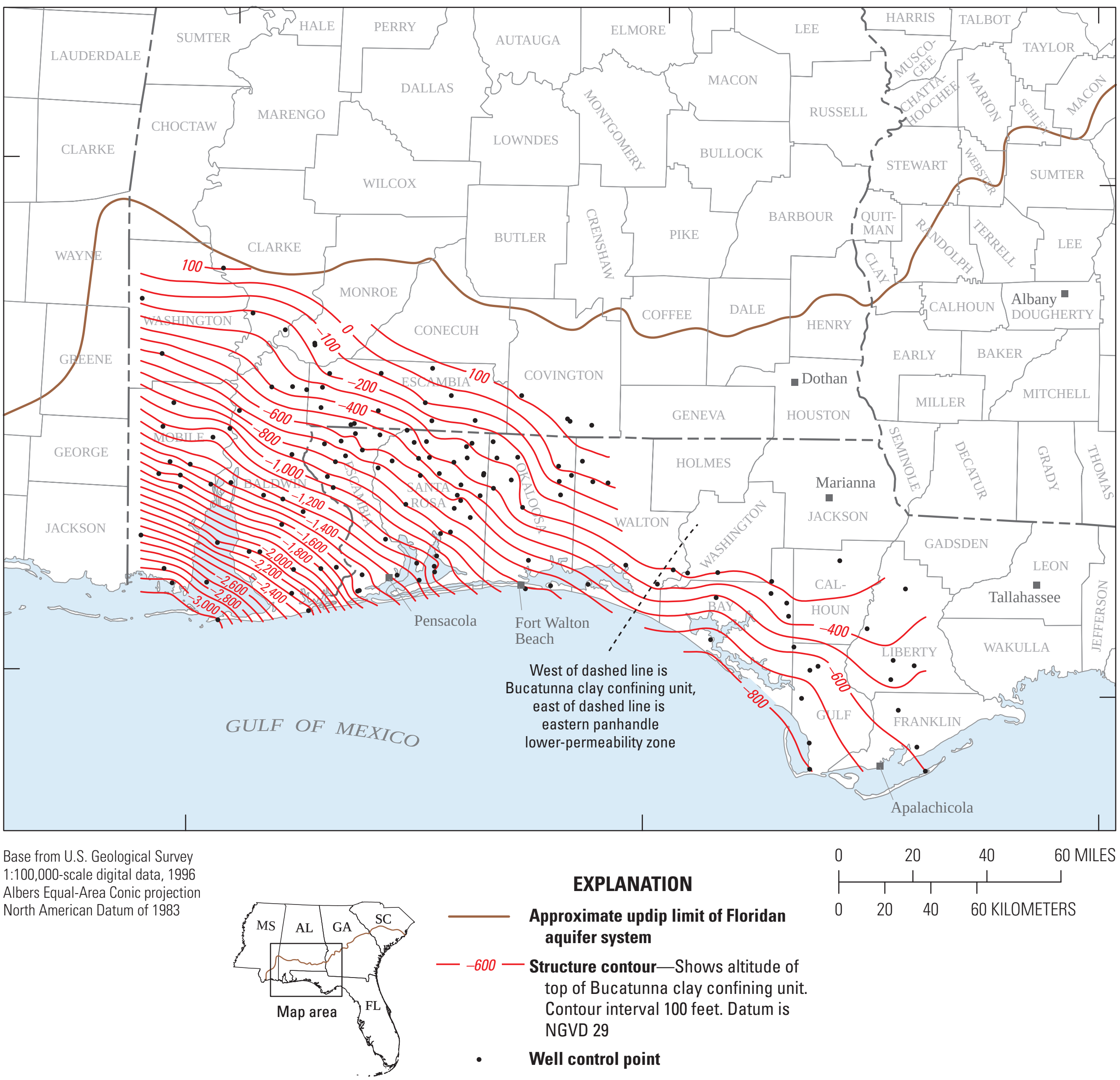


Figure 43. Altitude of the top of the Bucatunna clay confining unit, western panhandle Florida and southwestern Alabama.

is withdrawn for municipal supply. A few miles north of the Fort Walton Beach area, however, the water level in the Lower Floridan aquifer was reported to be only 1 to 6 ft higher than in the Upper Floridan aquifer, indicating much less hydraulic separation there.

Miller (1986) extended MCUV farther east of the BCCU on the basis of limited geophysical and lithologic data to include lower permeability sediments at an approximate age-equivalent horizon. Mapping conducted as part of this study further extends the clayey sand and marl region of the BCCU into parts of Bay, Gulf, Franklin, Liberty, and Calhoun Counties, Fla. (fig. 43), and is given the designation “eastern Panhandle lower permeability zone.” Based on lithology and limited test drilling data, this region of the unit probably acts as a leaky semiconfining unit between the Upper and Lower Floridan aquifers.

Lower Floridan Aquifer

The Lower Floridan aquifer includes all permeable and less-permeable zones below (1) the MAPCU in peninsular Florida, (2) the BCCU in the western Florida panhandle and contiguous areas in southwestern Alabama, and (3) the LISAPCU in southeastern Alabama, Georgia, western South Carolina and northern Florida. Although hydraulic head and water-quality data are used to help define the position of the Lower Floridan aquifer within the Floridan aquifer system, as previously described, lithostratigraphic composite units were used to divide the system. The top of the Lower Floridan aquifer was constructed from the base of one of the following units: the BCCU, LISAPCU, or MAPCU. The resulting surface of the transitional area shown in figure 44 represents the top of one or more permeable zones of the Lower Floridan aquifer and may not necessarily be representative of one or the other overlapping middle composite and confining units.

The subregional areas and units of the Lower Floridan aquifer include the

- undifferentiated Lower Floridan aquifer in the northern part of the aquifer system;
- updip clastic units of the Lisbon, Claiborne, and Gordon aquifers;
- Lower Floridan aquifer beneath the BCCU;
- Lower Avon Park permeable zone (LAPPZ);
- glauconite marker unit; and
- Oldsmar permeable zone, containing the
    - Boulder Zone in southern Florida (saline water zones), and
    - Fernandina permeable zone in northeastern Florida and southeastern Georgia (fresh- and saline-water zones).

Undifferentiated Lower Floridan Aquifer: Northern Part of Aquifer System—Over much of the northern half of the study area, excluding the extreme updip clastic part of the revised Floridan aquifer system, the Lower Floridan aquifer is undifferentiated beneath the LISAPCU and BCCU (fig. 45). In the northern coastal areas of Georgia and South Carolina, the strata that compose the Lower Floridan aquifer include limestone, dolomitic limestone, and dolomite that lie within the middle to lower part of the Avon Park Formation or equivalent middle Eocene formations (pl. 2). In the Savannah and Hilton Head Island areas, this aquifer includes permeable zones 4 and 5 of McCollum and Counts (1964) and grades into the updip, clastic Gordon aquifer (Williams and Gill, 2010). The base of the Lower Floridan aquifer in the northern coastal region generally is marked by low-permeability limestone and marl in the lower part of the Avon Park Formation. Because the permeability of these rocks is much lower than the permeability of the overlying carbonate rocks, a zone of less active groundwater movement is marked by an increase in salinity below the base of the aquifer system. In some areas, higher salinity water also is present in the lowermost part of the Lower Floridan aquifer.

In northeastern Florida and southeastern Georgia, the Lower Floridan aquifer is much thicker than in areas to the north and comprises several discrete producing zones separated by intra-aquifer confining units. The top of the Lower Floridan aquifer (fig. 44) generally is mapped at the base of the first semiconfining unit separating the Upper Floridan aquifer from the first (uppermost) permeable zone of the Lower Floridan aquifer (Phelps and Spechler, 1997; Spechler, 2001). This surface is defined herein as the top of the first permeable zone below the LISAPCU (fig. 45). In this same area, however, the MAPCU also provides additional confinement between the first permeable zone of the Lower Floridan aquifer and slightly deeper permeable zones in the aquifer, as indicated by hydraulic head differences across these units and changes in water quality.

Updip Clastic Units: Lisbon, Claiborne, and Gordon Aquifers—In southwestern Georgia and southeastern Alabama, the Lisbon and Claiborne aquifers form updip clastic-equivalent aquifers of the Lower Floridan aquifer. In Georgia, with the exception of Dougherty County, southeastern Lee County, and southern Crisp County, the Claiborne aquifer is more productive than the Upper Floridan aquifer and is the major source of water for public-supply, industrial, and agricultural use. The Claiborne aquifer consists of the middle Eocene Claiborne Group, composed of the Tallahatta and Lisbon Formations. McFadden and Perriello (1983) indicated this aquifer generally consists of permeable sands in the Tallahatta Formation but may also include hydraulically connected sands of the Lisbon and Hatchetigbee Formations. These sands may be separated by less-permeable sand, silt, and clay. The Claiborne aquifer is confined above by clay beds in the Lisbon Formation and below by fine-grained sand and clay in the Tuscahoma Sand and Nanafalia Formations (pl. 2).

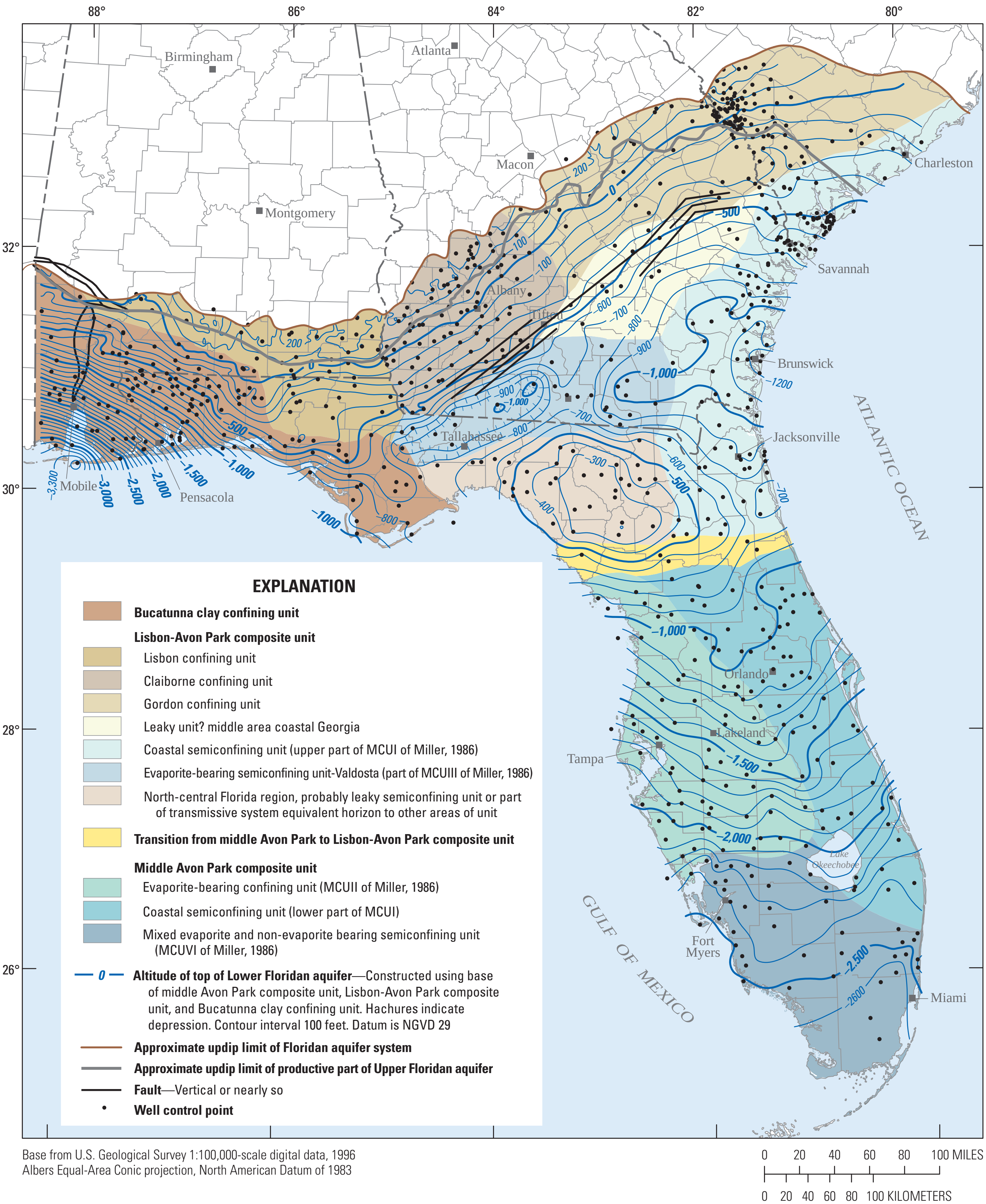


Figure 44. Altitude of the top of the Lower Floridan aquifer and overlying units, southeastern United States.

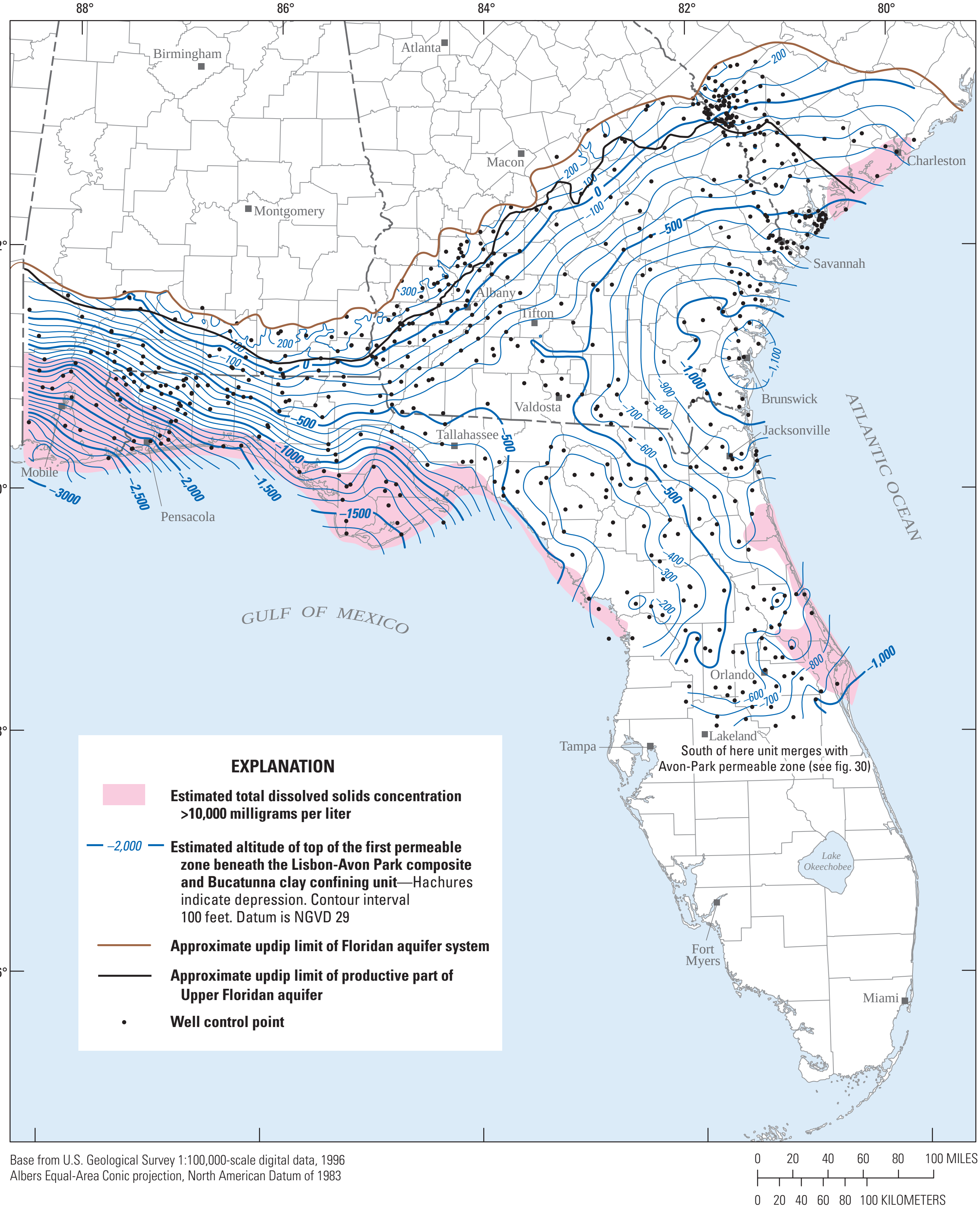


Figure 45. Altitude of the top of the first permeable zone beneath the Lisbon-Avon Park composite unit and Bucatunna clay confining unit and estimated total dissolved solids concentration, southeastern United States.

The aquifer crops out locally along incised stream channels near its updip extent in Early, Calhoun, Randolph, Sumter, Lee, and Dooly Counties, Ga.

In South Carolina and east-central Georgia, the Gordon aquifer (Brooks and others, 1985) forms the updip clastic equivalent of the Lower Floridan aquifer. In Georgia, the Gordon aquifer consists of middle Eocene interbedded sand, silt, and clay and is equivalent to the Hatchetigbee and Tallahatta Formations and the lower part of the Lisbon Formation in western Georgia (Brooks and others, 1985). The Gordon aquifer is overlain and confined by the late-middle Eocene Lisbon-McBean confining unit and is equivalent to the Lisbon Formation in western and central Georgia, where it generally consists of massive glauconitic marl interbedded with calcareous clayey sand and fossiliferous limestone over most of its extent (Brooks and others, 1985). The Gordon aquifer is underlain by the late Paleocene Baker Hill-Nanafalia unit and is equivalent to the Tuscahoma and Nanafalia Formations of western Georgia and the Black Mingo Group of South Carolina. In its northern extent, the aquifer is composed of thinly laminated silty sand that locally contains dark-gray carbonaceous clay. Toward the south, these sediments grade to increasingly calcareous, highly fossiliferous, light-gray glauconitic limestone interbedded with very coarse quartz sand.

In the extreme updip areas in Georgia and South Carolina, the Gordon aquifer and Upper Three Runs aquifer coalesce to form the Steel Pond aquifer (Aadland and others, 1995). In these areas, including northern Washington, Jefferson, and Burke Counties, Ga., and parts of Aiken, Barnwell, and Bamberg Counties, S.C., the Upper and Lower Floridan aquifers generally are considered a single hydraulic unit.

Lower Avon Park Permeable Zone: Peninsular Florida—In peninsular Florida, the LAPPZ is composed of a series of thin, discontinuous permeable zones between the MAPCU and the glauconite marker unit. Stratigraphically, the LAPPZ mostly lies within the lower third of the Avon Park Formation but may locally include permeable zones higher up in the middle Eocene section where it could locally merge with the (upper) Avon Park permeable zone. In west-central and southwestern Florida, the LAPPZ includes the first permeable zone below the evaporite-bearing confining unit (MCUII of Miller, 1986) and also includes several deeper permeable and less-permeable zones grouped into a thicker, lumped unit bounded by the overlying MAPCU and underlying glauconite marker unit. In southern Florida, the uppermost part of the LAPPZ most closely correlates to LF1 of Reese and Richardson (2008) and is equivalent to the lower permeable zone of Miller (1986) (table 10).

Generally, the top of the LAPPZ (fig. 46) is identified by a noticeable increase in permeability below the evaporite- or non-evaporite-bearing rocks of the MAPCU (for example, see pls. 16–19). This zone is mapped throughout much of peninsular Florida and merges with the undifferentiated Lower Floridan aquifer in Georgia where the Avon Park Formation thins and becomes less permeable. The configuration of this zone generally conforms to the regional dip of rocks in the Avon Park Formation and is affected by regional structures including the Peninsular arch and Ocala platform (figs. 10 and 46). From its structural high in north-central Florida, the zone dips gently northeastward into the Southeast Georgia embayment, southwestward into the Southwest Georgia embayment, and southward into the South Florida basin. The altitude of the top of the LAPPZ ranges from about –600 ft in north-central Florida to about –2,600 ft in extreme southern Florida.

The permeability of the LAPPZ varies widely across peninsular Florida. A highly permeable section is present in east-central Florida, as indicated at the northern end of cross section *K–K′* near ORF–60 (fig. 39, pl. 17). In that area, the top of the Lower Floridan aquifer is marked by increases in borehole resistivity and by an increase in secondary porosity, fractures, and solution cavities (O'Reilly and others, 2002). To the southeast, McGurk and Presley (2002) differentiated the Lower Floridan aquifer into upper and lower permeable zones separated by a semiconfining unit on the basis of geophysical logs and flowmeter traverses across the thick interval of the Lower Floridan aquifer in a test well in south-central Orange County (Barnes Ferland and Associates Inc., 1996). O'Reilly and others (2002) noted that the characteristics of the semiconfining unit separating the upper and lower permeable zones in the Lower Floridan aquifer were similar to those of middle confining unit MCUVIII (Miller, 1986), but they did not have sufficient data to extend this unit farther north from where it was originally mapped. In this report, the upper permeable zone, semiconfining unit, and lower permeable zone have been assigned to the LAPPZ, glauconite marker unit, and Oldsmar permeable zone, respectively. Descriptions of the hydrogeologic characteristics of the LAPPZ and Oldsmar permeable zone at select wells are summarized in table 11.

Table 10. Comparison of terminologies for zones in the Lower Floridan aquifer.

Miller (1986)	McGurk and Presley (2002)	This report
Lower permeable zone	Upper permeable layer	Lower Avon Park permeable zone
Middle confining unit MCUVI or MCUVIII	Lower semiconfining layer	Glauconite marker unit
Boulder Zone	Lower permeable layer	Oldsmar permeable zone

Table 11. Characteristics of the lower Avon Park permeable zone and Oldsmar permeable zone at selected test sites.

[ft, foot; LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone; APT, aquifer performance test; gal/min, gallon per minute; psi, pound per square inch; ft^2/day, foot squared per day; T, transmissivity; (gal/min)/ft, gallon per minute per foot of drawdown; RO, reverse osmosis; WTP, water treatment plant; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant; SFWMD, South Florida Water Management District; SWFWMD, Southwest Florida Water Management District; OUC, Orlando Utilities Commission; S, storage coefficient (dimensionless); TD, total depth; NA, not applicable; SJRWMD, St. Johns River Water Management District]

Test site	Well identifier	Zone	Depth of unit below land surface (ft)	Top (ft)	Bottom (ft)	Thickness (ft)	Formation
Broward County, Fla., Deerfield Beach IW-1	DFB-IW1	LAPPZ	2,472–2,782	2,472	2,782	310	Lower part of Avon Park Formation
		OLDSPZ	3,014–3,512	3,014	3,512	498	Oldsmar Formation
Collier County, Fla., North Collier Water Reclamation Facility Injection Well 1	NCWRF-IW1	LAPPZ	2,500–2,966	2,500	2,966	466	Lower part of Avon Park Formation
		OLDSPZ	2,966–3,570	2,966	3,570	604	Oldsmar Formation
Hendry County, Fla., City of Clewiston RO WTP IW	CLEW_IW-1	LAPPZ	2,161–2,650	2,161	2,650	489	Lower part of Avon Park Formation
		OLDSPZ	2,780–3,530	2,780	3,530	750	Oldsmar Formation
Polk County, Fla., Kissimmee Basin, Lower Floridan aquifer Recon	POF-27/28	LAPPZ	1,366–1,800	1,366	1,800	434	Lower part of Avon Park Formation
		OLDSPZ	2,050–2,425	2,050	2,425	375	Oldsmar Formation
Marion County, Fla., Blitch Plantation	ROMP132	LAPPZ	848–988	848	988	140	Lower part of Avon Park Formation
		OLDSPZ	1,248–1,650	1,248	1,650	402	Oldsmar Formation

Table 11. Characteristics of the lower Avon Park permeable zone and Oldsmar permeable zone at selected test sites.—Continued

[ft, foot; LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone; APT, aquifer performance test; gal/min, gallon per minute; psi, pound per square inch; ft^2/day, foot squared per day; T, transmissivity; (gal/min)/ft, gallon per minute per foot of drawdown; RO, reverse osmosis; WTP, water treatment plant; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant; SFWMD, South Florida Water Management District; SWFWMD, Southwest Florida Water Management District; OUC, Orlando Utilities Commission; S, storage coefficient (dimensionless); TD, total depth; NA, not applicable; SJRWMD, St. Johns River Water Management District]

Well identifier	Hydrogeologic zones and lithology	Hydraulic properties	Notes
DFB-IW1	Upper 100 ft is a dark olive brown well indurated vuggy dolostone with cavernous porosity. Lower 100 ft is limestone and dolostone with cavernous porosity.	This zone not tested but acoustic televiewer log indicates vuggy interval from 2,540 to 2,570 ft with round and lenticular openings and a vuggy interval from 2,700 to 2,770 ft with small vugs and distinct 1-inch to 2-inch wide bedding plane openings.	Consulting report for Deerfield Beach Concentrate Injection Well (Emily Richardson, South Florida Water Management District, written commun., 2010)
	Massive, light and dark gray, well indurated, microcrystalline to very finely crystalline, dolosone. Acoustic televiewer indicates mostly vuggy and cavernous porosity and some fractured zones associated with large horizontal bedding plane openings.	Injection zone: 3,020–3,520 ft. A 1,403 gal/min injection rate caused a 34 psi well head pressure increase and a 4 psi bottom hole increase. T is estimated to be 40,000 ft^2/day based on specific injectivity.	
NCWRF-IW1	Moderate yellowish brown to dark yellowish brown to black, well indurated, microcrystalline to medium grained, dolosone. Vuggy and cavernous in sections.	LF1 and LF2 are undifferentiated in this well. Injection zone: 2,575–3,250 ft. A 11,800 gal/min injection rate produced a specific injectivity of 410 (gal/min)/ft. T was not estimated for the injection interval.	Well completion report for North Collier Water Reclamation Facility (Emily Richardson, South Florida Water Management District, written commun., 2010)
	Olive gray to dark yellowish brown, moderately to well indurated, crystalline, coarse to medium grained, dolostone. Vuggy to cavernous, with abundant secondary crystal growth in and around vug openings and some fracture planes.		
CLEW_IW-1	Dark brown and yellowish brown, hard, very fine to medium crystalline dolostone and very pale dolomitic limestone grading down into mostly dolostone. Vuggy and open fractures indicated by secondary crystal growth on well cuttings.	Pumping flowmeter survey indicates diffuse inflow throughout this interval. Borehole video indicates alternating intervals of fractured and non-fractured dolostone. A packer test in the interval 2,510–2,532 ft indicated an estimated transmissivity of about 23,000 ft^2/day for that 20-ft interval.	Well completion report for City of Clewiston concentrate injection system (Emily Richardson, South Florida Water Management District, written commun., 2010)
	This interval is entirely composed of hard, brown to dark gray, well indurated, microcrystalline to very fine crystalline dolostone. Slightly vuggy to vuggy. Gypsum and anhydrite in interval 3,400–34,80 ft.	Constant rate injection test of interval from 2,749–3,505 ft indicated well head pressure increase of 34 psi and bottom hole pressure increase of 29 psi. Specific injectivity using the increase in bottom hole pressure is 100 (gal/min)/ft.	
POF-27/28	From optical televiewer log, abundant lenticular and round dissolution openings occur throughout this unit. Porous rock intervals throughout. Distinct horizontal rubble zone from 1,635–1,645 ft.	Flowmeter survey indicates production from the interval 1,550–1,640 ft. Most of the inflow occurs along the rubble zone at 1,635 ft.	Geophysical and flowmeter logs (Emily Richardson, South Florida Water Management District, written commun., 2010)
	Optical televiewer log indicates lenticular and round dissolution openings and porous beds throughout the section. A large fracture zone cuts across borehole at 2,200 ft. Below this tight fractures and sparse dissolution openings dominate the secondary porosity features.	A discrete flow zone is indicated from the flowmeter survey at the 2,200 ft fracture zone. Inflections on fluid logs support this is the dominant flow zone in this unit. No flow is indicated below 2,200 ft.	Optical televiewer logs (Mike Wacker, U.S. Geological Survey, written commun., 2010)
ROMP132	Mostly grayish orange, well indurated, packstones and wackestones grading downward into brown to orange dolostones and mudstones.	Four packer tests conducted in this interval indicated estimated hydraulic conductivities ranging from 2 ft/day to 110 ft/day and averaging 44 ft/day.	SWFMWD Blitch Plantation report (Janosik, 2011)
	Unit is in the Oldsmar Formation consisting almost entirely of yellowish brown, well indurated, cryptocrystalline to microcrystalline dolostone; in part calcareous, highly altered, vuggy with associated iron staining.	Five packer tests conducted in this interval indicated estimated hydraulic conductivities ranging from 6 ft/day to 320 ft/day and averaging 167 ft/day.	

Table 11. Characteristics of the lower Avon Park permeable zone and Oldsmar Permeable zone at selected test sites.—Continued

[ft, foot; LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone; APT, aquifer performance test; gal/min, gallon per minute; psi, pound per square inch; ft²/day, foot squared per day; T, transmissivity; (gal/min)/ft, gallon per minute per foot of drawdown; RO, reverse osmosis; WTP, water treatment plant; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant; SFWMD, South Florida Water Management District; SWFWMD, Southwest Florida Water Management District; OUC, Orlando Utilities Commission; S, storage coefficient (dimensionless); TD, total depth; NA, not applicable; SJRWMD, St. Johns River Water Management District]

Test site	Well identifier	Zone	Depth of unit below land surface (ft)	Top (ft)	Bottom (ft)	Thickness (ft)	Formation
Marion County, Fla., Ross Pond	ROMP119.5	LAPPZ	981–1,270	981	1,270	289	Lower part of Avon Park Formation
		OLDSPZ	1,440–TD	1,440	TD	NA	Oldsmar Formation
Orange County, Fla., OUC Southeast Test Well	W-17480	LAPPZ	1,140–1,610	1,140	1,610	470	Lower part of Avon Park Formation
		OLDSPZ	1,851–2,130	1,851	2,130	279	Oldsmar Formation
Orange County, Fla., Reedy Creek Improvement District SFWMD test	ORF-60	LAPPZ	1,150–1,525	1,150	1,525	375	Lower part of Avon Park Formation
		OLDSPZ	1,700–2,095	1,700	2,095	395	Oldsmar Formation
Polk County, Fla., SE Polk County, Well field DEW	PO0225	LAPPZ	1,500–1,920	1,500	1,920	420	Lower part of Avon Park Formation
		OLDSPZ	2,200–TD	2,200	TD	NA	Oldsmar Formation
Polk Co. Fla., Progress Energy	ROMP45.5	LAPPZ	1,730–2,150	1,730	2,150	420	Lower part of Avon Park Formation
		OLDSPZ	2,390–TD	2,390	TD	>310	Oldsmar Formation

Table 11. Characteristics of the lower Avon Park permeable zone and Oldsmar permeable zone at selected test sites.—Continued

[ft, foot; LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone; APT, aquifer performance test; gal/min, gallon per minute; psi, pound per square inch; ft^2/day, foot squared per day; T, transmissivity; (gal/min)/ft, gallon per minute per foot of drawdown; RO, reverse osmosis; WTP, water treatment plant; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant; SFWMD, South Florida Water Management District; SWFWMD, Southwest Florida Water Management District; OUC, Orlando Utilities Commission; S, storage coefficient (dimensionless); TD, total depth; NA, not applicable; SJRWMD, St. Johns River Water Management District]

Well identifier	Hydrogeologic zones and lithology	Hydraulic properties	Notes
ROMP119.5	Yellowish gray, well indurated, microcrystalline, dolostone, and yellowish gray and moderately indurated packstones and wackestones. Organic layers and lamina common throughout section. Vuggy and moldic porosity common.	Six packer tests conducted in this interval indicated estimated hydraulic conductivities ranging from 50 ft/day to 140 ft/day and averaging 61 ft/day.	SWFMWD Ross Pond report (LaRoche, 2012)
	Only 25 ft of this unit described. Dark yellowish brown, well indurated microcrystalline dolostone, fractured and vuggy.	Zone not tested.	
W-17480	Dark brown microcrystalline dolostone with vuggy porosity. Productive interval from 1,140 to 1,320 ft is described as "hard rock with cavities dispersed throughout." This unit is the "Lower Floridan aquifer upper permeable layer" of McGurk and Sego (1999).	Flowmeter survey run while pumping 920 gal/min and open to entire interval of the Lower Floridan aquifer from 1,070 to 2,000 ft indicates about 45 percent of the flow enters borehole from upper producing interval from 1,140 to 1,320 and about 50 percent from a discrete interval from 1,906 to 1,934 ft.	Well completion report for Orange and Southeast Test Wells (Barnes, Ferland and Associates, Inc, 1996; McGurk and Sego, 1999)
	Dark brown to gray, microcrystalline, vuggy, dolostone. Productive interval from 1,850 to 2,000 ft is described as "hard rock with a few thin cavities." This unit is the "Lower Floridan aquifer lower permeable layer" of McGurk and Sego (1999).		
ORF-60	Correlates to the lower part of the Avon Park Formation; consists of dark brown, well indurated, sucrosic dolostone with some beds of tan, friable, packstone. White to gray sticky clay and anhydrite mark the base of this unit. Identified as Lower Floridan aquifer "zone A" in the construction report.	Pumping from well when open from 1170 to 1280 ft at 1,152 gal/min gives a specific capacity of 68 (gal/min)/ft. Estimated T is 18,500 ft^2/day based on specific capacity. Flowmeter log indicates major flow zone at 1,150 ft.	SFWMD report WS-20 (Bennett and Rectenwald, 2004)
	Grayish brown to gray, well indurated, dolostone interbedded with very light orange to grayish brown wackestone and limestone. Identified as Lower Floridan aquifer "zone B" in the construction report.	Pumping flowmeter survey indicates diffuse production zones in the interval from 1,725 to 2,000 ft. An aquifer performance test was not conducted in this interval.	
PO0225	Light brown dolomitic limestone and light brown to brown, fine grained, vuggy, crystalline dolostone. A light gray micritic gypsiferous limestone marks the base of this unit. Flowmeter log indicates multiple flow zones.	APT using a well open from 1,400 to 2,100 ft pumping 2000 gal/min produced about 10 ft of drawdown in observation well located 200 ft away. T estimated to be about 16,000 ft^2/day and S was estimated to be 3.6×10^{-4}.	Construction and testing report southeast Polk County deep exploratory well (Jeffrey Davis, St. Johns River Water Management District, written commun., 2010)
	Lithology not described in report but correlated to a massive dolomitic section in Oldsmar Formation. Static flowmeter log from test hole when open from 900 to 2,400 ft indicated flow moving downward from the Upper Floridan aquifer and flowing back into the deeper interval 2,320–2,370 ft taking about two-thirds of total flow.	Pumping flowmeter survey indicates flow enters borehole from about 2,200 to 2,400 ft. Major producing zone is from 2,320 to 2,400 ft.	
ROMP45.5	Highly heterogenous unit consisting of grayish orange to yellowish brown, vuggy dolostone, mudstone, wackestone, and packstone. Gypsum filled vugs, molds and fractures throughout. Thin (< 1 ft thick) beds of anhydrite also present.	Four packer tests in this interval indicated estimated hydraulic conductivities ranging from 0.03 ft/day to 0.01 ft/day and averaging 0.08 ft/day. This interval is non-characteristically low-permeability for this unit.	SWFMWD Progress Energy well site report (Horstman, 2011)
	Mostly grayish brown to moderate yellowish brown, cryptocrystalline to medium grained, dolostone interbedded with mudstones, wackestones, and packstones. Intercrystalline and nodular gypsum common throughout interval. Vuggy and fracture porosity common.	Two packer tests in this interval gave estimated hydraulic conductivities of 9 ft/day and 16 ft/day, respectively. Unit contains zones of steep fractures based on core photographs.	

Table 11. Characteristics of the lower Avon Park permeable zone and Oldsmar Permeable zone at selected test sites.—Continued

[ft, foot; LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone; APT, aquifer performance test; gal/min, gallon per minute; psi, pound per square inch; ft^2/day, foot squared per day; T, transmissivity; (gal/min)/ft, gallon per minute per foot of drawdown; RO, reverse osmosis; WTP, water treatment plant; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant; SFWMD, South Florida Water Management District; SWFWMD, Southwest Florida Water Management District; OUC, Orlando Utilities Commission; S, storage coefficient (dimensionless); TD, total depth; NA, not applicable; SJRWMD, St. Johns River Water Management District]

Test site	Well identifier	Zone	Depth of unit below land surface (ft)	Top (ft)	Bottom (ft)	Thickness (ft)	Formation
Camden Co. Ga., St. Marys Test Well Deep	33D073 and 33D074	LAPPZ	1,390–1,650	1,390	1,650	260	Lower part of Avon Park Formation
		OLDSPZ	1,830–>TD	1,830	>TD	NA	Oldsmar Formation
Glynn County, Ga., CSSI GA Ports Authority USGS TW 29	34H495	LAPPZ	1,405–1,680	1,405	1,680	275	Lower part of Avon Park Formation
		OLDSPZ	1,940–2,110	1,940	21,10	170	Oldsmar Formation

Table 11. Characteristics of the lower Avon Park permeable zone and Oldsmar permeable zone at selected test sites.—Continued

[ft, foot; LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone; APT, aquifer performance test; gal/min, gallon per minute; psi, pound per square inch; ft^2/day, foot squared per day; T, transmissivity; (gal/min)/ft, gallon per minute per foot of drawdown; RO, reverse osmosis; WTP, water treatment plant; USGS, U.S. Geological Survey; WWTP, wastewater treatment plant; SFWMD, South Florida Water Management District; SWFWMD, Southwest Florida Water Management District; OUC, Orlando Utilities Commission; S, storage coefficient (dimensionless); TD, total depth; NA, not applicable; SJRWMD, St. Johns River Water Management District]

Well identifier	Hydrogeologic zones and lithology	Hydraulic properties	Notes
33D073 and 33D074	Mostly of yellowish gray fossiliferous limestone with some pale brown dolomitic limestone and dark gray dolostone. Dolostone and limestone with gypsum marks base of this unit. Yellowish gray, glauconitic, cherty, limestone and yellowish brown, dense and porous, dolostone. Noticeable increase in artesian flow during drilling at a depth of 2,050 ft indicates major flow zone.	Flowmeter survey inconclusive because of large bore-hole diameter. Hydraulic head in well open from 1,360 to 1,500 ft (33D073) averaged 35.8 ft above NGVD 29 between 2002 and 2010. Hydraulic head in well open from 1,840 to 2,004 ft (33D074) averaged 45.7 ft above NGVD 29 between 2002 and 2010. Hydraulic head difference is about 10 ft across confining unit separating these zones.	Data from files of the USGS and from SJRWMD Field Services Preliminary Data St. Marys, Georgia Aquifer System Monitor Well: Floridan SM-1 (33D074), Brooks (2006). Also see Falls and others (2005b) and Peck and others (2005)
34H495	Mostly yellowish gray dense dolostone and yellowish gray limestone. Porous intervals throughout. Yellowish gray to very light gray, glauconitic limestone with olive gray dense and porous dolostone intervals. Base of this unit is marked by a yellowish gray foraminiferal peloidal limestone of lower permeability	Fluid logs inconclusive in identifying specific flow zones. Void identified 1,673–1,676 ft during drilling. Flow and pressure dramatically increased at 2,079 ft suggesting a flow zone. Increase in salinity below 2,100 ft.	Data on file at the USGS office in Norcross, Ga. Also see Falls and others (2005b)

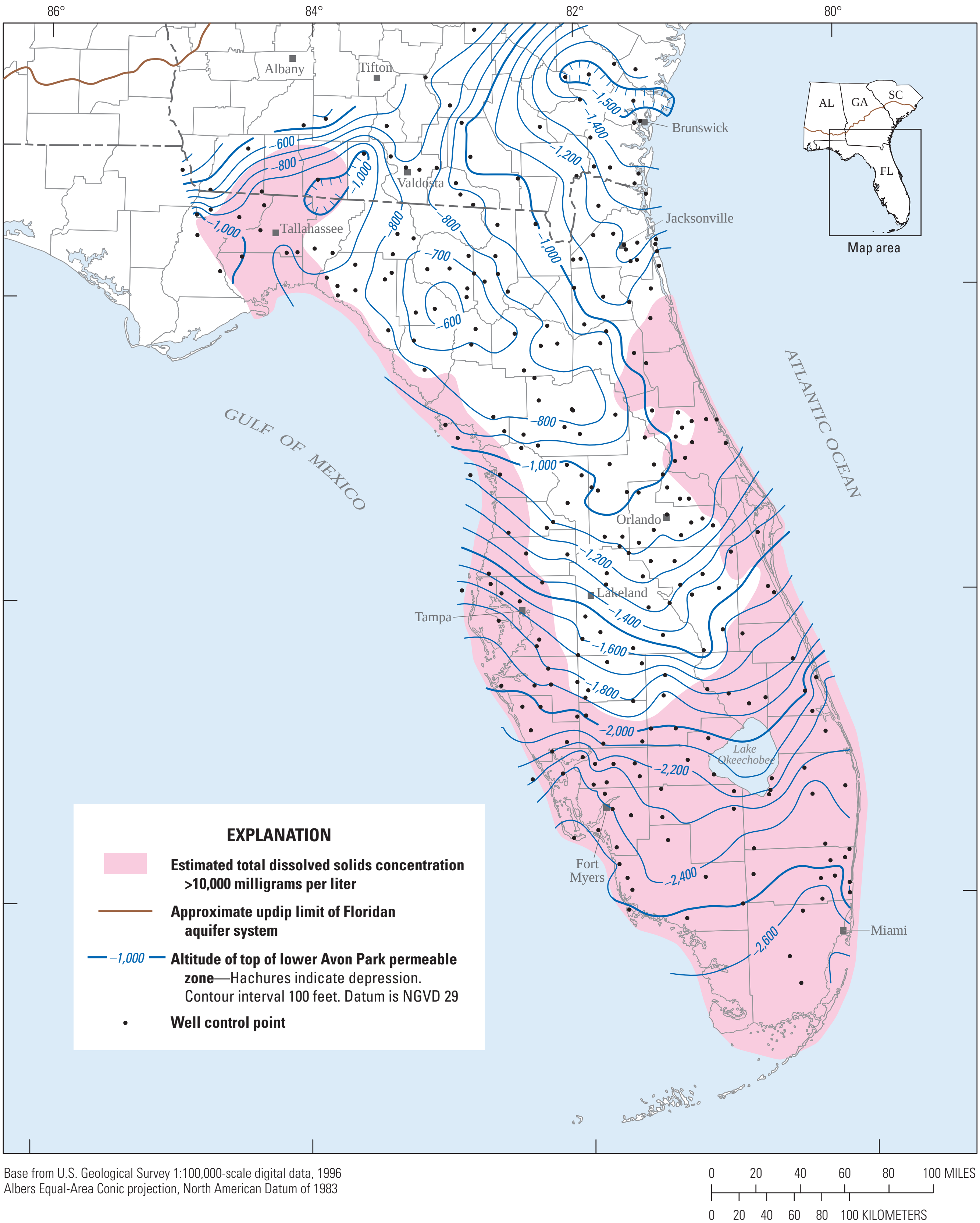


Figure 46. Altitude of the top of the lower Avon Park permeable zone below the middle Avon Park composite unit and estimated total dissolved solids concentration, peninsular and northeastern Florida and southern Georgia.

Glauconite Marker Unit: Peninsular Florida—Over much of peninsular Florida, a distinctive lower permeability unit lies deep within the Floridan aquifer system near its base. This unit is given the informal designation "glauconite marker unit" herein because it is mapped on and associated with the glauconite marker horizon of Reese and Richardson (2008). The unit is mapped and defined on the basis of geophysical log markers and not strictly on the presence of lower permeability rocks, although the glauconite marker unit is believed to be less permeable than the rocks above and below it. The strata that form this unit are mostly within the uppermost part of the Oldsmar Formation, but may locally include the lowermost part of the Avon Park Formation. In general, the unit consists of fine-grained, locally argillaceous, micritic to finely pelletal limestone with minor interbedded dolostone. Glauconite may not be present in this unit across its entire extent and therefore cannot be used as a distinguishing characteristic; instead, the unit is identified by a distinctive gamma-ray marker (Reese and Richardson, 2008). Based on its lithology, the unit probably is semiconfining but locally may be more or less confining depending on areal variations in lithology and the presence or absence of vuggy or fracture porosity. Core and hydraulic data collected from the glauconite marker unit indicate that its hydraulic properties are similar to those of the OCAPLPZ. Core-analysis results indicate the matrix permeability of the unit is lower than that of the OCAPLPZ and slightly higher than that of the MAPCU.

Borehole geophysical log characteristics of the glauconite marker unit include

- a uniformly low resistivity response across generally fine-grained limestones;
- an enlarged borehole, characteristic of poorly to moderately indurated rocks;
- relatively high but uniform porosity, as indicated by interval transit time on the sonic log or by high neutron or density porosity;
- an elevated gamma-ray response relative to the typically lower response of rocks in the overlying Avon Park Formation; and
- a distinctive group of gamma-ray correlation marker peaks located near the top of the unit, as shown in figures 18 and 47 (areal extent shown in figure 19).

In well BR0444 in Brevard County, Fla. (fig. 47, pl. 1), the glauconite marker used to map this unit is a subtle, yet distinctive, gamma-ray peak located near the top of the Oldsmar Formation. It should be clarified that the term "glauconite marker" refers only to the gamma-ray correlation peak and thus is not synonymous with the glauconite marker unit introduced here. The glauconite marker unit is mapped on the basis of its generally uniform low-resistivity log response, high porosity, and typical washed-out borehole interval as indicated on caliper logs. The base of this unit is identified by a sharp increase in resistivity indicative of lower porosity dolostone in the underlying Boulder Zone or equivalent permeable zones of the Oldsmar permeable zone.

The altitude of the top of the glauconite marker unit within the Lower Floridan aquifer was mapped using the glauconite marker as a guide wherever possible, in addition to borehole resistivity and other logs as described previously (fig. 48). The only area where the unit could not be mapped with any reliability was in southwestern Florida where the gamma-ray marker and the characteristically low resistivity response were difficult to discern in borehole geophysical logs, probably as a result of extensive fracturing observed in this part of the geologic section. The glauconite marker unit therefore was not extended into parts of southwestern Florida, although it may also be present there.

In southern Florida, the glauconite marker unit replaces middle confining unit MCUVIII of Miller (1986), which was mapped along beds of micritic and finely pelletal limestone in the middle part of the Oldsmar Formation. The areal extent of the MCUVIII region of the glauconite marker unit is shown in figure 48. Miller (1986) mapped the MCUVIII coincident with the Boulder Zone and extended the unit a little north of the Boulder Zone where it was thought to grade laterally into permeable parts of the Lower Floridan aquifer. Test drilling had indicated the presence of thin beds of permeable dolomite, but the overall permeability of the unit was thought to be relatively low (Miller, 1986).

Since the mid-1980s, numerous test wells have been drilled in southeastern and southwestern Florida to characterize the deeper saline parts of the Floridan aquifer system for purposes of deep injection and aquifer storage and recovery. In Brevard County, Duncan and others (1994a) described the hydrogeology at several deep injection test sites tapping the Boulder Zone, and described the "glauconite marker interval" as a non-fractured, glauconitic, micritic limestone located above the Boulder Zone. In other parts of southeastern Florida (Duncan and others, 1994b) and generally throughout southern Florida (Reese and Richardson, 2008), the "glauconite marker interval" appears to consist of locally glauconitic, soft micritic limestone similar to that described by Miller (1986). This unit may also be equivalent to lower permeability rocks previously delineated and referred to by the FGS as the "lower Avon Park confining zone" (Duncan and others, 1994a). Available data from core and hydraulic testing indicate the glauconite marker unit may be relatively heterogeneous, having properties that vary greatly depending on the lithologic character of the rock and on the presence of vuggy or cavernous porosity (fig. 42, table 12).

O'Reilly and others (2002) described the characteristics of a semiconfining unit in the Lower Floridan aquifer in south-central Florida as being similar to those of middle confining unit MCUVIII of Miller (1986). McGurk and Sego (1999) identified the semiconfining unit in a test well in south-central Orange County from approximately 1,600 to 1,800 ft

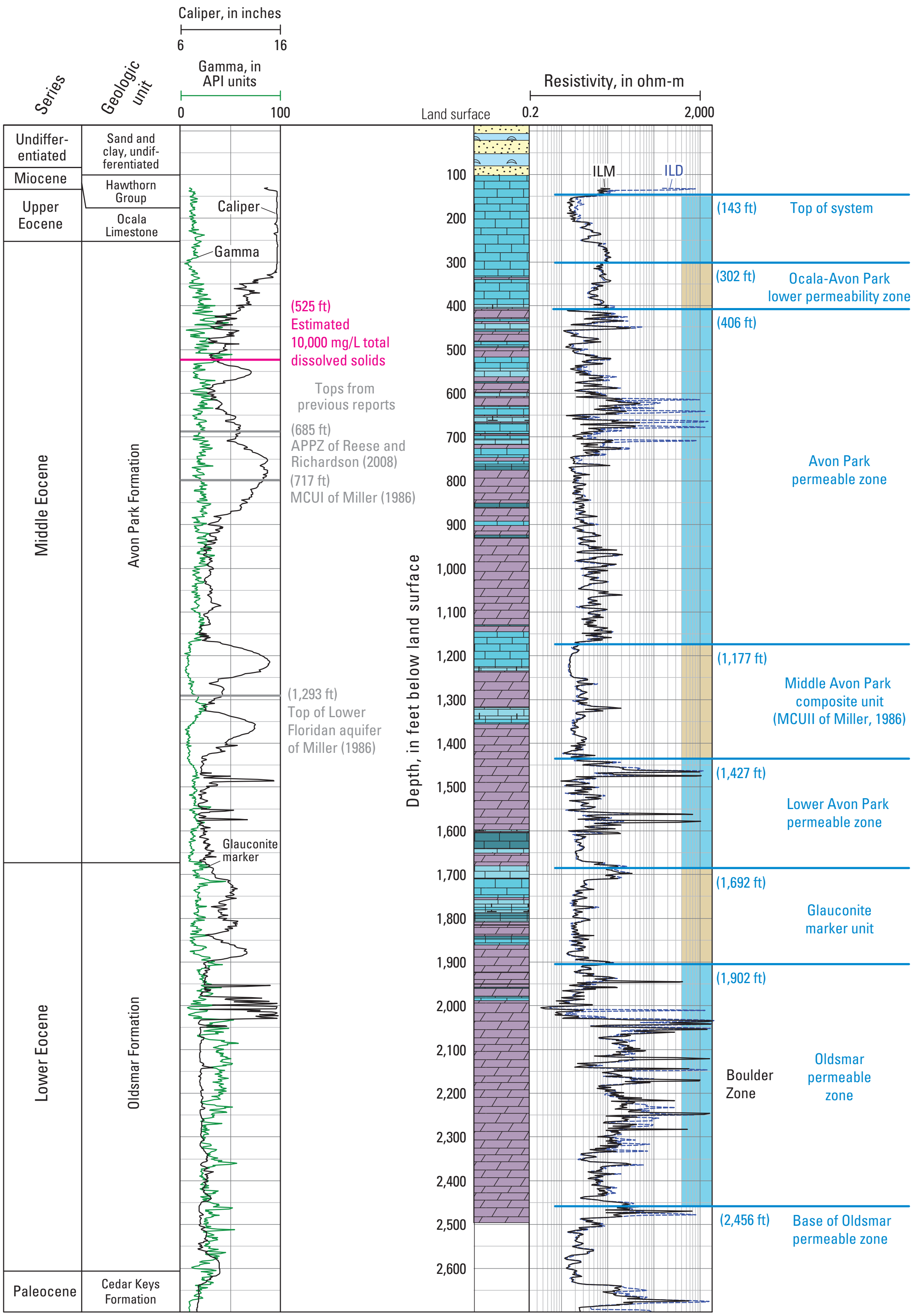


Figure 47. Geophysical log characteristics of the glauconite marker unit, and other hydrogeologic units in the Merritt Island deep injection well, Brevard County, Florida. [API, American Petroleum Institute; ohm-m, ohm-meter; ILD, deep induction; ILM, medium induction; APPZ, Avon Park permeable zone; mg/L, milligrams per liter; site BR0444 located on plate 1; see plate 21 for lithologic symbol descriptions]

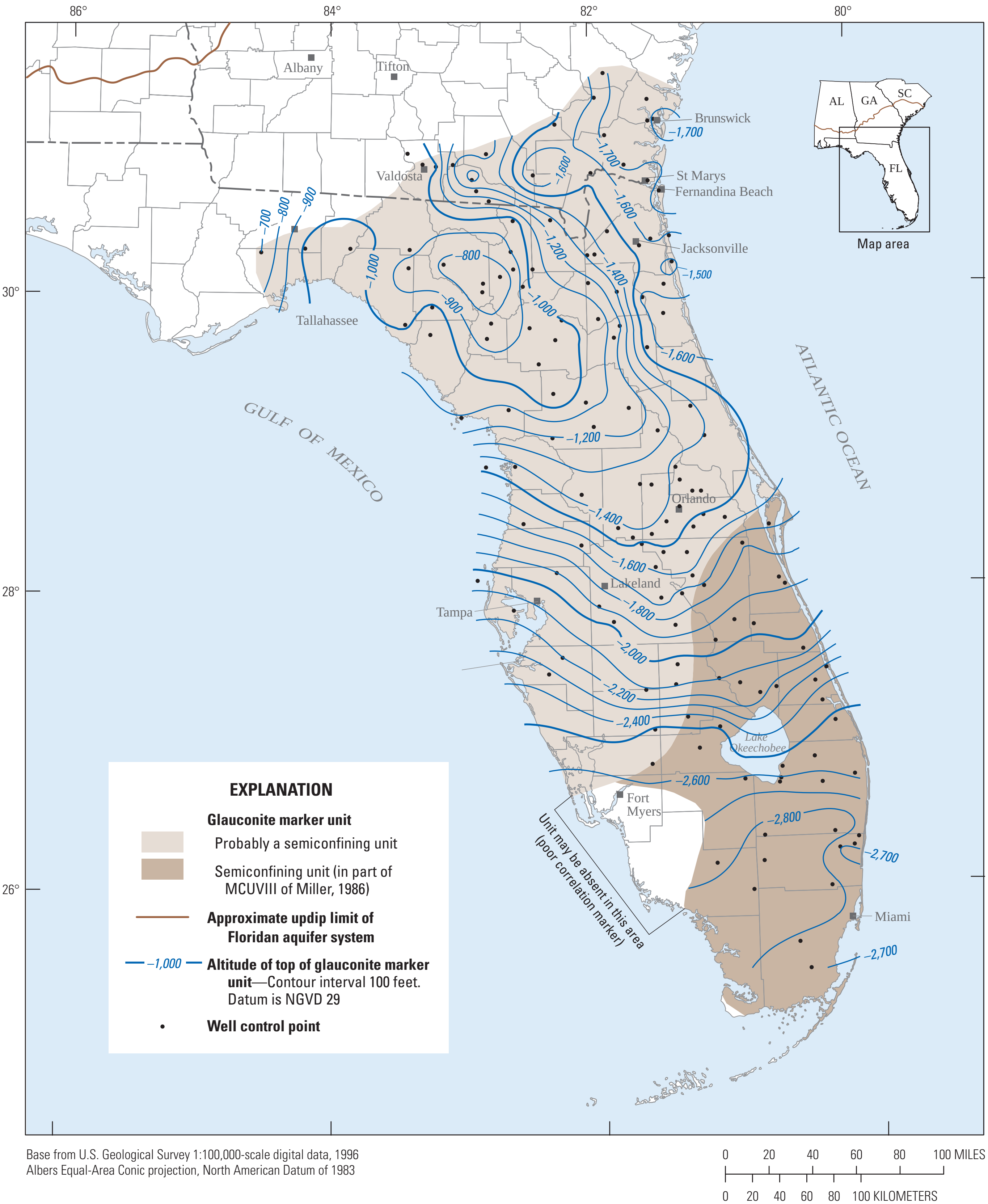


Figure 48. Altitude of the top of the glauconite marker unit, peninsular and northeastern Florida and southeastern Georgia.

Table 12. Hydraulic conductivity of the glauconite marker unit in peninsular Florida determined from packer tests.

[ft/day, foot per day; ft, foot; average is the average thickness of the intervals from packer tests; data compiled from South Florida Water Management District DBHYDRO database and reports of the Southwest Florida Water Management District]

County	Minimum (ft/day)	Maximum (ft/day)	Average (ft/day)	Median (ft/day)	Count	Average thickness (ft)
Brevard	0.04	0.99	0.39	0.47	7	12
Marion	72	73	73	73	2	62
Martin	0.6	3.5	2.0	2.1	5	17
Okeechobee	1.8	5.3	3.1	2.1	3	19
Orange	0.12	0.12	0.12	0.12	1	70
Palm Beach	0.08	3.5	1.2	0.65	4	58
St. Lucie	0.02	2.20	1.00	0.96	7	33

below land surface using a borehole camera survey, packer testing, and geophysical logs. Packer test results across the interval from 1,722 to 1,792 ft indicated a specific capacity of 0.1 to 0.2 gallon per minute per foot (gal/min)/ft, an estimated transmissivity of 8.13 ft^2/d, and an estimated horizontal hydraulic conductivity of 0.12 ft/d using the open interval of the packer test as the unit thickness (table 12).

In a core collected near Polk City, Fla., Navoy (1986) describes a correlated interval from 1,796 ft below land surface downward as consisting of very pale orange to light gray, partially glauconitic, micritic limestone, soft pelletal limestone, and medium-brown argillaceous limestone with some interval of vug-filling anhydrite. This interval is similar in lithology to cores collected in ROMP45.5 in southwestern Polk County (fig. 2, pl. 1), which also represent the glauconite marker unit. The hydraulic conductivity of the unit, determined from four packer tests in the interval between 2,151 and 2,557 ft below land surface, ranged from 0.02 to 4 ft/d and averaged 1.3 ft/d (Horstman, 2011).

In northwestern Marion County in north-central Florida, Janosik (2011) described a core collected from the interval correlated to the glauconite marker unit as very light orange, well-indurated, laminated mudstone and well-indurated dolomitic wackestones, dolostones, and packstones. Results from two packer tests indicated the hydraulic conductivity of this interval ranged from 63 to 73 ft/d, considerably higher than in southern Florida (table 13). No other deep test wells or data were available to assess the hydraulic properties of this unit in north-central Florida, and the degree of confinement, if any, provided in this area is therefore presently unknown.

In northeastern Florida and southeastern Georgia, the glauconite marker unit (fig. 48) consists of micritic limestone and locally gypsiferous dolomite and is not equivalent to any of the confining units previously mapped by Miller (1986), but it appears to directly overlie the Fernandina permeable zone. In this area, the glauconite marker unit is tightly confining, as indicated by water-level data collected from several monitoring well sites before, during, and after major industrial plant shutdowns near Fernandina Beach in Nassau County, Fla., St. Mary's in Camden County, Ga., and Brunswick in Glynn County, Ga. At Fernandina Beach, pumping from the Upper Floridan aquifer at two large paper plants was shut down on two occasions—one shutdown lasting 2 weeks and another lasting more than a month. The amount of reduced pumpage during the shutdowns was not reported, but hydrographs presented in Brown (1984) indicate that water levels in the Upper Floridan aquifer responded immediately after each shutdown, rising about 30 ft, while the water level in the deeper Fernandina permeable zone did not respond to the decreased pumpage. In Brunswick, groundwater-level monitoring data from the early 1990s to 2010 (U.S. Geological Survey, 2013) indicate that similar plant shutdowns have occurred, thus providing test cases for determining the relative degree of interconnection between the Upper and Lower Floridan aquifers and the hydraulic connection within zones in the Lower Floridan aquifer. During these shutdowns, water levels in the Upper Floridan aquifer and shallower zones of the Lower Floridan aquifer below the LISAPCU and MAPCUs responded to decreased pumpage, whereas the water level in the Fernandina permeable zone did not respond (U.S. Geological Survey, 2013, station 34H500, location shown on pl. 1).

Oldsmar Permeable Zone: Peninsular Florida—The Oldsmar permeable zone includes all extremely permeable zones and otherwise less permeable zones that lie between the glauconite marker unit and base of the massive dolostone unit in the Oldsmar Formation. This zone is characterized by extensive fracturing and development of cavernous porosity (solution zones) mostly within a massive dolostone unit in the Oldsmar Formation, as indicated by hydraulic test data collected by the SWFWMD and SFWMD as well as data presented in numerous engineering reports of deep injection test wells. The zone may also locally include permeable zones in the upper part of the Cedar Keys Formation. The extent and configuration of the top of the Oldsmar permeable zone are shown in figure 49.

Table 13. Range of transmissivity values determined for various hydrogeologic units in the Floridan aquifer system.

[ft²/day, foot squared per day; ft, foot; unit thickness is an average thickness of the hydrogeologic unit at the wells represented in the specified county, this thickness may include intra-aquifer slow-permeability zones; median K_h, median hydraulic conductivity determined by dividing median value by unit thickness; UF, Upper Floridan aquifer; Clbrn, Claiborne aquifer; Grdn, Gordon aquifer; SPZ_UF, Suwannee permeable zone/uppermost permeable zone; APPZ, Avon Park permeable zone (upper); LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone, LF, Lower Floridan aquifer; OCAPLPZ, Ocala-Avon Park lower permeability zone]

County	Unit	[1]Transmissivity (ft²/day)				Number of tests	Unit thickness (ft)	Median K_h (ft/day)
		Minimum	Maximum	Average	Median			
				Alabama				
Covington	UF	200	200,000	73,000	20,000	3	139	140
Escambia	UF	1,700	1,700	1,700	1,700	1	427	4
Escambia	UF_Clbrn	3,400	3,400	3,400	3,400	1	1,020	3.3
Geneva	UF_Clbrn	400	400	400	400	1	340	1.2
Houston	UF	140	140	140	140	1	18	7.6
Houston	UF_Clbrn	2,000	2,000	2,000	2,000	1	339	5.9
Houston	Clbrn-Grdn	130	130	130	130	2	300	0.43
				Florida				
Alachua	UF	21,000	25,000	24,000	24,000	4	280	87
Baker	UF	15,000	15,000	15,000	15,000	1	156	96
Bay	UF	500	660,000	38,000	4,300	22	738	5.8
Brevard	SPZ_UF	5,000	170,000	32,000	10,000	13	410	24
Brevard	UF	3,000	7,500	5,300	5,300	2	454	12
Brevard	APPZ	45,000	45,000	45,000	45,000	1	488	93
Brevard	LAPPZ_OLDSPZ	29,000	29,000	29,000	29,000	1	1,495	20
Brevard	OLDSPZ	280,000	280,000	280,000	280,000	1	982	290
Broward	SPZ_UF	1,300	44,000	18,000	19,000	24	315	61
Broward	APPZ	4,800	10,000	7,500	8,000	6	354	23
Broward	LAPPZ_OLDSPZ	120,000	13,000,000	4,500,000	140,000	3	1,922	71
Broward	OLDSPZ	59,000	13,000,000	4,500,000	400,000	3	1,018	390
Calhoun	UF	1,000	7,300	3,300	3,000	8	646	4.6
Charlotte	SPZ_UF	500	8,900	4,400	4,400	8	373	12
Charlotte	APPZ	140,000	260,000	200,000	200,000	2	815	240
Charlotte	LAPPZ	27,000	61,000	44,000	44,000	2	116	380
Charlotte	OLDSPZ	140,000	140,000	140,000	140,000	1	1,271	110
Citrus	UF	38,000	38,000	38,000	38,000	1	218	170
Citrus	APPZ	200,000	2,800,000	1,100,000	210,000	3	187	1,100
Clay	UF	7,800	7,800	7,800	7,800	1	339	23
Clay	UF_LF	9,100	87,000	38,000	33,000	10	1,589	21
Collier	SPZ_UF	7,100	380,000	69,000	26,000	8	618	41
Collier	LAPPZ_OLDSPZ	1,900,000	1,900,000	1,900,000	1,900,000	1	1,688	1,100
Columbia	UF	30,000	36,000	33,000	33,000	3	279	120
De Soto	SPZ_UF	560	130,000	20,000	6,700	12	303	22
De Soto	APPZ	3,600	1,600,000	370,000	160,000	10	739	220
Duval	UF	9,100	190,000	27,000	20,000	29	299	67
Duval	UF_LF	2,100	200,000	37,000	23,000	33	1,567	15
Escambia	UF	920	920	920	920	1	867	1.1

Table 13. Range of transmissivity values determined for various hydrogeologic units in the Floridan aquifer system.—Continued

[ft²/day, foot squared per day; ft, foot; unit thickness is an average thickness of the hydrogeologic unit at the wells represented in the specified county, this thickness may include intra-aquifer slow-permeability zones; median K_h, median hydraulic conductivity determined by dividing median value by unit thickness; UF, Upper Floridan aquifer; Clbrn, Claiborne aquifer; Grdn, Gordon aquifer; SPZ_UF, Suwannee permeable zone/uppermost permeable zone; APPZ, Avon Park permeable zone (upper); LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone, LF, Lower Floridan aquifer; OCAPLPZ, Ocala-Avon Park lower permeability zone]

County	Unit	[1]Transmissivity (ft²/day)				Number of tests	Unit thickness (ft)	Median K_h (ft/day)
		Minimum	Maximum	Average	Median			
Florida—Continued								
Flagler	UF	4,600	61,000	29,000	28,000	15	356	79
Franklin	UF	45,000	45,000	45,000	45,000	1	1,339	33
Gadsden	UF	1,200	30,000	9,000	4,400	16	560	7.8
Gadsden	UF_LF	400	400	400	400	1	1,230	0.33
Gilchrist	UF	650,000	650,000	650,000	650,000	1	204	3,200
Glades	SPZ_UF	240	27,000	14,000	14,000	2	175	77
Glades	APPZ	6,200	26,000	15,000	12,000	3	778	15
Gulf	UF	1,000	6,600	2,800	2,500	6	971	2.6
Hamilton	UF	190,000	190,000	190,000	190,000	1	330	580
Hardee	SPZ_UF	400	170,000	49,000	13,000	7	228	57
Hardee	APPZ	25,000	9,300,000	1,000,000	270,000	11	823	320
Hendry	SPZ_UF	3,500	24,000	13,000	13,000	6	189	67
Hendry	OCAPLPZ	3,600	3,600	3,600	3,600	1	356	10
Hendry	APPZ	1,400	560,000	280,000	280,000	2	541	520
Hendry	OLDSPZ	27,000	27,000	27,000	27,000	1	1,276	21
Hernando	UF	8,800	8,800	8,800	8,800	1	294	30
Hernando	APPZ	57,000	57,000	57,000	57,000	1	770	73
Hernando	UF_APPZ	43,000	2,100,000	1,100,000	1,100,000	2	680	1,600
Highlands	SPZ_UF	330	6,600	2,600	1,700	4	218	8
Highlands	APPZ	5,500	70,000	41,000	48,000	8	787	61
Hillsborough	SPZ_UF	4,700	1,000,000	100,000	62,000	35	280	220
Hillsborough	APPZ	15,000	740,000	100,000	47,000	43	659	71
Holmes	UF	2,000	4,000	3,600	4,000	5	366	11
Holmes	UF_LF	13,000	13,000	13,000	13,000	1	619	21
Indian River	SPZ_UF	5,500	100,000	33,000	32,000	18	415	78
Indian River	APPZ	5,900	73,000	23,000	7,500	5	494	15
Indian River	OLDSPZ	1,500,000	1,500,000	1,500,000	1,500,000	1	1,109	1,400
Jackson	UF	600	50,000	8,100	5,000	28	352	14
Jefferson	UF	210,000	210,000	210,000	210,000	1	475	450
Lake	SPZ_UF	3,700	100,000	52,000	52,000	2	239	220
Lake	UF	4,300	150,000	40,000	30,000	8	298	99
Lake	APPZ	96,000	480,000	290,000	290,000	2	361	800
Lake	LAPPZ	740,000	740,000	740,000	740,000	1	364	2,000
Lee	SPZ_UF	2,000	70,000	14,000	9,000	18	579	15
Lee	APPZ	64,000	64,000	64,000	64,000	1	771	83
Lee	LAPPZ	67,000	67,000	67,000	67,000	1	211	320
Lee	OLDSPZ	43,000	43,000	43,000	43,000	1	1,254	34

Table 13. Range of transmissivity values determined for various hydrogeologic units in the Floridan aquifer system.—Continued

[ft²/day, foot squared per day; ft, foot; unit thickness is an average thickness of the hydrogeologic unit at the wells represented in the specified county, this thickness may include intra-aquifer slow-permeability zones; median K_h, median hydraulic conductivity determined by dividing median value by unit thickness; UF, Upper Floridan aquifer; Clbrn, Claiborne aquifer; Grdn, Gordon aquifer; SPZ_UF, Suwannee permeable zone/uppermost permeable zone; APPZ, Avon Park permeable zone (upper); LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone, LF, Lower Floridan aquifer; OCAPLPZ, Ocala-Avon Park lower permeability zone]

County	Unit	[1]Transmissivity (ft²/day)				Number of tests	Unit thickness (ft)	Median K_h (ft/day)
		Minimum	Maximum	Average	Median			
Florida—Continued								
Leon	UF	10,000	1,300,000	220,000	200,000	17	599	330
Levy	UF	26,000	26,000	26,000	26,000	1	246	100
Levy	APPZ	20,000	20,000	20,000	20,000	1	438	46
Liberty	UF	3,000	3,000	3,000	3,000	2	659	4.6
Manatee	SPZ_UF	3,900	290,000	45,000	15,000	13	330	44
Manatee	OCAPLPZ	8	8	8	8	1	220	0.035
Manatee	APPZ	2,900	280,000	130,000	100,000	14	894	120
Marion	UF	1,600	2,300,000	650,000	78,000	19	200	390
Marion	APPZ	72,000	340,000	210,000	210,000	2	484	420
Martin	SPZ_UF	9,200	38,000	16,000	13,000	16	297	43
Martin	APPZ	1,700	310,000	98,000	78,000	7	535	150
Miami-Dade	SPZ_UF	4,200	68,000	20,000	14,000	15	264	53
Miami-Dade	APPZ	4,300	4,300	4,300	4,300	1	484	8.9
Miami-Dade	LAPPZ_OLDSPZ	3,200,000	25,000,000	14,000,000	14,000,000	2	1,550	9,000
Nassau	UF	17,000	170,000	54,000	30,000	5	338	89
Okaloosa	UF	640	26,000	9,700	7,500	16	651	12
Okeechobee	SPZ_UF	680	21,000	5,300	3,700	11	228	16
Okeechobee	APPZ	2,600	590,000	97,000	5,600	12	605	9.3
Orange	SPZ_UF	7,900	7,900	7,900	7,900	1	390	20
Orange	UF	3,500	750,000	170,000	77,000	18	312	250
Orange	APPZ	64,000	140,000	90,000	80,000	4	383	210
Orange	LAPPZ	18,000	690,000	410,000	460,000	18	369	1,200
Orange	UF_LF	82,000	460,000	270,000	270,000	2	2,176	120
Osceola	SPZ_UF	4,000	24,000	13,000	11,000	13	213	54
Osceola	UF	2,000	160,000	48,000	27,000	15	375	73
Osceola	APPZ	5,700	270,000	99,000	78,000	13	449	170
Osceola	LAPPZ	37,000	200,000	130,000	140,000	3	339	410
Palm Beach	SPZ_UF	1,400	110,000	25,000	14,000	20	294	49
Palm Beach	APPZ	4,500	220,000	56,000	23,000	11	508	45
Palm Beach	LAPPZ	68,000	68,000	68,000	68,000	1	732	93
Palm Beach	OLDSPZ	40,000	670,000	280,000	200,000	4	1,068	190
Pasco	UF	40,000	40,000	40,000	40,000	1	349	110
Pasco	UF_APPZ	19,000	300,000	65,000	51,000	26	697	73
Pinellas	SPZ_UF	1,400	59,000	25,000	27,000	26	275	97
Pinellas	OCAPLPZ	200	200	200	200	1	277	0.72
Pinellas	APPZ	110,000	2,900,000	1,200,000	1,200,000	6	931	1,300
Pinellas	LAPPZ_OLDSPZ	2,500	2,500	2,500	2,500	1	1,783	1.4

Table 13. Range of transmissivity values determined for various hydrogeologic units in the Floridan aquifer system.—Continued

[ft[2]/day, foot squared per day; ft, foot; unit thickness is an average thickness of the hydrogeologic unit at the wells represented in the specified county, this thickness may include intra-aquifer slow-permeability zones; median K_h, median hydraulic conductivity determined by dividing median value by unit thickness; UF, Upper Floridan aquifer; Clbrn, Claiborne aquifer; Grdn, Gordon aquifer; SPZ_UF, Suwannee permeable zone/uppermost permeable zone; APPZ, Avon Park permeable zone (upper); LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone, LF, Lower Floridan aquifer; OCAPLPZ, Ocala-Avon Park lower permeability zone]

County	Unit	[1]Transmissivity (ft²/day)				Number of tests	Unit thickness (ft)	Median K_h (ft/day)
		Minimum	Maximum	Average	Median			
				Florida—Continued				
Polk	SPZ_UF	450	110,000	40,000	16,000	29	319	51
Polk	UF	9,000	14,000	12,000	12,000	2	319	36
Polk	APPZ	11,000	600,000	140,000	83,000	8	644	130
Polk	LAPPZ	16,000	17,000	17,000	17,000	2	407	42
Polk	LAPPZ_OLDSPZ	190,000	190,000	190,000	190,000	1	1,197	160
Putnam	UF	17,000	110,000	44,000	39,000	10	352	110
Santa Rosa	UF	7,800	19,000	13,000	13,000	2	813	16
Sarasota	SPZ_UF	1,000	35,000	14,000	9,600	13	328	29
Sarasota	APPZ	5,000	300,000	100,000	58,000	8	831	69
Seminole	SPZ_UF	1,700	42,000	17,000	13,000	5	103	130
Seminole	UF	1,200	34,000	15,000	8,900	9	346	26
Seminole	APPZ	13,000	13,000	13,000	13,000	1	414	33
Seminole	UF_LF	160,000	160,000	160,000	160,000	1	387	410
St. Johns	UF	8,700	86,000	30,000	24,000	28	421	57
St. Lucie	SPZ_UF	3,300	250,000	32,000	15,000	17	352	42
St. Lucie	APPZ	23,000	1,100,000	180,000	66,000	9	575	110
St. Lucie	LAPPZ	13,000	13,000	13,000	13,000	1	406	31
St. Lucie	OLDSPZ	270,000	280,000	280,000	280,000	2	1,003	270
Sumter	UF	7,600	1,800,000	440,000	140,000	12	183	750
Sumter	APPZ	410,000	4,500,000	2,000,000	1,500,000	4	378	3,900
Sumter	UF_LF	44,000	600,000	200,000	68,000	5	1,939	35
Suwannee	UF	300,000	450,000	380,000	380,000	2	346	1,100
Taylor	UF	130,000	130,000	130,000	130,000	1	361	350
Volusia	UF	2,200	160,000	23,000	15,000	59	340	44
Volusia	UF_LF	4,500	4,500	4,500	4,500	1	1,931	2.3
Walton	UF	500	24,000	10,000	8,000	19	628	13
Washington	UF	1,000	200,000	130,000	200,000	3	368	540
				Georgia				
Appling	UF	6,700	48,000	21,000	20,000	9	358	56
Bacon	UF	21,000	72,000	41,000	29,000	3	413	70
Baker	UF	7,600	42,000	21,000	14,000	3	145	95
Ben Hill	UF	6,700	22,000	16,000	16,000	7	420	38
Ben Hill	UF_Clbrn	13,000	13,000	13,000	13,000	1	818	16
Berrien	UF	1,700	360,000	89,000	32,000	11	264	120
Brantley	UF	13,000	13,000	13,000	13,000	1	358	37
Brooks	UF	8,200	19,000	14,000	14,000	2	373	36
Bryan	UF	70,000	70,000	70,000	70,000	1	267	260

Table 13. Range of transmissivity values determined for various hydrogeologic units in the Floridan aquifer system.—Continued

[ft²/day, foot squared per day; ft, foot; unit thickness is an average thickness of the hydrogeologic unit at the wells represented in the specified county, this thickness may include intra-aquifer slow-permeability zones; median K_h, median hydraulic conductivity determined by dividing median value by unit thickness; UF, Upper Floridan aquifer; Clbrn, Claiborne aquifer; Grdn, Gordon aquifer; SPZ_UF, Suwannee permeable zone/uppermost permeable zone; APPZ, Avon Park permeable zone (upper); LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone, LF, Lower Floridan aquifer; OCAPLPZ, Ocala-Avon Park lower permeability zone]

County	Unit	[1]Transmissivity (ft²/day)				Number of tests	Unit thickness (ft)	Median K_h (ft/day)
		Minimum	Maximum	Average	Median			
Georgia—Continued								
Bryan	LF	8,300	8,300	8,300	8,300	1	531	16
Bulloch	UF	530	31,000	5,800	4,300	25	162	27
Bulloch	UF_LF	10,000	10,000	10,000	10,000	1	725	14
Burke	UF	200	7,300	1,900	720	12	110	6.6
Burke	Clbrn-Grdn	150	6,500	3,000	2,700	10	156	17
Calhoun	UF	42,000	42,000	42,000	42,000	1	66	640
Calhoun	Clbrn-Grdn	250	250	250	250	1	125	2
Camden	UF	19,000	130,000	80,000	98,000	5	398	250
Camden	LAPPZ	13,000	13,000	13,000	13,000	1	383	34
Camden	UF_LF	43,000	43,000	43,000	43,000	1	1,861	23
Candler	UF	17,000	83,000	50,000	50,000	2	169	300
Charlton	UF	7,800	23,000	15,000	15,000	2	277	55
Chatham	UF	20,000	80,000	36,000	33,000	15	234	140
Chatham	Clbrn-Grdn	8,200	10,000	9,100	9,100	2	376	24
Coffee	UF	8,500	600,000	230,000	150,000	4	393	370
Coffee	UF_Clbrn	25,000	25,000	25,000	25,000	1	691	36
Colquitt	UF	270	150,000	32,000	8,000	18	234	34
Colquitt	UF_Clbrn	3,300	3,300	3,300	3,300	1	706	4.7
Cook	UF	880	210,000	60,000	20,000	15	299	67
Crisp	UF	600	27,000	9,500	8,000	6	124	65
Crisp	Clbrn-Grdn	600	6,900	5,000	6,300	4	167	37
Decatur	UF	350	1,300,000	150,000	43,000	13	364	120
Decatur	UF_LF	19,000	19,000	19,000	19,000	1	1,046	18
Dooly	UF	2,300	2,300	2,300	2,300	1	94	24
Dooly	Clbrn-Grdn	450	12,000	4,500	3,000	7	115	26
Dougherty	UF	1,300	280,000	54,000	21,000	34	200	100
Dougherty	Clbrn-Grdn	1,300	5,300	3,100	3,100	13	236	13
Early	UF	2,300	100,000	37,000	29,000	14	76	380
Early	Clbrn-Grdn	400	400	400	400	1	205	2
Effingham	UF	5,000	51,000	20,000	17,000	19	151	110
Emanuel	UF	3,200	7,500	6,100	6,800	4	166	41
Evans	UF	22,000	56,000	37,000	37,000	5	219	170
Glynn	UF	23,000	280,000	78,000	64,000	39	466	140
Grady	UF	390	430,000	110,000	4,800	4	274	18
Irwin	UF	4,900	49,000	14,000	11,000	35	440	24
Jeff Davis	UF	8,000	19,000	14,000	14,000	2	324	42
Jeff Davis	UF_Clbrn	8,800	8,800	8,800	8,800	1	636	14

Table 13. Range of transmissivity values determined for various hydrogeologic units in the Floridan aquifer system.—Continued

[ft²/day, foot squared per day; ft, foot; unit thickness is an average thickness of the hydrogeologic unit at the wells represented in the specified county, this thickness may include intra-aquifer slow-permeability zones; median K_h, median hydraulic conductivity determined by dividing median value by unit thickness; UF, Upper Floridan aquifer; Clbrn, Claiborne aquifer; Grdn, Gordon aquifer; SPZ_UF, Suwannee permeable zone/uppermost permeable zone; APPZ, Avon Park permeable zone (upper); LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone, LF, Lower Floridan aquifer; OCAPLPZ, Ocala-Avon Park lower permeability zone]

County	Unit	[1]Transmissivity (ft²/day)				Number of tests	Unit thickness (ft)	Median K_h (ft/day)
		Minimum	Maximum	Average	Median			
Georgia—Continued								
Jefferson	UF	380	1,200	920	1,100	3	37	31
Jefferson	Clbrn-Grdn	810	4,000	2,700	2,800	6	215	13
Jenkins	UF	16,000	16,000	16,000	16,000	1	84	190
Jenkins	Clbrn-Grdn	180	23,000	8,200	1,500	3	216	6.9
Lanier	UF	130,000	130,000	130,000	130,000	1	335	400
Laurens	Clbrn-Grdn	4,300	7,200	5,800	5,800	2	184	31
Lee	UF	4,000	79,000	35,000	43,000	5	123	350
Lee	Clbrn-Grdn	180	2,500	1,500	1,700	4	142	12
Liberty	UF	90,000	160,000	140,000	150,000	8	256	570
Liberty	Clbrn-Grdn	4,000	7,000	5,500	5,500	2	346	16
Long	UF	250,000	250,000	250,000	250,000	1	302	830
Lowndes	UF	11,000	94,000	48,000	40,000	7	369	110
Macon	Clbrn-Grdn	2,600	2,900	2,700	2,700	2	78	35
McIntosh	LF	6,000	6,000	6,000	6,000	1	585	10
Miller	UF	21,000	150,000	83,000	83,000	2	219	380
Mitchell	UF	2,200	220,000	85,000	90,000	15	316	290
Mitchell	UF_Clbrn	3,400	3,400	3,400	3,400	1	795	4.3
Montgomery	UF	850	15,000	6,100	5,000	5	214	23
Montgomery	UF_LF	630	5,500	3,100	3,100	2	491	6.2
Pierce	UF	13,000	13,000	13,000	13,000	1	460	28
Pulaski	UF_Clbrn	9,800	9,800	9,800	9,800	1	337	29
Randolph	UF_Clbrn	8,400	8,400	8,400	8,400	1	72	120
Richmond	UF	2,000	2,000	2,000	2,000	1	56	36
Richmond	Clbrn-Grdn	300	300	300	300	1	150	2
Screven	UF	1,900	15,000	6,000	4,100	5	173	24
Screven	Clbrn-Grdn	1,300	3,500	2,400	2,400	2	196	12
Seminole	UF	27,000	110,000	54,000	41,000	5	212	190
Sumter	UF	200	4,100	1,900	1,800	4	39	45
Sumter	Clbrn-Grdn	2,400	14,000	6,100	3,500	6	68	52
Tattnall	UF	7,100	41,000	19,000	13,000	6	270	47
Tattnall	UF_Clbrn	9,400	31,000	20,000	20,000	2	690	29
Telfair	UF	3,200	41,000	14,000	7,900	5	280	28
Telfair	UF_Clbrn	6,700	76,000	30,000	8,200	3	636	13
Terrell	UF	2,000	2,000	2,000	2,000	1	3	660
Terrell	Clbrn-Grdn	500	500	500	500	1	142	3.5
Thomas	UF	1,400	560,000	110,000	27,000	14	432	62
Thomas	UF_LF	400	920	660	660	2	679	0.97

Table 13. Range of transmissivity values determined for various hydrogeologic units in the Floridan aquifer system.—Continued

[ft²/day, foot squared per day; ft, foot; unit thickness is an average thickness of the hydrogeologic unit at the wells represented in the specified county, this thickness may include intra-aquifer slow-permeability zones; median K_h, median hydraulic conductivity determined by dividing median value by unit thickness; UF, Upper Floridan aquifer; Clbrn, Claiborne aquifer; Grdn, Gordon aquifer; SPZ_UF, Suwannee permeable zone/uppermost permeable zone; APPZ, Avon Park permeable zone (upper); LAPPZ, lower Avon Park permeable zone; OLDSPZ, Oldsmar permeable zone, LF, Lower Floridan aquifer; OCAPLPZ, Ocala-Avon Park lower permeability zone]

County	Unit	[1]Transmissivity (ft²/day)				Number of tests	Unit thickness (ft)	Median K_h (ft/day)
		Minimum	Maximum	Average	Median			
				Georgia—Continued				
Tift	UF	160	180,000	49,000	29,000	10	309	93
Toombs	UF	290	290	290	290	1	166	1.7
Toombs	UF_LF	4,100	29,000	12,000	9,800	7	458	21
Turner	UF	1,300	17,000	7,500	7,900	13	362	22
Twiggs	UF_Grdn	32,000	37,000	34,000	34,000	6	71	480
Twiggs	Clbrn-Grdn	8,700	8,700	8,700	8,700	1	80	110
Ware	UF_LF	150,000	1,100,000	610,000	570,000	3	1,315	440
Washington	UF	2,700	2,700	2,700	2,700	1	16	170
Washington	UF_Grdn	720	2,700	1,700	1,700	2	105	16
Washington	Clbrn-Grdn	710	13,000	4,800	2,500	7	175	14
Wayne	UF	220,000	280,000	250,000	250,000	8	408	610
Wheeler	UF	2,900	8,200	6,300	7,800	3	219	36
Wheeler	UF_LF	3,300	3,300	3,300	3,300	1	581	5.7
Wilcox	UF	3,900	3,900	3,900	3,900	1	357	11
Wilkinson	Clbrn-Grdn	3,300	14,000	9,300	11,000	5	83	130
Worth	UF	1,600	110,000	17,000	5,300	16	303	18
				South Carolina				
Allendale	UF	2,900	3,900	3,400	3,300	3	251	13
Allendale	Clbrn-Grdn	500	7,100	2,900	1,200	9	212	5.7
Bamberg	UF	670	670	670	670	1	167	4
Barnwell	UF	170	170	170	170	1	169	1
Barnwell	Clbrn-Grdn	800	5,900	3,000	2,800	6	111	25
Beaufort	UF	790	110,000	37,000	26,000	50	154	170
Beaufort	UF_LF	530	27,000	8,700	6,700	17	870	7.7
Beaufort	LF	4,400	8,200	6,300	6,300	4	414	15
Colleton	UF_LF	900	900	900	900	1	465	1.9
Colleton	Clbrn-Grdn	2,000	2,000	2,000	2,000	1	103	19
Hampton	UF	1,200	12,000	7,300	6,100	7	189	32
Jasper	UF	35,000	67,000	47,000	48,000	12	132	360
Jasper	Clbrn-Grdn	6,000	6,000	6,000	6,000	1	407	15

[1]Transmissivity rounded to two significant digits.

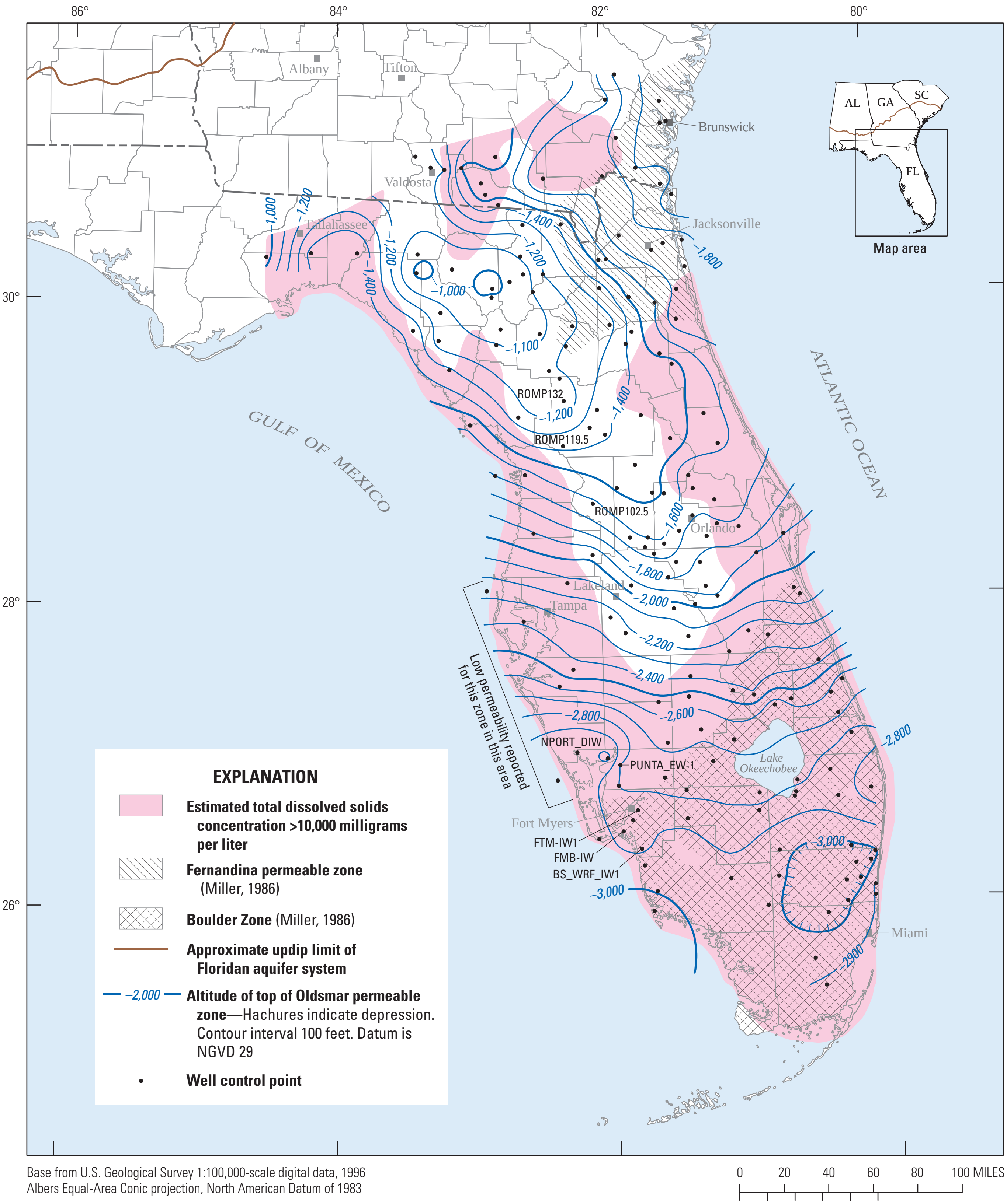


Figure 49. Altitude of the top of the Oldsmar permeable zone and estimated total dissolved solids concentration, peninsular and northeastern Florida and southeastern Georgia.

In northeastern Florida and southeastern Georgia, the Oldsmar permeable zone is restricted to the upper part of the Fernandina permeable zone as previously defined (Miller, 1986) and locally includes permeable zones in the upper part of the Cedar Keys Formation in Brunswick, Ga. (Jones and others, 2002). A deeper, cavernous zone consisting of Late Cretaceous rocks also was included in the Fernandina permeable zone by Miller (1986); however, this deeper zone is excluded herein from the Oldsmar permeable zone. This deeper, cavernous zone is grouped into a deeper brackish and saline aquifer system that is either below the Floridan aquifer system or poorly connected to it across lower permeability evaporitic rocks of the Cedar Keys Formation (fig. 36, pl. 13).

In central Florida, the Oldsmar permeable zone is the deepest basal freshwater zone of the Floridan aquifer system. Test data from wells in Marion County at ROMP132 (Janosik, 2011) and ROMP119.5 (LaRoche, 2012), and in Sumter County at ROMP102.5 (fig. 49) (J.J. LaRoche, Southwest Florida Water Management District, written commun., 2011) indicate fracture and cavernous porosity in the massive dolostone unit of the Oldsmar Formation. Hydraulic conductivity determined from packer tests was either higher or nearly as high in the Oldsmar permeable zone as in the Upper Floridan aquifer (Janosik, 2011; LaRoche, 2012).

The Oldsmar permeable zone may be transmissive throughout much of peninsular Florida. A notable exception is in Pinellas County of west-central Florida where the correlated interval is reported to consist of gypsiferous limestone and dolomite in a deep exploratory test well (Hickey, 1979). Farther south, in Sarasota, Charlotte, and Lee Counties, shallower transmissive zones of the Avon Park Formation are used for deep-well injection (Hickey, 1977, 1982; Hickey and Barr, 1979; Hickey and Spechler, 1979; Hickey and Vecchioli, 1986; Hutchinson, 1992), and, as a result, much less data have been collected from the Oldsmar permeable zone along Florida's southwestern coast.

Because the Oldsmar permeable zone encompasses a broad area having a wide range of hydraulic conditions, there are some areas where this zone is probably not as permeable as in other areas. In Sarasota County, for example, the Oldsmar permeable zone appears to have relatively lower permeability. At the North Port deep injection well (NPORT_DIW, pl. 1), the correlated interval to the Oldsmar permeable zone is a finely crystalline, sucrosic dolostone starting at a depth of about 2,900 ft below land surface. After hydraulic testing, however, the injection well was completed in the shallower permeable zones in the Avon Park Formation (CH2M Hill, 1988), possibly indicating this zone was not permeable enough to be included in the wastewater injection receiving zone. Similar results were obtained at a deep exploration test well (Punta_EW–1, fig. 2, pl. 1) for the City of Punta Gorda in Charlotte County, Fla. (Water Resource Solutions Inc. and Boyle Engineering Corp., 2000). Borehole geophysical logs from this well indicate a much thicker massive dolostone interval at this location than at the North Port deep injection well. A temperature log collected after the injection test, however, indicated that the major receiving zones for the injected water were located in the lower part of the Avon Park Formation (specifically, the LAPPZ) and not in the Oldsmar permeable zone.

Farther south in Lee County, the permeability of the Oldsmar permeable zone apparently increases. The injection zone at Fort Myers Beach (FMB–IW, pl. 1) and Fort Myers (FTM–IW1, pl. 1) encompasses the Oldsmar permeable zone as well as shallower zones within the lower Avon Park Formation (CH2M Hill, 1998), and the injection zone at Bonita Springs (BS–WRF–IW1, pl. 1) is almost entirely within the Oldsmar permeable zone (CH2M Hill, 2004).

In southern Florida, the highly transmissive interval consisting mostly of massively bedded dolostone with cavernous and fracture permeability is called the Boulder Zone. This term was first used by drillers to describe a cavernous dolomite interval in southern Florida and then later applied by Kohout (1965) and further described and mapped by Miller (1986). The name is derived from the large "boulders" of dolomite that are dislodged while drilling through the cavernous interval and results in difficult drilling (Miller, 1986). Cavernous sections have been described along different vertical intervals within the Lower Floridan aquifer and typically span several hundred feet. These zones may interconnect vertically across a thick part of the Oldsmar Formation and may be hydraulically connected to other formations. Although the Boulder Zone does not extend much beyond where it was originally mapped by Miller (1986), because of its stratigraphic position, it is considered herein to be part of the more extensive Oldsmar permeable zone.

Thickness of the Lower Floridan Aquifer—The Lower Floridan aquifer ranges in thickness from only a few feet in the updip outcrop areas to more than 1,900 ft in southwestern Florida and more than 2,200 ft in the eastern part of the Florida panhandle (fig. 50). As with the Upper Floridan aquifer, a major factor affecting the thickness of the Lower Floridan aquifer is the depth and configuration of the lower permeability units that form the middle confining unit. The Lower Floridan aquifer is thick where the top is picked on a shallow lower permeability unit and thin where the top is picked on a deeper lower permeability unit. In the western part of the Florida panhandle, for example, the thickness of the Lower Floridan aquifer ranges from 800 to more than 1,400 ft compared to a thickness of only 100 to 400 ft for the Upper Floridan aquifer. In this area, the shallow BCCU separates the Upper and Lower Floridan aquifers. Additionally, the total thickness of the Lower Floridan aquifer includes intra-aquifer semiconfining units.

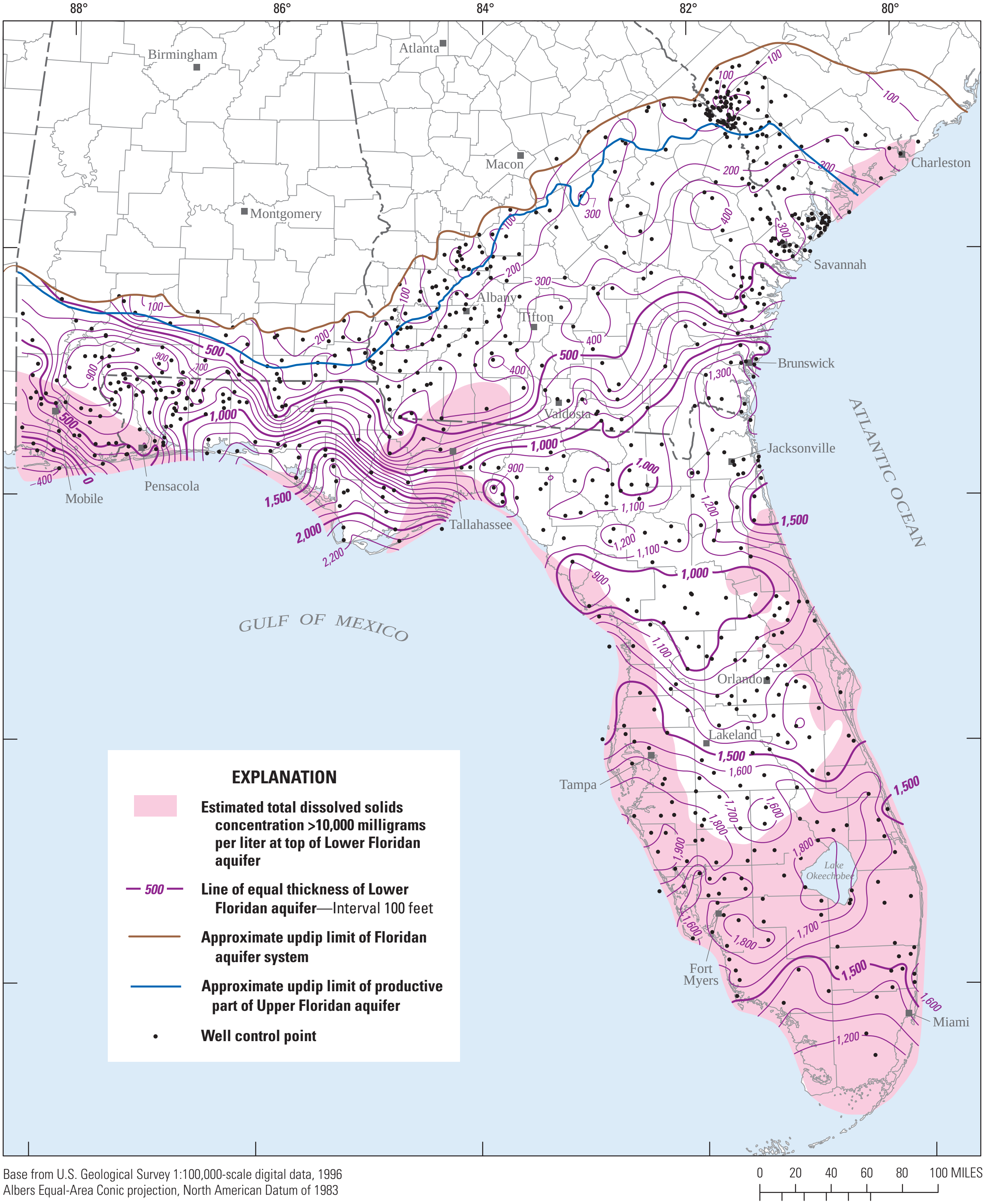


Figure 50. Thickness of the Lower Floridan aquifer and estimated total dissolved solids concentration, southeastern United States.

Hydraulic Properties and Regional Variations in Permeability

The hydraulic properties of the limestones and dolostones that form the Floridan aquifer system vary greatly by location depending on a variety of factors, including the original texture and post-depositional alteration of the rock. Much of the data collected to determine the hydraulic properties of the Floridan aquifer system and its confining and semiconfining units were compiled from previously published reports and numerous deep-well injection tests along Florida's southeastern and southwestern coasts (Kuniansky and Bellino, 2012).

Hydraulic data were evaluated in the context of the revised framework by comparing open intervals of the wells or the depths of core samples and placing these data into one or more of the newly defined units and zones. The following discussion is based on the range and variations in permeability observed in these units.

Factors Controlling Regional Variations in Permeability

Large-scale variations in permeability and the hydraulic properties of the individual rock units that compose the Floridan aquifer system are dependent on many different but closely related geologic factors, including the following:

1. Rock type and texture
    a. Evaporitic rocks deposited in a sabkha or upper tidal-flat environment are generally of low permeability because low-porosity rocks with pore-filling cements tend to form in these areas.
    b. Soft, poorly indurated argillaceous limestone deposited in an offshore, moderate-depth environment is highly porous but tends to be less prone to development of secondary porosity than non-argillaceous limestone and dolostone and, hence, is not usually associated with increased permeability.
    c. "Clean," loosely packed, grain-supported limestones deposited in a high-energy environment tend to have higher primary porosity and permeability than fine-grained matrix-supported limestone; thus, these rocks are more susceptible to increased groundwater flow and dissolution.
    d. Dolomitic limestone and dolostone tend to be more prone to fracturing and cavernous porosity development than softer, less-indurated limestone, possibly because they are more brittle and tend to break rather than bend under regional tectonic stress.
    e. Sucrosic (saccharoidal) dolostone consisting of a loosely packed mosaic of crystals commonly has higher primary porosity and permeability than a microcrystalline or cryptocrystalline low-porosity dolostone and may be more susceptible to increased groundwater flow and dissolution.
2. Degree of confinement and proximity to recharge
    a. In thinly confined or unconfined areas, rain falls directly on the limestone aiding in dissolution in the near-surface environment. The rain absorbs carbon dioxide as it falls forming weak carbonic acid, which increases secondary porosity and permeability via dissolution of the carbonate rocks generally within 300 ft of land surface (Miller, 1999).
    b. In thickly confined areas, depending on the length of the flow path and residence time, groundwater becomes saturated with dissolved limestone, and may less aggressively dissolve the deeper rocks.
3. Structure
    a. Joints and fractures enhance movement of water through the rock column. Enlargement of joints can result from dissolution along joint faces as water moves through these features, leading to increased permeability. A decrease in permeability also may be possible, such as in areas where fractures become filled with material that is less permeable than the host rock through mineral precipitation or sedimentation.
    b. Bedding planes form weaknesses in the rock where enhanced dissolution and development of cavernous porosity can occur, similar to that observed in modern-day cave systems; this "fabric-selective" dissolution can be an important process in thinly bedded carbonate rock sequences and along major lithologic and formation contacts that may have been exposed to subaerial karst development during the time of deposition or shortly after burial.
4. Diagenesis
    a. Dolomitization can increase or decrease porosity depending on the original texture and composition of the host rock; in addition, dolomitization can change the physical properties of the rock by making it more or less prone to mechanical fracturing.
    b. Secondary precipitation or dissolution of evaporitic minerals can decrease or increase, respectively, effective porosity and thus permeability.

Considered in combination, the aforementioned factors influencing development of secondary porosity and increased or decreased permeability in the Floridan aquifer system can be quite complex, depending on the original rock type and texture, the types of structures locally present, position of the rock column to the modern-day or paleo-flow system, and the post-depositional diagenetic processes that can alter the original texture and lithology of the rock. Even with this complexity, there are some consistent patterns that tend to develop within the aquifer system under similar hydrogeologic conditions. One such pattern is the development of subregional “strata-bound” zones of increased permeability along major lithologic contacts and within certain types of carbonate rock. The APPZ described by Reese and Richardson (2008) in central and southern Florida is one example where permeable zones commonly develop within, or at the contacts of, low-porosity dolomitic sections, possibly indicating that lithology strongly controls the permeability distribution within the aquifer system in that area. In subregional characterizations of west-central Florida, Ryder (1978) and Ryder and others (1980) described that most of the water supplied to municipal wells open to the entire Upper Floridan aquifer is derived from two 50- to 100-ft thick, areally extensive, highly fractured dolomitic sections in the Avon Park Formation, thus indicating the importance of these zones to the movement of groundwater through the aquifer system (Knochenmus and Robinson, 1996). Similar patterns of cavernous porosity associated with dolomitic rocks also have been described in northeastern Florida and southeastern Georgia (Williams and Spechler, 2011).

Another pattern is the presence of extensive beds of soft argillaceous limestone that tend to be much less fractured and less prone to the development of cavernous porosity. Because of the lack of interconnected vuggy and cavernous openings, these beds tend to behave more as semiconfining units within the system, except where the rock is exposed or near the land surface and karst is prevalent.

The presence of structure, such as persistent, open jointing or development of openings along bedding planes, are common patterns of permeability enhancement that develop in carbonate rocks of the Floridan aquifer system. Nearly all of the ATV images and borehole video surveys reviewed during this investigation show high-angle joints that cut across some of the rocks that are either part of the aquifer or part of one of the middle confining or semiconfining units of the aquifer system. These fractures may form conduits for water movement from one unit to another or connect other permeable horizons within the aquifer system (fig. 14). In Brunswick, Ga., for example, Gregg and Zimmerman (1974) and Wait (1965) described an area of the Upper Floridan aquifer that had become contaminated by saltwater moving upward along fractures suspected to extend across the confining beds that separate the freshwater and brackish-water zones. The rate of upward movement of the brackish water seemed to be a function of the rate of water-level decline. The movement of brackish and saline water along fractures into the freshwater part of the aquifer system has been investigated in other areas by Phelps and Spechler (1997), Spechler (1994), and Tihansky (2005). Saltwater intrusion by means of this process may greatly limit the availability of potable water in areas of heavy pumping.

Aquifer Transmissivity

The carbonate rocks that compose the Floridan aquifer system have highly variable hydraulic properties, including porosity and permeability, for the reasons previously discussed. Transmissivity within the aquifer system has been reported over a range of more than six orders of magnitude, from less than 8 ft^2/d to greater than 9,000,000 ft^2/d, with the majority of values ranging from 10,000 to 100,000 ft^2/d (Kuniansky and Bellino, 2012). Where the aquifer is unconfined or thinly confined, infiltrating water dissolves the rock and transmissivity tends to be relatively high. Where the aquifer is thickly confined, less dissolution occurs and transmissivity tends to be lower. In the first regional map depicting transmissivity variation across the aquifer, Miller (1986) showed that transmissivity values exceed 250,000 ft^2/d where the aquifer system is either unconfined or thinly confined. In areas where the aquifer is thickly confined, Miller (1986) indicated lower transmissivity was related primarily to textural changes and secondarily to the thickness of the rocks. Micritic limestone in southern Florida and in the updip outcrop areas was identified as having much lower transmissivity than elsewhere in the system.

An updated regional transmissivity map was produced for the Upper Floridan aquifer as defined by Miller (1986) meaning the entire system where the middle of the system is leaky (fig. 51) by contouring log-transformed transmissivity estimated from aquifer performance and specific capacity tests (Kuniansky and Bellino, 2012; Kuniansky and others, 2012). The map generally is similar to the one produced by Miller (1986), with higher transmissivity corresponding to unconfined areas and lower transmissivity corresponding to the confined areas.

A comparison of Miller’s (1986) original and revised transmissivity maps here indicates several differences:

- In the Dougherty Plain of southwestern Georgia, both maps show an area of high transmissivity resulting from the development of karst; however, the revised map shows somewhat lower overall transmissivity for this area than portrayed in the original map.

- Southwest of the Dougherty Plain, the original map shows a wide band of high transmissivity in the central part of the Florida panhandle. The updated map, constructed with a greater number of data points, shows much lower overall transmissivity for this area.

- Although both maps depict a narrow band of lower permeability rocks that are part of the Gulf Trough, the extent of this lower permeability area has been refined in this study (pls. 4 and 5). On the basis of the yield and location for approximately 9,000 active wells included in the agricultural well inventory data provided by the Georgia Environmental Protection Division Agricultural Permitting Unit, Tifton, Ga. (Edward Rooks, written commun. 2011), development of high yielding wells within the lower permeability area in the Gulf Trough is unlikely and suggests low transmissivity in these areas. Krause

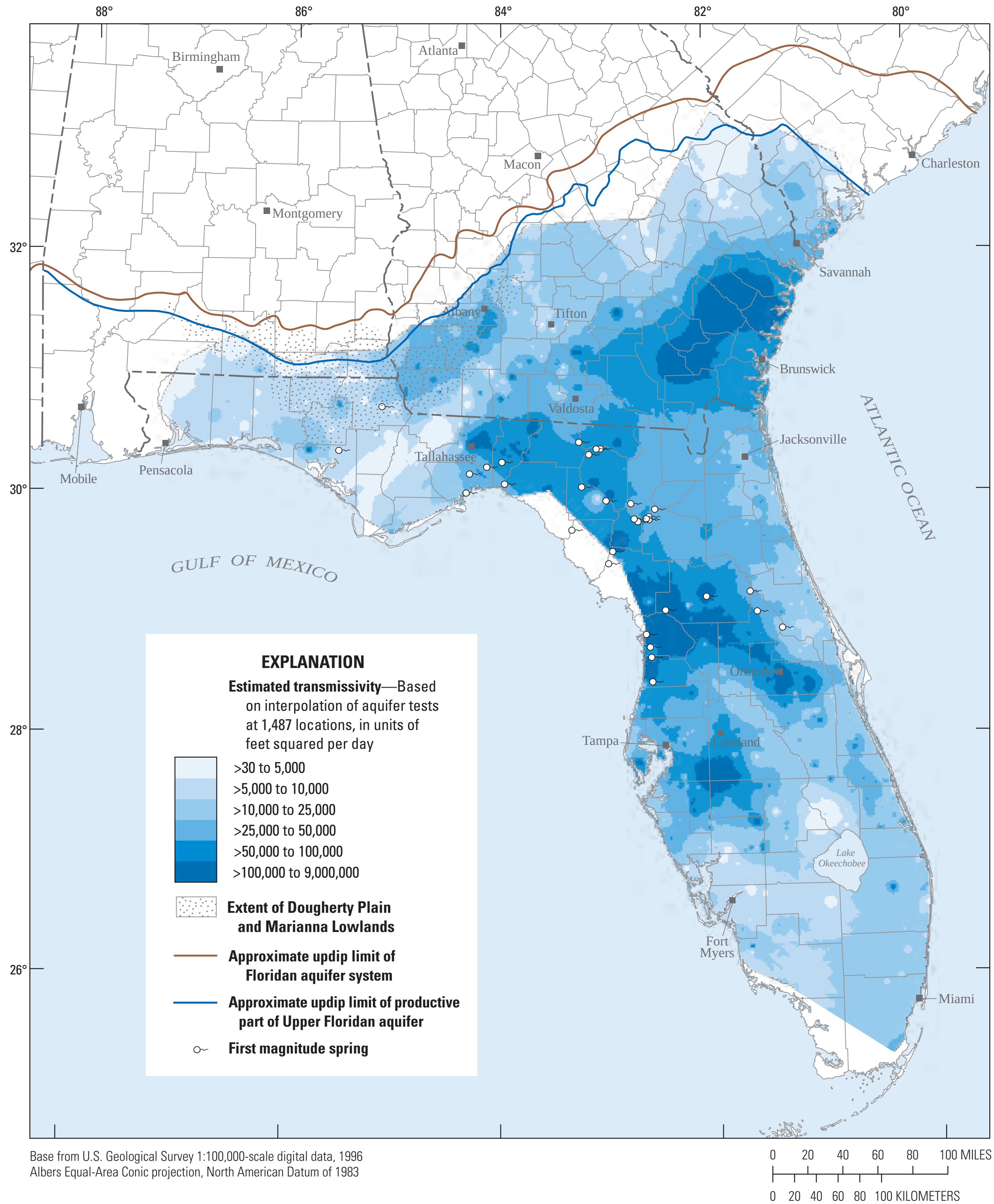


Figure 51. Estimated transmissivity of the Floridan aquifer system, southeastern United States (modified from Kuniansky and others, 2012).

and Randolph (1989) reported that the transmissivity values inside the trough were less than 1,000 ft^2/d on the basis of specific capacity data. Payne and others (2005) simulated a regional groundwater flow using a hydraulic conductivity value of 2 ft/d inside the Gulf Trough area.

- In peninsular Florida, the overall high-and-low transmissivity pattern shown in both maps is similar; however, the gradation from the highly transmissive part of the Floridan aquifer system in east-central and west-central Florida to the less transmissive part in southern Florida has been refined in the revised map as a result of additional data.

- A distinct area of low transmissivity not shown on the original map extends northward along the Kissimmee River (see figure 9 for location) from Lake Okeechobee (fig. 51); the cause of the low transmissivity in this area is unknown. The low transmissivity extends into and affects the APPZ in this same area and also appears to correspond to an increasing trend in dissolved solids and sulfate in the Upper Floridan aquifer (Sprinkle, 1989).

As previously described, the Upper Floridan aquifer in central and southern Florida can be divided into the uppermost permeable zone, OCAPLPZ, and APPZ. Thus, the transmissivity map presented in figure 51 is only a general portrayal of the undifferentiated transmissivity from an aggregate of all three zones of the Upper Floridan aquifer in these areas. To characterize the differences in transmissivity between the zones, the open intervals of wells contained in the transmissivity data (Kuniansky and Bellino, 2012) were used to categorize the tests into one or more units and (or) zones. From this, a statistical summary of transmissivity was produced for each county, grouped by zone (table 13). In some counties, only one test was available for a distinct zone or aquifer, and in these cases the minimum, maximum, average, and median values are the same. In other counties, such as Duval in northeastern Florida, numerous tests have been conducted. In that county, a nearly equal number of tests are reported for the Upper Floridan aquifer category and the combined Upper and Lower Floridan aquifers category (table 13). Both hydrogeologic unit categories have similar average and median transmissivity values, suggesting similar hydraulic properties for the Upper Floridan aquifer and the combined Upper and Lower Floridan aquifer wells. Slightly higher transmissivity values for the first permeable zone of the Lower Floridan aquifer were observed by Franks and Phelps (1979), who reported transmissivity values of 100,000 and 300,000 ft^2/d for two wells that penetrated about 700 ft of the Floridan aquifer system, open to the Upper Floridan aquifer and first permeable zone of the Lower Floridan aquifer in Duval County. These values could not be assigned to any specific wells in the database of Kuniansky and Bellino (2012).

In west-central Florida, the largest vertical contrast in transmissivity within the Upper Floridan aquifer is between the uppermost permeable zone and the APPZ. As an example, an aquifer performance test at ROMP28 (pl. 1) in Polk County yielded a transmissivity value of 333 ft^2/d for the Suwannee permeable zone compared to a transmissivity of 59,000 ft^2/d for the underlying APPZ (DeWitt, 1998). Although this is an extreme case, similarly large differences have been reported in tests conducted elsewhere in southwestern Florida, such as Manatee, Hardee, and De Soto Counties (table 13). The thickness and permeability of the APPZ decrease north of the Pasco-Hernando County line (Ron Basso, Southwest Florida Water Management District, written commun., 2013).

The degree of contrast between the uppermost permeable zone and APPZ varies across the region and generally diminishes toward its northern and southern extents. To show this trend, aquifer test data were grouped into six geographic areas and presented in boxplots showing the range of transmissivity for each respective zone (fig. 52). As described previously, the greatest contrast between the two permeable zones is in southwest Florida (area 2, fig. 52) and in central and east-central areas of Florida (areas 4 and 5, fig. 52). Farther north in areas such as Hillsborough, Pasco, and other counties of west-central Florida (area 1, fig. 52), the transmissivity of the Avon Park permeable zone is only slightly higher than that of the Suwannee permeable zone. The reason for the reduced contrast in the northern area is probably a combination of decreasing transmissivity in the APPZ and increasing transmissivity in the uppermost permeable zone.

Along the southeastern coast of Florida in Martin and St. Lucie Counties (area 5, fig. 52), fairly large transmissivity contrasts were identified in comparisons between the uppermost permeable zone and APPZ (Reese, 2004). In this area, the aquifer is thickly confined and the contrast between the two permeable zones is great. Farther south, however, the differences in transmissivity become progressively less pronounced in Palm Beach County (Reese and Memberg, 2000). In Broward and Miami-Dade Counties, the relation is reversed and the transmissivity of the APPZ is generally less than that observed for the uppermost permeable zone of the Upper Floridan aquifer (area 6, fig. 52). Reese and Richardson (2008) noted that the decreasing southward trend in transmissivity of the APPZ may be related to a transition from mostly higher permeability fractured dolostone units in the north to mostly lower permeability limestone units in the south (delineated area, fig. 30).

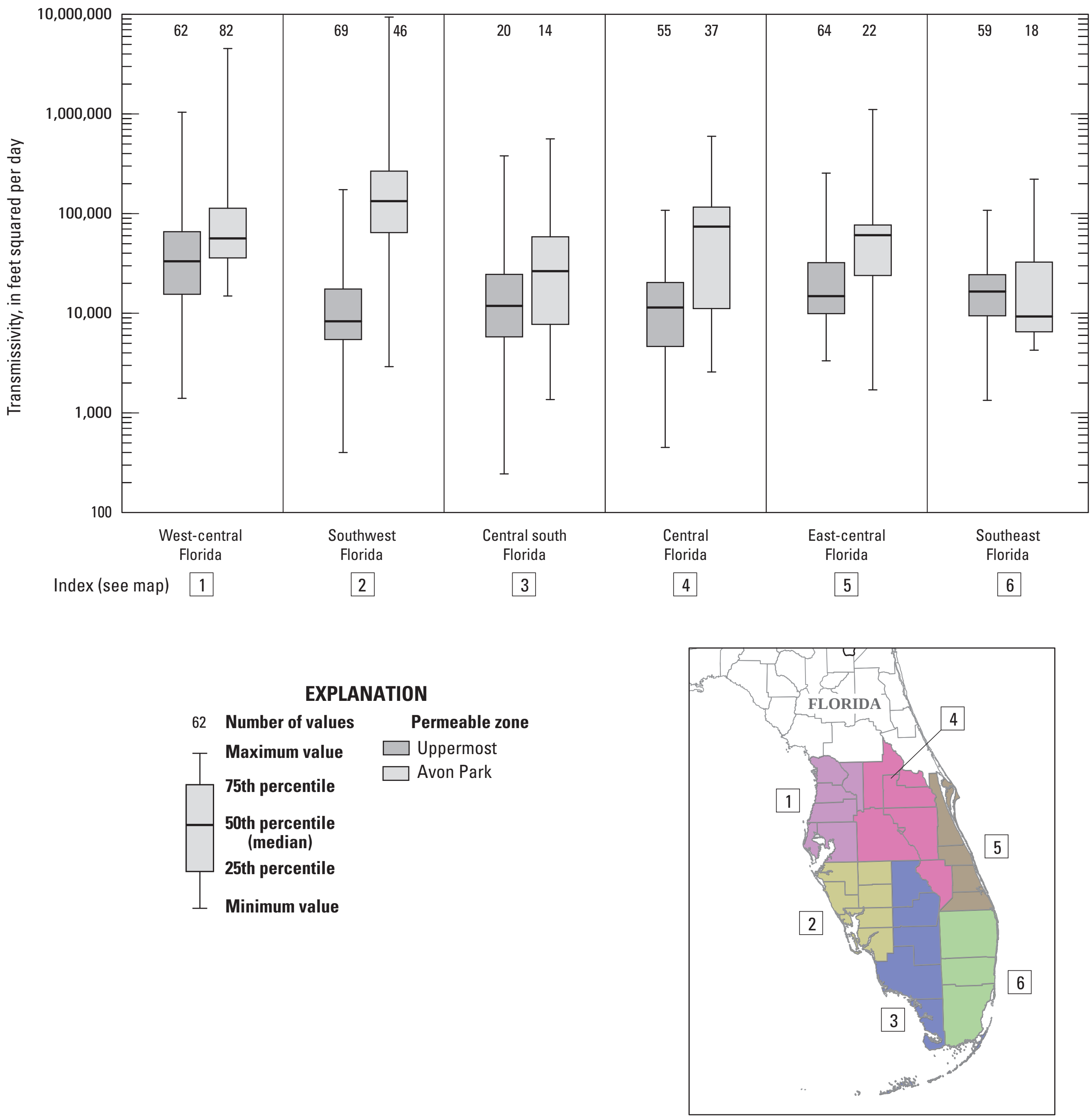


Figure 52. Boxplots showing variation in transmissivity of the uppermost permeable zone and the Avon Park permeable zone from aquifer performance and specific capacity tests (data compiled from South Florida Water Management District DBHYDRO database and reports of the Southwest Florida Water Management District).

Hydraulic Conductivity From Core Samples

The heterogeneous nature of the rocks that form the Floridan aquifer system and its individual higher and lower permeability zones results in an overlap in values of hydraulic properties reported for the zones. Hydraulic conductivity values can range over many orders of magnitude, even within a single borehole or borehole section. One of the primary factors creating this wide variability is the development of secondary porosity (specifically, vugs and solution openings), which results in extremely high permeability. Because large vugs and solution openings generally are not represented in core samples, the hydraulic conductivity values obtained through core analysis are usually much lower than those determined from aquifer and packer tests, which test a larger volume of the unit. The analyses of cores collected from lower permeability zones at deep-well injection sites thus tend to skew the hydraulic conductivity statistics toward the lower end of the range of possible values.

The hydraulic conductivity values summarized in table 14 were derived from core samples obtained from both higher and lower hydraulic conductivity units of the Floridan aquifer system as identified using large-scale tests, like aquifer performance tests. One surprising result of comparing hydraulic conductivity determined from cores representing the Floridan aquifer system is that the range in values for samples collected from highly productive zones is similar to that of samples collected from less-productive zones. The similarity among the various units and zones seems to suggest that matrix permeability of the carbonate rocks forming the aquifer probably is more uniform than otherwise would be suggested by other types of hydraulic testing. In addition, the median horizontal to vertical hydraulic-conductivity ratio of all core samples, which ranges from 1.3 to 3.4, indicates a nearly isotropic rock matrix at the core scale. The uniform matrix permeability and isotropic conditions observed in both transmissive and less-permeable zones indicates that the development of medium- to large-scale secondary porosity is primarily responsible for the observed distribution of permeability variations in the Floridan aquifer system.

Table 14. Horizontal and vertical hydraulic conductivity values from core sample data for various hydrogeologic units of the Floridan aquifer system.

[ft/day; foot per day; H/V median, horizontal to vertical hydraulic conductivity ratio median value for unit; SUWPZ, Suwannee permeable zone; UPZ, uppermost permeable zone; OCAPLPZ, Ocala-Avon Park low permeability zone; APPZ, Avon Park permeable zone; MAPCU, middle Avon Park composite unit; GlaucUnit, glauconite marker unit; OLDSPZ, Oldsmar permeable zone; data compiled from South Florida Water Management District DBHYDRO database and reports of the Southwest Florida Water Management District. Summary statistics includes core analysis data from the following Florida counties: Brevard, Broward,Charlotte, Collier, DeSoto, Glades, Hendry, Hillsborough, Lee, Manatee, Martin, Miami-Dade, Okeechobee, Osceola, Palm Beach, Pinellas, Polk, Sarasota, St. Lucie]

Hydrogeologic unit	Conductivity direction	Hydraulic conductivity (ft/day)				H/V median	Count
		Minimum	Maximum	Average	Median		
SUWPZ/UPZ	Horizontal	1.2×10^{-5}	1.7×10^{2}	1.4	4.8×10^{-1}	1.5	897
	Vertical	4.1×10^{-7}	6.2	7.5×10^{-1}	1.5×10^{-1}		94
OCAPLPZ	Horizontal	3.8×10^{-7}	1.9	2.3×10^{-1}	1.6×10^{-1}	1.3	876
	Vertical	6.6×10^{-8}	2.3	1.1×10^{-1}	2.6×10^{-2}		115
Upper APPZ	Horizontal	8.6×10^{-9}	3.7×10^{1}	8.3×10^{-1}	1.2×10^{-1}	1.3	2,042
	Vertical	1.1×10^{-8}	9.9×10^{1}	1.2	4.9×10^{-2}		329
MAPCU	Horizontal	2.0×10^{-9}	5.4	3.2×10^{-1}	9.5×10^{-3}	1.3	110
	Vertical	5.6×10^{-9}	4.8	3.2×10^{-1}	9.6×10^{-3}		138
Lower APPZ	Horizontal	3.3×10^{-9}	1.5×10^{1}	3.9×10^{-1}	3.1×10^{-2}	1.3	257
	Vertical	4.7×10^{-10}	1.7×10^{1}	3.2×10^{-1}	2.0×10^{-2}		315
GlaucUnit	Horizontal	7.1×10^{-8}	7.7	4.5×10^{-1}	4.3×10^{-2}	1.4	101
	Vertical	6.9×10^{-10}	9.8	4.2×10^{-1}	2.2×10^{-2}		128
OLDSPZ	Horizontal	4.8×10^{-7}	5.7×10^{-1}	6.4×10^{-2}	8.5×10^{-4}	3.4	15
	Vertical	3.7×10^{-7}	6.8	4.1×10^{-1}	4.2×10^{-4}		17

Groundwater Flow

Recharge, flow, and natural discharge in the Floridan aquifer system are largely controlled by the degree of confinement provided by upper confining units, the interaction of streams and rivers with the aquifer in its unconfined areas, and the interaction between fresh and saline water along the coastlines. Bush and Johnston (1988) described the predevelopment and 1980 flow system using a combination of simulations and data from a regional synoptic potentiometric map developed from more than 2,700 measurements made during May 1980. They reported that in 1980, about 3 billion gallons per day were pumped from the aquifer for all uses, and this rate was estimated to be equal to approximately 20 percent of the estimated predevelopment recharge and discharge. At that time, withdrawals from the system resulted in long-term regional declines in hydraulic head of more than 10 ft in three broad areas of the aquifer system, including coastal Georgia and adjacent South Carolina to northeastern Florida, west-central Florida, and the Florida panhandle (Bush and Johnston, 1988).

Regional groundwater movement is controlled by major recharge and discharge patterns developed within the Floridan aquifer system. Recharge occurs along broad areas, such as near potentiometric highs located along central peninsular Florida, whereas discharge occurs in the coastal areas along the Gulf of Mexico and Atlantic Ocean by diffuse leakage through the upper confining unit to low lying areas (Bush and Johnston, 1988). In some areas, a mixture of upward and downward gradients exists, such as in southwestern Georgia and north-central Florida. The complex flow paths result from the highly dissected karst plain where recharge-discharge patterns are governed by the interaction of a coupled groundwater and surface-water system. The major natural discharge areas of the aquifer system are mostly in the vicinity of springs and rivers in the unconfined areas of the system, along the Atlantic and Gulf coastlines, and in a broad area of southern Florida where upward flow gradients exist in the confined part of the system (diffuse discharge as defined by Bush and Johnston, 1988).

The development of secondary porosity and increased permeability in the carbonate rocks is controlled, in part, by the location and rate of recharge and discharge, as indicated by the similarities in transmissivity among different areas that also have karst features (figs. 12 and 51). Patchy areas of recharge and discharge in north-central Florida and across west-central and east-central Florida are the result of complex recharge and discharge through karst-conduit systems.

Distribution of Pumpage

The depths of active pumping wells and the hydrogeologic units that these wells tap provide insight into the more substantial water-producing units of the Floridan aquifer system. The distribution of pumpage is dependent upon several factors, including (1) water quality in the various aquifers or zones, (2) the intended use of the water, and (3) the depth and yield of the freshwater aquifers capable of meeting demand. If the water quality and yield of the shallowest aquifer are satisfactory, then this aquifer typically is the principal aquifer developed in any given area.

Of the 163 counties in the study area, 131 counties, or 80 percent, primarily withdraw groundwater from the Floridan aquifer system (table 15). In these counties, the Floridan is relatively close to land surface and capable of supplying large quantities of freshwater for most uses. In the remaining counties, the principal aquifers include the surficial aquifer system (11 percent), intermediate aquifer system (2 percent), and other deeper aquifers (6 percent).

Within the Floridan aquifer system, the primary aquifers or zones tapped by production wells are the

- Upper Floridan aquifer, specifically, the uppermost permeable zone and APPZ,
- Lower Floridan aquifer below one or more of the middle composite units, and the
- combined Upper and Lower Floridan aquifers.

Although the Lower Floridan aquifer is pumped in a few areas, regionally, over 90 percent of all water pumped from the Floridan aquifer system is obtained from the Upper Floridan aquifer. In central and southern Florida, water is only withdrawn from the uppermost permeable zone or the APPZ of the Upper Floridan aquifer. In the Jacksonville (Duval County) and Orlando (Orange County) areas, a greater percentage of wells tap both the Upper Floridan aquifer and the first permeable zone of the Lower Floridan aquifer (table 15).

Table 15. Percent of permitted wells by aquifer or zone.

[UCU, upper confining unit; IAS, intermediate aquifer system or intermediate confining unit; UF, Upper Floridan aquifer; UPZ, upper permeable zone; APPZ, Avon Park permeable zone; LF, Lower Floridan aquifer; UF-LF, combined Upper and Lower Floridan aquifers; Other, other deeper aquifers. Yellow shading: predominantly surficial; green shading: predominantly IAS/ICU; blue shading: predominantly Floridan aquifer system; orange shading: predominantly other deeper aquifers. Statistics based on permit information provided by State permit programs and from Florida Water Management districts; NA, not applicable]

County	Total wells permitted	Total percentages		Percentage by aquifer or zone, classified wells						
		Unclassified	Classified	Surficial	UCU/IAS	UF/UPZ	UF-APPZ	LF	UF-LF	Other
Alabama										
Baldwin	228	18	82	98	2	0	NA	0	0	0
Clarke	11	55	45	0	80	0	NA	0	0	20
Coffee	69	43	57	0	0	0	NA	3	0	97
Conecuh	10	0	100	0	0	10	NA	60	0	30
Covington	40	20	80	6	0	9	NA	34	6	44
Dale	46	17	83	0	0	0	NA	0	0	100
Escambia	64	11	89	46	21	25	NA	7	2	0
Geneva	38	32	68	4	0	8	NA	58	12	19
Henry	48	46	54	0	0	0	NA	23	4	73
Houston	116	20	80	0	0	26	NA	34	3	37
Mobile	283	7	93	92	8	0	NA	0	0	0
Monroe	37	8	92	26	26	0	NA	3	0	44
Washington	35	11	89	32	26	35	NA	3	3	0
Florida										
Alachua	749	14	86	6	0	94	NA	0	0.2	0
Baker	53	2	98	17	29	54	NA	0	0.0	0
Bay	186	11	89	29	6	65	NA	0	0	0
Bradford	141	8	92	12	22	65	NA	0	0	0
Brevard	1,141	32	68	30	2	66	1	1	0	0
Broward	2,789	4	96	96	0	2	0	1	0.1	0
Calhoun	57	7	93	0	11	79	NA	0	9	0
Charlotte	1,047	8	92	34	49	14	2	1	0	0
Citrus	385	7	93	1	0	79	20	0	0	0
Clay	256	22	78	8	21	69	2	0	1	0
Collier	4,129	4	96	74	25	1	0	0.3	0.0	0
Columbia	396	17	83	1	0	99	NA	0	0	0
De Soto	1,815	6	94	4	19	25	52	0	0	0
Dixie	175	15	85	1	0	99	NA	0	0	0
Duval	445	13	87	13	4	64	3	1	15	0
Escambia	333	2	98	98	1	0	NA	2	0	0
Flagler	406	29	71	33	0	66	NA	0	0	0
Franklin	54	7	93	8	24	68	NA	0	0	0
Gadsden	135	4	96	0	3	92	NA	0	5	0
Gilchrist	343	8	92	0	0	97	3	0	0	0
Glades	446	1	99	65	17	9	9	0	0	0
Gulf	51	4	96	6	37	55	NA	2	0	0
Hamilton	296	19	81	3	1	96	NA	0	1	0
Hardee	2,142	9	91	6	16	18	61	0	0	0
Hendry	2,598	10	90	79	19	1	0	0	0	0
Hernando	572	10	90	0	0	68	32	0	0.2	0

Table 15. Percent of permitted wells by aquifer or zone.—Continued

[UCU, upper confining unit; IAS, intermediate aquifer system or intermediate confining unit; UF, Upper Floridan aquifer; UPZ, upper permeable zone; APPZ, Avon Park permeable zone; LF, Lower Floridan aquifer; UF-LF, combined Upper and Lower Floridan aquifers; Other, other deeper aquifers. Yellow shading: predominantly surficial; green shading: predominantly IAS/ICU; blue shading: predominantly Floridan aquifer system; orange shading: predominantly other deeper aquifers. Statistics based on permit information provided by State permit programs and from Florida Water Management districts; NA, not applicable]

County	Total wells permitted	Total percentages		Percentage by aquifer or zone, classified wells						
		Unclassified	Classified	Surficial	UCU/IAS	UF/UPZ	UF-APPZ	LF	UF-LF	Other
Florida—Continued										
Highlands	1,968	2	98	49	4	5	42	0	0	0
Hillsborough	3,793	8	92	4	4	64	29	0	0	0
Holmes	44	11	89	0	3	79.5	NA	3	15	0
Indian River	1,289	55	45	18	5	69	8	0.2	0	0
Jackson	472	5	95	0	0	97	NA	0	2	0
Jefferson	147	20	80	0	7	93	NA	0	0	0
Lafayette	280	19	81	0	0	100	NA	0	0	0
Lake	1,374	18	82	3	1	76	19	1	1	0
Lee	4,646	6	94	26	66	7.9	0.0	0.3	0	0
Leon	270	31	69	1	3	96	NA	0	0	0
Levy	706	16	84	1	0	98	1	0	0	0
Liberty	45	9	91	10	10	78	NA	0	2	0
Madison	312	15	85	0	0	100	NA	0	0	0
Manatee	1,849	9	91	1	16	43	40	0	0	0
Marion	1,250	28	72	2	0	95	2	0.1	1	0
Martin	1,831	4	96	94	1	2	3	0.3	0	0
Miami-Dade	6,108	6	94	99	0	0	0	0.4	0	0
Monroe	15	13	87	54	8	38	0	0.0	0	0
Nassau	151	14	86	15	8	75	2	1	1	0
Okaloosa	296	4	96	36	2	50	NA	10	2	0
Okeechobee	1,047	5	95	62	13	9	15	0	1	0
Orange	1425	12	88	11	11	64	6	5	3	0
Osceola	885	6	94	13	2	75	9	0	0	0
Palm Beach	5,241	9	91	98	0	0.5	0.8	1	0.1	0
Pasco	1427	8	92	1	0	59	40	0	0	0
Pinellas	538	5	95	2	4	83	11	0	0	0
Polk	5626	8	92	8	1	54	36	0	0.2	0
Putnam	600	26	74	3	0	94	NA	0	2	0
Santa Rosa	175	6	94	82	7	9	NA	2	1	0
Sarasota	1,105	5	95	3	58	34	4	0.1	0	0
Seminole	641	34	66	3	0	87	9	0	0.2	0
St. Johns	169	18	82	52	11	37	NA	0	0	0
St. Lucie	2,452	6	94	60	3	24	13	0	0	0
Sumter	755	26	74	1	0	75	21	0	2	0
Suwannee	719	27	73	0	0	99	NA	0	0	0
Taylor	131	8	92	10	0	90	NA	0	0	0
Union	104	7	93	33	2	65	NA	0	0	0
Volusia	1,697	20	80	6	0	94	NA	0	0	0
Wakulla	71	8	92	2	2	97	NA	0	0	0
Walton	228	6	94	31	4	43	NA	10	11	0
Washington	70	9	91	2	3	86	NA	0	9	0

Table 15. Percent of permitted wells by aquifer or zone.—Continued

[UCU, upper confining unit; IAS, intermediate aquifer system or intermediate confining unit; UF, Upper Floridan aquifer; UPZ, upper permeable zone; APPZ, Avon Park permeable zone; LF, Lower Floridan aquifer; UF-LF, combined Upper and Lower Floridan aquifers; Other, other deeper aquifers. Yellow shading: predominantly surficial; green shading: predominantly IAS/ICU; blue shading: predominantly Floridan aquifer system; orange shading: predominantly other deeper aquifers. Statistics based on permit information provided by State permit programs and from Florida Water Management districts; NA, not applicable]

County	Total wells permitted	Total percentages		Percentage by aquifer or zone, classified wells						
		Unclassified	Classified	Surficial	UCU/IAS	UF/UPZ	UF-APPZ	LF	UF-LF	Other
Georgia										
Appling	165	53	47	4	0	95	NA	0	1	0
Atkinson	266	80	20	0	0	100	NA	0	0	0
Bacon	355	73	27	4	0	96	NA	0	0	0
Baker	464	19	81	0	0	92	NA	2	6	0
Ben Hill	312	72	28	0	0	95	NA	0	5	0
Berrien	767	85	15	1	0	97	NA	0	2	0
Bleckley	261	60	40	12	0	21	NA	0	63	4
Brantley	71	82	18	0	0	100	NA	0	0	0
Brooks	272	34	66	0	0	99	NA	0	1	0
Bryan	14	64	36	0	0	100	NA	0	0	0
Bulloch	499	68	32	0	0	97	NA	0	3	0
Burke	240	48	52	0	0	12	NA	0	74	14
Calhoun	390	57	43	0	0	0	NA	2	59	39
Camden	52	27	73	5	3	74	NA	0	18	0
Candler	229	83	17	0	0	76	NA	0	24	0
Charlton	17	71	29	0	0	100	NA	0	0	0
Chatham	150	33	67	4	0	70	NA	0	26	0
Clinch	48	54	46	0	0	100	NA	0	0	0
Coffee	717	82	18	0	0	93	NA	1	6	0
Colquitt	1,215	79	21	0	0	88	NA	0	12	0
Cook	425	64	36	0	0	100	NA	0	0	0
Crisp	482	59	41	2	0	57	NA	2	40	0
Decatur	692	16	84	0	0	97	NA	0.2	2	0
Dodge	477	67	33	0	0	92	NA	0	8	0
Dooly	494	34	66	2	0	22	NA	0	60	16
Dougherty	258	13	87	0	0	77	NA	4	10	8
Early	649	33	67	0	0	64	NA	18	13	5
Echols	71	51	49	0	0	100	NA	0	0	0
Effingham	59	51	49	3	0	83	NA	0	14	0
Emanuel	139	58	42	0	0	86	NA	0	14	0
Evans	237	75	25	0	0	100	NA	0	0	0
Glynn	117	41	59	6	1	93	NA	0	0	0
Grady	341	63	37	0	0	95	NA	0	5	0
Houston	189	35	65	6	0	2	NA	0	21	70
Irwin	1,080	79	21	0	0	98	NA	1	1	0
Jeff Davis	235	74	26	0	0	93	NA	0	7	0
Jefferson	224	56	44	1	0	6	NA	0	86	7
Jenkins	134	39	61	0	0	56	NA	0	44	0
Johnson	30	50	50	0	0	20	NA	0	73	7
Lanier	79	49	51	0	0	100	NA	0	0	0
Laurens	211	58	42	1	0	50	NA	0	40	9
Lee	487	31	69	0	0	40	NA	15	35	9

Table 15. Percent of permitted wells by aquifer or zone.—Continued

[UCU, upper confining unit; IAS, intermediate aquifer system or intermediate confining unit; UF, Upper Floridan aquifer; UPZ, upper permeable zone; APPZ, Avon Park permeable zone; LF, Lower Floridan aquifer; UF-LF, combined Upper and Lower Floridan aquifers; Other, other deeper aquifers. Yellow shading: predominantly surficial; green shading: predominantly IAS/ICU; blue shading: predominantly Floridan aquifer system; orange shading: predominantly other deeper aquifers. Statistics based on permit information provided by State permit programs and from Florida Water Management districts; NA, not applicable]

County	Total wells permitted	Total percentages		Percentage by aquifer or zone, classified wells						
		Unclassified	Classified	Surficial	UCU/IAS	UF/UPZ	UF-APPZ	LF	UF-LF	Other
Georgia—Continued										
Liberty	26	46	54	0	0	100	NA	0	0	0
Long	40	75	25	20	0	80	NA	0	0	0
Lowndes	233	51	49	0	0	99	NA	0	1	0
Macon	262	37	63	2	0	1	NA	0	8	90
McIntosh	23	57	43	0	0	100	NA	0	0	0
Miller	641	3	97	0	0	99	NA	1	1	0
Mitchell	917	23	77	0	0	97	NA	0.3	2	0
Montgomery	122	77	23	0	0	71	NA	0	29	0
Pierce	343	57	43	1	0	99	NA	0	0	0
Pulaski	394	53	47	1	0	31	NA	0	65	2
Randolph	338	74	26	0	0	0	NA	2	0	98
Richmond	131	50	50	0	0	3	NA	0	8	89
Screven	243	35	65	0	0	74	NA	0	23	3
Seminole	526	6	94	0	0	98	NA	1	1	0
Sumter	467	42	58	4	0	5	NA	0	41	50
Tattnall	693	82	18	0	0	88	NA	0	12	0
Telfair	233	55	45	0	0	96	NA	0	4	0
Terrell	396	52	48	0	0	4	NA	40	5	51
Thomas	258	43	57	0	0	98	NA	0	2	0
Tift	877	70	30	0	0	98	NA	0	2	0
Toombs	400	80	20	0	0	64	NA	0	36	0
Treutlen	77	86	14	0	0	91	NA	0	9	0
Turner	782	74	26	0	0	87	NA	1	13	0
Twiggs	51	55	45	0	0	9	NA	0	48	43
Ware	162	66	34	0	0	100	NA	0	0	0
Washington	109	55	45	6	0	4	NA	0	49	41
Wayne	78	35	65	2	0	98	NA	0	0	0
Wheeler	244	77	23	0	0	91	NA	0	9	0
Wilcox	581	67	33	0	0	88	NA	0	12	0
Wilkinson	39	36	64	0	0	0	NA	0	12	88
Worth	838	59	41	0	0	88	NA	0.3	12	0
South Carolina										
Aiken	79	85	15	0	0	0	NA	58	0	42
Allendale	41	93	7	0	0	0	NA	67	0	33
Barnwell	64	86	14	0	0	0	NA	44	0	56
Beaufort	372	13	87	9	0	80	NA	10	0	1
Berkeley	66	41	59	0	0	0	NA	72	0	28
Charleston	80	35	65	0	0	4	NA	60	0	37
Colleton	56	54	46	0	0	0	NA	69	0	31
Dorchester	53	13	87	0	0	2	NA	78	0	20
Hampton	66	97	3	0	0	50	NA	0	0	50
Jasper	46	13	87	0	0	70	NA	30	0	0

Brackish and Saline Zones in the Floridan Aquifer System

Throughout most of Florida and along the coastal regions of other areas in this report, brackish and saline-water zones are present in the deep part of the Floridan aquifer system. These zones greatly limit the amount of available fresh groundwater and affect the overall thickness of the active freshwater groundwater flow system. For this study, the freshwater-saltwater interface, defined as 10,000 mg/L TDS concentration, was mapped using geophysical logs and supplemented with data from water-quality samples and time-domain electromagnetic soundings to define the position of the interface. Additional salinity calculations from geophysical logs were used to create profiles across the thick sequence of carbonate rocks that form the aquifer system. Several profiles suggest zones of fresher water may be moving beneath more saline water in different parts of the aquifer system.

Prior to this study, a basic assumption about the Floridan aquifer system was that there is a stable freshwater-saltwater interface that exists at depth, rises seaward, and ultimately intersects the top of the aquifer in response to the buoyancy of freshwater "floating" on seawater (Bush and Johnston, 1988). Although this is the case in most of the coastal areas of the Floridan aquifer system, the position of the freshwater-saltwater interface is also governed by the large differences in transmissivity between the Upper and Lower Floridan aquifers and the confining and composite units. In the most extreme cases, large volumes of water have moved laterally through the preferential flow zones of the aquifer into offshore areas beneath the ocean in the confined part of the system on the Atlantic coast near Fernandina Beach, Fla. (Johnston and others, 1982). Freshwater within the Upper Floridan aquifer extends offshore on the Atlantic coast south of Hilton Head Island, S.C., to south of Jacksonville, Fla., and within the Lower Floridan aquifer from south of Savannah, Ga., to Jacksonville, Fla. (Sprinkle, 1989; Barlow, 2003; Payne and others, 2005). Stringfield (1966) noted that deep circulation of water in aquifers depends on (1) altitude of, proximity to, and rate of recharge on unconfined areas; and (2) the opportunity for discharge at submarine outcrops or through springs and diffuse upward leakage into the overlying formations (near coastal wetlands and incised streams).

As a result of preferential flow through the permeable parts of the aquifer system, salinity reversals (or inversions) are not only common but suggest freshwater may be moving beneath more saline water in areas previously excluded from the active flow system. These inversions, (verified by a limited amount of sampling data) could be the result of fresher groundwater moving preferentially through more transmissive zones deep within the aquifer system either as part of the modern flow system or as a result of freshwater movement during lower sea-level stands. Although the extent of salinity inversion in the Floridan aquifer system is not presently known, preferential movement of groundwater through highly transmissive zones into offshore areas may represent undocumented offshore groundwater movement.

Data compiled from selected geophysical-log analysis sites provide several examples of apparent salinity inversions in different areas of the aquifer system (table 16). Salinity variation in the aquifer was characterized using fully or partially digitized logs from approximately 300 wells to determine TDS concentrations by means of spot calculations in select zones or along profiles. Enough data points were included in the analysis to determine the altitude of the salinity boundaries and, thus, assess brackish and saline waters in the Floridan aquifer system and qualitatively assess stratified salinity inversions, in different parts of the aquifer system, and determine where salinity inversions were present.

On the basis of geophysical log analysis and available deep groundwater samples, four areas of suspected or known salinity inversion were identified in the study area.

1. West-central Florida—A relatively thick interval of apparent fresh-to-brackish water appears to be present in permeable zones of the Lower Floridan aquifer beneath the MCUII region of the MAPCU.

2. East-central Florida—Isolated zones or pockets of apparent fresh-to-brackish water appear to be present in the Oldsmar permeable zone beneath the glauconite marker unit.

3. Southern Florida—Slightly less saline water is present in the APPZ creating an apparent salinity inversion with respect to overlying brackish water in the uppermost permeable zone of the Upper Floridan aquifer.

4. Northwestern peninsular Florida—Fresh- and brackish-water zones appear to be present in the Oldsmar permeable zone of the Lower Floridan aquifer, suggesting potential offshore freshwater movement beneath saline zones in the Upper Floridan aquifer.

A map showing the altitude of the base of the fresh-to-brackish-water zone (top of the salinity transition zone with TDS concentration greater than 10,000 mg/L) was constructed to show the general configuration of the freshwater-saltwater interface and areas of potential salinity inversions (fig. 53). The map indicates that, within the northern inland areas of peninsular Florida and part of extreme southern Georgia, freshwater is present throughout the entire thickness of the aquifer down to the physical base of the system. In this area, data used to construct the map shown in figure 53 represent the base of the aquifer system. This area extends throughout most of the central peninsular region where evaporite-bearing rocks of the Cedar Keys Formation form the base of the aquifer system and is thought to represent the base of the freshwater flow system (see cross section *O–O′* in fig. 40). For example, in a deep test well located in the western part of Orange County, Fla., near Orlando, freshwater was present throughout the entire permeable part of the aquifer system and became saline only a short distance into the evaporitic deposits (Geraghty and Miller Inc., 1977).

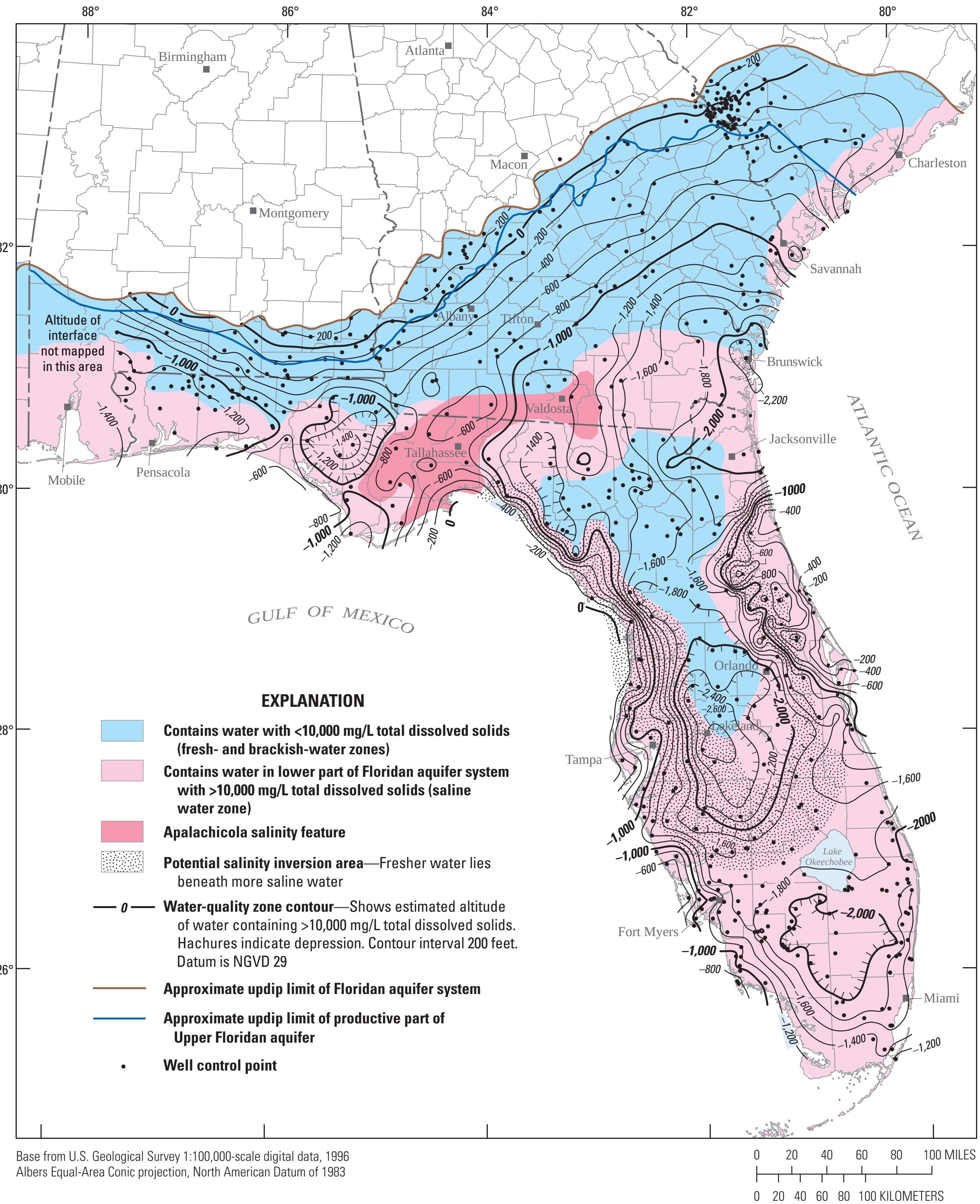


Figure 53. Estimated altitude of the 10,000-milligrams-per-liter (mg/L) total dissolved solids boundary, southeastern United States.

Table 16. Vertical salinity variations in various formations and hydrogeologic units of the Floridan aquifer system.

[ft, foot; mg/L, milligrams per liter; AP, Avon Park Formation; APPZ, Avon Park permeable zone; MAPCU, middle Avon Park composite unit; ILD, induction log deep; DT, interval transit time; ILD/DT, TDS computed using resistivity porosity method; LAPPZ, lower Avon Park permeable zone; Olds, Oldsmar Formation; GlaucUnit, glauconite marker unit; OLDSPZ, Oldsmar permeable zone; CK, Cedar Keys Formation; Lower CU, Lower confining unit of the Floridan aquifer system; Suw, Suwannee Limestone; Ocala, Ocala Limestone; UF, upper Floridan aquifer; ?, uncertainty in TDS estimate; wells, water sample from well; PT, packer test (water sample); LN, long normal, shading indicates apparent fresher water below more saline water]

Formation/aquifer/zone	Depth below land surface (ft)	Estimated total dissolved solids concentration (mg/L)	Method
P350—DR. R.C. GARBY #1—Citrus County, Fla.			
AP/APPZ-MAPCU	300–950	10,000–35,000	ILD/DT
AP/LAPPZ	950–1,300	1,000–3,000	ILD/DT
Olds/GlaucUnit	1,300–1,750	10,000–35,000	ILD/DT
Olds/OLDSPZ	1,750–2,100	1,000–5,000	ILD/DT
Olds-CK/LowerCU	>2,100	>35,000	ILD/DT
P236—SCHROEDER #1—Manatee County, Fla.			
AP/APPZ	1,240–1,700	<1,000	ILD/DT
AP/MAPCU	1,700–1,900	1,000–3,000	ILD/DT
AP/LAPPZ	1,900–2,300	10,000–20,000	ILD/DT
Olds/OLDSPZ	2,700–2,900	4,000–5,000	ILD/DT
P759 —St. Petersburg Bank and Trust #35-4—Manatee County, Fla.			
Suw-Ocala/UF	600–1,600	<1,000	ILD/DT
AP/MAPCU	1,600–2,000	20,000–40,000	ILD/DT
AP/LAPPZ	2,000–2,300	10,000–15,000	ILD/DT
Olds/GlaucUnit	2,300–2,600	20,000–30,000	ILD/DT
Olds/OLDSPZ	2,600–2,900	5,000–7,000?	ILD/DT
P743 —Larken Co. #8-4—Pasco County, Fla.			
Suw/UF	300–1,100	<1,000	ILD/DT
Ocala/UF	1,100–1,325	3,000–10,000	ILD/DT
AP/APPZ	1,325–2,100	<1,000	ILD/DT
AP/MAPCU	2,100–2,320	1,000–10,000	ILD/DT
AP/LAPPZ	2,320–2,435	<1,000	ILD/DT
Olds/GlaucUnit	2,435–2,678	3,000–35,000?	ILD/DT
Olds/OLDSPZ	2,900–3,000	1,000–20,000?	ILD/DT
P597—Kaiser Deep Disposal Well—Polk County, Fla.			
Suw-Ocala-AP/UF	300–1,180	<1,000	ILD/DT
AP/MAPCU	1,180–1,620	3,000–6,000	ILD/DT
AP/LAPPZ	1,620–2,100	5,000–10,000	ILD/DT
Olds/GlaucUnit	2,100–2,400	3,000–5,000	ILD/DT
Olds/OLDSPZ	2,600–2,800	5,000–8,000	ILD/DT

Table 16. Vertical salinity variations in various formations and hydrogeologic units of the Floridan aquifer system.—Continued

[ft, foot; mg/L, milligrams per liter; AP, Avon Park Formation; APPZ, Avon Park permeable zone; MAPCU, middle Avon Park composite unit; ILD, induction log deep; DT, interval transit time; ILD/DT, TDS computed using resistivity porosity method; LAPPZ, lower Avon Park permeable zone; Olds, Oldsmar Formation; GlaucUnit, glauconite marker unit; OLDSPZ, Oldsmar permeable zone; CK, Cedar Keys Formation; Lower CU, Lower confining unit of the Floridan aquifer system; Suw, Suwannee Limestone; Ocala, Ocala Limestone; UF, upper Floridan aquifer; ?, uncertainty in TDS estimate; wells, water sample from well; PT, packer test (water sample); LN, long normal, shading indicates apparent fresher water below more saline water]

Formation/aquifer/zone	Depth below land surface (ft)	Estimated total dissolved solids concentration (mg/L)	Method
PB-1196/1197—CITY OF JUPITER RO—Palm Beach County, Fla.			
Ocala/UF	1,060–1,470	3,360–4,590 (chloride)	Wells
AP/APPZ	1,470–1,650	2,000–2,500 (chloride)	Wells
ROMP45.5—SWFWMD PROGRESS ENERGY—Polk County, Fla.			
Suw-Ocala/UF	290–900	<500	PT/LN
AP/APPZ	900–1,450	2,000–3,000	PT/LN
AP/MAPCU	1,450–1,800	20,000–30,000	PT/LN
AP/LAPPZ	1,800–2,450	10,000–25,000	PT/LN
Olds/OLDSPZ	2,450–2,700	3,000–10,000	PT/LN
GA-GLY9—USGS TEST WELL TW-26—Glynn County, Ga.			
Ocala/UF	700–960	380–520	PT
AP/UF	960–1,455	520–1,430	PT
AP/LF	1,455–1,690	380–520	PT
AP-Olds/LF	1,690–2,150	630–1,250	PT
Olds-CK/LF	>2,150	>9,400	PT

The freshwater-saltwater interface rises sharply south of Polk County, Fla., and then plateaus at an altitude of about –1,700 to –2,000 ft in south-central Florida, including all of Glades and Hendry Counties and most of Okeechobee, Martin, Palm Beach, and Broward Counties. The configuration of the interface and the presence of a relatively thick brackish-water zone in the Upper Floridan aquifer could be controlled by the preferential movement of fresher water along the APPZ. Outward from the central peninsular areas, the interface rises sharply along the eastern and western coasts and is apparently influenced by the buoyancy of the freshwater moving on top of the saltwater wedge (for example, see cross sections *O–O′* through *Q–Q′* on pls. 21–23).

In the updip part of the Floridan aquifer system, freshwater is present throughout the entire vertical extent of the system, with a notable exception of extreme southwestern Georgia and the east-central Florida panhandle where a saline zone is present in the lower part of the aquifer system. In that area, brackish and saline waters are present in the Floridan aquifer system and the area is informally named the “Apalachicola salinity feature” herein (fig. 53). Based on salinity mapping conducted as part of this study, this feature appears to extend from the southern part of several Georgia counties along the Georgia-Florida state line (Seminole, Decatur, Grady, Thomas, Brooks, and Lowndes Counties), into the Florida panhandle, including all of Leon and Wakulla Counties and parts of Gadsen, Jefferson, Liberty, Franklin, and Gulf Counties (see cross section *H–H′* on pl. 14). The exact source of this feature is unknown; however, it seems to be associated with fine-grained sediments of the Southwest Georgia embayment (Kellam and Gorday, 1990; Schmidt, 1984) that may have resulted in trapped or incompletely flushed connate water.

Another area of increased salinity in the Floridan aquifer system is a newly mapped, disconnected zone of brackish to saline water that lies near the base of the aquifer system near Valdosta, Ga., and shown as part of the Apalachicola salinity feature (fig. 53 and pl. 14). Because of its shape and position, the area of increased salinity is probably connate water trapped in carbonate rocks near the base of the aquifer system and isolated from greater permeability rocks above. This area also is coincident with the location of lower permeability rocks associated with evaporitic rocks of the MAPCU in the vicinity of Valdosta, Ga., and may explain its presence there. High-salinity zones also are present in other parts of the aquifer system and mostly associated with previously mapped low-permeability units, confining beds, and high-permeability zones in the coastal areas of the aquifer system. These zones include saline connate water apparently trapped in the evaporite unit of the MAPCU in southwestern Florida and in saline parts of the APPZ in coastal areas.

Using the approximate altitude of the 10,000-mg/L TDS concentration boundary, the thickness of the freshwater part of the aquifer system can be approximated (fig. 54). The term “freshwater” is loosely used to describe the thickness of the groundwater in the aquifer system containing 10,000 mg/L TDS or less. The freshwater thickness map was constructed by subtracting the altitude of the top of the aquifer system (fig. 22, pl. 4) from the altitude of the 10,000-mg/L horizon (fig. 53).

Several assumptions were made in determining the freshwater thickness of the aquifer system:

1. The freshwater-saltwater interface is sharp and is represented by the altitude of the 10,000-mg/L TDS concentration boundary, as shown in figure 53.
2. The thickness of the freshwater part of the aquifer can be approximated by subtracting the portion of the aquifer below the altitude of the 10,000-mg/L TDS concentration boundary;
3. The entire thickness of the aquifer above the 10,000-mg/L TDS concentration boundary contains freshwater.
4. The freshwater-saltwater interface is smooth and does not contain inverted sections (freshwater below saltwater), which are known to exist in some areas as previously described.

Because these assumptions are not met everywhere, the freshwater thickness map should only be considered an approximation of actual conditions; however, this map helps to generally show the effective thickness of active fresh groundwater flow within the Floridan aquifer system.

In central and southern Florida, the configuration of the freshwater part of the Floridan aquifer system resembles that of a freshwater lens formed on an island. The thickest areas of freshwater are located along the central axis of the peninsula, coincident with potentiometric highs, and the thinnest areas are located along the coastal regions where the potentiometric surface is lowest. The shape of the freshwater lens suggests that the density difference between fresh and saline water is a principal controlling factor; however, lower permeability rocks in the center of the peninsula also control the vertical thickness. Most of the 1,000- to 1,200-ft-thick zone of freshwater in south-central Florida is actually brackish water ranging from 3,000 to 6,000 mg/L TDS concentration (Reese, 1994, 2000, 2002, 2004; Reese and Memberg, 2000). As previously described, this brackish water probably is the result of fresher water moving along large transmissivity contrasts within the main body of the aquifer beneath more saline water, causing salinity inversions in some areas.

Geologic controls, rather than density differences, become particularly important farther north along the peninsula, where the base of the freshwater in the Floridan aquifer system is coincident with low-permeability rocks of the lower confining unit. In that region, the shape and thickness of the freshwater part of the Floridan aquifer system is controlled by permeability contrasts among geologic units rather than by density differences alone. In northeastern Florida and southeastern Georgia, for example, the freshwater part of the aquifer system coincides with a highly permeable zone near the aquifer system base that dips and thickens toward the Atlantic Ocean, ultimately resulting in movement of freshwater a great distance offshore (Johnston and others, 1982). In that region,

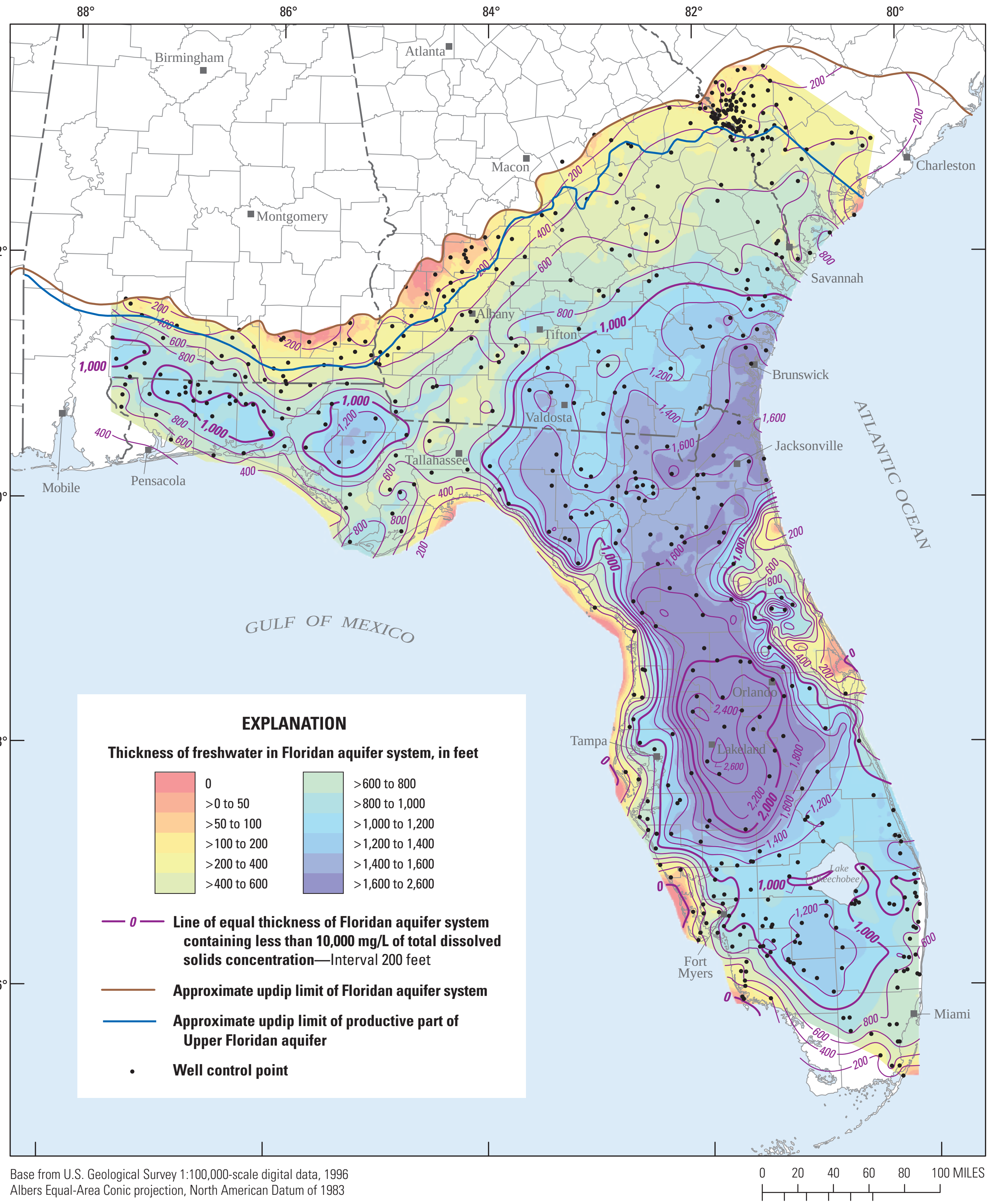


Figure 54. Estimated thickness of the fresh- and brackish-water zones of the Floridan aquifer system, southeastern United States.

the pattern is one of general thickening of the freshwater zone closer to the coastline, which is in contrast to the pattern previously described for southern Florida. However, the altitude of the recharge area along the Fall Line is over 400 ft and in close proximity to the coastline in southeast Georgia resulting in high artesian pressure prior to development. The higher pressure in this area would result in the freshwater-saltwater interface further offshore than in peninsular Florida.

In the western part of the Apalachicola salinity feature, the active freshwater flow system is about 600 to 800 ft thick, or less than half of the total thickness of the Floridan aquifer system, as indicated by comparing figures 25 and 53. This salinity feature is coincident with a groundwater divide in the potentiometric surface of the Upper Floridan aquifer that extends through Gadsden and Liberty Counties, Fla., originally delineated as the divide between the Dougherty Plain-Apalachicola basin and the Thomasville-Tallahassee groundwater basins by Bush and Johnston (1988). Although freshwater would be expected at greater depths in the vicinity of high water levels near a groundwater divide, the apparent opposite is true for this area, indicating that salinity in this area likely is affected by geologic controls.

Summary

The hydrogeologic framework for the Floridan aquifer system has been updated for Florida and parts of Georgia, Alabama, and South Carolina by incorporating new borehole geophysical and flowmeter log data into a regional and subregional framework that describes the major and minor units and zones of the system. The revised boundaries of the Floridan have been mapped by taking into account results from local studies along with regional correlations.

The updated framework generally conforms to the original framework established by the U.S. Geological Survey in the 1980s, with the greatest revisions made to the internal boundaries of the Upper and Lower Floridan aquifers and to the individual higher and lower permeability zones within these two regional aquifers. The additional higher and lower permeability zones can be used to progressively subdivide the system for assessing groundwater and surface-water interaction, saltwater intrusion, and offshore movement of groundwater. The extent and altitude of the freshwater-saltwater interface in the aquifer system was mapped to define the freshwater part of the flow system.

Geophysical log patterns were used to map the major and minor units and zones of the aquifer system and to aid in further delineating these units and zones in the future. The log patterns vary somewhat regionally and must be used with other criteria for mapping the units and zones, such as lithology, hydraulic testing, and water-quality and water-level data. The hydraulic properties of the various units and zones, determined from packer tests or from laboratory analysis of core samples, were highly variable and reflect local changes in lithology and development of secondary porosity and permeability. Overall, the local heterogeneity of these units makes it difficult to make regional generalizations.

The Floridan aquifer system behaves as one aquifer over much of its extent. The system is still subdivided vertically into two aquifer units, namely the Upper and Lower Floridan aquifers. In the previous framework, discontinuous numbered middle confining units (MCUI–VII) were used to subdivide the system. Some of these individually numbered middle confining units overlapped each other vertically. Previously, where units overlapped, the least permeable rock unit within the middle part of the system was used to subdivide it. In areas where lower permeability rocks are not present within the middle part of the system, the system was previously considered one aquifer and named the Upper Floridan aquifer. In the intervening years, additional detailed data have been collected locally, resulting in the assignment of some of the same lithostratigraphic units in the Floridan aquifer system to the Upper or Lower Floridan aquifer in different parts of Florida. Additionally, some of the numbered middle confining units were found to be semiconfining, very leaky, or to have hydraulic properties within the same order of magnitude as the aquifers above, below, or both above and below. Although the term “confining unit” is not totally abandoned within this revised framework, a new term “composite unit” is introduced for lithostratigraphic units that cannot be defined as either a confining unit or an aquifer unit over their entire extent. This approach is a departure from the previous framework of the late 1980s, in that stratigraphy is used to consistently subdivide the aquifer system into upper and lower aquifers across the State of Florida. This lithostratigraphic mapping approach does not change the concept of flow within the system. Areas of differing hydraulic properties of composite units are delineated to indicate where the Upper and Lower Floridan aquifers behave as one aquifer system. The revised framework uses stratigraphic names for the composite units within the middle part of the Floridan aquifer system rather than numbers. Additionally, distinctly different permeability zones (extremely cavernous or vuggy higher permeability zones or lower permeability zones) are mapped within the Upper and Lower Floridan aquifers and stratigraphic names are used for those zones.

The uppermost hydrogeologic unit in the study area is the surficial aquifer system. It contains the Biscayne aquifer in southeastern Florida and the sand and gravel aquifer in the westernmost area of the Florida panhandle; both aquifers are a primary source of groundwater in their respective areas. Elsewhere, the surficial aquifer system forms an irregular blanket of marginal marine, terrace, and alluvial sediments that stores water that recharges the underlying Floridan aquifer system.

The Floridan aquifer system comprises a thick sequence of mostly Tertiary carbonate rocks that are hydraulically connected to varying degrees. The presence or absence of an upper confining unit determines whether the aquifer is confined or unconfined and is a principal control on recharge and discharge developed in the aquifer system. In thickly confined areas, an upper confining unit greatly restricts water movement between the surficial and Floridan aquifer systems. In thinly confined or unconfined areas, large quantities of water recharge the Floridan through karst features, by downward leakage from the surficial aquifer system, or in west-central Florida, by interaction with the intermediate aquifer system.

The previously mapped top of the Floridan aquifer system was updated using data compiled from previous studies and databases of multiple agencies listed in the Acknowledgments. The top of the aquifer is mapped as the uppermost surface of a vertically continuous sequence of carbonate rocks that is characteristic of the aquifer system. The irregular surface of the top of the system was formed, in part, by karstification in unconfined or thinly confined areas.

The base of the aquifer system was extended farther downward from previous mapping in the northern part of the study area to incorporate hydraulically connected coastal plain aquifers that are equivalent to the Lower Floridan aquifer. In peninsular Florida, the base was not revised substantially because it is mapped on the basis of a distinctive massive bedded anhydrite unit that is easily recognized in geophysical logs. However, a relatively lower permeability unit located above the massive anhydrite sequence may locally form the base of the active groundwater flow system. Within the Upper Floridan aquifer of central and southern Florida, the subregionally extensive Avon Park permeable zone is incorporated into the revised regional framework. This permeable zone is mapped in this study as an aggregate of several permeable zones in the upper part of the Avon Park Formation that lie above one or more subregional evaporitic or non-evaporitic intervals of the underlying composite unit. The aggregate Avon Park permeable zone is overlain everywhere by the Ocala-Avon Park lower permeability zone, which behaves as a semiconfining unit within the Upper Floridan aquifer. This lower permeability zone, in turn, is overlain by the uppermost permeable zone of the Floridan aquifer system, which includes the Suwannee permeable zone, Hawthorn producing zone, or the undifferentiated Upper Floridan aquifer.

The previously mapped numbered middle confining units of the aquifer system were substantially revised on the basis of new test drilling information. These seven discontinuous units originally used to divide the system into the Upper and Lower Floridan aquifers were reassigned to one or more composite units in the middle part of the aquifer system or included in the Upper or Lower Floridan aquifer. The revised nomenclature uses stratigraphically associated terms wherever possible to group permeable and less-permeable zones within a stratigraphic context to make it easier to connect these units across large regions.

The numbered middle confining units are redefined into two composite units and one confining unit: the Lisbon-Avon Park composite unit (LISAPCU) in the northern half of the study area, the middle Avon Park composite unit (MAPCU) in peninsular Florida, and the Bucatunna clay confining unit in the western panhandle of Florida. Each composite unit is further subdivided into regions on the basis of spatial variation in the lithology and relative degree of confinement provided to the overlying and underlying units. In the extreme updip part of the aquifer system, the LISAPCU is composed of lower permeability clays and finer grained sediments that separate the overlying mostly carbonate Upper Floridan aquifer from the underlying Lisbon, Claiborne, and Gordon aquifers, each of which are updip clastic equivalents of the carbonate Lower Floridan aquifer. In the coastal region of Georgia and South Carolina, the LISAPCU is characterized by a semiconfining to very leaky unit where minimal hydraulic head differences exist between the aquifers.

In peninsular Florida, the MAPCU is the principal composite unit separating the Upper and Lower Floridan aquifers and consists of evaporitic and non-evaporitic rocks in the middle part of the Avon Park Formation. The evaporitic facies of this unit forms a non-leaky confining unit that effectively separates the Upper and Lower Floridan aquifers in the central and southwestern parts of the Florida peninsula. To the south, this unit grades by way of a facies change into a mixed evaporitic and non-evaporitic carbonate unit that generally acts as a semiconfining unit. The non-evaporitic facies of this unit extends along the Atlantic Coast from southeastern Florida to northeastern Florida, where the unit is semiconfining. Much smaller hydraulic head differences are observed across the semiconfining unit than across the evaporitic confining unit.

Below the MAPCU, permeable zones in the lower Avon Park Formation form the lower Avon Park permeable zone (LAPPZ). The LAPPZ is mapped as a relatively thick zone of higher permeability with some lower permeability rocks that lie between the MAPCU and the glauconite marker unit. Freshwater parts of the LAPPZ are used for water supply in east-central Florida, where the zone is part of the Lower Floridan aquifer.

A new basal permeable zone is mapped throughout the Florida peninsula, and slightly into southeastern Georgia, that incorporates the previously established Boulder Zone and Fernandina permeable zone; this more extensive unit is called the Oldsmar permeable zone. The Oldsmar permeable zone appears to have higher permeability, far greater than the cavernous areas of the Boulder and Fernandina permeable zones, and contains freshwater in the central peninsula area. This newly delineated areally extensive basal unit containing freshwater may influence the movement of freshwater water through the deepest part of the aquifer system toward the discharge areas. The Oldsmar permeable zone, which is part of the Lower Floridan aquifer, is of interest because it may be an important alternative source of water where it is confined (and isolated) beneath the Upper Floridan aquifer and may be important to the offshore movement of groundwater in areas previously unknown.

The Oldsmar permeable zone is overlain by the glauconite marker unit, which derives its name from a gamma-ray marker first used in southeastern Florida to map a glauconitic, fine-grained lower permeability unit above the Boulder Zone. The gamma-ray marker has been found to be subregionally extensive and, when coupled with a low-resistivity response that is characteristic of the interval, it forms a distinct mappable horizon in the lower part of the aquifer system. The glauconite marker unit is thought to be a semiconfining unit similar to other lower permeability units in the Floridan aquifer system.

The regional extent and altitude of the freshwater-saltwater interface was mapped using geophysical logs, water-sampling data from deep wells, and time-domain electromagnetic soundings. The interface is represented by the approximate 10,000-milligrams-per-liter total-dissolved-solids concentration boundary that separates mostly fresh and brackish water from the mostly saline water beneath it. Because the new map is based on well-log data and not a calculated interface using a theoretical density contrast, geologically controlled salinity variations are portrayed within the interior of the aquifer. Additional salinity calculations from geophysical logs were used to create profiles across the thick sequence of carbonate rocks of the aquifer system. Several profiles suggest zones of fresher water may be moving beneath more saline water along the deeper transmissive part of the Floridan aquifer system in west-central Florida and along the upper west coast of the Florida peninsula, thus indicating potential offshore movement of freshwater in these areas. Two subregional salinity features were identified as a result of the salinity mapping conducted as part of this study. The first is informally named the "Apalachicola salinity feature," which is present within a thick accumulation of fine-grained carbonate rocks in the Southeast Georgia embayment. In this area, saltwater is contained in the lower part of the Floridan aquifer system and the thickness of the effective freshwater flow system is greatly reduced. The second feature is a previously unmapped, disconnected zone of brackish to saline water that lies near the base of the aquifer system along the Georgia-Florida state line. Because of its shape and position, this feature probably is connate water trapped in fine-grained carbonate rocks near the base of the Floridan aquifer system and isolated from higher permeability rocks above. High-salinity zones are indicated in other parts of the aquifer system and mostly are associated with previously mapped low-permeability units and confining beds and high-permeability zones in the coastal areas of the aquifer system.

Large-scale variations in regional hydraulic properties of individual rock units that compose the Floridan aquifer system are the result of several different factors, including (1) rock type and texture; (2) the degree of relative confinement or outcrop and proximity to recharge that can enhance the development of large-scale secondary porosity and increase in permeability, through karstification in some places; (3) the presence of structures such as joints, fractures, and weaknesses along bedding planes, along which secondary dissolution can occur, thereby increasing permeability; and (4) post-depositional diagenesis, which can greatly increase or decrease porosity through dolomitization or dissolution processes. Collectively, these factors indicate that the local variation in permeability of individual zones is more complex than can be described in the regional context of this framework.

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