Effects of Aquifer Heterogeneity on Ground-Water Flow and Chloride Concentrations in the Upper Floridan Aquifer near and within an Active Pumping Well Field, West-Central Florida

By A.B. Tihansky

Prepared in cooperation with

Pinellas County and Tampa Bay Water

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Conversion Factors and Datums

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.06309	liter per second
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day
Specific capacity		
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter
Transmissivity*		
foot squared per day (ft^2/d)	0.09290	meter squared per day

*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.

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = (1.8 x °C) + 32

Vertical coordinate information is referenced to the *"National Geodetic Vertical Datum of 1929 (NGVD of 1929)."*

Horizontal coordinate information is referenced to the *"North American Datum of 1927 (NAD 27)."*

Acronyms and Additional Abbreviations

$\delta^{18}O$	delta oxygen-18
δD	delta deuterium
EM	Electromagnetic
EW	Eldridge-Wilde
FDEP	Florida Department of Environmental Protection
ICU	Intermediate confining unit
meq	milliequivalent
MCU	Middle confining unit
mg/L	milligrams per liter
NWHWRAP	Northwest Hillsborough Water Resources Assessment Project (SWFWMD)
RAAX	trade name for optical borehole logging tool
ROMP	Regional Observation Monitoring Program (SWFWMD)
ROMP-TR	Transect wells of (SWFWMD) ROMP program
$^{87}Sr/^{86}Sr$	Strontium-87/strontium-86
SAS	Surficial aquifer system
SWFWMD	Southwest Florida Water Management District
TDS	Total dissolved solids
T	transmissivity
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey
μS/cm	microsiemens per centimeter
yr	year

Effects of Aquifer Heterogeneity on Ground-Water Flow and Chloride Concentrations in the Upper Floridan Aquifer near and within an Active Pumping Well Field, West-Central Florida

By A.B. Tihansky

Abstract

Chloride concentrations have been increasing over time in water from wells within and near the Eldridge-Wilde well field, near the coast in west-central Florida. Variable increases in chloride concentrations from well to well over time are the combined result of aquifer heterogeneity and ground-water pumping within the Upper Floridan aquifer. Deep mineralized water and saline water associated with the saltwater interface appear to move preferentially along flow zones of high transmissivity in response to ground-water withdrawals. The calcium-bicarbonate-type freshwater of the Upper Floridan aquifer within the study area is variably enriched with ions by mixing with introduced deep and saline ground water. The amount and variability of increases in chloride and sulfate concentrations at each well are related to well location, depth interval, and permeable intervals intercepted by the borehole.

Zones of high transmissivity characterize the multilayered carbonate rocks of the Upper Floridan aquifer. Well-developed secondary porosity within the Tampa/Suwannee Limestones and the Avon Park Formation has created producing zones within the Upper Floridan aquifer. The highly transmissive sections of the Avon Park Formation generally are several orders of magnitude more permeable than the Tampa/Suwannee Limestones, but both are associated with increased ground-water flow. The Ocala Limestone is less permeable and is dominated by primary, intergranular porosity. Acoustic televiewer logging, caliper logs, and borehole flow logs (both electromagnetic and heat pulse) indicate that the Tampa/Suwannee Limestone units are dominated by porosity owing to dissolution between 200 and 300 feet below land surface, whereas the porosity of the Avon Park Formation is dominated by fractures that occur primarily from 600 to 750 feet below land surface and range in angle from horizontal to near vertical. Although the Ocala Limestone can act as a semiconfining unit between the Avon Park Formation and the Tampa/Suwannee Limestones, seismic-reflection data and photolinear analyses indicate that fractures and discontinuities in the Ocala Limestone are present within the southwestern part of the well field. It is possible that some fracture zones extend upward from the Avon Park Formation through the Ocala, Suwannee, and Tampa Limestones to land surface. These fractures may provide a more direct hydrologic connection between transmissive zones that are vertically separated by less permeable stratigraphic units.

Ground water moves along permeable zones within the Upper Floridan aquifer in response to changes in head gradients as a result of pumping. Borehole geophysical measurements, including flow logs, specific conductance logs, and continuous monitoring of specific conductance at selected fixed depths, indicate that borehole specific conductance varies substantially with time and in response to pumping stresses. Ground-water mixing between hydrogeologic units likely occurs along highly transmissive zones and within boreholes of active production wells. Ground-water movement and water-quality changes were greatest along the most transmissive zones.

Variable mixing of three water-type end members (freshwater, deepwater, and saltwater) occurs throughout the study area. Both deepwater and saltwater are likely sources for elevated chloride and sulfate concentrations in ground water. Mass-balance calculations of mixtures of the three end members indicate that deepwater is found throughout the aquifer units. Samples from wells within the southwestern part of the well field indicate that deepwater migrates into the shallow permeable units in the southwestern part of the well field. Deepwater contributes to elevated sulfate and chloride concentrations, which increase with depth and are elevated in wells less than 400 feet deep.

The greatest increases in chloride concentrations over time are found in water from wells closest to the saltwater interface. Ground water with a saltwater influence occurs primarily within the Avon Park producing zone nearest the saltwater interface, deeper in the aquifer system. Because chloride concentrations in saltwater are greater than those associated with deepwater, even small percentages of saltwater have a substantial effect on chloride concentrations. The highest percentages of saltwater are found in ground water from 600 to 750 feet deep within the transmissive zone of the Avon Park Formation. Specific conductance logs and long-term chloride concentration data indicate that saltwater may move preferentially inland along this transmissive zone. Chloride concentrations range from 5,000 to more than 15,000 milligrams per liter between 640-780 feet below land surface in wells less than 1 mile southwest of the well field. Elevated chloride concentrations in the well field are highest in wells where the potentiometric surface has been lowered.

Lowered ground-water levels associated with the Eldridge-Wilde well field affect the regional potentiometric surface of the Upper Floridan aquifer and may provide the potential to induce saltwater movement along transmissive zones of enhanced secondary porosity. From 1997 to 2000, water with elevated chloride concentrations migrated into the Eldridge-Wilde well field within the highly transmissive zone of the Avon Park Formation between 600-750 feet below land surface. In 2000, chloride concentrations reached 250 milligrams per liter in monitor wells tapping this production zone beneath the center of the well field. Isotopic analyses of deuterium, oxygen-18, and strontium-87/strontium-86 indicate that saltwater mixing is a primary source of the observed chloride.

Introduction

Chloride concentrations affect the quality and quantity of potable ground water in Pinellas County and other parts of coastal Florida. The Pinellas County peninsula (fig. 1) is surrounded by saltwater, and fresh ground-water resources are limited. Historically, Pinellas County has had difficulty supplying potable water from local ground-water sources. The first well fields were located near downtown St. Petersburg, in southeastern Pinellas County, but over time the ground-water supply became brackish. As demands for freshwater increased, supply wells were drilled in the northeastern part of the County where coastal influences and ground-water chloride concentrations were lowest.

The Eldridge-Wilde (EW) well field is less than 10 miles from the coast in northeastern Pinellas County and northwestern Hillsborough County (figs. 1, 2). The well field occupies about 2,000 acres and is one of the largest well fields in west-central Florida in terms of areal extent and volume of water withdrawn.

The EW well field was constructed in 1954, and well-field operations began in 1956. Pre-development ground-water levels and flow patterns were affected once the well field began operating (Black, Crow, and Eidsness, Inc., 1970). Within the first several years of operation, potentiometric-surface maps of the area indicated decreased heads in both the Upper Floridan and the surficial aquifers. Between 1981 and 1986, the demand for increased production led to the deepening of 23 wells into the highly productive Avon Park Formation.

In 1975, chloride concentrations in ground water from the southwestern part of the well field were less than 20 mg/L. By 1985, chloride concentrations in wells 2A and 3B (fig. 2) had increased to 28 mg/L, and by 1996, concentrations had increased to more than 100 mg/L. Chloride concentrations also increased to more than 20 mg/L in surrounding wells in the southwestern part of the well field. Analyses of chloride trends indicated that chloride concentrations could be anomalous, changing over time and spatially throughout the well field with no apparent pattern (Yobbi and others, 1996). These anomalous patterns suggested that specific features within the hydrogeologic framework control ground-water movement in the well field. Explanations for the different trends and rates of increases in chloride concentrations between wells included aquifer heterogeneity, preferential ground-water movement, structural features, and the influence of ground-water withdrawals.

In 1998, the U.S. Geological Survey (USGS), in cooperation with Pinellas County and Tampa Bay Water, initiated a study to investigate the hydrogeologic controls affecting sources of water to wells and to characterize the continuity of flow among wells. The study also provided an opportunity to investigate various techniques for delineating hydrogeologic controls on ground-water flow within the study area. This effort combined borehole and surface geophysical techniques with ground-water flow measurements and water-quality data to evaluate how structural features and aquifer heterogeneity affect the hydrogeologic and water-quality characteristics of aquifer units. The information presented in this report is provided to help water managers, planners, and others make scientifically based decisions regarding well-field management strategies in heterogeneous aquifers.

Purpose and Scope

This report describes the hydrogeologic framework and factors affecting the patterns of chloride concentrations observed in ground water within and adjacent to the EW well field. This report describes the methods of investigation, and combines historical data with data collected between 1998 and 2000 to describe the hydraulic characteristics and water quality within a heterogeneous multilayered aquifer system. Surface- and borehole-geophysical data were analyzed and compared with hydrologic and water-quality data (table 1). The hydrogeologic framework describes the hydraulic properties of the aquifer units and their respective producing zones. The history and

Base from U.S. Geological Survey digital data, 1972.
Albers Equal-Area conic Projection,
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 1. Location of study area and selected wells in surrounding regions, west-central Florida.

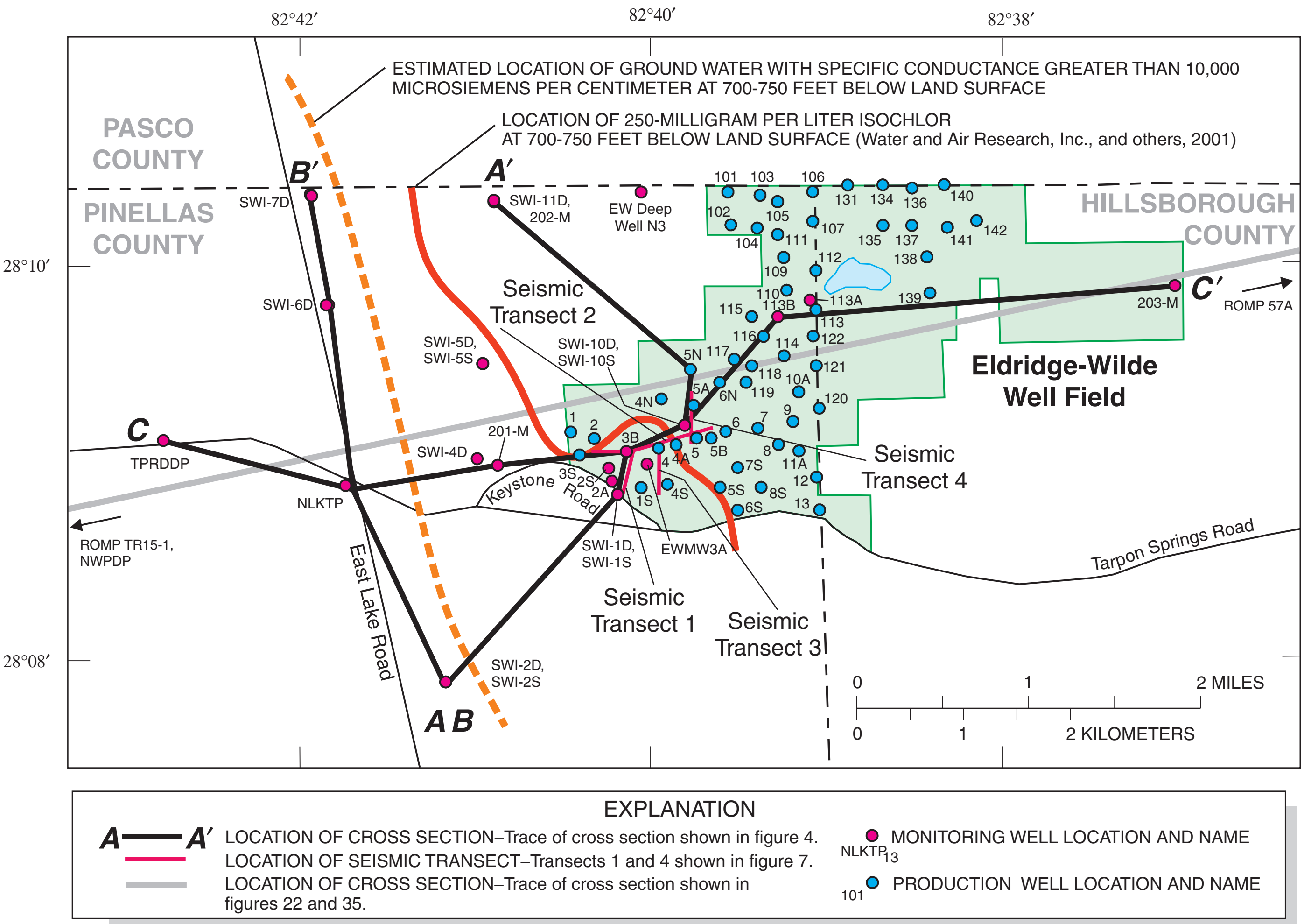

Figure 2. Location of the Eldridge-Wilde well field and adjacent areas showing locations of wells, transects, and cross-sections.

effects of ground-water development are related to their influence on ground-water movement and water quality. Ground-water quality characteristics and the distribution of chloride concentrations are described in terms of spatial, temporal, and vertical variations. A three-way mixing model is presented to describe observed concentrations of chloride from various permeable zones. The data were synthesized into a conceptual model, describing aquifer characteristics and ground-water flow to explain how hydrogeologic features affect the observed distribution of chloride within the ground-water system.

Previous Investigations

Many reports have been written on the hydrology at the EW well field, including reports associated with well-field construction and well construction and engineering (Black, Crow, and Eidsness, Inc., 1970; Gee and Jenson, Inc., 1981a,b, 1983; Nettles and Vandor, Inc., 1983, 1985, 1986, 1988a,b; Nettles and Associates, Inc., 1989, 1990, 1991a,b,c; 1992a,b,c).

Stewart (1968) and Joyner and Gerhart (1980) looked at the effects of pumping on the hydrology of the area and location of the saltwater/freshwater interface. A predevelopment potentiometric-surface map of the Upper Floridan aquifer was constructed by Johnston and others (1980). Potentiometric maps of the EW well field were prepared from 1978 to 1982 by the USGS (Hutchinson and Mills, 1977; Ryder and Mills, 1977a,b, 1978; Wolansky and others, 1978a,b; Wolansky, and others, 1979; Joyner and Gerhart, 1980; Yobbi, and others, 1980a,b,c; Yobbi and Woodham, 1981; Yobbi and Barr, 1982; Barr, 1982, 1983).

Hydraulic properties for aquifer units have been described in many previous investigations and from records compiled by the Southwest Florida Water Management District (SWFWMD), the USGS, and various consultants (Black, Crow, and Eidsness, Inc., 1970; Geraghty & Miller, Inc., 1976a,b; Gee and Jenson, Inc., 1981a,b; Ryder, 1981; Gee and Jenson, Inc., 1983; Nettles and Vandor, Inc., 1985; Miller, 1986; Southwest Florida Water Management District, 1996a,b). Hydraulic characteristics for aquifer units within southwestern Florida were summarized by

Table 1. Types of data collected or analyzed at selected wells located within the study area.

[Well locations shown in figures 1 and 2]

Well name	Type of data		
	Continuous monitoring station	Geophysical log	Water quality
2A	X	X	X
3B	X	X	X
5N		X	X
113-B		X	X
201-M	X	X	X
202-M		X	X
203-M		X	X
EW Deep Well N3	X		
EWMW3A		X	X
NLKTP			X
SWI-1D	X	X	X
SWI-1S	X	X	X
SWI-2D		X	X
SWI-2S		X	X
SWI-4D		X	
SWI-5D		X	
SWI-5S		X	
SWI-6D		X	X
SWI-7D		X	X
SWI-10D	X	X	X
SWI-10S	X	X	X
SWI-11D		X	X
TPRDDP			X

the Southwest Florida Water Management District (2000a), and the stratigraphic framework of the region and detailed local descriptions of the stratigraphy were described by Green and others (1995). Hammes (1992) and Loizeaux (1995) focused on the sequence stratigraphy and hydrologic properties of the Suwannee and Ocala Limestones, respectively.

Little published work relates large-scale structural features to local hydrogeologic trends. Within EW, photolinear features identified by Nettles and Vandor, Inc. (1988a) were presented to explain the observed anomalous trends in ground-water chloride concentrations. North of EW, Miller (1977) conducted a fracture trace analysis at the Cross Bar Ranch well field to select production well sites with optimum yields. Williams (1985), Nettles and Vandor, Inc. (1988b), and Diodato (1999) mapped photolinear features and correlated them to enhanced specific well capacity and ground-water quality anomalies. Spechler (1983) found that upward leakage of high chloride waters coincided with observed structural photolinear features in the Tarpon Springs area. Heath and Smith (1954) established that a sinkhole on the western shore of Lake Tarpon connects the lake to a spring vent in Tarpon Springs along the Gulf of Mexico. Hunn (1974) further described the influence of karst features on water quality in the Lake Tarpon region. Spechler (1994), and Odum and others (1997, 1999) used seismic-reflection data techniques to identify large-scale breccia pipes that can create avenues of ground-water movement, linking the ocean to inland water resources.

Surface and borehole geophysical methods have been used to identify structural features associated with ground-water flow in west-central Florida. Safko and Hickey (1992), Duerr (1995), Metz and Brendle (1996), and Knochenmus and Bowman (1998) used borehole geophysical techniques to identify and measure ground-water flow in wells open to multiple aquifers to observe interaquifer flow via open boreholes.

Investigations that have focused on describing the location of the saltwater interface in the west-central Florida coastal region include Cherry (1966), Stewart (1968), Geraghty & Miller (1976a, b), Causseaux and Fretwell (1982), Nettles and Vandor, Inc. (1988a,b), Sprinkle (1989), Maddox and others (1992), and Trommer (1993). A USGS data release (1985) and Yobbi and others (1996) identified water-quality trends in selected public-supply well fields. Other analyses regarding well-field operations and ground-water quality have been done by Geraghty & Miller (1976a,b), HydroGeologic, Inc. (1992), and Southwest Florida Water Management District (1990, 1995, 1996a,b, 2000b). The location of the saltwater interface and 250-mg/L isochlor line presented in the 1996 annual report by Blasland, Bouck, and Lee (1997), and reports by Water and Air Research, Inc. (2000), and Water and Air Research, Inc., and others (2001) were particularly helpful to this study.

Definition of Terms

The following naming conventions and definition of terms are used in this report. Within the scientific community there are specific water-quality designations that delineate water type, ionic concentration, and potability. The conventions used in this report follow previously published work. The three primary chemical water types that mix within the study area are: sodium-chloride water, calcium-carbonate water, and calcium-sulfate water. Sodium-chloride water reflects a seawater origin, and within this report is referred to as *saltwater*.

Calcium-carbonate water reflects the chemical signature of water that has interacted only with the carbonate aquifer minerals, with no influence of seawater. Calcium-carbonate water is referred to as *freshwater*. Ground water that moves along deep flow paths within the Upper Floridan aquifer interacts with evaporite units that contain gypsum, thus enriching the ground water with various ions including calcium and sulfate. Ground water enriched with calcium and sulfate is referred to as *deepwater*.

In the study area, deepwater along the saltwater interface moves to the surface as a result of density differences and regional flow (Cooper and others, 1964). This mechanism, which introduces deepwater into shallower depths, is referred to as *upwelling*. The process by which ground-water withdrawals create upward head gradients that induce deepwater to move upward is *upconing*. Both upwelling and upconing are associated with calcium sulfate-enriched water occurring at shallower depths.

The *saltwater interface* is the contact zone between freshwater and saltwater. Under natural conditions, the boundary between freshwater and saltwater in coastal regions depends on the balance of forces in a dynamic system that can create a contact zone that varies in thickness. Normally, freshwater moves seaward at a rate that is related to the head above sea level in the freshwater aquifer. *Saltwater intrusion* results when freshwater heads decrease and saltwater migrates inland. Generally, the location of the saltwater interface approaches land surface near the coast and increases in depth landward. Freshwater and saltwater mix within a transition zone, but the locations of the interface and the transition zone are not stationary—they are in dynamic equilibrium, moving laterally and vertically depending on the head and movement of freshwater in the aquifer.

The position of the saltwater interface within the ground-water system has previously been identified and delineated by chloride concentrations, total dissolved solids concentrations, and specific-conductance ranges (Causseaux and Fretwell, 1982; Sprinkle, 1989; Maddox and others, 1992; Richter and Kreitler, 1993; Trommer, 1993). Salinity as described in this report is based on the following ranges of concentrations of total dissolved solids (TDS) (Hutchinson, 1992): freshwater, from 0–500 mg/L; slightly saline water, from greater than 500–3,000 mg/L; moderately saline water, from greater than 3,000–10,000 mg/L; very saline water, from greater than 10,000–36,000 mg/L; and brine, in excess of 36,000 mg/L.

For this report, chloride concentrations and specific conductance are used to delineate saltwater and to indicate mixing. *Saltwater* (seawater) is defined as water having at least 19,000 mg/L chloride, TDS concentration of at least 34,500 mg/L, or specific conductance value of at least 50,000 µS/cm. *Freshwater* is defined as water having a chloride concentration of 20 mg/L or less, and specific conductance value of less than 500 µS/cm. The area in which the water quality falls between freshwater and saltwater is defined as the *transition zone*. Because chloride, TDS and specific conductance values vary widely in this zone, the chloride concentration commonly is measured to delineate where water becomes nonpotable. Causseaux and Fretwell (1982) mapped the 250-mg/L isochlor as the saltwater interface because this is the boundary where chloride concentrations exceed the Florida Department of Environmental Protection (FDEP) maximum drinking water contaminant level. Ground water containing approximately 1 percent seawater can increase chloride concentrations to the FDEP's maximum potable limits. Within the study area, the 250-mg/L isochlor generally corresponds to a specific conductance value of 1,000 µS/cm (which is TDS concentration less than 1,000 mg/L). Moderately saline water, with specific conductance values greater than 10,000 µS/cm, and chloride concentrations greater than 1,000 mg/L, indicates a predominant influence of *seawater*.

In this report, both the 10,000-µS/cm specific conductance isoline and the 250-mg/L isochlor have been mapped to delineate the saltwater/freshwater interface, although they each represent varying levels of saline water present in the ground water within the study area. Water exceeding 250 mg/L of chloride is considered nonpotable and, therefore, represents the upper boundary of the saltwater interface. Where specific conductance of ground water exceeds 10,000 µS/cm in the study area, ground water becomes moderately saline and indicates that saltwater is likely influencing ground-water chemistry.

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The completion of several critical tasks for this study depended on a number of individuals within and outside of the USGS. Locating and obtaining historical data depended on the assistance of several individuals. Within the Pinellas County Utilities Department: Dave Slonena provided many valuable reports on the EW well construction and modification history; Bruce Weber was helpful by providing historical water-quality data, occasional field assistance, and contacts for operational questions; Oz Wiesner provided the historical geophysical logs and calibration data; Jim Sanders and Royce Rarick at the Keller Water Plant provided additional well-field operational data and field support. Terry Thomas of Tampa Bay Water provided historical data and information regarding changes in monitoring efforts and additional work being conducted at the well field during this study. Bob Evans of SWFWMD provided one photolinear interpretation, as well as providing assistance and materials to Dave Diodato (USGS), who performed another photolinear interpretation. Borehole geophysical logging efforts would not have been possible without the help of John Williams (USGS–Office of Ground Water) and Alton Anderson who provided field assistance. Additional help with geophysical logging and interpretation was provided by the geophysical logging group within the USGS National Research Program: Fred Paillet, Richard Hodges, and Barbara Corland. High-resolution land-seismic reflection data collection, processing, and interpretation were completed with help from the USGS Hazards Group in Denver, Colorado, and many thanks are due to Jack Odum and Bill Stephenson for their assistance. Strontium isotope data were analyzed by Jon Martin at the University of Florida, and sample splits for quality assurance were run by Tom Bullen of the USGS. Bruce Weber with the Pinellas County Utilities Department, Jim Inman of the University of South Florida, Peter Swarzenski of the USGS, and personnel from the SWFWMD's Regional Observation Monitoring Program (ROMP) provided sampling assistance. Bob Bretnall with HSW Engineering, Inc., provided feedback during data analysis. Within the USGS, Laura Sacks, Dan Duerr, Ron Miller, Arturo Torres, Mario Fernandez, and Darren Meadows assisted with data management, analysis, and synthesis. Jane Eggleston provided editorial assistance in developing the draft report.

Methods

Geologic, hydraulic, photolineament, geophysical, and water-quality data were used to assess the influence of geologic features on ground-water flow and distribution of chloride in the study area. Most geophysical methods are subject to multiple interpretations that benefit from, and commonly require, corroborative data from other sources. In this study, interpretations of surface and borehole geophysical data were related to water-quality data and historical information compiled during the study. A conceptual hydrogeologic model for the generalized movement of ground water was then developed for the area. The types and locations for various data-collection efforts are shown in table 1.

Data Compilation

Lithology and stratigraphy were reviewed from descriptions provided in previous reports of cuttings and cores collected during the drilling of wells in the study area (Black, Crow and Eidsness, Inc., 1970; Nettles and Associates, Inc., 1989-1992). Lithologic logs and drilling records from more than 30 production and monitor wells were used to correlate the stratigraphy within the study area and to construct geologic sections.

Hydraulic properties for specific geologic units were obtained from aquifer test data as well as borehole and core measurements. Porosity, transmissivity, hydraulic conductivity, and specific capacity values representing both large sections of the Upper Floridan aquifer and individual stratigraphic units were compiled.

Ground-water pumping data from 1956 to 2001 were compiled as were published water-level maps for the well-field area from predevelopment to 2000.

Historical water-quality data from 1970 to 2000, collected by the USGS and Pinellas County, were used to look at increasing trends in chloride concentrations, to identify sites to be sampled for additional water-quality analysis, and to better understand where and to what extent changes in the chemical composition of ground water have occurred. Historical data obtained from Pinellas County were thoroughly reviewed, and only samples for which the difference between the laboratory and field specific conductance was less than 10 percent were used for additional analysis.

Photolineament Analysis

Photolineaments are surface expressions of lineaments and fractures caused by tectonics and earth tides. Structural failure due to dissolution and collapse may also create fractures and faults that can propagate upward through unconsolidated materials to land surface, where they can be seen as linear features on aerial photographs. Accuracy in locating photolinear features depends on the source photography and the method used to convert images to map projections.

Two photolineament analyses were done in the EW well field, using multiple types of aerial photographs at different scales and spanning a timeframe of more than 50 years. Diodato (1999) identified photolinear features using black and white photographs dating from 1971 at the scale of 1:20,697 using methods described by Lattman (1958), Spratt (1996), and Parizek and Diodato (1995). A map of apparent lineaments and fracture traces was prepared following methods described by Colwell (1960), using black and white photographs dating from 1938 and 1957 at the 1:20,000 scale and using a 1995 color infrared image at the 1:40,000 scale (Bob Evans, Southwest Florida Water Management District, written commun., 1999). All identified photolinear features were transferred to the USGS Elfers topographic quadrangle 1:24,000-scale base map using a Bausch & Lomb zoom-transfer scope.

High-Resolution Seismic-Reflection Surveys

Land-based high-resolution seismic-reflection surveys were run to investigate subsurface stratigraphic characteristics and discontinuities within the southwestern region of the EW well field with an emphasis on determining if fractures or fracture zones could be identified using methods similar to those used by Odum and others (1997). Four seismic transects were run ranging from 1,356 to 3,612 ft, and covering a total length of 8,397 ft (fig. 2). The southwestern part of the well field was selected to corroborate the locations of photolinear features, relate the extent of elevated chloride concentrations to any observed subsurface geologic structure, and collect multiple intersecting seismic transects.

Seismic data were collected using a Mini-SOSIE high-resolution seismic-reflection technique (Barbier, 1983; Stephenson and others, 1992), and using 28-Hertz resonant-frequency geophones and a 60-channel seismograph. Three geophones per receiver station were arranged in a cluster (point) array at each station. Stations were spaced 16.4 ft apart. Data-collection parameters were designed to image features with a moderately high degree of resolution 100-800 ft below land surface. Detailed resolution, especially at shallow depth, was sacrificed to obtain deeper penetration.

Noise generated by typical well-field operations (pipeline flow, running well pumps, and underground culverts) combines to variably degrade the strength and clarity of the recorded seismic signal. In some cases, the data quality was improved by removing the noise through processing of the seismic data. In other cases, the noise and associated interference could not be removed sufficiently to improve the data quality. Available geologic data were correlated with seismic data using wells located in close proximity to transects. Types of reflectors and trends in the seismic-reflection data were correlated with lithologic changes or formation boundaries described in the well logs for 5N, 5A, 1, 2, 2A, 4S, 5, 4A, 4, SWI-1S, SWI-1D, 3B, SWI-10S, SWI-10D, and 5B (fig. 2). The stratigraphic and structural features identified in the seismic-reflection data were compared to photolinear features and borehole geophysical logs.

Borehole Geophysical Techniques

Borehole geophysical logs provide information about the stratigraphic, structural, and fluid properties of the hydrogeologic environment. Borehole geophysical data were collected at 13 wells within the study area and were correlated with the seismic-reflection data to identify structural features and lateral continuity of stratigraphic units and water-producing zones within the hydrogeologic framework. Borehole geophysical logging methods followed standards outlined in Keys (1990). Most of the logs were collected using a downhole digital system and tools, although an analog heat-pulse tool and logging system were used for additional flow logging at several sites to compare tools and techniques.

Logging data were collected during three time periods that had different hydrologic conditions: August-September 1998, March-April 1999, and March 2000. The August-September 1998 period was coincident with the annual rainy season, which is characterized by less ground-water pumping and higher ground-water levels. The March-April 1999 period represented the annual dry season, characterized by greater ground-water pumping rates and lower ground-water levels. The March 2000 period represented a drought period with greater than normal ground-water pumping rates and extremely low ground-water levels.

Caliper and acoustic televiewer logs are useful in identifying fractures, washout zones, and zones of enhanced porosity in the geologic units. Acoustic televiewer logs are used to further characterize borehole conditions, formational character, and porosity type, but at greater resolution than caliper logs. The acoustic televiewer method provides a continuous, 360-degree sonic image of the borehole from which borehole features such as fractures, bedding planes, vugs, and caverns can be identified in the open borehole. The 360-degree view provides a continuous image of any structure intersecting the borehole. Bedding planes and horizontal features appear as flat lines. Fractures or features that intersect the borehole at an angle appear as sinusoidal curves with the amplitude of the curve indicative of relative dip angle. By using the maximum and minimum heights of these curves, the dip angle of identified fractures can be measured. Although the caliper and acoustic televiewer data provide information about the variability in borehole diameter, neither log was used to infer the presence of water-producing zones or ground-water flow. Caliper and acoustic televiewer logs were compared, and consistent patterns in borehole-diameter changes were used to characterize geologic properties and lateral extent of specific stratigraphic units. Acoustic televiewer logs are limited to boreholes less than 12 in. in diameter. As a result, acoustic televiewer logging was limited to the lower Ocala Limestone and the Avon Park Formation because of substantially enlarged boreholes or washout zones present in the shallow units.

Caliper logs, in combination with other borehole techniques, provide a useful method for estimating the types and size of porosity, especially at the formational scale (Cunningham, 2004a,b). Acoustic caliper logs, when combined with acoustic televiewer data, provided images that could be related to types and extent of porosity. Enlarged borehole conditions do not necessarily indicate effective secondary porosity. Although core data provide a good idea of effective primary porosity or small-scale secondary porosity, the presence of large-scale porosity within an aquifer unit requires additional verification before it can be classified as effective secondary porosity or be used to indicate how and where ground-water movement occurs. In this study, the observations of porosity characteristics using caliper and acoustic televiewer logs were correlated to temperature, flow, and fluid resistivity logs to evaluate features that were associated with ground-water flow.

Water-quality profiles and apparent water-producing zones were identified using fluid resistivity or fluid conductance and fluid temperature logs. Fluid resistivity logs were converted to specific conductance by dividing 10,000 by the resistivity, in ohm-meters. Specific conductance logs obtained from the same well at different dates were compared to identify temporal variability in ground-water quality. Water-quality samples were collected at discrete depths within the borehole to calibrate the fluid conductance logs. Specific conductance logs without point-sample calibration information were analyzed for trends only.

Flow logs using both heat pulse and electromagnetic (EM) flow meters were collected and compared to determine their suitability in assessing ground-water flow. Ideally, flow logs should be collected under steady-state conditions. Because water levels often fluctuated during logging, however, the most effective method for detecting flow zones in a particular borehole was to collect multiple logs at each well under different conditions.

Flow logs were collected under ambient and pumping conditions, with and without a diverter, and in the trolling and stationary mode. Borehole flow was constricted by using a diverter to increase flow across the sensor and, therefore, increase the sensitivity of the measurement. The best data were obtained using a large diverter and high gain settings. These conditions reduced the effects of borehole diameter, thus providing more consistent borehole conditions for flow measurements. The EM flow log tool was preferred for flow logging because it contains specific conductance and temperature sensors, which are useful in identifying flow related to water-quality changes. The heat-pulse flow meter was used whenever the EM flow log tool was inoperable.

In west-central Florida, washout zones occur during well construction where lithologic units are not competent enough to maintain a consistent borehole diameter. Borehole volume is a critical element in obtaining accurate fluid-flow measurements. Variable borehole diameter alters the cross-sectional area of the borehole and changes the borehole volume. Stationary flow measurements were made at discrete points in the borehole so that the borehole volume could be held constant. Flow logs collected while the probe was moving up or down the borehole (trolling or moving) are affected by the changing borehole diameter, which affects the apparent velocity of borehole fluids. Both trolling and stationary logs were corrected for borehole-volume effects by calibrating to measurements made in the well casing and recalculating flow using diameter measurements for borehole volumes obtained from the caliper logs. Associated changes in water quality, observed using fluid conductance logs, were related to measured flow and geologic structure to evaluate where ground-water flow occurs.

Water-Quality Data Collection and Analysis

Historical and contemporary water-quality data were used to analyze trends and to document the spatial and temporal changes in ground-water quality. Isotopic samples for delta oxygen-18 ($\delta^{18}O$), delta deuterium (δD) and strontium 87/strontium 86 ($^{87}Sr/^{86}Sr$), were analyzed to provide further chemical evidence of sources and mixing mechanisms for ground water. The δD and $\delta^{18}O$ data, in conjunction with chloride concentrations, were used to help identify sources of salinity. Strontium isotopic data were used to identify sources of salinity, ground-water mixing, and relative ages of aquifer materials that contribute strontium to ground water. Strontium isotopes ($^{87}Sr/^{86}Sr$) have varied in seawater over geologic time, so the measured ratio of $^{87}Sr/^{86}Sr$ in water can be valuable for distinguishing sources and ages of aquifer materials in contact with ground water.

Water-quality data were collected from 23 wells. Samples were collected from the 13 wells logged during this study and from 10 additional wells selected to represent possible chloride sources and ground-water mixing end-members within the study area. For quality-assurance purposes, duplicate water samples were collected for 10 percent of the samples. Well volume was purged three times and water samples were collected after temperature, specific conductance, pH, and dissolved oxygen measurements had stabilized.

All ground-water samples were collected and analyzed for major ions using standard USGS methods (Wilde and Radtke, 1998). Temperature, specific conductance, pH, and dissolved oxygen were monitored using a flow-through chamber. Alkalinity was determined in the field by titration with sulfuric acid. Strontium samples and two prepared $^{87}Sr/^{86}Sr$ standards were analyzed at the University of Florida according to methods discussed by Pin and Bassin (1992). Split samples were run for 4 of the total (22) $^{87}Sr/^{86}Sr$ samples. Unfiltered water samples were collected in poly seal-capped glass bottles for δD and $\delta^{18}O$ analysis.

Continuous water-level and specific-conductance data at fixed depths in eight boreholes were collected by the USGS from 1993 to 2000. During this study, three new sites (wells 2A, 3B, and 201-M) were instrumented with data loggers to continuously monitor water levels and specific conductance. Temperature-compensated specific conductance probes were installed at two fixed depths in each well.

Hydrogeology

Ground-water flow patterns are related to lithologic and hydraulic properties of the aquifer and to hydraulic gradients. Within the EW well field, ground-water flow patterns mainly are controlled by the hydraulic properties of the geologic units, pumping rates, and the location of the saltwater/freshwater interface. These factors also affect the ground-water quality within and near the EW well field.

The distribution of hydraulic properties is complex. Lithologic differences and structural features create heterogeneous distributions of porosity and permeability. Florida is underlain by carbonate rocks that have been altered by karst processes. Limestone and dolomite units are variably riddled with fractures, enlarged bedding planes and geologic contacts, vugs, and caverns of various sizes (Hickey, 1982; Robinson, 1995; Knochenmus and Robinson, 1996). Structural features formed as a result of dissolution collapse or fractures associated with larger structural mechanisms create zones along which water moves preferentially. Features indicating the presence of preferential flow networks within the study area include fractures, lineaments, and collapsed dissolution features, which can extend across stratigraphic units, thereby facilitating ground-water flow in multiple directions. Well-developed networks of conduits and preferred flow zones facilitate rapid lateral and vertical mixing of ground water. Clays and fine-grained materials form confining units or produce semiconfined conditions, impeding ground-water flow.

Hydrogeologic Framework

The hydrogeologic units underlying the study area are, in descending order, the surficial aquifer system (SAS), the intermediate confining unit (ICU), the Upper Floridan aquifer (UFA), and the middle confining unit (MCU) (fig. 3). These units generally correspond to the stratigraphic units identified in the study area (fig. 4). The uppermost water-bearing unit, the SAS, is predominantly sand. The sand deposits are underlain by ICU clays (primarily of the Hawthorn Group) that separate the UFA from the SAS. The degree of confinement between the SAS and UFA varies depending on the clay content within the undifferentiated surficial deposits and the Tampa Member of the Hawthorn Group. The UFA is a multilayered sequence of relatively high and low permeability carbonate units. The UFA is confined below by the MCU where evaporite minerals are present within the carbonate units, thereby reducing the permeability. Formation names are based upon the geologic definitions of Scott (1988) and are equivalent to those used by the Florida Geological Survey. Lithologic descriptions are primarily from Green and others (1995).

<table>
<tr><th>SERIES</th><th colspan="2">STRATIGRAPHIC UNIT</th><th>GENERAL LITHOLOGY</th><th colspan="2">HYDROGEOLOGIC UNIT</th></tr>
<tr><td rowspan="2">Holocene to Pliocene</td><td colspan="2">Undifferentiated Sands and Clays</td><td>Quartz sand, silty sand, clayey sand, peat, shell</td><td colspan="2">surficial aquifer system</td></tr>
<tr><td rowspan="2">Hawthorn Group</td><td></td><td>Clay, minor quartz sand, phosphate, fine-grained dolomite, residual limestone</td><td colspan="2">intermediate confining unit</td></tr>
<tr><td>Miocene</td><td>Tampa Member of the Arcadia Formation</td><td>Limestone, minor quartz sand, phosphate, chert, clay, fine-grained dolomite</td><td rowspan="5">Upper Floridan aquifer</td><td rowspan="2">Tampa/Suwannee producing zone</td></tr>
<tr><td>Oligocene</td><td colspan="2">Suwannee Limestone</td><td>Limestone, packstone to grainstone, trace quartz sand, organics, variable dolomite and clay content, highly fossiliferous, vuggy</td></tr>
<tr><td rowspan="3">Eocene</td><td colspan="2">Ocala Limestone</td><td>Limestone, micritic,chalky, very fine- to fine-grained, soft, poorly indurated, trace organics, clays and dolomite, abundant foraminifera</td><td>Ocala semiconfining unit
Ocala/Avon Park producing zone</td></tr>
<tr><td colspan="2" rowspan="2">Avon Park Formation</td><td rowspan="2">Limestone, dolomite, and evaporites
Limestone and dolomite interbeds typical in upper part, deeper beds are continuous dolomite with increasing evaporites at base
Limestone is fine-grained, tan, recrystallized packstone with variable amounts of organic-rich laminations near top
Dolomite is hard, brown, sucrosic in texture and commonly fractured
Evaporites occur in dolomite as interstitial gypsum and anhydrite with evaporite filling pore space and as interbeds in the lower part</td><td>Avon Park producing zone</td></tr>
<tr><td colspan="2">Middle confining unit</td></tr>
</table>

Figure 3. Generalized hydrostratigraphy for the study area. Modified from Black, Crow, and Eidsness, Inc. (1970); Ryder (1981); Trommer (1992); Green and others (1995); Southwest Florida Water Management District (1996a,b); Arthur and others (2001).

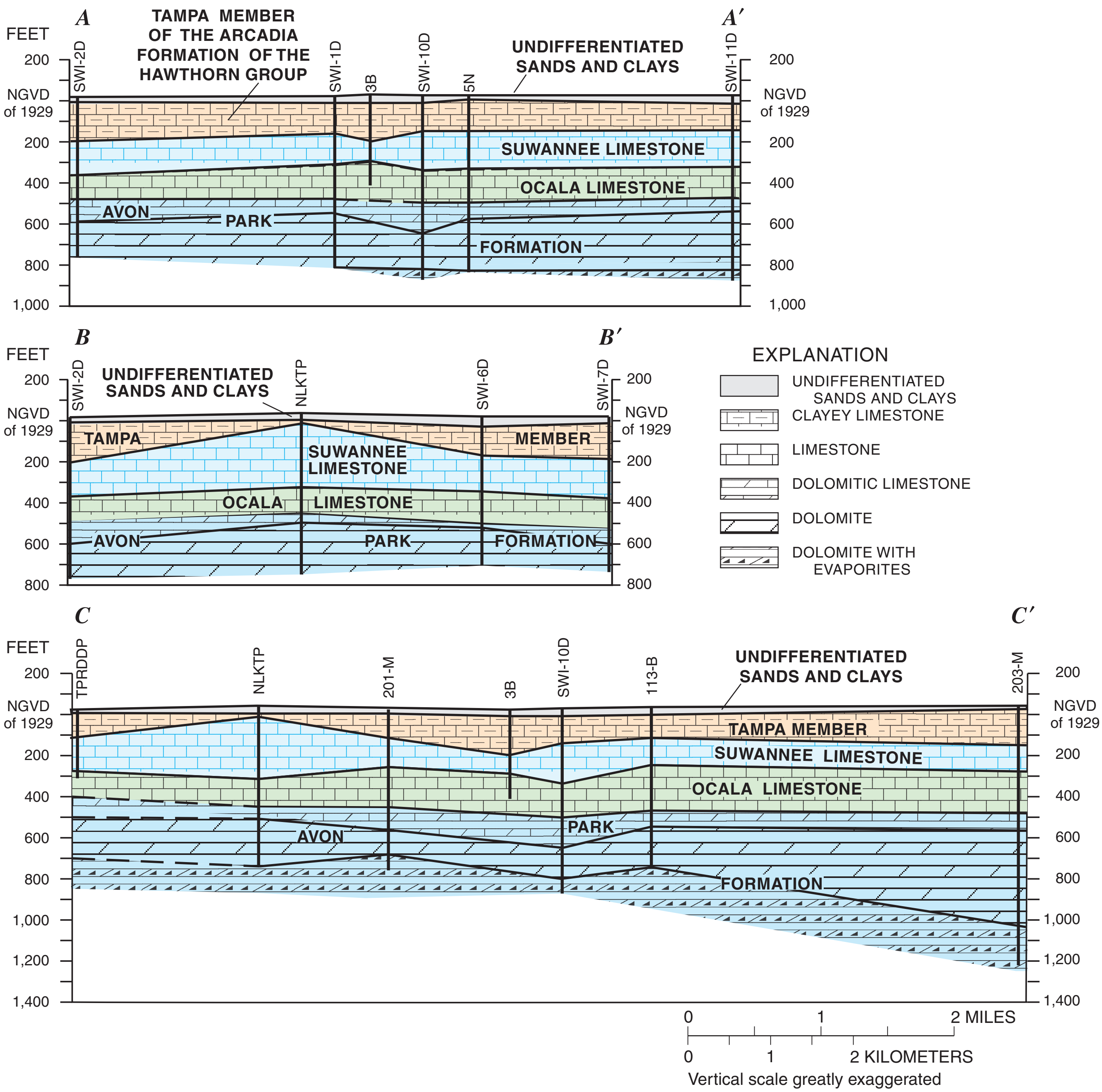


Figure 4. Stratigraphic sections *A-A′*, *B-B′*, and *C-C′* through the study area. Locations of sections are shown in fig. 2. Stratigraphic contacts are based on geologic data from Black, Crow, and Eidsness, Inc. (1970); Gee and Jenson, Inc. (1981a,b); Nettles and Vandor, Inc. (1983); Nettles and Associates, Inc. (1989, 1991b,c; 1992b,c).

Surficial Aquifer System

The SAS consists of fine to very fine quartz sand, silt, clayey sand, and shell fragments. In the vicinity of the study area, the SAS is thickest along the margins of Lake Tarpon, west of the EW well field, where the SAS consists of paleodune deposits. The SAS generally is 10 to 50 ft thick but can be more than 80 ft thick where paleodune deposits are present (Green and others, 1995). In the wells used for stratigraphic control in this study, the measured thickness of the SAS ranges from 12 to 50 ft with an average thickness of 32 ft. Although the SAS is seldom used for potable water supplies, it provides recharge to lakes, ponds, and the UFA.

Intermediate Confining Unit

The low permeability ICU comprises undifferentiated siliciclastic sediments of the Hawthorn Group, which consists of predominantly clay minerals with minor amounts of quartz sand, phosphate, fine-grained dolomite, and some residual limestone. The ICU is less than 25 ft thick within the study area (Green and others, 1995). In the northeastern part of the EW well field, where the ICU thins, the UFA is less confined and may receive direct recharge through sands of the SAS. Sinkholes are common in this region, and breaches occurring in the ICU can reduce the effective confinement in localized areas (Sinclair and others, 1985; Green, and others, 1995; Diodato, 1999). A sinkhole along the western shore of Lake Tarpon is connected to Spring Bayou in Tarpon Springs by way of a subsurface conduit within the limestone (Heath and Smith, 1954). Where the ICU thickens near the western edge of the EW well field, the water table mounds (Ryder and Mills, 1977a,b; Wolansky and others, 1978b).

Upper Floridan Aquifer

The UFA is a thick sequence of limestone, dolomitic limestone, dolomite, and interbedded dolomite and evaporites. The UFA includes, in descending order from youngest to oldest, the following geologic units: the Tampa Member of the Hawthorn Group, the Suwannee Limestone, the Ocala Limestone, and the Avon Park Formation. These carbonate units vary in texture, lithology, and hydraulic properties (figs. 3, 5), reflecting the various types of carbonate sedimentary depositional environments of west-central Florida.

The Tampa Member ranges from 15 to 200 ft thick, but averages about 140 ft thick within the study area. The Tampa Member has a highly variable lithology that is predominantly limestone, but also contains quartz sand, clay, phosphate, chert, and fine-grained dolomite (fig. 3).

The Suwannee Limestone, of Early Oligocene age, is a shallow-water carbonate characterized by cream to tan, crystalline, biomicritic packstone to grainstone that contains quartz sand, variable dolomite, clay and other minor impurities. The terms grainstone, packstone, and wackestone (Dunham, 1962) refer to granular carbonates with no mud, grain supported with some mud, and predominantly mud (mud supported but more than 10 percent grains), respectively. The Suwannee Limestone is highly fossiliferous, containing gastropods, pelecypods, echinoids, miliolids, and other benthic formaminifera, and can be vuggy due to the abundant gastropod and pelecypod casts and molds. The Suwannee Limestone consists of three major depositional megacycles that are interrupted by repeated subaerially exposed surfaces (Hammes, 1992); grain size generally increases in the upper part of each cycle. The subaerially exposed surfaces increase in frequency within the uppermost megacycle, ultimately marking the end of Suwannee deposition. During the exposure periods, extensive karst features, enhanced porosity, and caliche crusts developed that are characteristic features of the Suwannee Limestone (Hammes, 1992).

In the study area, the top of the Suwannee Limestone generally is at 150 to 200 ft below NGVD of 1929 and extends to nearly 400 ft below NGVD of 1929; the average thickness of the unit is 160 ft. Hammes (1992) found that variations in thickness are influenced by proximity to large-scale structural features of tectonic origin. The gamma ray geophysical log typically shows high background deflection for the Suwannee Limestone; the Suwannee-Ocala Limestone contact is readily distinguishable on the log by the sharp drop in gamma activity observed in the underlying Ocala Limestone (Green and others, 1995) (fig. 5).

The Ocala Limestone represents 4.5 million years of continuous subaqueous carbonate sedimentation during the Late Eocene (Carter and others, 1989; Loizeaux, 1995). The irregular upper surface of the Ocala Limestone is characterized by onlapping of the Suwannee Limestone, indicating a period of nondeposition and associated erosion, which is believed to have been associated with a drop in sea level, although evidence of subaerial exposure is not present (Loizeaux, 1995). The Ocala Limestone comprises 12 sedimentary facies within 3 major identifiable sequences that, together, reflect an increase in water depth upward in the sedimentary record.

The top of the Ocala Limestone is at an elevation of approximately 300 to 470 ft below NGVD of 1929, and the unit has an average thickness of 170 ft within the study area. The Ocala Limestone is a pure carbonate unit that ranges from a fine-grained pelagic wackestone to a mixed skeletal grainstone with substantial variation in grain type, size, cementation, and porosity (Loizeaux, 1995). The unit is characterized by soft to semi-indurated micritic limestone containing abundant foraminifera (*Camerina* sp.) and echinoid fragments loosely bound in the limestone matrix. The upper 120 ft of the Ocala Limestone consists mostly of foraminifera, and corresponds to a low gamma-ray deflection on the geophysical log. The foraminifera-rich sections are very poorly indurated, appearing in well cuttings as carbonate sand, and causing severe caving problems during drilling. Caliper logs typically show distinctive patterns where the Ocala Limestone is either highly variable or has been washed out by drilling activity (fig. 5). Dolomitic lenses increase in the lower part of the Ocala Limestone.

The contact between the Ocala Limestone and the underlying Avon Park Formation is an unconformity resulting from subaerial exposure of the Avon Park. The contact commonly is associated with a distinctive black to brown hardpan that contains poorly cemented, friable organic silts and silica sand, which correspond to a large gamma-ray deflection on the geophysical log (fig. 5).

The underlying Avon Park Formation is a peritidal carbonate with associated evaporites that was dolomitized contemporaneously with deposition under arid conditions and intermittently restricted seawater circulation. Lithologic data indicate that the unit was deposited in very shallow marine water with deposits containing cyclic tidal-flat and shoaling-upward sequences alternating with shallow, open-marine carbonate units. The typical

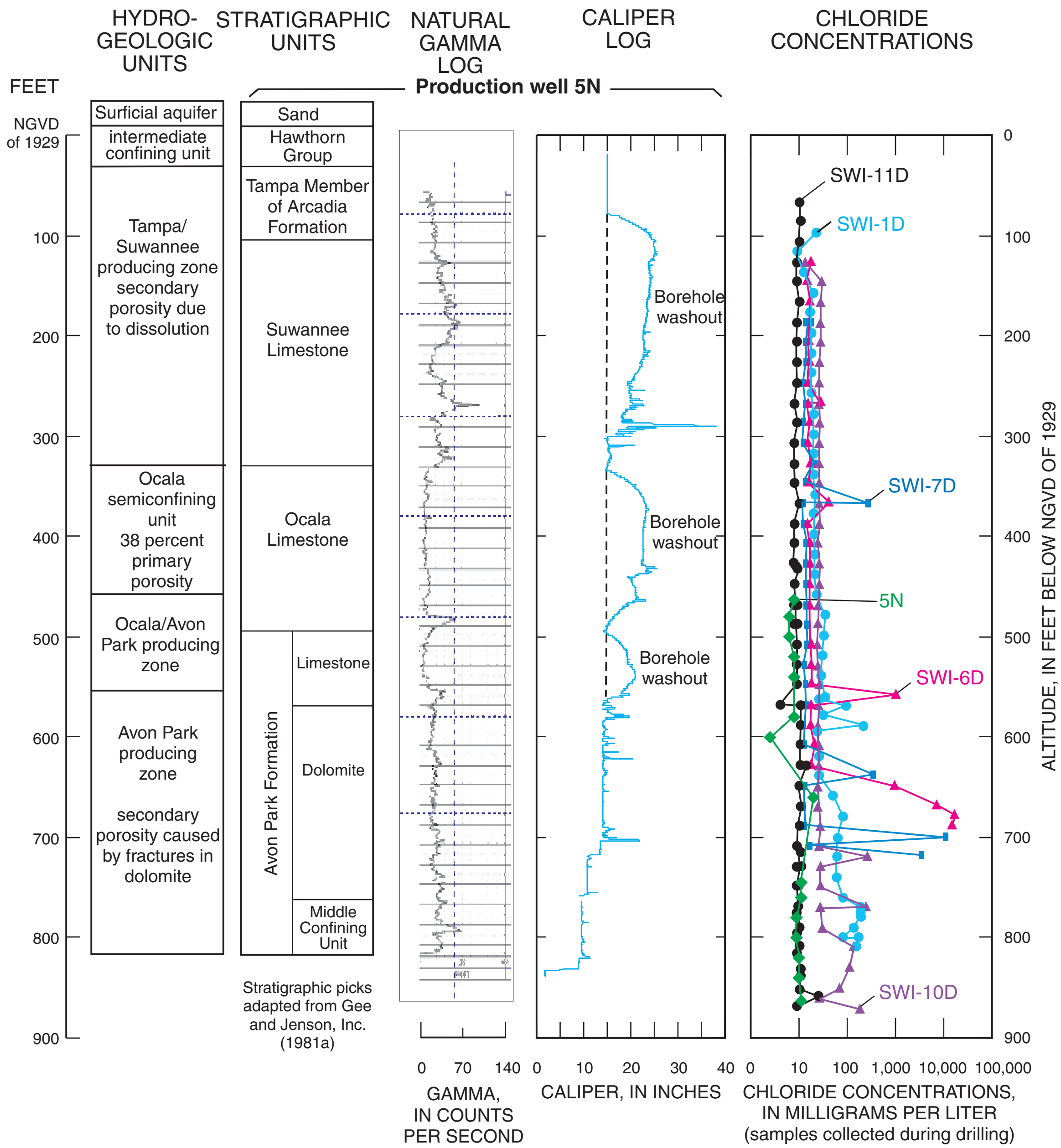


Figure 5. Detailed hydrostratigraphic column of the study area with representative geophysical logs and chloride concentrations with depth. Based on data from Black, Crow, and Eidsness, Inc. (1970); Geraghty & Miller Inc. (1976b); Hickey (1982); Miller (1986); Knochenmus and Thompson (1991); Trommer (1992); Green, and others (1995); Knochenmus and Robinson (1996); Knochenmus and Swenson (1996); Southwest Florida Water Management District (1996a,b, 2000a); Broska and Barnette (1999); and Metz and Sacks (2001).

shoaling-upward sequences include mudstone, packstone/grainstone overlain by mudstone wackestone, algal laminated mudstone, and some nodular gypsum and(or) anhydrite. A limestone unit with organic-rich layers (peat) and abundant seagrass fossils generally characterizes the upper part of the Avon Park Formation. Where present, the limestone consists of a brown, well-lithified, biosparite and the foraminifera *Dictyoconus americanus*. The dolomite is hard, brown, and massive. Toward the base of the Avon Park Formation, interstitial infilling of void spaces with evaporitic gypsum or anhydrite increases. Although some short-lived subaerial exposure was common during deposition, no evidence of extensive subaerial diagenesis has been documented. The lower part of the Avon Park Formation is almost completely dolomitized and only the upper part contains limestone that has not been dolomitized (Cander, 1991).

Middle Confining Unit

The MCU is present where gypsum and anhydrite infill interstitial voids and form continuous beds within the dolomite units of the Avon Park Formation. Data describing the regional extent and lateral continuity of this hydrologic unit are sparse, but the MCU is present at approximately 1,100 ft below land surface in west-central Florida and pinches out eastward toward the middle of the Florida Peninsula (Miller, 1986; Hickey, 1990). The intergranular evaporites substantially reduce the permeability of the Avon Park Formation and restrict ground-water flow (Ryder, 1981, 1985; Miller, 1986, Southwest Florida Water Management District, 1996a,b, 2000a). The presence of excess calcium, sulfate, and strontium in downdip parts of the UFA, however, indicate that freshwater interacts and dissolves the interstitial evaporites that form the MCU (Cander, 1991). The MCU is considered to be the base of the UFA, and its presence is the lower limit of hydrologic units pertinent to this study.

Structural Characteristics and Lateral Continuity of Hydrogeologic Units

Structural characteristics and lateral continuity of hydrogeologic units were investigated to determine how these features affect ground-water movement. The lateral continuity of stratigraphic units, water-producing zones, and confining units within the hydrogeologic framework were evaluated by correlating data from photolineament analyses, land-based high-resolution seismic-reflection surveys, and borehole geophysical logs. These three methods resolve structural features at different scales, and results were compared to determine the existence and location of structural features.

Photolineaments within and near the EW well field were identified by Spechler (1983) and Nettles and Vandor, Inc. (1988b). Spechler (1983) identified several large-scale photolineaments within the region, building upon work by Vernon (1951). Nettles and Vandor, Inc.(1988b) identified a sparse number of large-scale photolinear features that trend northeast-southwest through the well field. In a study at the Cross Bar Ranch well field located north of the EW well field, 618 photolinear features of various lengths were identified, and more than 60 percent of the photolineaments showed a bimodal distribution in two dominant orientations: northwest-southeast and northeast-southwest (Williams, 1985).

Recent work by Diodato (1999) and Evans (Bob Evans, Southwest Florida Water Management District, written commun., 1999) identified 33 and 103 photolinear features, respectively, within the EW well field and surrounding area. Each used photographs at different scales but followed similar methods in transferring interpreted photolinear features to base maps. Methods for the photolineament analysis conducted by Nettles and Vandor Inc. (1988b) could not be determined and were not included in the analysis presented here. The same photolineaments were not identified by Diodato or Evans, nor do they share a similar dominant directional orientation (fig. 6). Photolineaments identified by Evans did not have a dominant direction of orientation; those identified by Diodato showed a nearly bimodal distribution of cumulative length and dominant orientation northeast-southwest, similar to one of the modes determined by Williams (1985). The northeast-southwest direction of photolinear features also corresponds to the observed increases in chloride concentrations found in ground-water samples from the southwestern part of the EW well field.

The origin of photolinear features likely affects their length and orientation. Williams (1985) observed that joints induced by earth tides result in short photolinear features, whereas large-scale tectonic structural origins create longer photolinear features. Comparing the Diodato and Evans data demonstrates that differences in the number and frequency of observed photolinear features may correspond to differences in origin, scale, source photography, and interpretation methods. The similarities between Williams (1985), Diodato (1999), and the orientation of chloride concentrations, however, indicate that structural control may exist, and is reflected as discernable photolinear features at land surface.

Geologic structure was investigated using land-based high-resolution seismic-reflection survey methods. Four seismic-reflection transects, run in the southwestern section of the EW well field, correlated well with geologic borehole data (fig. 7). Dolomite units, which are denser than limestone units, were detected as well-defined, high-amplitude reflectors in all four transects. Friable or soft limestone noted in geologic logs correlated, respectively, with discontinuities or very faint to nonexistent reflectors in some of the records. Records for transects 1 and 4 were of the highest quality and had good geologic information for correlation (fig. 7). The reflector corresponding to dolomite (about 300 ft below land surface) appeared clearly in the record for transect 4 and corresponds to dolomite noted in lithologic logs for wells SWI-10S and 10D (fig. 7B). Although geologic control was limited to shallow depths along transects 2 and 3, the laterally discontinuous presence of the dolomite reflector corresponded to the intermittent presence noted in other lithologic logs. The dolomite unit appears to be missing in the seismic record of transect 2 between monitoring well 3B and production well 4A, and was not noted in either of the lithologic logs.

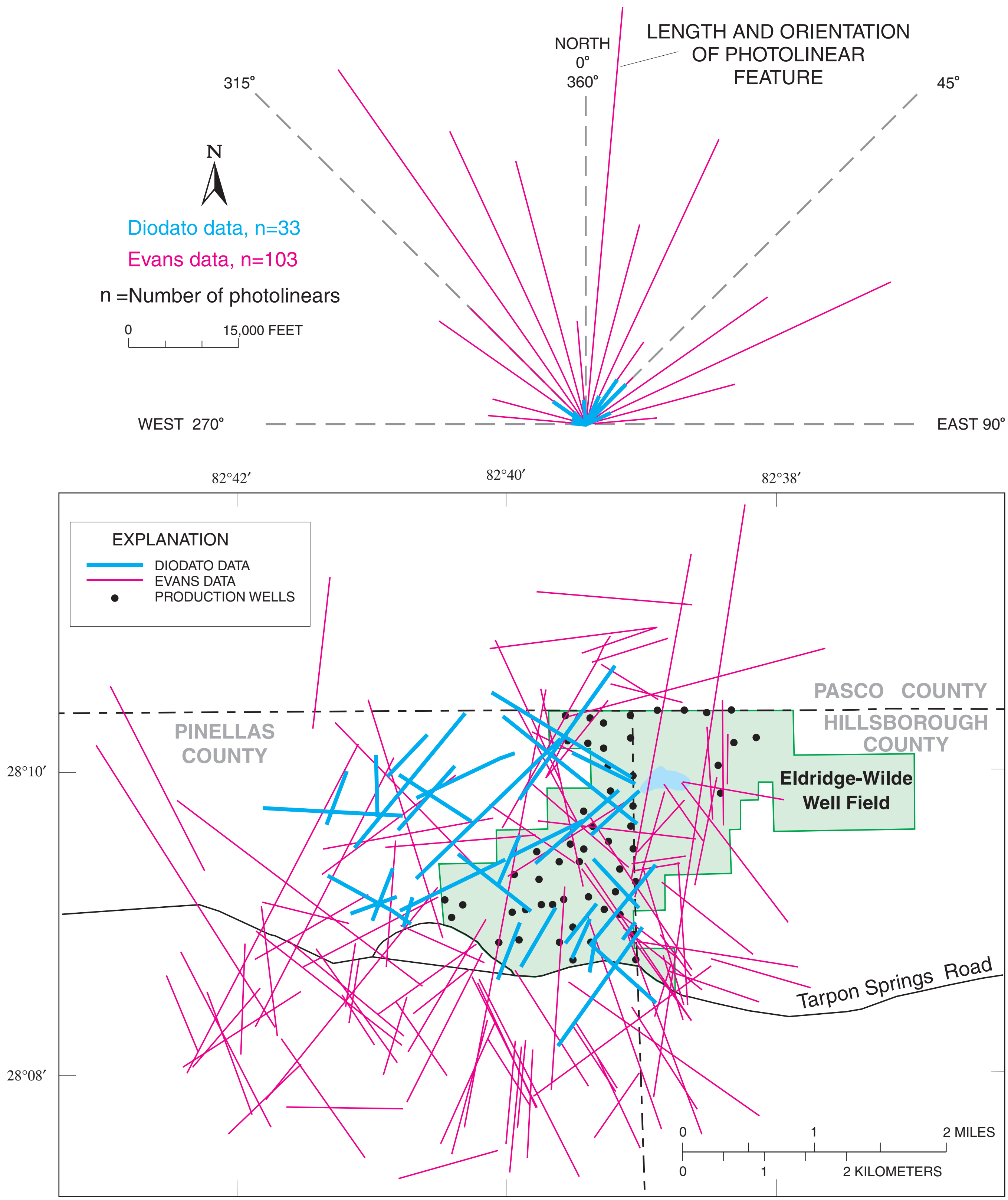


Figure 6. Location and orientation of fracture traces and photolineaments interpreted from aerial photographs. Modified from Diodato (1999) and Bob Evans, Southwest Florida Water Management District, written commun. (1999).

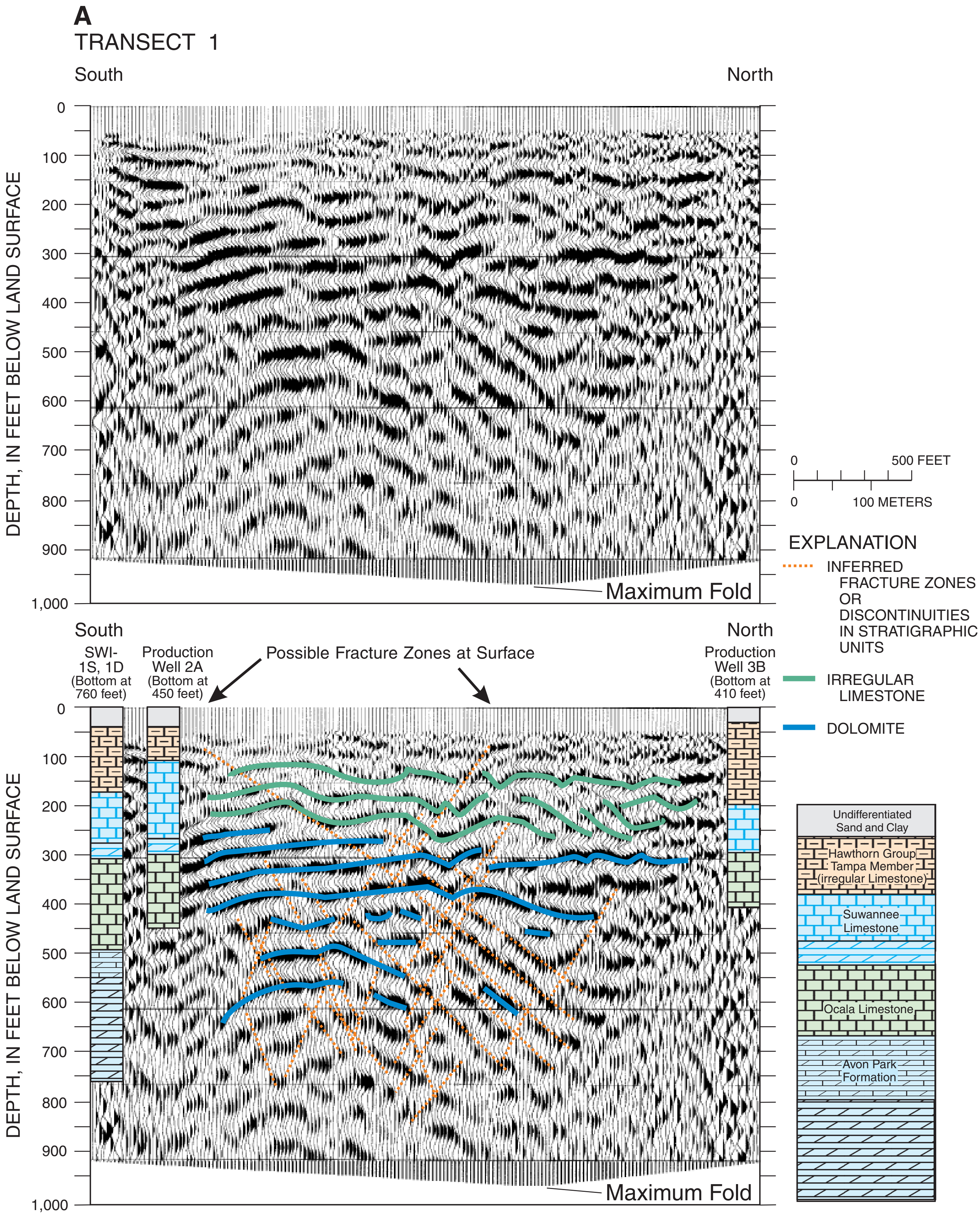


Figure 7. Seismic-reflection data for transects 1 (fig. 7A) and 4 (fig. 7B), with geologic correlation and interpretations of subsurface features. Locations of transects and control wells are shown in fig. 2.

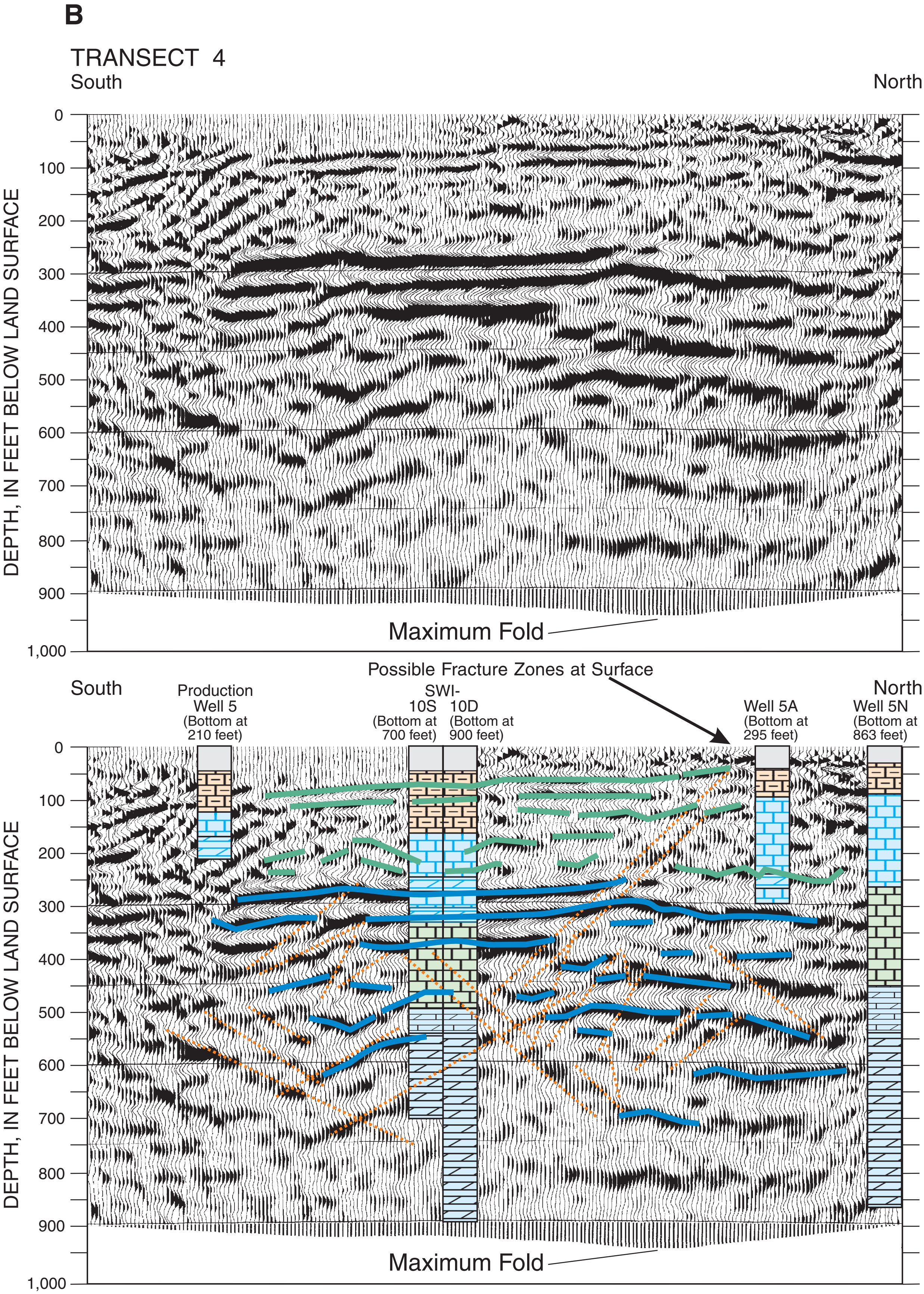


Figure 7. Seismic-reflection data for transects 1 (fig. 7A) and 4 (fig. 7B), with geologic correlation and interpretations of subsurface features. Locations of transects and control wells are shown in fig. 2. (Continued)

Along transects 1 and 4, dolomite present at the contact between the Suwannee and the Ocala Limestones correlated with a persistent, but intermittent reflector that divided the seismic data into two distinct seismic-data types. Above the lithologic contact, seismic-reflection characteristics include reflectors that are undulatory, discontinuous, and poorly defined, indicating an irregular karstic limestone. Below the contact, high-angle, high-amplitude, and discontinuous horizontal reflectors correspond to the lower Ocala Limestone and the Avon Park Formation. The undulatory reflectors observed in the seismic-reflection data correspond to the Suwannee Limestone and indicate dissolution mechanisms. Dissolution of bedding planes and the formation of caverns generally are best developed within the Suwannee Limestone (Hammes, 1992). The distinct reflection pattern in the seismic data for the Ocala Limestone and Avon Park Formation indicates that fractures associated with dolomitic units produce an identifiable seismic signature. Fractures are less common in the Tampa Member and Suwannee Limestone, but commonly are found in the lower Ocala Limestone and the Avon Park Formation (Gee and Jenson, Inc., 1981a).

Fractures or stratigraphic zones containing fractures were inferred on the seismic-reflection data where angular reflectors and disruption and discontinuities of reflectors were noted (fig. 7). Some of the inferred fractures or discontinuities were tentatively identified extending upward into the most shallow carbonate units (less than 50 ft below land surface), particularly in the area between wells 3B and 4A. Although photolinear features do not appear to cross transect 4, several photolinear features cross transects 1, 2, and 3. Several features are in the vicinity of wells 2A, 3B, 4S, and 4A. Fractures inferred in transects 2 and 3 also appear to extend into shallow geologic units. Along transect 4, the inferred fractures are more limited to the Avon Park Formation.

Fractures observed in the acoustic televiewer data corresponded to the change in the character of the seismic-reflection data. Individual fractures and caverns identified on the acoustic televiewer logs from selected wells in the lower Ocala Limestone and the Avon Park Formation are shown in figure 8. Fractures observed in the acoustic televiewer logs ranged from nearly horizontal to nearly vertical (85 degrees). Based on the sesimic-reflection surveys and acoustic televiewer data, structural disruption of laterally continuous units most likely occurs when the units are intersected by fractures. Fractures appear to dominate the lower part of the Ocala Limestone and the Avon Park Formation. The presence of individual fractures within the upper Ocala and much of the Suwannee Limestones could not be determined using the acoustic televiewer tool because the boreholes were enlarged by washout of these less competent units. The seismic-reflection data, however, indicate that fractures may extend upward into both the Ocala and Suwannee Limestones.

Structural features (photolineaments, fractures, or enlarged caverns) create pathways that could enhance ground-water flow and allow deep ground water to move into shallow aquifers. Sinkhole occurrence, water-quality changes, and increased specific capacities of wells tend to align along photolineaments, providing further evidence that deep structural features may be important in controlling ground-water flow patterns (Nettles and Vandor, Inc., 1988a,b; Diodato, 1999).

Fractures and other structural features may create preferential flow paths that cross stratigraphic units, connecting deep and shallow flow zones within the aquifer. The lateral continuity of the dolomite unit at the base of the Suwannee Limestone may also be an important control with respect to ground-water flow, because abrupt changes in lithology can create zones along which ground water moves preferentially.

Delineation and Hydraulic Properties of Permeable Zones

Hydraulic properties of the UFA, including porosity, hydraulic conductivity, transmissivity, and specific capacity were compiled from published aquifer tests within and near the study area. These data reflect the hydraulic properties for the entire UFA and for specific individual stratigraphic units (figs. 3, 5; table 2). In this study, these properties were correlated with features identified in the seismic-reflection data and the acoustic televiewer and caliper logs to determine how structural features influence hydraulic properties of the hydrogeologic units.

The heterogeneous distribution of permeability within the UFA reflects variations in lithologic characteristics, postdepositional alterations, lateral continuity of units, and structural features. Within the study area, the UFA comprises four distinct hydrogeologic units: the Tampa/Suwannee producing zone, the Ocala semiconfining unit, the Ocala/Avon Park producing zone, and the Avon Park producing zone (fig. 5). Generally, permeability ranges from moderate to high in the Tampa/Suwannee producing zone to very high in the Avon Park producing zone (fig. 9). Wells in west-central Florida with open intervals that span varying depths within the UFA have transmissivity values that range from 1,900 to more than 920,000 ft^2/d, with a maximum value of 1,200,000 ft^2/d (Ryder, 1981; Dames and Moore, 1988; CH2M Hill, Inc., 1990a,b; Southwest Florida Water Management District, 1996a,b, 2000a). Transmissivity within the fractured dolomites of the Avon Park producing zone can be greater than 800,000 ft^2/d. Near or within the EW well field, published estimates of transmissivity values for partial thicknesses of the UFA (within the Tampa-Suwannee Limestone and the Suwannee-Ocala Limestones) range from 35,400 to 58,800 ft^2/d. Transmissivity values for the entire thickness of the UFA in this same area range from 55,100 to 109,000 ft^2/d, reflecting the influence of the highly transmissive Avon Park producing zone (Southwest Florida Water Management District, 1996a,b, 2000a) (fig. 9, table 2). The overall permeability of the UFA mainly reflects the contributions from discrete permeable zones within the UFA. The Ocala semiconfining unit, with transmissivity values ranging from 3.8 to 1,000 ft^2/d, generally restricts vertical movement between the more permeable units, although structural features and discontinuities may locally provide hydraulic connections between the more permeable zones.

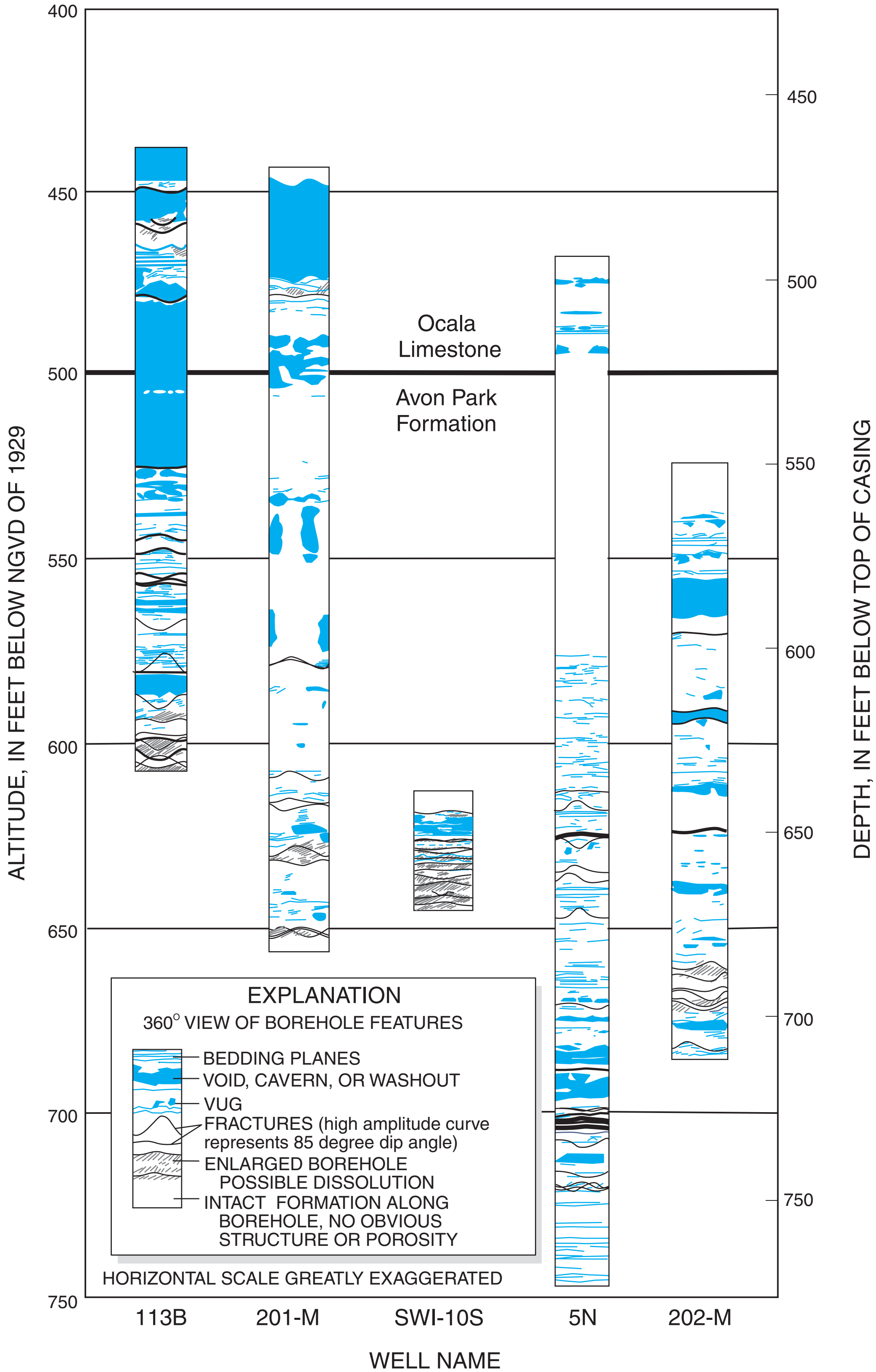


Figure 8. Acoustic televiewer log interpretations for selected boreholes located within the study area.

Table 2. Transmissivity values for selected depth intervals and specific stratigraphic units of the Upper Floridan aquifer within or near the Eldridge-Wilde well field.

[ft, feet; bls, below land surface; ft^2/d, feet squared per day; A, aquifer test; P, packer test. Data compiled from Southwest Florida Water Management District (SWFWMD), 1996a; 2000a]

Well name	Stratigraphic unit	Depth interval (ft bls)	Thickness (ft)	Transmissivity (ft^2/d)	Test type	Data source
EW PW-113	Upper Floridan aquifer (Tampa Member-Ocala, Suwannee Limestones-Avon Park Formation)	183 - 647	464	109,000	A	Nettles and Vandor, Inc. (1988a)
EW PW-134	Upper Floridan aquifer (Tampa Member-Ocala, Suwannee Limestones-Avon Park Formation)	84 - 777	693	93,600	A	Nettles and Vandor, Inc. (1988a)
WRAP-3D	Upper Floridan aquifer (Tampa Member-Ocala, Suwannee Limestones-Avon Park Formation)	173 - 1132	959	55,100	A	SWFWMD (1996a)
EW PW 5	Tampa Member-Suwanee Limestone	59 - 300	241	58,800	A	Wolansky and Corral (1985)
EW PW 4A	Tampa Member-Suwanee Limestone	74 - 210	136	40,100	A	Nettles and Vandor, Inc. (1988a)
EW PW 1	Tampa Member-Suwanee Limestone	173 - 380	207	35,400	A	Wolansky and Corral (1985)
WRAP-4D	Suwannee Limestone	180 - 579	399	7,700	A	SWFWMD (1996a)
WRAP-3D	Suwannee Limestone	173 - 500	327	3,000	A	SWFWMD (1996a)
EAST LAKE WELL 19	Suwannee-Ocala Limestones	250 - 450	200	47, 200	A	Nettles and Vandor, Inc. (1989)
WRAP-1D	Ocala Limestone	391 - 473	82	1,000	A	SWFWMD (1996a)
WRAP-4D	Ocala Limestone	437 - 579	142	284	P	SWFWMD (1996a)
WRAP-3D	Ocala Limestone	473 - 500	27	248	P	SWFWMD (1996a)
WRAP-3D	Ocala Limestone	380 - 398	18	70	P	SWFWMD (1996a)
WRAP-1D	Ocala Limestone	464 - 470	6	3.8	P	SWFWMD (1996a)
WRAP-1D	Avon Park Formation	660 - 691	31	168	P	SWFWMD (1996a)
McKAY CREEK injection site	Avon Park Formation	940 - 1,028	88	896,000	A	Hickey (1977, 1982)
WRAP-1D	Avon Park (evaporite units)	1,146 - 1,210	64	6.4	P	SWFWMD (1996a)
WRAP-3D	Avon Park (evaporite units)	1,061 - 1,107	46	3.0	P	SWFWMD (1996a)
WRAP-4D	Avon Park (evaporite units)	1,192 - 1,234	42	0.71	P	SWFWMD (1996a)

The higher transmissivity values observed in both the Tampa/Suwannee and the Avon Park producing zones are attributed to well-developed secondary porosity. Water-producing zones are associated with fractures, cavities, or solution-enhanced bedding planes that provide potential pathways for conduit flow. These features, if interconnected, can convey large quantities of water (Knochenmus and Robinson, 1996). Units with substantial intergranular (primary) porosity but less well-developed secondary porosity, such as the Ocala semiconfining unit, have relatively lower permeability, and separate the more permeable zones.

Caliper and acoustic televiewer logs can be used to characterize lithologic properties at individual boreholes, and, by combining information from multiple boreholes, to assess the lateral continuity of specific features or hydrologic units over a larger area. Properties, such as hardness, degree of cementation, and the type and regional extent of porosity development at the formation scale, can be correlated to measured hydraulic properties, such as hydraulic conductivity and transmissivity. Voids, vugs, bedding planes, and fractures were identified in caliper and acoustic televiewer logs from selected wells in the EW well field (fig. 8). Caliper data were used to identify specific borehole characteristics that may indicate general lithologic characteristics that influence hydraulic properties. Large washout areas in caliper logs commonly correlated to poorly lithified units (fig. 10). Consistent borehole diameter in a caliper log generally indicated a well-lithified unit. Fractures within dolomite units presented as discrete enlargements in the caliper record. Fractures were associated with the dolomitic units, and were most common within the Avon Park Formation (figs. 8, 10)

The type and extent of porosity development was evaluated for sections of the UFA using caliper and acoustic televiewer logs, which were then compared to porosity measurements determined from other investigations (figs. 5, 8).

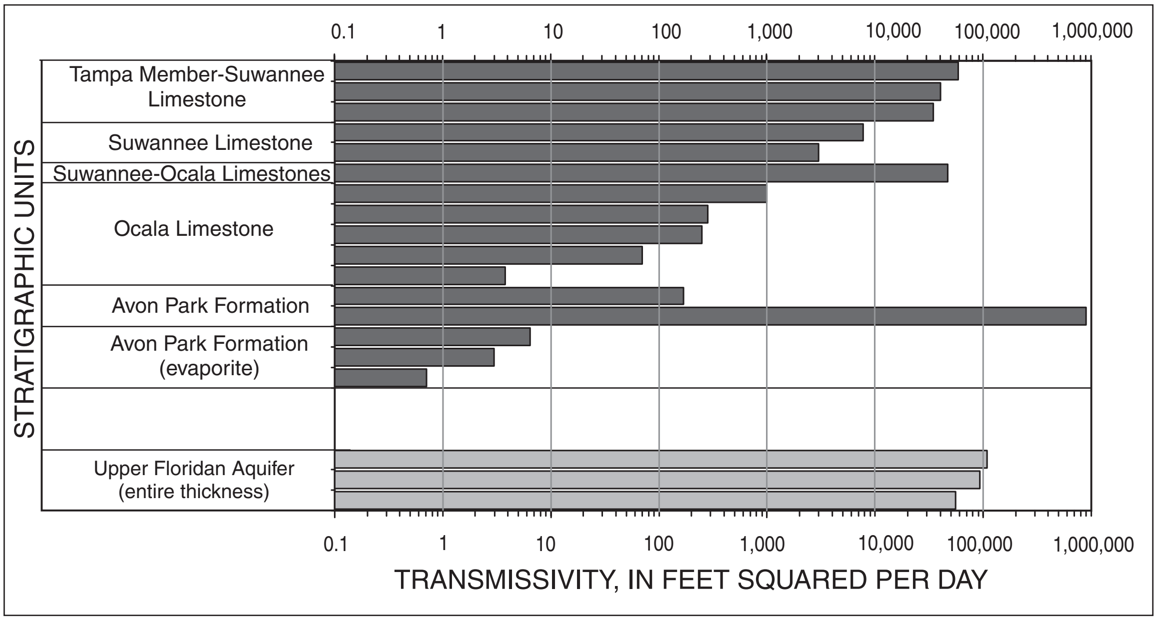


Figure 9. Transmissivity of selected depth intervals and specific stratigraphic units of the Upper Floridan aquifer within or near the Eldridge-Wilde well field. Site names and values are shown in table 2. Compiled from Southwest Florida Water Management District (1996a; 2000a).

Porosity within a particular unit may be very high, but the overall permeability of that unit may be low because the percentage of interconnected void space per total rock volume is low. For example, the Avon Park Formation has the lowest effective porosity compared to the Ocala Limestone, which has the highest effective porosity, and yet, the Avon Park Formation is nearly 3,000 times more transmissive than the Ocala Limestone. This difference indicates that hydraulic conductivity and porosity values determined from cores should be used cautiously, because they may not describe formation-scale properties. Effective porosities in the UFA measured in carbonate cores from six selected sites in west-central Florida, ranged from 2 to 49 percent (Knochenmus and Robinson, 1996; Southwest Florida Water Management District, 1996a).

Another method for delineating producing zones is to measure the specific capacity for individual wells. Specific capacity is the yield of the well per unit of drawdown in the water level, which is expressed as gallons per minute per foot of drawdown (gal/min/ft). Although specific capacity generally varies with duration of pumping, specific capacity measurements from wells with limited open-hole intervals can provide information about the productivity of specific units or features. Specific capacity can be measured repeatedly for a well. The original specific capacity is determined upon completion of a well. Subsequent specific capacity measurements can be made after a well is deepened or modified when the specific capacity of the well likely has changed. In this report, final specific capacity refers to the most recently reported specific capacity data available at the time of this report (app. A). Specific capacity data also can be used to calculate transmissivity values (Driscoll, 1986). Within the study area, calculated transmissivities for the production wells at EW using the final specific capacity values reported in appendix A ranged from 10,700 to 160,400 ft^2/d, with a median value of 46,800 ft^2/d.

Specific capacity values from multiple wells open to similar hydrogeologic units were compared to determine the effect of structural features, specific producing zones, or stratigraphic units on hydraulic properties. For 19 wells open to the Tampa Member and Suwannee Limestone (average well depth of 277 ft), the specific capacity values ranged from 39 to 320 gal/min/ft, with an average of 125 gal/min/ft (app. A., fig. 11). Thirty-four wells open to the Tampa Member and both the Suwannee and Ocala Limestones (average depth of 372 ft), had specific capacity values ranging from 13 to 600 gal/min/ft with an average of 121 gal/min/ft. The additional average well depth of 100 ft into the Ocala Limestone did not improve the average specific capacity, which reflects the lower transmissivity of the Ocala Limestone compared to other stratigraphic units composing the UFA. Twenty-three wells open to the Avon Park Formation (average depth of 771 ft), had specific capacity values that ranged from 86 to 563 gal/min/ft, with an average of 309 gal/min/ft. The increase in specific capacity resulted from these wells intersecting the highly permeable fracture zones within the Avon Park Formation (fig. 11a). The SWFWMD (1996a) documented a similar increase in specific capacity with depth in wells WRAP-1D, WRAP-3D and WRAP-4D, tapping a highly transmissive zone in the Avon Park Formation.

Within the well field, specific capacity values increase with increasing length of open hole. Specific capacity values for all 58 production wells in the EW well field range from 40 to 600 gal/min/ft, and average 208 gal/min/ft (Black, Crow, and Eidsness, Inc., 1970; Gee and Jenson, Inc., 1981a,b, 1983;

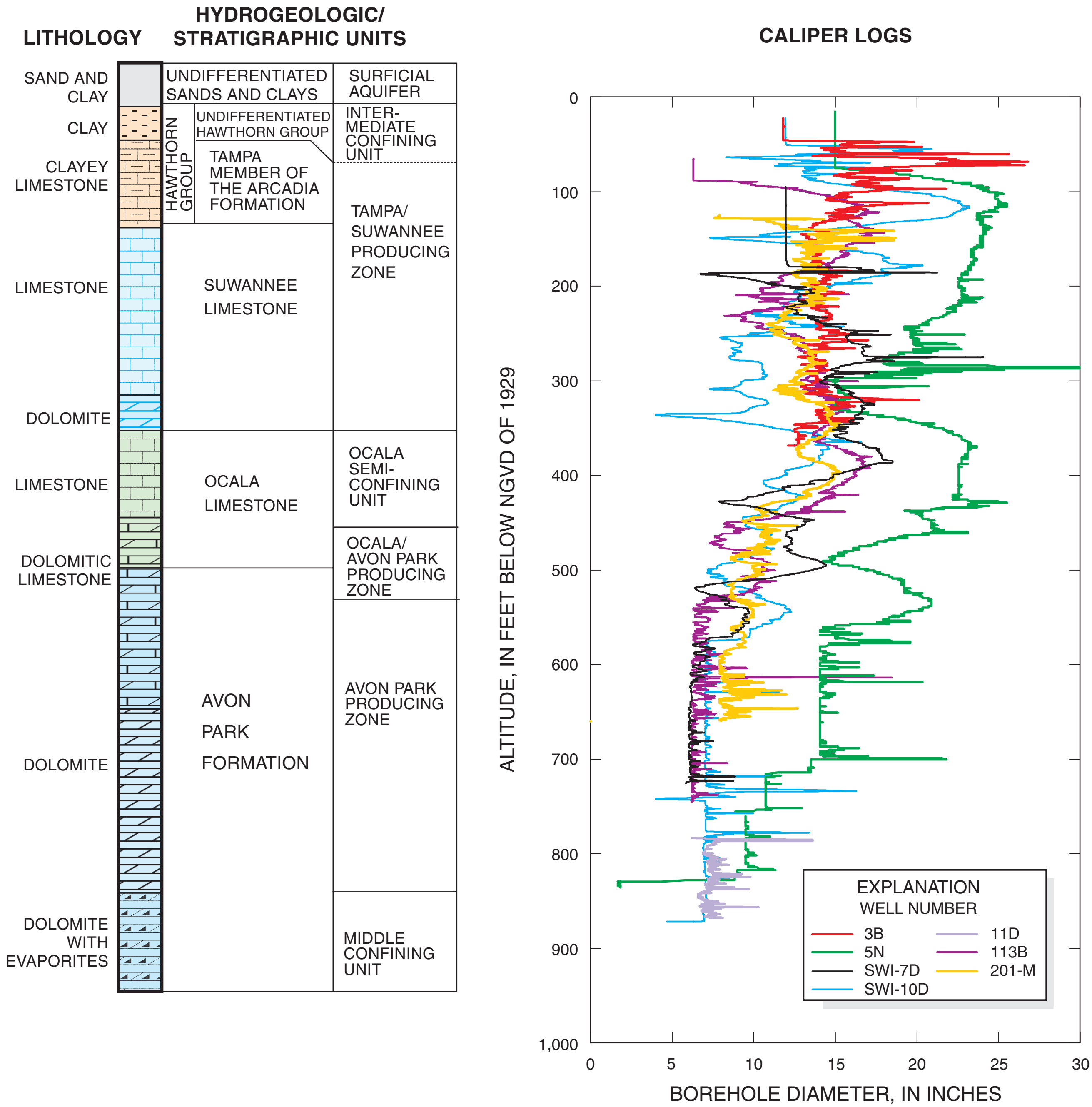


Figure 10. Hydrogeologic units, producing zones, lithology, and caliper logs collected at selected wells located within or near the Eldridge-Wilde well field. Well locations shown in fig. 2.

Nettles and Vandor, Inc., 1985) (fig. 11a). The highest specific capacity values are in the northern and eastern parts of the well field where production wells are deeper (average depth of 771 ft), open to multiple producing zones, and tap the Avon Park producing zone. Wells in the southwestern part of the well field have an average depth of 277 ft and tap only the Tampa Member and the Suwannee Limestone. These shallower wells have lower specific capacity values than the deeper wells. When specific capacity data are normalized to length of open-hole interval, however, data from different wells with different lengths of open hole are more comparable. Normalized specific-capacity data show that wells in the southwestern part of the well field have some of the highest specific capacity values within the well field (fig. 11b). The Tampa Member and the Suwannee Limestone apparently have substantial producing zones, which may be related to stratigraphic characteristics, porosity, structural features, and (or) discontinuities in the geologic framework (fig. 11b) (app. A).

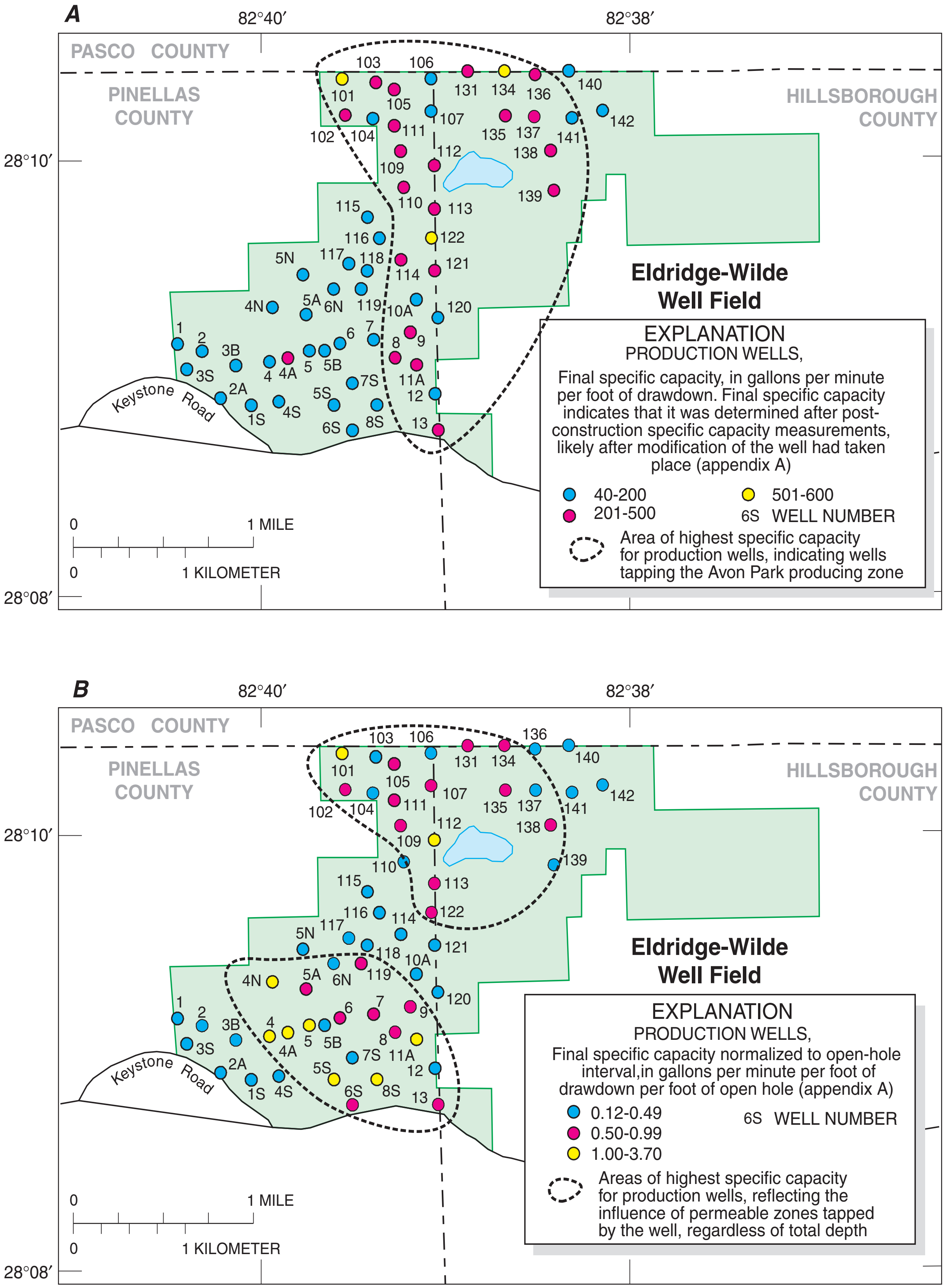


Figure 11. Specific capacity data for wells at the Eldridge-Wilde well field by (A) final specific capacity, and (B) final specific capacity normalized for length of open hole. Data are provided in appendix A; from Black, Crow, and Eidsness, Inc. (1970); Gee and Jenson, Inc. (1981a,b; 1983); Nettles and Vandor, Inc. (1985).

Tampa/Suwannee Producing Zone

Detailed studies at specific sites in Pinellas County have delineated at least three permeable zones and two semiconfining units within the Tampa Member and the Suwannee Limestone, indicating that some of these zones can be laterally continuous (Hickey, 1982; Knochenmus and Thompson, 1991; Knochenmus and Swenson, 1996; Broska and Barnette, 1999). Transmissivity values for the Tampa/Suwannee producing zone determined outside the well field but within west-central Florida range from 18,700 to 73,500 ft^2/d (Dames and Moore, 1988; Southwest Florida Water Management District, 1996a,b, 2000a) (fig. 9). These values are similar to values for the entire UFA and are some of the highest values determined for all stratigraphic units within the UFA. Normalized specific capacity data also indicate that the Tampa/Suwannee producing zone is an important producing zone within the EW well field. Within the well field, transmissivity values for the Tampa/Suwannee producing zone range from 35,400 to 58,800 ft^2/d (table 2) (Wolansky and Corral, 1985; Nettles and Vandor, Inc., 1988a). Wells 4, 4A, and 5, in the southwestern part of the well field, are open to this unit and all have normalized specific capacity values of 1 or greater (fig. 11b).

Porosity of the Tampa/Suwannee producing zone has been characterized as fractured and vuggy with cavities (Knochenmus and Robinson, 1996). Although porosity varies markedly within the Suwannee Limestone, the porosity range is similar to that of the Tampa Member, ranging from 21 to 42 percent (Knochenmus and Robinson, 1996). Primary pores in the grainstones and packstones in the Tampa Member are responsible for more than 75 percent of the rock porosity, which has been estimated to be 29 percent (Knochenmus and Robinson, 1996). Depending on clay content and borehole stability, the Tampa Member may be cased. Where the borehole is left open for a production well, caliper logs indicate that the unit is often washed out during drilling, likely a result of poor induration and high intergranular porosity (fig. 10). Boreholes open to the Tampa/Suwannee producing zone exhibit a wide range in caliper diameter between individual sites, indicating that the unit is highly variable in hardness and porosity (fig. 10). Enlarged borehole conditions typically extend 5 in. beyond the original borehole diameter (fig. 10). Because of the extent of cavity development, many of the observed fractures may be the result of cavity collapse and failure. Drilling techniques can affect caliper logs, as Safko and Hickey (1992) and Duerr (1995) suggested that borehole characteristics seen in caliper logs can be a result of drilling activity. Although drilling techniques do affect borehole characteristics, the resulting caliper logs reflect variations in lithologic properties.

Regionally, the Suwannee Limestone is well lithified and maintains a more consistent borehole diameter near the base, where dolomite commonly is present near the contact with the Ocala Limestone (fig. 10). Porosity within the Suwannee Limestone does not appear to correspond to vertical stratigraphic trends within the unit, indicating that secondary porosity is important (Hammes, 1992). The karst features that are characteristic of the Suwannee Limestone are responsible for much of the secondary porosity (Hammes, 1992). Ground-water flow and subsequent dissolution of limestone along these pathways maintain and enlarge these features, resulting in the productive zones observed within the Tampa Member and the Suwannee Limestone.

Ocala Semiconfining Unit

The Ocala Limestone is a fine-grained, pure limestone that is poorly indurated in parts of the unit, and contains abundant foraminifera. Because the Ocala Limestone likely was not subaerially exposed to any degree, the unit has maintained much of the original depositional properties and has less well-developed secondary porosity than the Suwannee Limestone (Loizeaux, 1995). Porosity in the Ocala Limestone ranges from 12 to 41 percent with an average of 32 percent (Loizeaux, 1995). Effective porosity measurements compiled by Knochenmus and Robinson (1996) for porosities classified as intergranular to moldic are slightly higher, ranging from 27 to 49 percent. Porosity can be associated with depositional facies, so if specific depositional facies are laterally extensive, they may have an effect on areal hydrologic properties. A zone of higher vertical conductivity within the Ocala Limestone has been mapped along a northeastern-southwestern trend through Pasco, Pinellas, and Hillsborough Counties. The higher vertical conductivity corresponds to a coarse-grained facies that is dominated by interparticle and macro porosity (Loizeaux, 1995).

Transmissivity in discrete depth intervals within the Ocala semiconfining unit at three wells surrounding the EW well field ranges from 3.8 to nearly 1,000 ft^2/d, averaging 320 ft^2/d (table 2, fig. 9). These data indicate the variability as well as the relatively low permeability of the Ocala Limestone compared to other stratigraphic units within the UFA. The higher transmissivity values usually correspond to the lower Ocala Limestone, which forms part of the Ocala/Avon Park producing zone.

Caliper logs for nearly all selected wells showed enlarged borehole conditions for the Ocala Limestone owing to the combination of poor induration and washouts created during well construction (fig. 10). The consistent appearance of the enlarged borehole conditions in all caliper logs indicate that this is characteristic of the stratigraphic unit and could be indicative of a regional trend. Enlarged boreholes in this zone make it difficult to collect borehole geophysical data, resulting in the lack of hydrogeologic information about this part of the Ocala Limestone.

Ocala/Avon Park Producing Zone

An increase in transmissivity within the lower Ocala Limestone and the Upper Avon Park Formation results in the Ocala/Avon Park producing zone. The increase in transmissivity is due to a combination of fractures and secondary porosity that were observed in caliper and acoustic televiewer logs in wells within the EW well field (figs. 8, 10). The Ocala

Limestone is characterized by intact units with vuggy porosity interspersed with large sections exhibiting enlarged borehole conditions similar to the Ocala semiconfining unit (at wells 5N, 113B, and 201M) (figs. 8, 10). Although it is nearly a pure limestone, the Ocala Limestone contains some chert and dolomitized sections near the base, which can be extremely hard. Fractures present in the lower parts of this unit are associated with dolomite. Large voids observed in acoustic televiewer data acquired from wells 113-B and 201-M at a depth 450 ft below NGVD of 1929 indicate the porosity is dominated by enlarged horizontal bedding planes. Acoustic televiewer data from deeper wells (202-M and 5N) show the frequency of fractures increasing with depth (fig. 8). This apparent enhanced secondary porosity is consistent with borehole video log data described by Knochenmus and Robinson (1996). Although these zones may have been created by drilling activity and (or) associated washout zones, the appearance of fractures and (or) large voids corresponds to higher transmissivity and specific capacity observed at the contact between the lower Ocala Limestone and the upper Avon Park Formation (table 2) (Southwest Florida Water Management District, 1996a). The combination of large solution-formed caverns and fractures likely increases the secondary porosity within the lower Ocala Limestone and the Upper Avon Park Formation (Hickey, 1982; Dames and Moore, 1988; Loizeaux, 1995; Knochenmus and Robinson, 1996; Southwest Florida Water Management District 1996a).

Avon Park Producing Zone

The Avon Park producing zone is the most important water-producing zone in the UFA in Florida. Fractured dolomite supplies the majority of water to wells open to the entire UFA (Ryder and Mills, 1978; Ryder, 1985; CH2M Hill, Inc.,1990a,b; HydroGeologic, Inc., 1992). Porosity derived from cores ranges from 2 to 25 percent, but core samples from this unit disproportionately represent the least permeable zones. Fracture porosity and formation-scale porosity cannot be measured at the core scale, therefore, hydraulic analyses of core materials are not an effective way to measure the overall permeability of this unit (Knochenmus and Robinson, 1996). The regional transmissivity values for the Avon Park Formation derived from aquifer tests at six sites in west-central Florida range from 98,000 to 1,200,000 ft^2/d (Dames and Moore, 1988). At McKay Creek, southwest of the study area, an 88-ft-long section of the Avon Park producing zone had a transmissivity of 896,000 ft^2/d (Hickey, 1982). Southeast of the well field at well WRAP-1D, a 30-ft-long section of the Avon Park producing zone had a transmissivity value of 168 ft^2/d (Southwest Florida Water Management District, 2000a).

The Avon Park Formation is approximately 300 ft thick, and is present at an elevation ranging from 475 to 775 ft below NGVD of 1929 (fig. 4). Limestone and dolomitic limestone are present primarily in the upper part of the formation as well as a fine-grained recrystallized packstone (fig. 10). Both the caliper and the acoustic televiewer logs show a marked change at approximately 525-550 ft below NGVD of 1929, corresponding to the increased presence of dolomite (figs. 8, 10). At this depth, borehole diameters are more constant than those observed at shallower depths, and washout sections are uncommon. The distinct change in rock fabric and porosity type marks the presence of continuous dolomite, which is hard, brown, sucrosic in texture, and highly fractured. From approximately 550 to 725 ft below NGVD of 1929, the acoustic televiewer logs show that porosity type is dominated by fractures that do not appear to be substantially enlarged by dissolution. The fractures range from near horizontal to more than 85 degrees from horizontal. Multiple fractures are present, cutting across one another and enlarging the borehole. The observed enlargements associated with fractures and their intersections may be the result of dissolution or drilling activity (Safko and Hickey, 1992).

Specific capacity values generally are greater than 200 gal/min/ft when wells intercept the highly transmissive fractured Avon Park producing zone (Southwest Florida Water Management District, 1996a) (fig. 11). The average original well depth of the 57 wells at the EW well field was 355 ft. In the 1980s, 21 wells at the EW well field were deepened to penetrate the Avon Park Formation. The original specific capacities of these wells ranged from 13 to 231 gal/min/ft with an average of 85 gal/min/ft of drawdown. After deepening the wells, specific capacities ranged from 121 to 563 gal/min/ft, with an average of 319 gal/min/ft of drawdown. The maximum increase in specific capacity was 400 gal/min/ft with an average increase of 230 gal/min/ft. By deepening the wells, the average specific capacity increased by more than 250 percent. Transmissivity calculated for EW production wells that were deepened into the Avon Park Formation had a median value of 90,600 ft^2/d.

No apparent pattern or lateral continuity of specific fractures was observed in the Avon Park producing zone, and the lateral continuity of specific fractures between two or more boreholes was not determined. Although the dominant orientation of the fractures is not known, the fractured unit is a consistent feature throughout Pinellas County (Hickey, 1982). A laterally continuous unit with substantial secondary porosity likely has extensive influence on ground-water movement throughout the region. If the fractures within this zone have a dominant orientation, ground-water movement would likely reflect this influence.

Middle Confining Unit

The transmissivity of the MCU was determined to range from 0.71 to 6.4 ft^2/d at WRAP wells 1D, 3D, and 4D, surrounding the EW well field (Southwest Florida Water Management District, 1996a). No fractures were detected in the televiewer data from well SWI-10D in the lower part of the Avon Park Formation where evaporites are present. Drilling reports for well SWI-10D confirmed this observation and indicated that the characteristic Avon Park fractured zone does not extend much deeper than 800 ft below NGVD of 1929 (Nettles and Associates, Inc., 1991c).

Ground-Water Development and Flow Patterns

The occurrence and quality of ground water within the study area changed as ground-water resources were developed within the EW well field. The spatial distribution and depth of production wells has expanded since the first 19 wells were drilled in the 1950s in the southwestern part of the well field (Black, Crow, and Eidsness, Inc.,1970) (app. A, fig. 12a). The wells were installed in a geometric orientation of three groups; two east-west oriented groups located in the northeastern and the southwestern parts of the well field and a group of wells oriented north to south linking the two east-west trending groups. Pumping zones also vary in a northeast-southwest pattern—the southwestern group of wells generally tap only the shallower Tampa/Suwannee producing zone; the remaining wells generally have large open-hole intervals tapping the entire thickness of the UFA.

Nineteen wells, drilled during the 1950s and located in the southwestern part of the present well-field property, penetrate the Tampa/Suwannee producing zone. Initially, the average well was 277 ft deep with 87 ft of casing and 193 ft of open hole (app. A). The shallowest well was 140 ft and the deepest was 346 ft. From 1960 to 1969, 34 additional wells were drilled. These new wells were constructed primarily to the north and east of the original wells and penetrated the Tampa/Suwannee producing zone and the Ocala semiconfining unit (fig. 12). The average depth was 372 ft, cased to 79 ft, with 289 ft of open hole. The shallowest well was 210 ft and the deepest well was 560 ft.

In the 1970s, five additional wells were drilled—two in the southwestern and three in the central parts of the well field (fig. 12). Wells drilled in the southwestern part of the well field (wells 2A and 3B) were 450 and 410 ft deep, respectively, and were slightly deeper than those drilled in the 1950s. In the central part of the well field, three new wells were drilled to 291, 770, and 809 ft below land surface. Open holes ranged from 168 to 731 ft, with the deeper wells penetrating the Avon Park producing zone.

From 1981 to 1986, 21 preexisting wells at the EW well field were deepened to an average depth of 769 ft (minimum depth of 647 ft and maximum depth of 863 ft) to penetrate the Avon Park producing zone (fig. 12a). The deepened wells were located primarily in the northern and eastern sections of the well field. In 1986, more than 40 percent of the 54 production wells active at the EW well field accessed the Avon Park producing zone. After the wells were deepened, nearly half of the EW well field water (43 percent) was produced from wells with more than 500 ft of open hole tapping the highly transmissive 600-750 ft zone.

Ground-Water Withdrawals and Water Levels

Annual daily average pumpage calculated for the well field from 1956 to 2000 indicates that the lowest production levels occurred in the 1950s when the well field was first put into use (fig. 13). From 1960 to 1970, withdrawals increased from 10 to 25 Mgal/d as the number and spatial extent of wells expanded into the northern part of the well field. Ground-water withdrawals peaked near 35 Mgal/d in June 1973. During this time, withdrawals were limited to the upper part of the UFA including the Tampa Member and the Suwannee and Ocala Limestones (fig. 13).

Although total pumpage peaked in 1973, annual daily average pumpage exceeded 25 Mgal/d for much of the 1980s (fig. 13). Although withdrawals fluctuated from 1975 through 1990, annual daily average pumpage remained above 25 Mgal/d from 1984 until 1991. Lower withdrawals (below 25 Mgal/d) occurred in 1981–1983, in 1993, and in 1995–1999, whereas high withdrawals (above 25 Mgal/d) occurred in 1984–1986, and 1988–1990. Drought conditions during 2000 resulted in increased pumpage. At full capacity in the late 1980s and early 1990s, 58 wells were in operation. In 2002, 36 wells remained operational.

Changes in ground-water flow patterns are the direct result of changing water levels caused by ground-water development. The configuration of the potentiometric surface in the EW well field is influenced by the location of pumping wells, their pumping rates at the time of measurement, and the spatial variation in hydraulic properties of the aquifer and recharge conditions. The mapped potentiometric surface of the UFA shows water-level contours for predevelopment and May 2000 (fig. 14). During predevelopment conditions, contours in the vicinity of the EW well field generally were parallel to the west coast of Florida (Bush and Johnston, 1988) and ground-water flow was from the east to west toward the Gulf of Mexico. In the vicinity of the EW well field, water levels declined 10 to 20 ft from predevelopment levels (Stewart and others, 1971). Potentiometric-surface maps from the 1970's and 1980's show a potentiometric low centered on the EW well field (fig. 15).

Potentiometric-surface maps of the EW well field were constructed for May 1972, and for May and September from 1976 through 1982 (Craig Hutchinson, U.S. Geological Survey, written commun., 1972; Hutchinson and Mills, 1977; Wolansky and others, 1978a; Johnston and others, 1980; Yobbi and others, 1980b; Barr, 1982). Representative maps for this period are shown in figure 15. During the period from 1972 to 1982, a persistent cone of depression was oriented northeast-southwest within the EW well field. To estimate the amount of ground-water decline associated with ground-water withdrawals, an altitude contour representative of the regional UFA potentiometric surface within the EW well field area unaffected by pumping was selected for each map (shown as red contours in figure 15). Declines in the potentiometric surface were estimated by calculating the difference between the representative regional potentiometric surface and the observed minimum altitude of the UFA (shown as bold blue contours in figure 15). Although the shape of the depression changed over time, water-level declines ranging from 6 to 18 ft below the representative regional ground-water level persisted (fig. 15). The change in the shape of the depression appears to be influenced by changes in withdrawal locations.

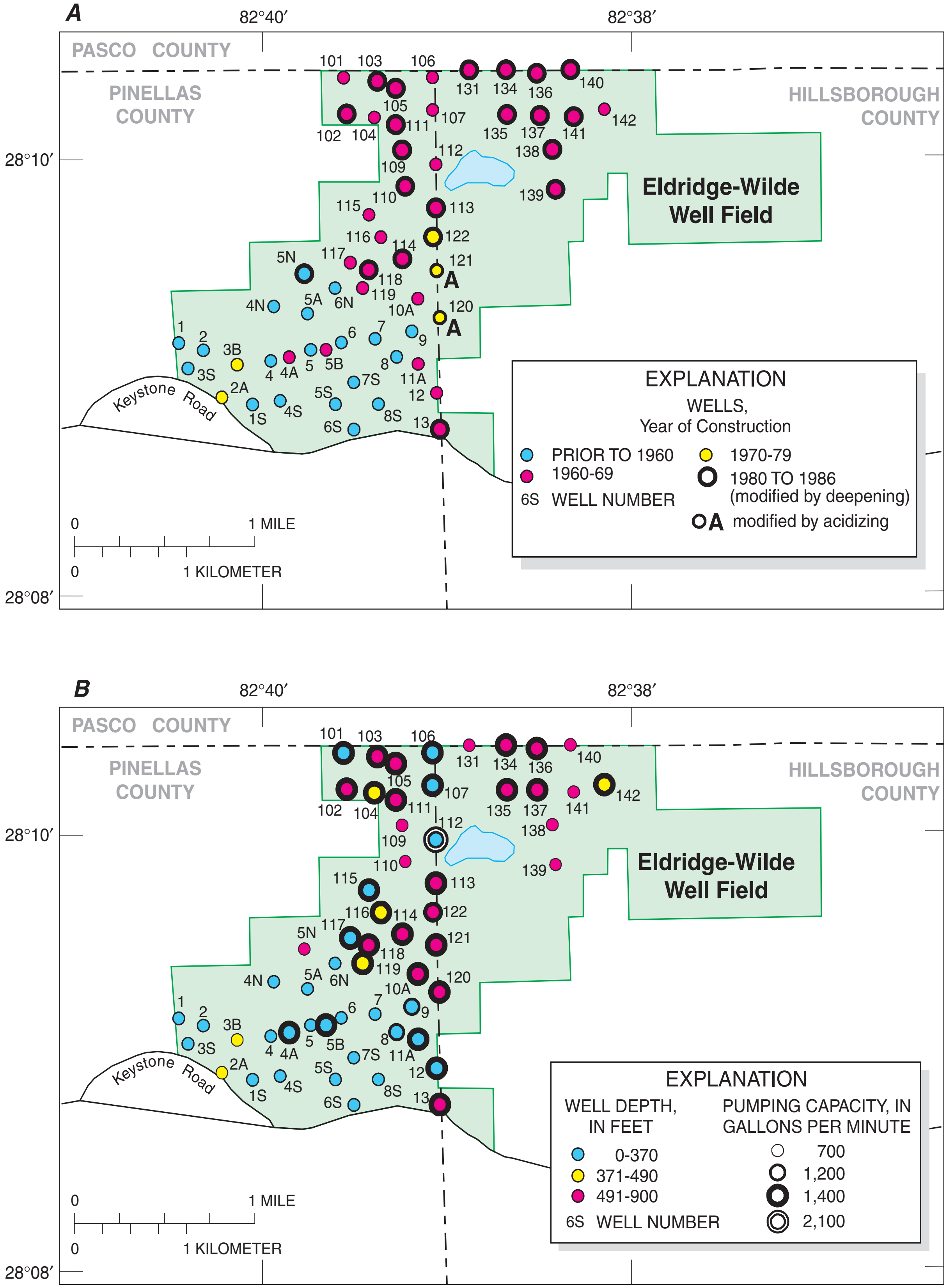


Figure 12. Selected wells at the Eldridge-Wilde well field showing (A) dates of well construction and wells that were deepened from original depth or acidized to increase production, and (B) final well depths and pumping capacity (2002). Data are in appendix A.

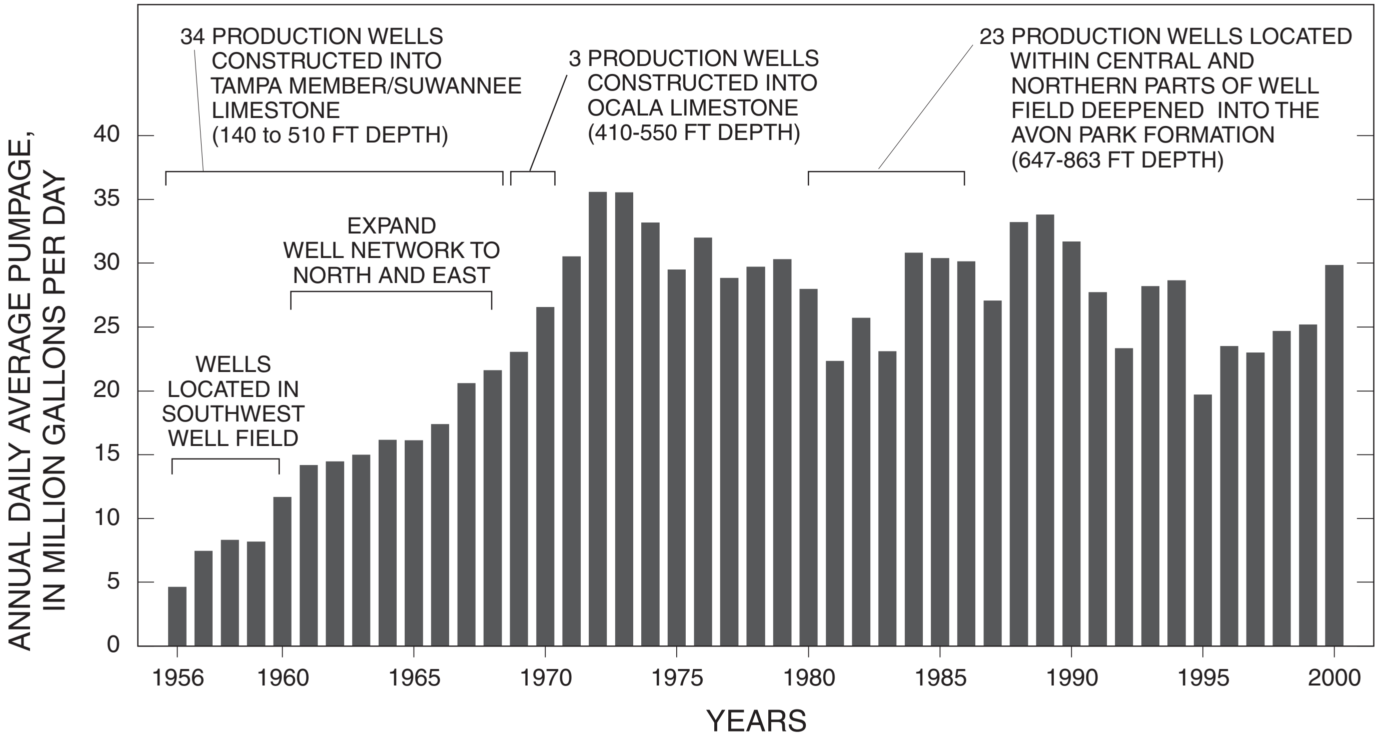


Figure 13. Ground-water withdrawals from the Eldridge-Wilde well field, 1956-2000. Data provided by Tampa Bay Water.

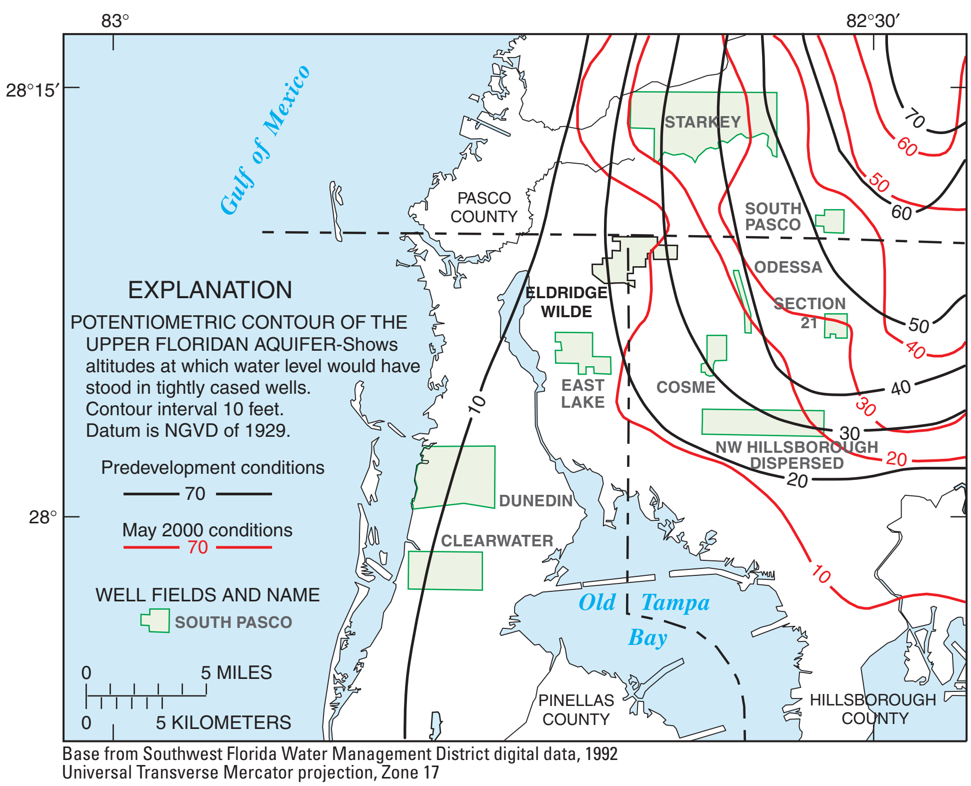
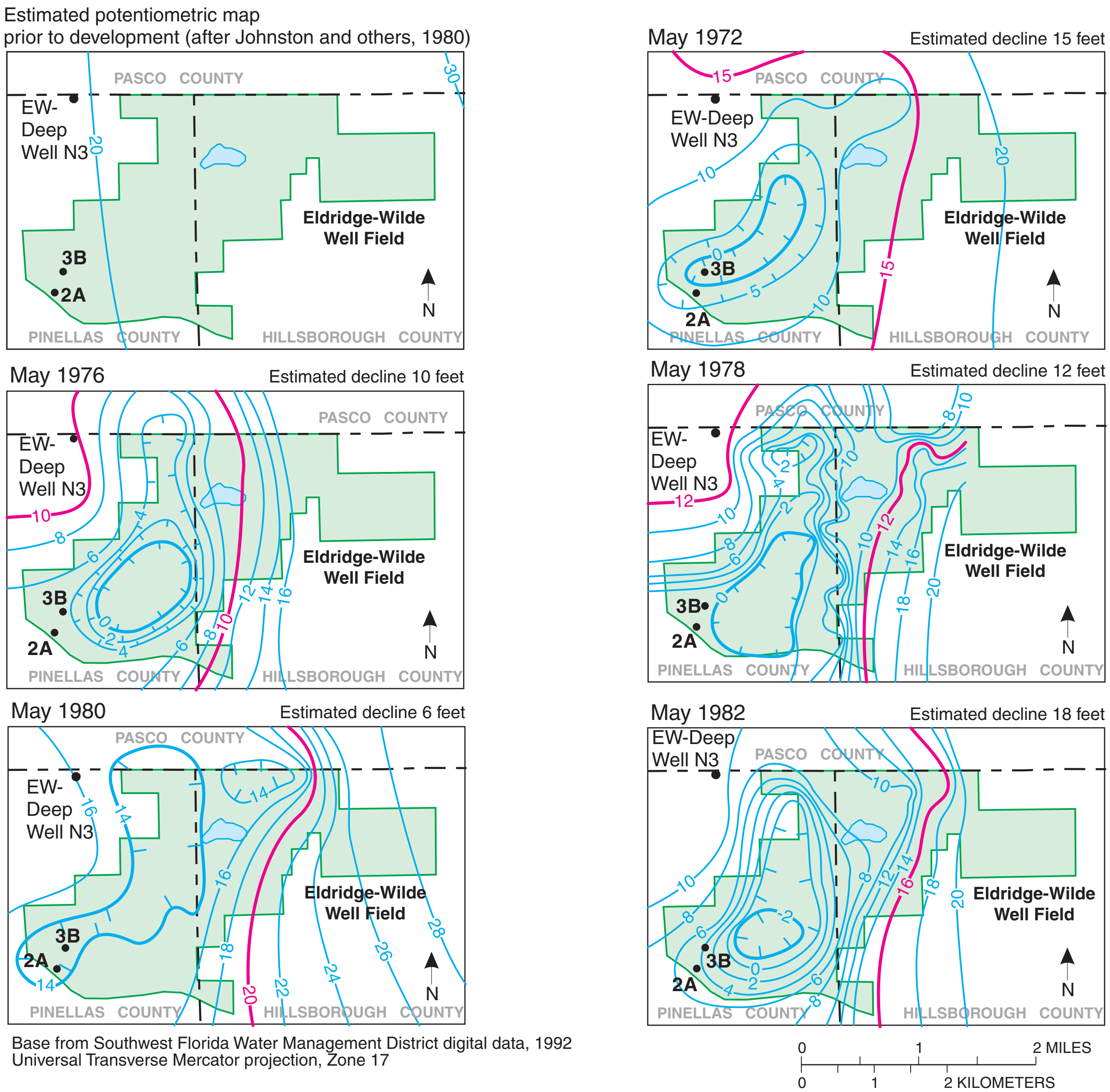


Figure 14. Regional potentiometric surface of the Upper Floridan aquifer for predevelopment conditions and May 2000 hydrologic conditions. Modified from Bush and Johnston (1988) and Duerr (2001).



EXPLANATION

— 8 — POTENTIOMETRIC CONTOUR OF THE UPPER FLORIDAN AQUIFER–Shows altitude at which water level would have stood in tightly cased wells. Contour interval is variable, in feet. Datum is NGVD of 1929. Hachures indicate depression.

—20— REPRESENTATIVE ALTITUDE OF THE REGIONAL POTENTIOMETRIC SURFACE OF THE UPPER FLORIDAN AQUIFER FOR THE ELDRIDGE-WILDE WELL FIELD AREA UNAFFECTED BY GROUND- WATER WITHDRAWALS.

—14— THE OBSERVED MINIMUM ALTITUDE OF THE UPPER FLORIDAN AQUIFER WITHIN THE ELDRIDGE-WILDE WELL FIELD.

Estimated decline 12 feet — ESTIMATED DECLINE–Is the water-level decline associated with well-field withdrawals calculated as the difference between the representative regional (shown in pink contours) and the observed minimum ground-water levels (shown as bold contours) within the Eldridge-Wilde well field.

• 2A — WELL LOCATION AND NAME

Figure 15. Semi-annual potentiometric-surface maps and estimated decline of the Upper Floridan aquifer at the Eldridge-Wilde well field from predevelopment of ground water to 1982. Modified from Hutchinson, U.S. Geological Survey, written commun. (1972); Hutchinson and Mills (1977); Wolansky and others (1978a); Johnston and others (1980); Yobbi and others (1980b); Barr (1982).

From 1972 through 1976, the cone of depression was centered over the southwestern part of the well field, coincident with locations of production wells (Geraghty & Miller, Inc.,1976a,b) (fig 15). From 1977 to 1980, as ground-water withdrawals expanded to the north, the cone of depression extended into the northeastern part of the well field. By 1982, the shape of the cone of depression was an enlarged, elongated, northeast-southwest trending trough across the expanded well field. Water-level declines and their areal extent vary seasonally. Water levels for May (the dry season) are consistently lower over a larger area than those for September. In May 1972, 1976, and 1978, ground-water levels in the southwestern part of the well field were below NGVD of 1929. In May 1982, the maximum decline was 2 ft below NGVD of 1929 and ground-water levels within a large part the well field were 18 ft below representative regional levels.

Although the potentiometric surface of the UFA in the EW well field has not been mapped since 1982, continuous water levels monitored at well EW Deep Well N3 provide a benchmark for water-level changes at the northern boundary of the well field (fig. 15). Because this well is located away from the center of the well field, water levels at this site provide a conservative estimate of water-level changes related to pumping. Water levels in well N3 declined from 1980 to 1990 (fig. 16). From 1990 through 2000, the declining trend was reduced, but larger seasonal changes in maximum and minimum water levels occurred from 1998-2000 (fig. 16). Monthly average water levels in well N3 from 1985 to 2001 were frequently lower than the maximum declines observed in 1982, the last year that potentiometric-surface maps were produced for the well field (fig. 16). Localized lowering of water levels in the vicinity of the EW well field also is shown on the regional potentiometric-surface map of the UFA for May 2000 (Duerr, 2001) (fig. 14). Minimum water levels for the period of record were recorded at EW Deep Well N3 in 2000; water levels were probably even lower within the cone of depression in the central part of the well field during 2000.

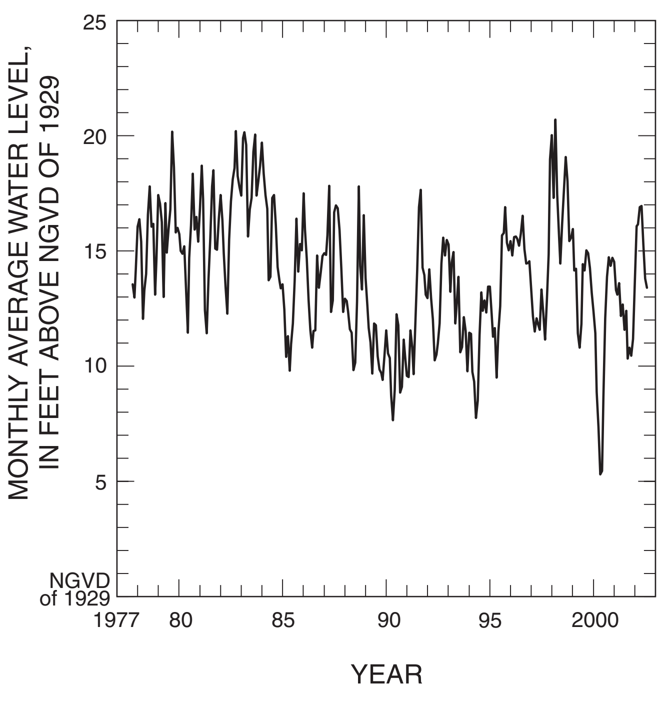


Figure 16. Water levels at Eldridge-Wilde Deep Well N3, 1977-2002. Well location shown in figs. 2 and 15.

Evidence of Ground-Water Flow Patterns from Borehole Logs

The location, extent, and type of permeable intervals present within the UFA at and near the EW well field affect ground-water levels, ground-water flow, and water quality. Permeable intervals, created by zones of increased transmissivities, fractures, and collapse features, provide a complex network of localized pathways for ground-water movement (fig. 17a-d). Zones of high hydraulic conductivities create preferred pathways along which ground water can move. Contrasts in geologic materials, such as abrupt changes in lithology, can produce zones along which ground water moves preferentially. Stratigraphic heterogeneity, occurring when enhanced secondary porosity develops along horizontal beds that produce enlarged bedding planes, results in preferential ground-water flow predominantly in a lateral direction (fig. 17a).

Structural heterogeneity attributed to fractures commonly produces preferential flow paths in a more vertical direction (fig. 17b). In combination, vertical and horizontal features can result in permeable intervals and flow path networks that can be laterally and vertically extensive (fig. 17c). Enhanced secondary porosity due to dissolution along these features can further expedite preferential ground-water movement (fig. 17c).

Pumping from a heterogeneous flow network can result in complex flow patterns (fig. 17d). As pumping lowers heads in the UFA, specific zones respond more readily than others. Head differences between the different permeable zones control the timing and direction of ground-water flow along various permeable zones. Depending on the head gradients and ground-water withdrawals, existing conduits can create pathways along which ground-water movement is intermittent. Withdrawals from multiple boreholes tapping multiple permeable zones can result in complex hydraulic head differences within and between wells, and can induce vertical internal borehole flow. In these instances, production wells function as large vertical conduits interconnecting permeable zones and other wells, and in some cases, degrading potable ground water with water from nonpotable zones (fig. 17d) (Spechler, 1994; Metz and Brendle, 1996).

The locations of flow zones, which are indicative of permeable intervals, were determined using flow logs and fluid conductance logs in the boreholes at wells 2A, 3B, 5N, and 201-M (figs. 18-21, respectively). In well 2A, two permeable intervals

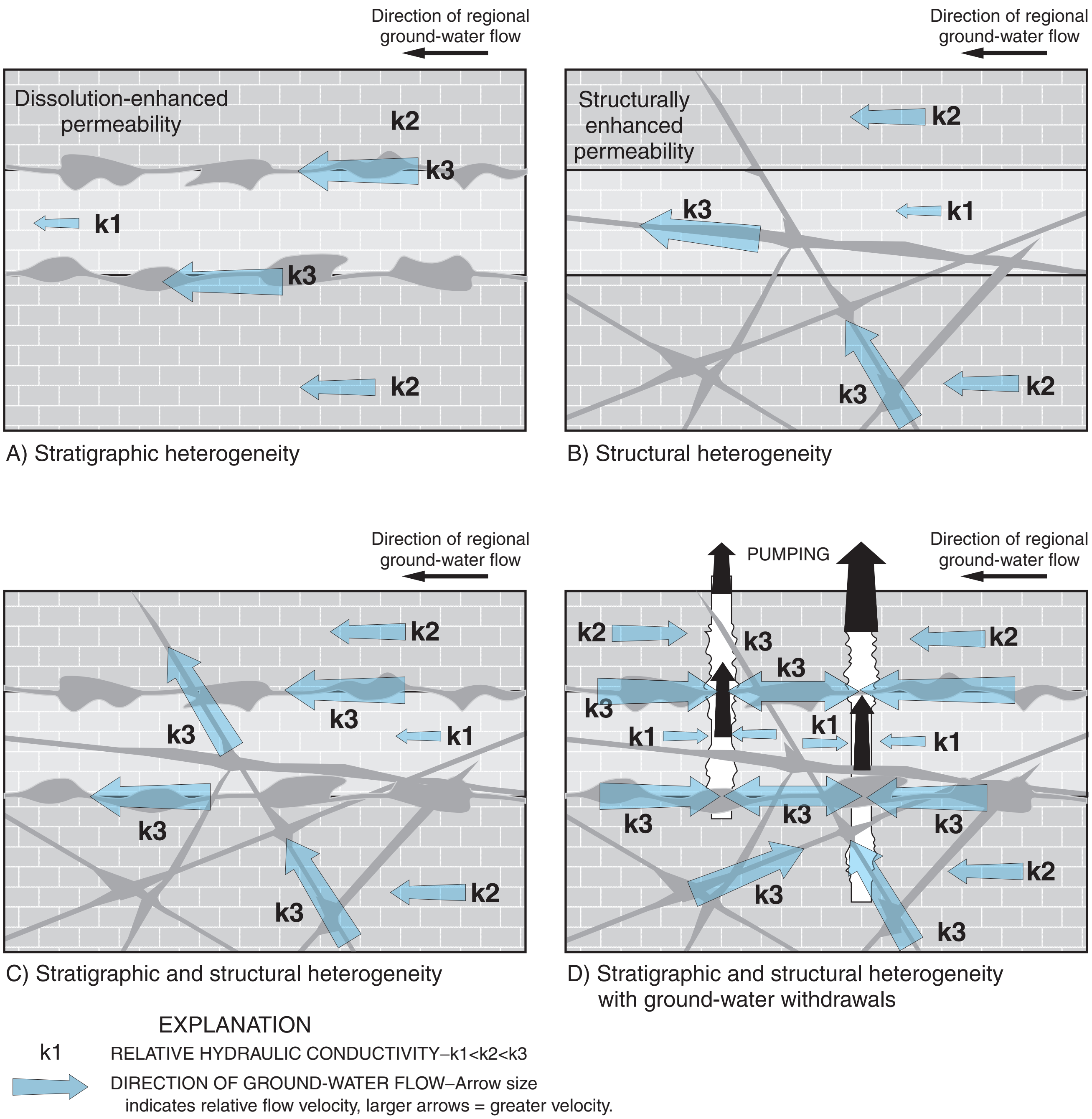


Figure 17. Conceptual illustration of types of aquifer heterogeneity and ground-water flow: (A) Stratigraphic, (B) Structural, (C) Stratigraphic and structural, (D) Stratigraphic and structural with ground-water withdrawals.

are present within the Tampa/Suwannee producing zone at depths of 140 and 290 ft below top of casing (fig.18). Under ambient conditions (shown in blue on logs), negligible flow was measured in the borehole. The ambient specific conductance logs indicated that water present from 113 to 150 ft below the top of casing, within the upper flow zone, was fresher than water from deeper in the well. Specific conductance increased at depths of about 150, 200, and 250 ft below top of casing. At pumping rates of 35 and 53 gal/min (53 gal/min not shown on fig. 18), increases in borehole flow were observed at two main depths: 115-140 and 290-300 ft below top of casing. Specific conductance logs indicate that the lowermost permeable zone (about 290 ft below top of casing), associated with the enlarged feature on the caliper log, contributes water that increases the specific conductance within the well. The flow measurements and specific-conductance logs indicate that the zone from 290 to 300 ft below top of casing contributed the greatest amount of flow (fig. 18). Under pumping conditions, specific conductance

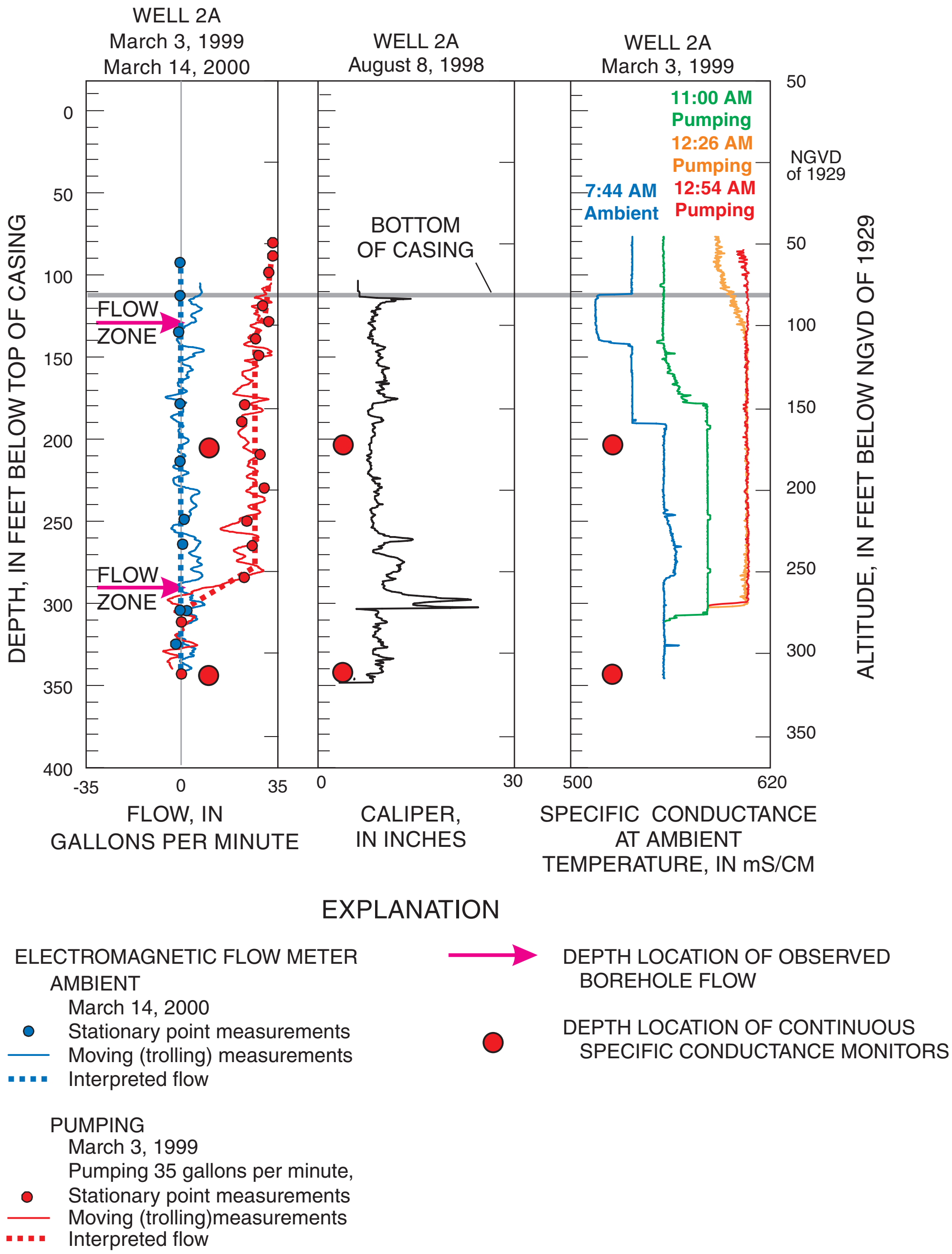


Figure 18. Flow, caliper, and fluid conductance logs at Eldridge-Wilde well 2A. Location of well shown in fig. 2.

within the entire borehole increased as water from the inflow zone at 290 ft below top of casing dominated the composition of water. Both observed flow zones (at the bottom of the borehole and below the casing) are associated with borehole enlargements that are possibly related to bedding structures and cavernous porosity in the Tampa Member and the Suwannee Limestone.

The water level was observed to be rising during logging in well 2A, even though the well was pumping. The water level rose a total of 1.1 ft, indicating that well-field operations likely were influencing the response of well 2A during the pumping flow log. Depending on well-field operations, the water from the lowermost permeable zone can dominate the composition of water in the borehole.

Although well 3B is located close to well 2A, the flow properties along the two boreholes differ substantially. The ambient flow log collected at well 3B using the electromagnetic (EM) flow meter on March 5, 1999, indicated very minor flow along the length of the borehole (fig. 19). The ambient specific conductance log indicated that specific conductance gradually increased with depth, the freshest water occurring at the base of the casing. Under pumping conditions of 37 gal/min, the flow

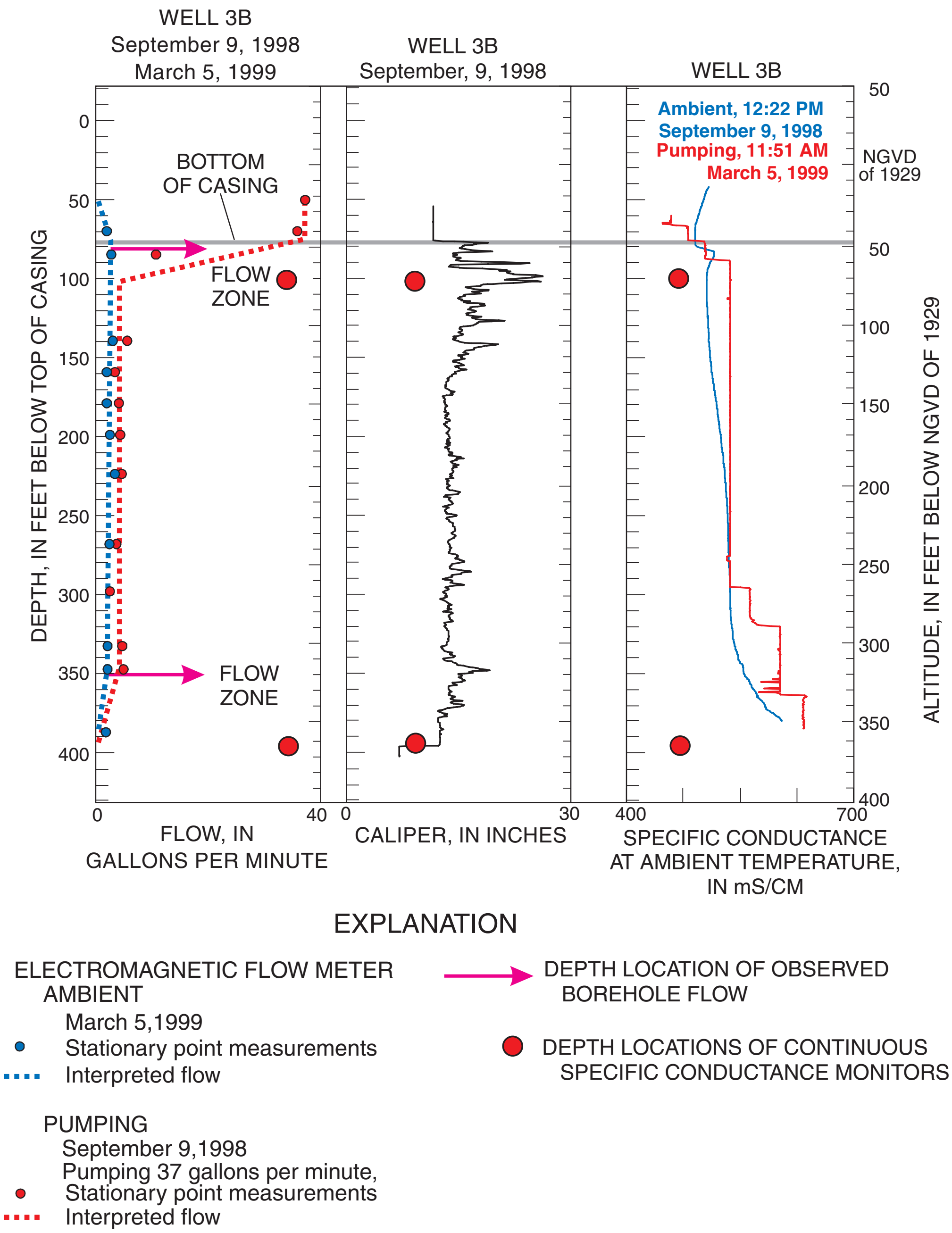


Figure 19. Flow, caliper, and fluid conductance logs at Eldridge-Wilde well 3B. Location of well shown in fig. 2.

log indicated that a minor flow zone exists at 350 ft below top of casing, and a major flow zone is present beneath the bottom of casing, corresponding to the enlarged section of the borehole. A log of specific conductance under pumping conditions indicates that water from below 300 ft below top of casing has a higher specific conductance than water from shallow depths. As water from the lower flow zone enters the well, it causes an increase in the specific conductance within the borehole. Similar to ambient conditions, under pumping conditions, water with a low specific conductance enters the borehole just below the casing, causing a decrease in the specific conductance (fig. 19).

In well 3B, borehole enlargements correspond to both flow zones where water-quality changes occurred. The majority of inflow occurred within the Tampa Limestone while a minor flow component is associated with the Tampa/Suwannee producing zone. Although the flow within the Tampa/Suwannee producing zone is minor, the specific conductance is higher than the water associated with the Tampa Limestone flow zone. The lower specific capacity of well 3B, when compared to well 2A (40 and 130 gal/min/ft, respectively), indicates that this well does not intersect additional substantial flow zones.

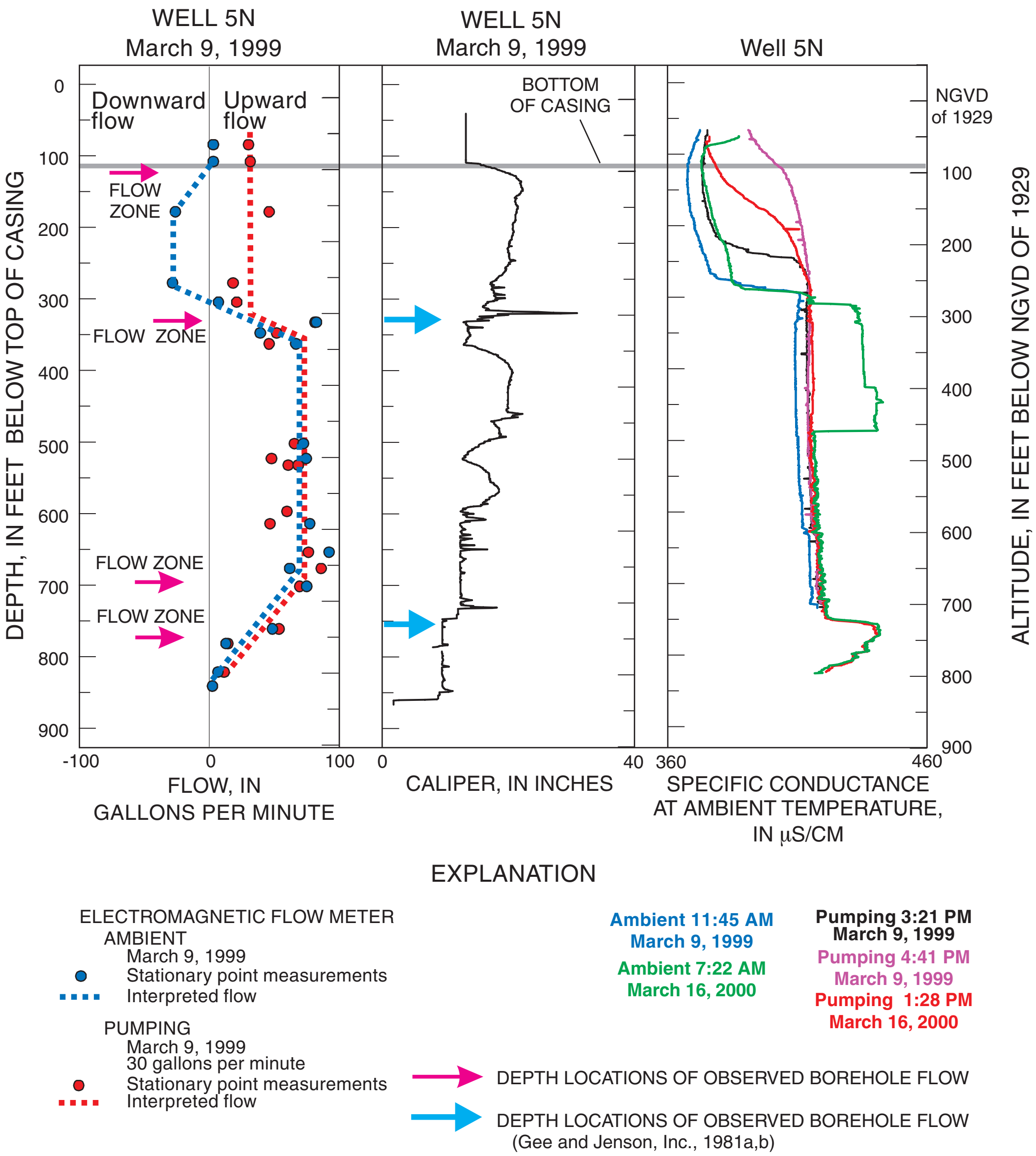


Figure 20. Flow, caliper, and fluid conductance logs at Eldridge-Wilde well 5N. Location of well shown in fig. 2.

Well 5N is in the central part of the well field and was deepened into the Avon Park Formation in 1980 (fig. 12). Total depth is 863 ft below land surface with 107 feet of casing (fig. 20). The specific capacity of this well increased from 39 to 122 gal/min/ft when it was deepened (app. A). Ambient and pumping flow logs were collected at well 5N using both the EM and the heat-pulse flow-meter tools. An enlarged section of the borehole between 100 and 300 ft below top of casing made flow measurements difficult in this interval. By comparing flow measurements under pumping and ambient conditions, flow was measured across this interval, but exact depths of inflow or outflow were not determined. At the 300-ft-depth interval along the contact between the Suwannee and Ocala Limestones, the borehole was intact and flow measurements were made with consistent responses below this depth. Flow zones were identified at 150, 300-330, 700, and 760-780 ft below top of casing. These flow zones coincide with flow zones previously identified by Gee and Jenson Inc. (1981a,b) (fig. 20). Specific conductance logs indicate that the water-producing zones have differing water-quality properties (fig. 20). Water with the highest specific conductance enters the well at 780 ft below top of casing. Under ambient conditions, freshwater enters the well, most likely from just below casing, and flows downward to the 300-330 ft zone. The highest measured inflow based on two different flow measurement methods on two separate dates, was from the zone at 700 ft below top of casing. Minor flow from the 780-800 ft zone was observed during both ambient and pumping conditions. Both caliper and acoustic

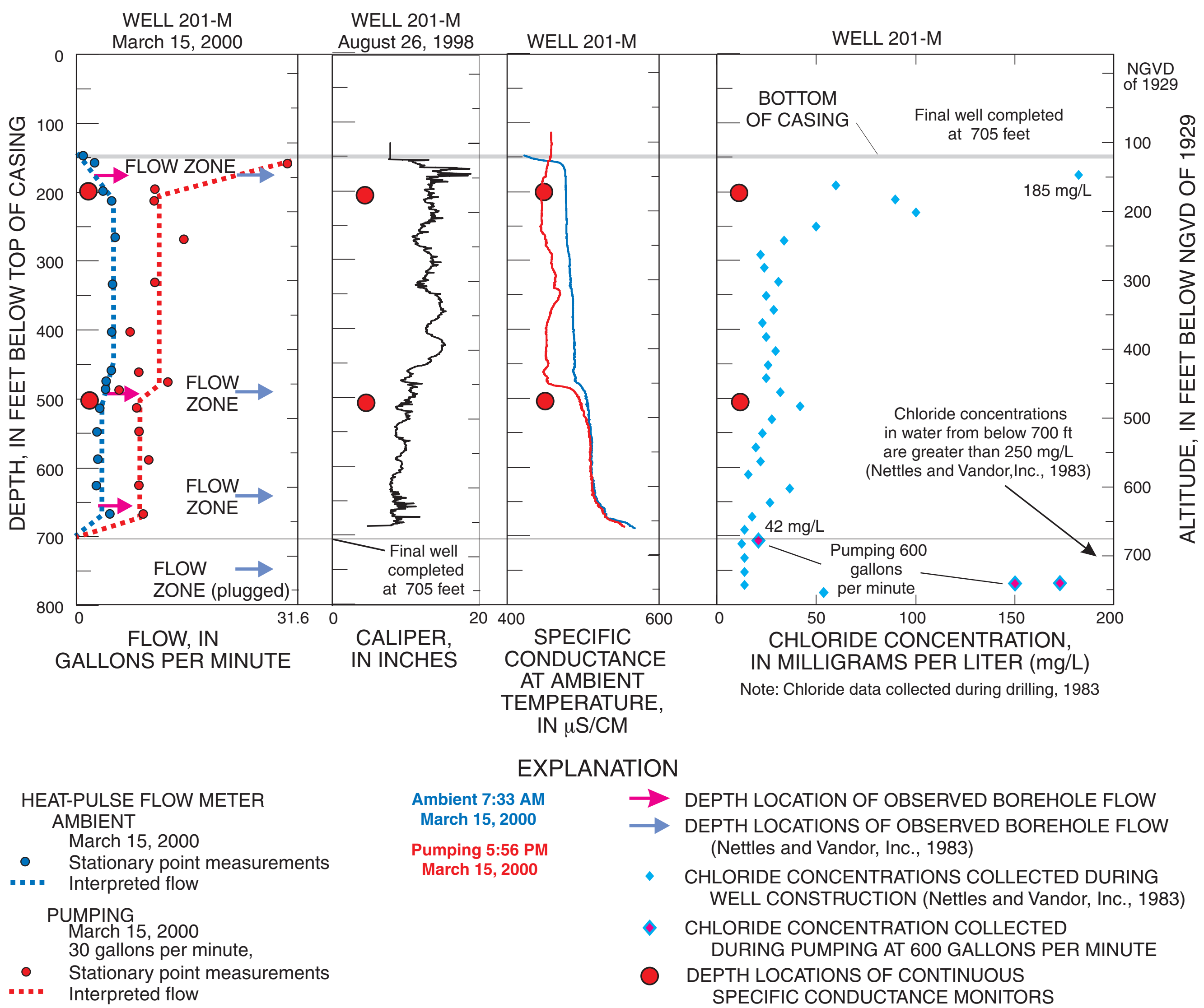


Figure 21. Flow, caliper, and fluid conductance logs and chloride concentrations obtained during drilling at well 201-M west of the Eldridge-Wilde well field. Location of well shown in fig. 2.

televiewer data indicated that fractures were present from approximately 630 to 750 ft below top of casing (figs. 8, 10). The inflow zone between 700 and 750 ft below top of casing corresponded to substantial borehole enlargement and several fractures within the Avon Park producing zone.

Flow measurements can correspond to water-quality changes and can be affected by adjacent pumping stresses. Measurements of flow in well 5N under ambient conditions indicated that inflow and outflow occurred in the borehole that might be related to pumping at nearby wells. Logs showed that flow comes into the borehole about 800 ft below top of casing, increases at about 675 ft, and then decreases at the 300-330 ft zone, where ground water apparently exits the borehole at the Tampa/Suwannee producing zone (fig. 20). The strong borehole flow under ambient conditions indicates that the 300-330 ft zone may be connected to other wells pumping from that zone.

Specific conductance logs of well 5N indicate that changes in specific conductance along the length of the borehole also are related to the amount of flow contributed by each permeable zone (fig. 20). On March 9, 1999, the ambient specific conductance log showed an increase of approximately 50 µS/cm at 300 ft below top of casing. On March 16, 2000, the ambient specific conductance log showed a similar increase at the 300 ft zone, with a decrease at 500 ft, and another 20-µS/cm increase at 750 ft below top of casing. Although these are small changes, they indicate that water quality varies along the borehole in response to changes in flow along specific permeable intervals. Ambient conditions probably were different for the two logged dates, which likely could affect the relative contributions from each permeable interval. The specific conductance of water from the 300 to 330 ft below top of casing interval is unknown because ground water was exiting the borehole along this permeable interval when all flow logs were collected. The slight increase in the ambient specific conductance log on March 16, 2000, however, indicates that the zone may have slightly higher fluid conductivities.

Water from below 750 ft below top of casing has a slightly higher specific conductance than shallower intervals and appears to be diluted as flow moves up the borehole. Although much of the internal flow exits the borehole at the 300 ft depth, water with the higher specific conductance eventually affects the water quality of the uppermost freshwater zone (fig. 20).

Enlarged secondary porosity features correspond to the permeable intervals at well 5N. Acoustic televiewer data show that enlarged bedding planes account for the enlarged caliper features observed from 300 to 350 ft below top of casing near the contact between the Suwannee and Ocala Limestones (fig. 20). These features transmit substantial quantities of water, and the horizontal orientation may indicate lateral continuity between this flow zone and other production wells. Although some horizontal bedding features exist within the Avon Park Formation, permeable intervals within the Avon Park producing zone are associated primarily with vertically extensive fractures (Hickey, 1982). Enlarged open-hole conditions and a distinct fracture exist within the 5N borehole at 700 ft below top of casing. Fractures are present from 650 to 750 ft below top of casing. From 750 to 775 ft below top of casing, enlarged horizontal bedding planes are present but distinct fractures are not observed.

Well 201-M is constructed similarly to deep wells having large open-hole intervals in the northern part of the well field. Well 201-M is less than 1 mi west of the well field and ground-water levels generally are higher than in the well field (figs. 1, 2, 15). When well-field pumping is high, ground water may flow from this area east toward the well field. Downward flow was observed in the borehole during drilling in 1983 (Nettles and Vandor, Inc.,1983). Historical specific conductance logs at 201-M, collected under ambient conditions on different dates, showed opposite trends. Changes in specific conductance occurred within the upper 300 ft below top of casing and below 450 ft below top of casing. In one log, the specific conductance increased gradually with depth and in the other log, the specific conductance decreased with depth.

At well 201-M, pumping flow logs, collected using the heat-pulse flow meter, showed increased inflow of about 20 gal/min at 200 ft below top of casing. An increased inflow of about 3 gal/min occurred at 475 ft below top of casing corresponding to a change in specific conductance. These changes coincide with the Ocala Limestone/Avon Park Formation contact (fig. 21). Specific conductance logs, collected during ambient and pumping conditions on March 15, 2000, showed a specific conductance of about 500 μS/cm, with values increasing slightly at approximately 475 ft below top of casing and increasing with depth below 475 ft. Under pumping conditions, the specific conductance log on March 15, 2000, showed increasing values with depth, with better definition of distinct water-quality changes and associated depth zones corresponding to flow zones measured by Nettles and Vandor, Inc. (1983).

At well 201-M, the flow zones are associated with enlarged borehole sections within the Tampa /Suwannee, the Ocala/Avon Park, and the Avon Park producing zones. Limited acoustic televiewer data from 480 to 680 ft below top of casing identified 11 fractures within the Avon Park Formation, ranging in dip angle from 63 to 82 degrees (fig. 8). These fractures are in conjunction with enlarged horizontal bedding planes, which appear to be the structural control for the enlarged borehole intervals.

Sources and Variability of Chloride in Ground Water

The variability of chloride in ground water within the study area results from the influence of nearby sources for chloride ions and the variable mixing of three water types: calcium-bicarbonate, sodium-chloride, and calcium-sulfate. The two most likely sources for chloride in the well field are seawater and deep mineralized ground water (fig. 22a,b). Because seawater contains chloride concentrations that are higher than other available sources, even small contributions of seawater can substantially affect concentrations in ground water. Sources of chloride at concentrations with a similar magnitude to seawater, such as those associated with residual saline water, halite solution, natural saline water, oil and gas brines, agricultural effluent, or saline seeps, have not been found in the hydrogeologic framework of the study area (Sprinkle, 1989; Richter and Kreitler, 1993). Seawater contains approximately 19,000 mg/L of chloride (approximately 50,000 μS/cm specific conductance). In nearly all coastal areas within Florida, wells that fully penetrate the UFA have chloride concentrations approaching that of seawater (Sprinkle, 1989). Ground water with specific conductance greater than 10,000 μS/cm and chloride concentrations greater than 15,000 mg/L is present at 700-750 ft below land surface less than 2 mi south and west of the EW well field (figs. 1, 2).

The lateral inland movement of modern seawater (lateral encroachment) has been recognized as a source of chloride in ground water throughout Florida (Cooper and others, 1964; Trommer, 1993; Southwest Florida Water Management District, 1996b; Barlow, 2003). In coastal regions, seawater encroachment occurs when ground-water levels in an aquifer are lowered, reversing head gradients and allowing seawater to displace freshwater (fig. 22a). Ground-water levels are lowered during pumping, especially under drought conditions (Cooper and others, 1964).

Another potential source of chloride is deep ground water that is ion enriched, reflecting long ground-water residence times in contact with aquifer minerals in the regional flow system (Sprinkle, 1989). Although chloride ions accumulate along ground-water flow paths, they do not commonly reach levels similar to seawater concentrations. Deep ground water becomes ionically enriched as rock-water interactions increase the total dissolved solids (TDS) and the overall salinity of ground water. Chloride is enriched in deep ground water because it is a conservative ion and is seldom removed by

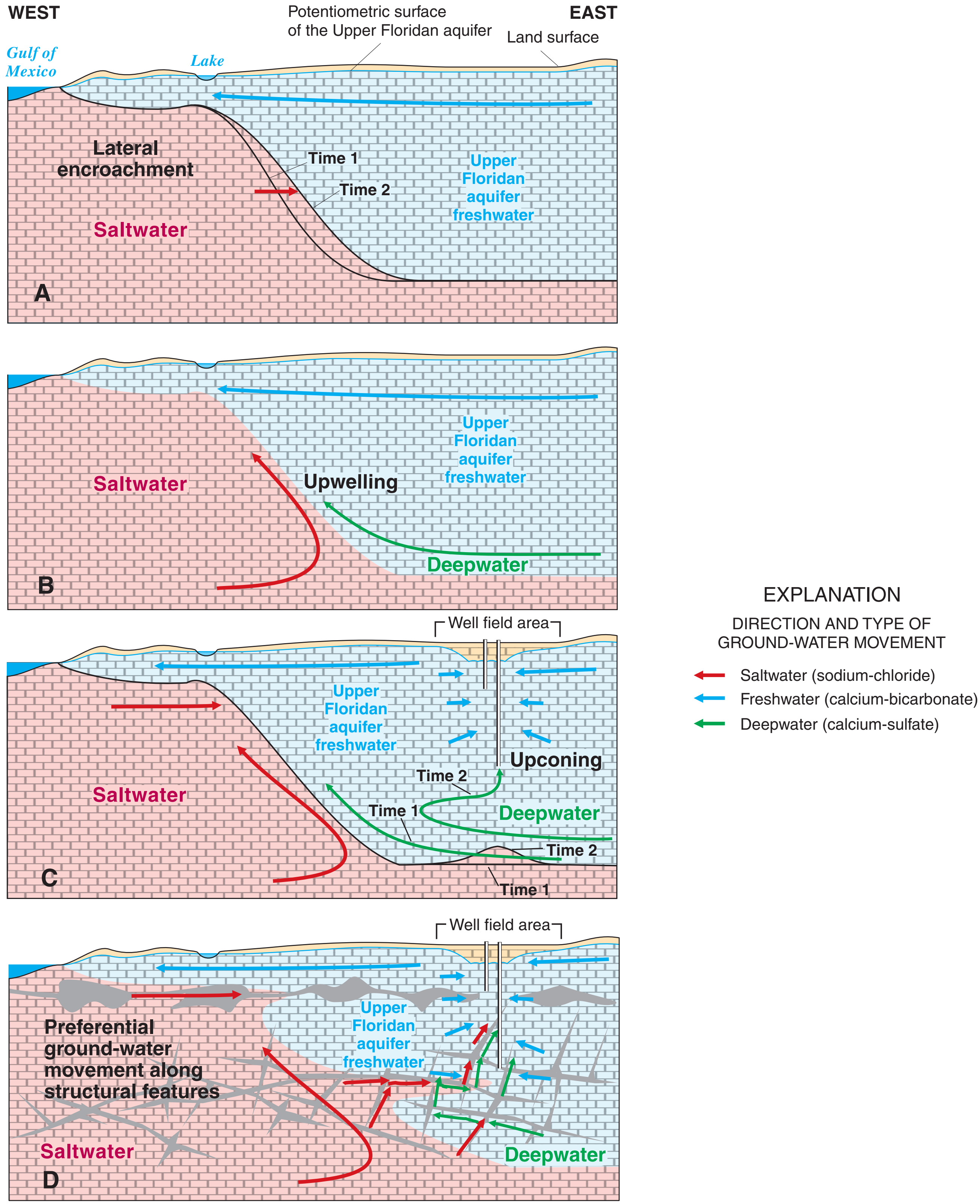


Figure 22. Schematic sections illustrating possible physical processes for movement and introduction of chloride within the fresh ground-water system of the Upper Floridan aquifer: (A) lateral encroachment of the saltwater/freshwater interface, (B) upwelling of deep mineralized ground water along the boundary of the saltwater interface, (C) upconing induced by ground-water withdrawals, and (D) localized movement of ground water along fractures and permeable intervals.

geochemical reactions (Sprinkle, 1989; Richter and Kreitler, 1993). Gypsum dissolution and ground-water movement along the base of the UFA typically enriches deeper ground water with calcium, sulfate, and chloride. Chloride and sulfate concentrations in a representative deep ground-water sample from the top of the MCU within the study area were 290 and 1,800 mg/L, respectively.

In discharge areas, ground water within the UFA from deep regional flow paths has the potential to move upward (a process known as upwelling) into shallower parts of the aquifer as it approaches the denser saltwater (fig. 22b). This process is part of regional ground-water flow and is a common phenomenon in coastal regions, including west-central Florida (Cooper and others, 1964; Miller, 1986; Bush and Johnston, 1988; Sprinkle, 1989; Maddox and others, 1992; ERM, 2000; Barlow, 2003). Even if natural upwelling does not occur, the presence of ionically enriched water at depth can provide a source for increased concentrations of chloride and other ions within potable ground-water supplies.

Another mechanism that may introduce deep mineralized water into fresh ground-water resources is upconing. Ground-water withdrawals, and the associated changes in potentiometric head gradients, can induce upconing. Upconing is a process by which pressure head gradients induce upward movement of deep ionically enriched water into the freshwater aquifer (fig. 22c). The presence of elevated sulfate concentrations is a common indicator of the chemical influence of the upconing process.

Along the coast, ground-water chemistry is influenced both by seawater and deepwater. Where aquifer units are heterogeneous, higher salinity ground water can flow preferentially through zones of enhanced permeability either by upward or lateral movement when water levels in the upper zones (Tampa/Suwannee) of the UFA are lowered relative to deeper zones (Ocala/Avon Park) (fig. 22d).

Increases in chloride concentrations observed in wells within the southwestern part of the EW well field indicate that a source of chloride exists near the well field; however, changes in chloride concentrations can vary significantly between wells and over time. Chloride trends determined for the same well can indicate no trend or both an increasing and decreasing trend, depending on the statistical techniques and period of record used for analysis (Nettles and Vandor, Inc., 1988b; SDI Environmental Services Inc., 1993; Southwest Florida Water Management District, 1995, 1996a,b, 2000a,b; Yobbi and others, 1996; Montgomery Watson Americas, Inc., 2001; Water and Air Research, Inc. and others, 2001).

Temporal and Spatial Variations

Temporal and spatial variations in chloride concentrations within the study area were examined by analyzing chloride concentrations at selected wells over time and examining annual isochlor maps from 1975 through 2001. Examples of temporal trends in chloride concentration from selected wells are shown in figure 23. Chloride levels at well 2A reached a maximum of 111 mg/L in 1989. Annual average chloride concentrations in selected wells at the well field increased from 10 mg/L in 1975 to more than 70 mg/L in 1995 (Leggette, Brashears and Graham, 1995, 1996; Water and Air Research, Inc. and others, 2001) (fig. 24), which represents a 600-percent increase; this is not the maximum reported value but an annual average of reported monthly values. Chloride concentrations at selected wells began increasing gradually in the late 1970s and 1980s, but the rate of increase became more rapid in the late 1980s and early 1990s coincident with the deepening of wells into the Avon Park Formation.

Chloride concentrations in ground water near the well field have been monitored in wells between Lake Tarpon and the EW well field (fig. 1). Southwest of the well field, the 250-mg/L isochlor, representing the upper boundary of the saltwater/freshwater interface, is less than 300 ft deep (Southwest Florida Water Management District, 1990). Ground water from a well adjacent to Salt Lake Bayou (WRAP 37F, fig. 1), with an open hole 64 to 74 ft below land surface, currently has chloride concentrations near 1,000 mg/L and has shown an increasing trend from approximately 800 to 1,000 mg/L from 1991 to 2000 (Southwest Florida Water Management District, 2000b). From 1970 to 1996, increasing chloride concentrations also were observed in ground water 2 - 3 mi south and west of the EW well field. At the NLKTP well (tapping the Avon Park producing zone) and the TPRDDP well (tapping the Tampa/Suwannee producing zone), chloride concentrations increased from 8,000 to 18,000 mg/L and from 50 to 65 mg/L, respectively (Yobbi and others, 1996: see fig. 2 for well locations). At the TPRDDP well, analysis of chloride concentrations from 1978 to 1999 indicated increasing trends with concentrations ranging from 44 to 70 mg/L (Causseaux and Fretwell, 1982; Trommer, 1993; Yobbi and others, 1996). Increasing trends from 1991 to 2000 also were observed in the Avon Park producing zone southwest of the well field (well WRAP-1D), where chloride concentrations increased from 900 to 1,300 mg/L, and northwest of the well field (well WRAP-3D), where chloride concentrations increased from 900 to 1,000 mg/L. Farther south (well WRAP-4D), chloride concentrations were lower and showed a smaller increase from 25 to 30 mg/L (Southwest Florida Water Management District, 2000b).

Within the well field, temporal trends were determined for each well. Chloride-concentration trends for the period of record were characterized by the type of variability in the data, whether concentrations increased above 20 mg/L, and whether the concentrations were constant or fluctuated monthly. Type-0 wells show no increase and little variability in chloride concentrations. Type-1 wells have a consistent, well-defined increase in chloride concentrations over 20 mg/L. Type-2 wells have fluctuating monthly chloride concentrations, possibly with distinct spikes but an overall increase in chloride concentration greater than 20 mg/L. Type-3 wells show no increase (generally below 20 mg/L) with low variability, but have distinct spikes in chloride concentrations, representing discrete pulses of water with elevated chloride concentrations entering the well (fig. 23).

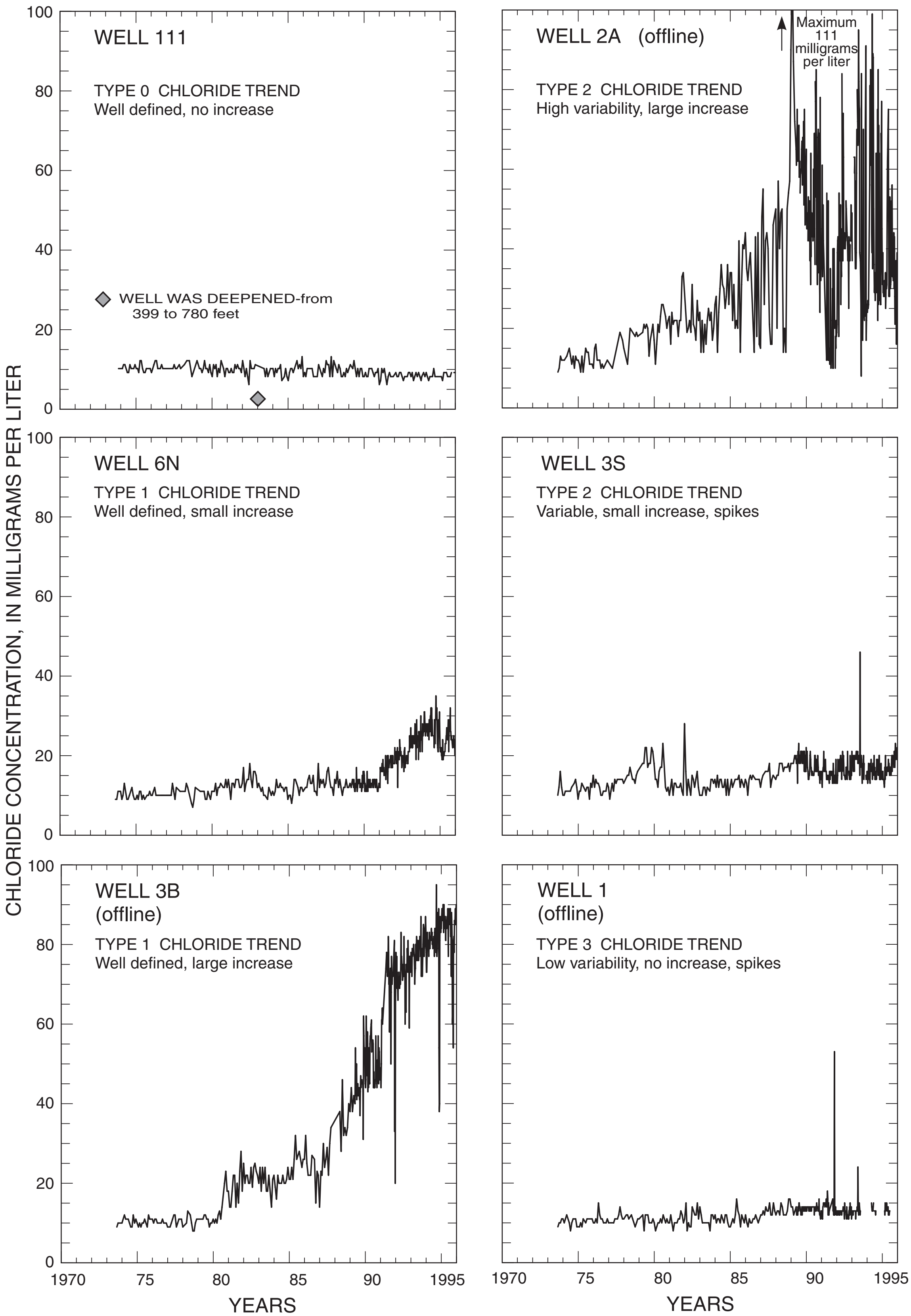


Figure 23. Chloride concentrations and types of trends identified in water from the Upper Floridan aquifer in selected wells at the Eldridge-Wilde well field. Locations of wells shown in fig. 2.

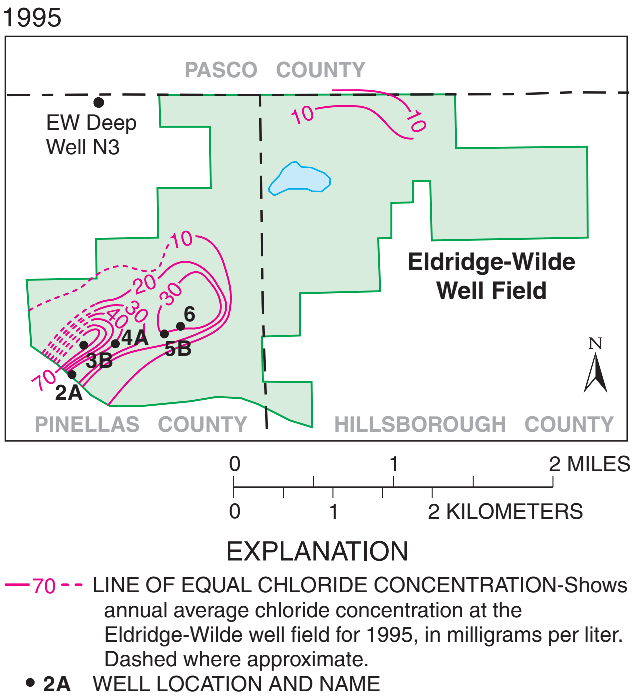


Figure 24. Distribution of annual average chloride concentrations in water from the Upper Floridan aquifer at the Eldridge-Wilde well field for 1995. Modified from Water and Air Research and others (2001).

The increased depth of production and capacity of the well field were accompanied by increases in specific conductance (caused by increasing chloride and sulfate concentrations) in a number of production wells. The greatest increases in chloride concentrations were observed during the late 1980s and early 1990s, as the well-deepening program was completed and the deeper wells tapping the Avon Park producing zone were brought online (figs. 13, 23). Maximum chloride concentrations were not observed in wells penetrating the Avon Park producing zone, but were found in wells in the southwestern part of the well field that generally were less than 500 ft deep (Water and Air Research, Inc. and others, 2001).

Spatial variations in chloride concentrations within the study area were analyzed by examining the annual isochlor maps from 1975 through 2001. The annual average isochlor contours, like the potentiometric-surface contours, are oriented northeast-southwest through the well field. The highest chloride concentrations are centered over wells 3B and 6, near the maximum cone of depression in the potentiometric surface located near high-pumping wells 4A and 5B (fig. 24). An overlay of the potentiometric-surface maps and the average chloride concentrations at the production wells for 1976 and 1980 shows that the greatest increases in chloride concentrations coincide with the area of the well field where the deepest part of the cone of depression occurs (fig. 25). During the late 1980s and early 1990s, some wells had greater increases in chloride concentrations than others. The largest increases in chloride concentrations were within the southwestern part of the well field in the vicinity of the cone of depression (figs. 24, 25).

Changes in the regional potentiometric surface from predevelopment conditions to 2000 show that water levels have been lowered within the region between the EW well field and the coast (fig. 14). As a result, it is likely that both the rate and direction of ground-water flow, especially within the southwestern part of the well field, have changed. Increasing chloride

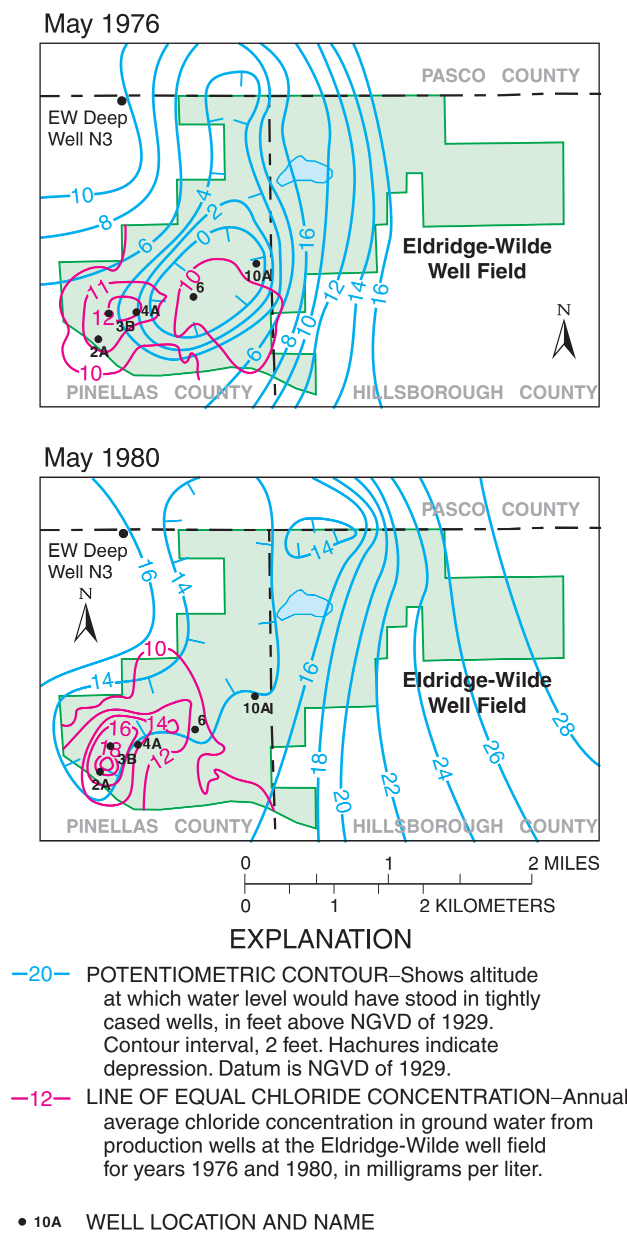


Figure 25. Relation between the potentiometric surface of the Upper Floridan aquifer and chloride concentrations in ground water from the Upper Floridan aquifer at the Eldridge-Wilde well field.

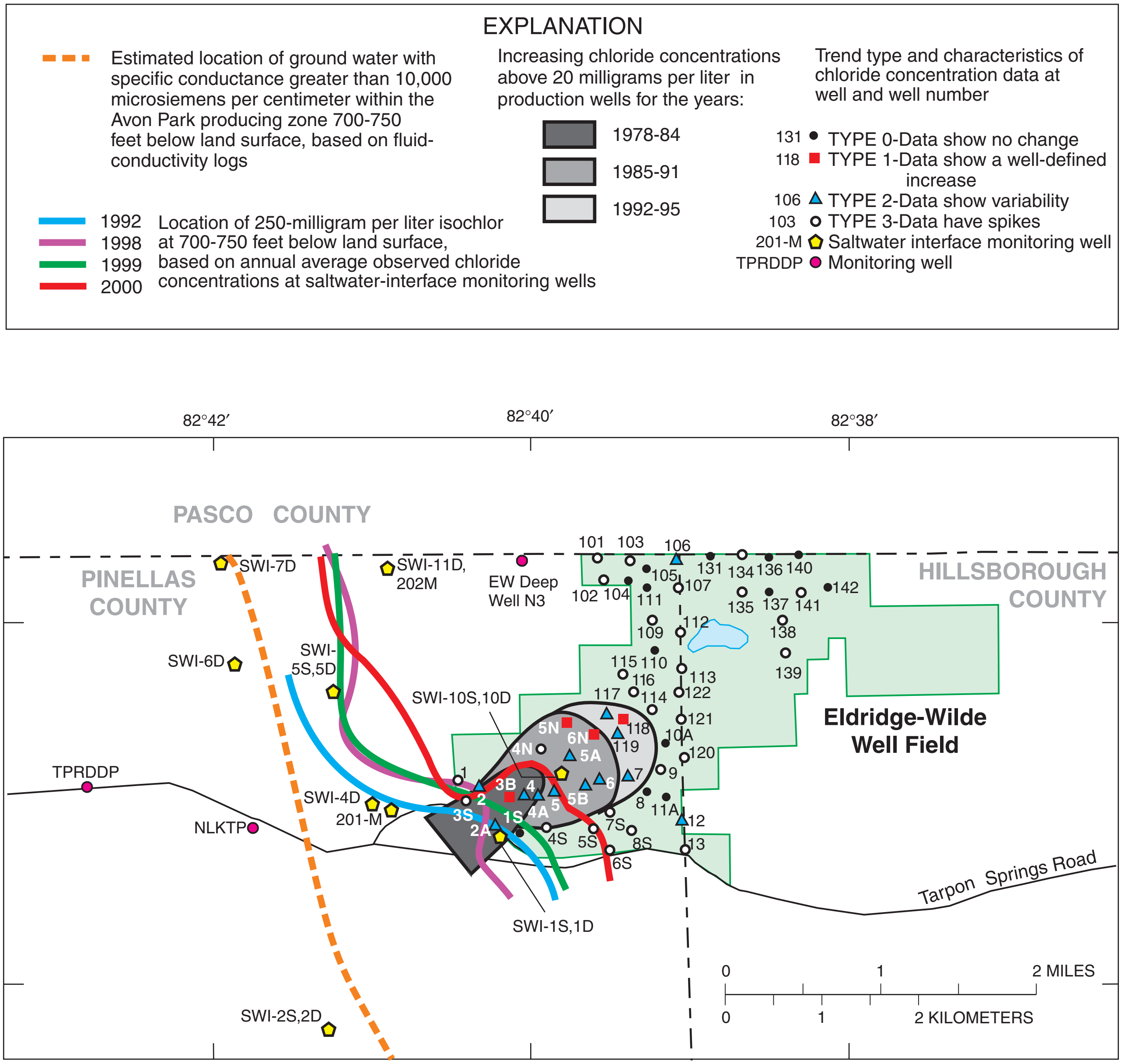


Figure 26. Temporal and spatial distribution of chloride concentrations in ground water from the Upper Floridan aquifer at the Eldridge-Wilde well field, including the type of chloride concentration trend, where and when chloride concentrations exceeded 20 mg/L and isolines for the 250-mg/L chloride concentration and the 10,000-µS/cm specific conductance values. Location of 250-mg/L isochlor modified from Water and Air Research, Inc., and others (2001).

concentrations within the Tampa/Suwannee producing zone observed at well TPRDDP indicate that chloride may be moving along this producing zone. Increases in the specific conductance logs observed at this depth interval at wells 2A and 3B, and the presence of elevated chloride concentrations observed between 150 and 250 ft below land surface at well 201-M during drilling (fig. 21), also indicate that higher chloride concentrations may occur along this producing zone.

Chloride concentrations varied temporally and spatially at the well field (fig. 26). The four type-1 wells, showing well-defined increases in chloride concentrations, are 3B, 5N, 6N and 118: these four wells are within the central area of the southwestern part of the well field. This is the same area that shows a northeast-southwest trend in the isochlor map and the depressed potentiometric surface shown in figure 25. Surrounding these wells are 11 type-2 wells, characterized by increasing chloride trends but with a more variable range. Type-3 wells are characterized by spikes in chloride concentrations and are found throughout the well field. Data from types 2 and 3 indicate that ground water with elevated chloride concentrations migrates into the well field, but only periodically enters the capture zone of each production well. Wells showing no change in chloride concentrations (type-0) are located predominantly in the northern part of the well field (fig. 26).

Chloride concentrations in production wells first increased above 20 mg/L in the southwestern part of the well field during the period from 1978 to 1984, then concentrations increased toward the northeast from 1985 to 1995 (fig. 26). Declines of more than 10 ft in the potentiometric surface have been observed since 1972 (fig. 15). These potentiometric changes coincided with the first increases in chloride concentrations observed in production wells in the southwestern part of the well field. During the early 1990s, chloride concentrations in these wells increased more rapidly than those in other areas of the well field. Maximum chloride concentrations greater than 100 mg/L were observed in water from wells 2A and 3B. Although wells in the central part of the well field also showed increases in the early 1990s, concentrations typically were less than 40 mg/L.

The type of chloride trend identified in a production well corresponds to the well's location (fig. 26). Wells with clearly increasing trends in chloride concentrations are located more toward the center of well field. Wells that exhibit increased chloride concentrations but with greater variability are located closer to the well-field boundaries. The 250-mg/L isochlor in the Avon Park Formation (700-750 ft below land surface) shows northeasterly movement from the southwestern part of the well field along the same central axis as the observed increases in chloride concentrations at the production wells; however, the location of the isochlor appears to have oscillated over time.

In seawater mixtures, the chloride concentration and specific conductance are consistently related and, therefore, specific conductance can be used to indicate chloride concentrations (Ron Miller, U.S. Geological Survey, written commun., 2000). At the saltwater interface, increases in specific conductance can be attributed to increases in chloride concentrations. Therefore, near the saltwater interface, increases in specific conductance indicate saltwater mixing. Increases in sulfate associated with deepwater mixing, however, can elevate specific conductance above the seawater mixing line. Therefore, inland of the saltwater interface, increases in specific conductance can be attributed to mixing with both saltwater and deepwater.

Temporal changes in specific conductance in ground water were observed in logs and in continuous data collected at fixed depths in selected wells. Continuous specific conductance data were collected by the USGS, in cooperation with Pinellas County, from 1993 to 1998 at sites SWI-1S, SWI-1D, SWI-7D, SWI-10S, and SWI-10D to analyze the movement of the saltwater/freshwater interface over time (figs. 27-30). These wells are named with the prefix "SWI" (for saltwater interface), because they were specifically constructed to monitor the saltwater/freshwater interface within and surrounding the EW well field. Each well was equipped with a specific conductance probe set at a selected depth within the Avon Park Formation (500, 670, 680, 700, 730, or 850 ft below land surface). In four of the five wells, specific conductance fluctuated daily. In many cases, increases in specific conductance were associated with ground-water level declines, but not always.

Continuously monitored wells that were closer to the saltwater interface and that had open-hole intervals penetrating the fractured Avon Park producing zone showed the greatest ranges and the largest increases in specific conductance. Within the Avon Park producing zone, increases in specific conductance always occurred as water levels declined, but the changes in specific conductance ranged from less than 100 μS/cm at well SWI-10D to more than 10,000 μS/cm at well SWI-7D (figs. 30 and 29, respectively). At the 500-ft depth (well SWI-1S), specific conductance ranged from about 600 to more than 700 μS/cm, but at greater depths, increased more than 1,000 μS/cm (wells SWI-1D, SWI-10S, SWI-7D). At SWI-1S and SWI-10S, the greatest increases in specific conductance coincided with periodic water-level declines (figs. 27 and 30, respectively). At SWI-1D, tidal effects influenced both water levels and specific conductance, although the tidal signature sometimes was overwhelmed (fig. 28). Tidal effects caused water levels to change nearly 2 ft and specific conductance to range approximately 100 μS/cm over a complete tidal cycle (fig. 28). Although changes in water levels associated with tidal cycles were correlated with changes in specific conductance, the changes related to the tidal signal were superimposed on longer-term trends in both the water-level and specific conductance data. Similar tidal effects were not observed at the other continuous monitoring sites.

The greatest changes in specific conductance were observed at SWI-7D as water levels declined. Ground-water levels higher than 14 ft above NGVD of 1929 generally corresponded to a constant specific conductance value (near 5,000 μS/cm), but when water levels declined below this level, specific conductance values increased by an order of magnitude, approaching that of seawater (fig. 29). Similar responses to water-level changes occurred at wells SWI-1S and SWI-10S (figs. 27 and 30, respectively), although the increases in specific conductance were not as large as those observed at SWI-7D.

During the study, three additional wells (2A, 3B and 201-M) were instrumented to collect continuous specific conductance data from two fixed-depth intervals from December 1999 through January 2001 (fig. 31). Changes in the specific conductance of ground water over time at specific depth intervals were associated with changes in water levels and pumping. Wells 2A and 3B were selected because they have the highest chloride concentration values (maximum values exceeded 80 mg/L) and are located within the well-field cone of depression (figs. 15, 25). Well 201-M was selected to observe effects outside of the well field. During the low water levels of May 2000, water-level data were not available at wells 2A and 3B because of instrumentation problems related to the low water levels. Therefore, data from nearby well 2S were used to indicate the approximate water levels for the area near those wells.

Water-quality changes recorded in the boreholes reflect the influence of dominant flow zones. In general, changes in water levels at wells 2A, 3B, and 201-M were accompanied by changes in specific conductance similar to those observed at the SWI wells previously discussed, in that the highest recorded specific conductance values at all three wells corresponded to the greatest declines in water levels and the highest reported

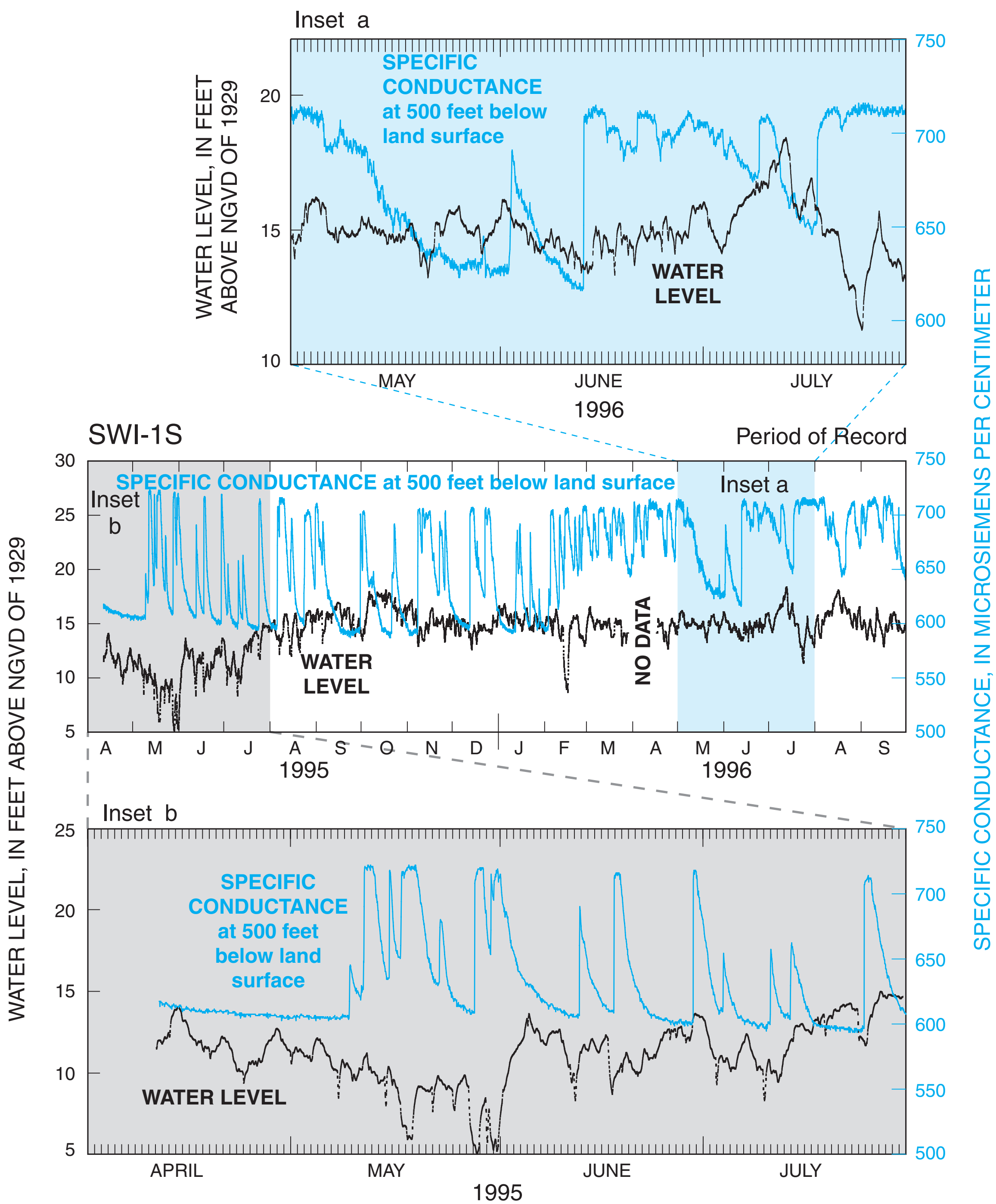


Figure 27. Water levels and specific conductance of water from fixed depths at well SWI-1S, April 1995–September 1996.

pumpage values (figs. 27-30). The presence of an additional fresh flow zone near the top of the casing at well 2A appears to keep the overall specific conductance in the borehole at well 2A lower than well 3B. Both wells appear to be connected to a flow zone between 290 and 350 ft below land surface where the water has a specific conductance of about 800 µS/cm (figs. 18, 19). At well 3B, however, the two monitored depths responded inversely to each other with the specific conductance sensor at the 100-ft depth recording decreases while the sensor at the 390-ft depth recording slight increases (fig. 31b). Data from well 3B indicate two flow zones with different specific conductance—a shallow zone with a low specific conductance and a deep zone with a high specific conductance. With a baseline specific conductance of about 800 µS/cm, it appears that little dilution by other flow zones occurs in this well. By comparison, at well 2A, baseline specific conductance was between 400 and

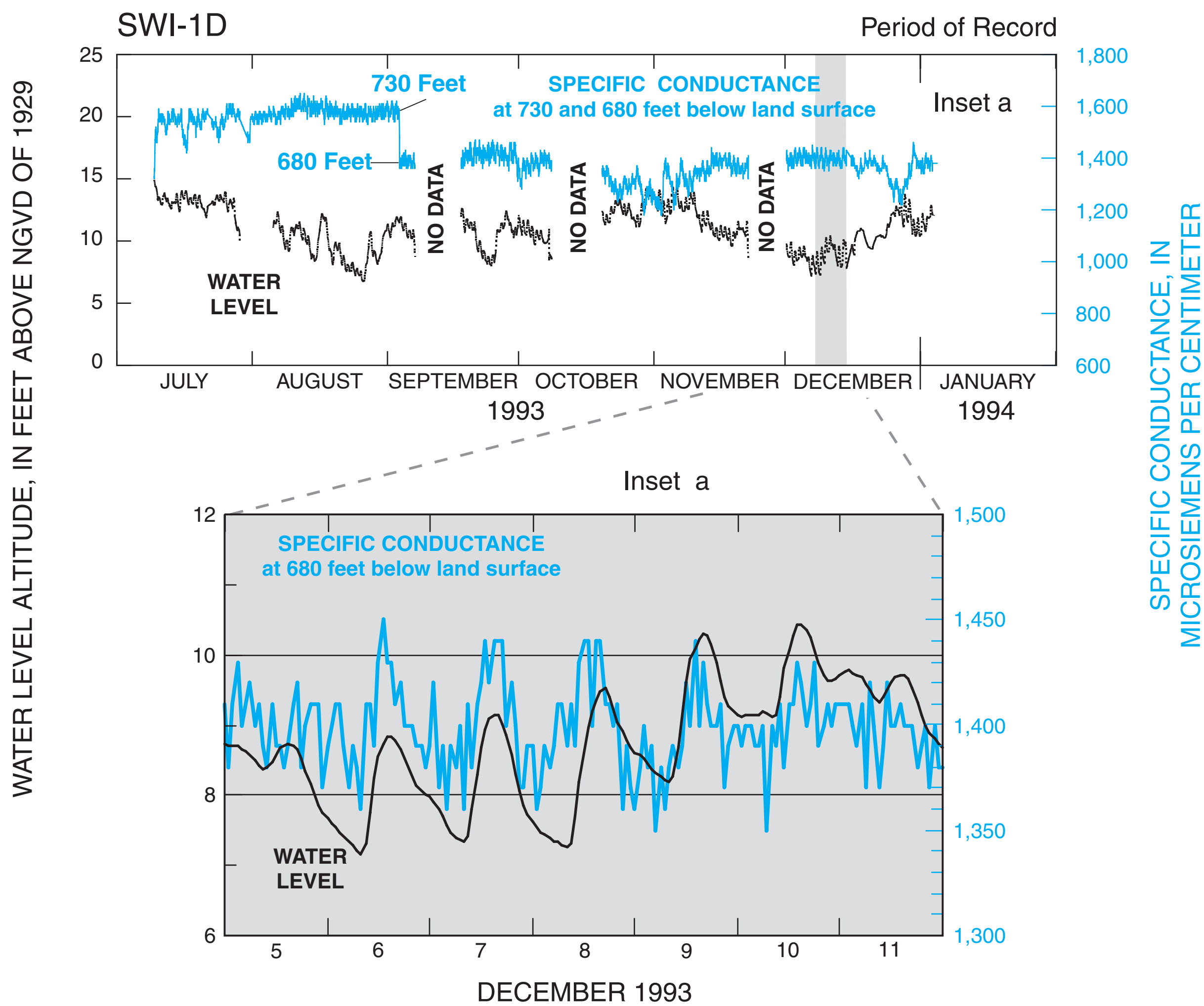


Figure 28. Water levels and specific conductance of water from fixed depths at well SWI-1D, July 1993–January 1994.

500 µS/cm with only intermittent values reaching about 800 µS/cm. The trend in water quality within the borehole at well 2A is controlled by a specific flow zone identified at 290 ft below top of casing using borehole flow and specific conductance log data (fig 18a). The continuous monitoring sensors were located above and below the flow zone. The shallow sensor at 200 ft recorded events that occurred as high conductance water entered the well at 290-300 ft and moved up the borehole, exiting below the top of the casing along another flow zone.

Total daily pumpage at production wells 1-13 (a total of 26 wells), in the southwestern part of the well field, was compared to daily rainfall and water-level response at wells 2A, 3B, 201-M and 2S (fig. 32). Pumpage in the northern part of the well field was not considered, but may have a measurable affect on the changes observed at wells 2A, 3B, and 201-M. During this study, pumping in the southwestern part of the well field was relatively low, averaging less than 10 Mgal/d, except during the dry season (May) when ground-water pumping increased in response to increased demand.

The highest reported pumpage coincides with the dry season and the lowest ground-water levels (December 1999 to June 2000; fig. 32). During the wet season (June through early September 2000), water levels increased and pumping was less; however, in late September and early October 2000, pumpage exceeded 15 Mgal/d (fig. 32). From January to August 2000, water levels at 201-M generally were about 2 ft higher than those at wells 2A and 3B, indicating lowered water levels associated with pumpage at the EW well field (fig. 32). Water levels at well 2A generally were lower than those at 201-M, but generally higher than at well 3B. The head difference between wells 2A and 3B was used to indicate the potential for ground-water flow between these two wells and, consequently, the extent that water quality might be affected by ground-water flow from the west where increased chloride concentrations are present at shallow depths. When water levels at 2A are lower than at 3B, the head difference is negative and the flow gradient is southwest toward well 2A. When water levels at 2A are higher than at 3B, the head difference is positive and the flow gradient is toward northeast well 3B. During most of the study, the flow

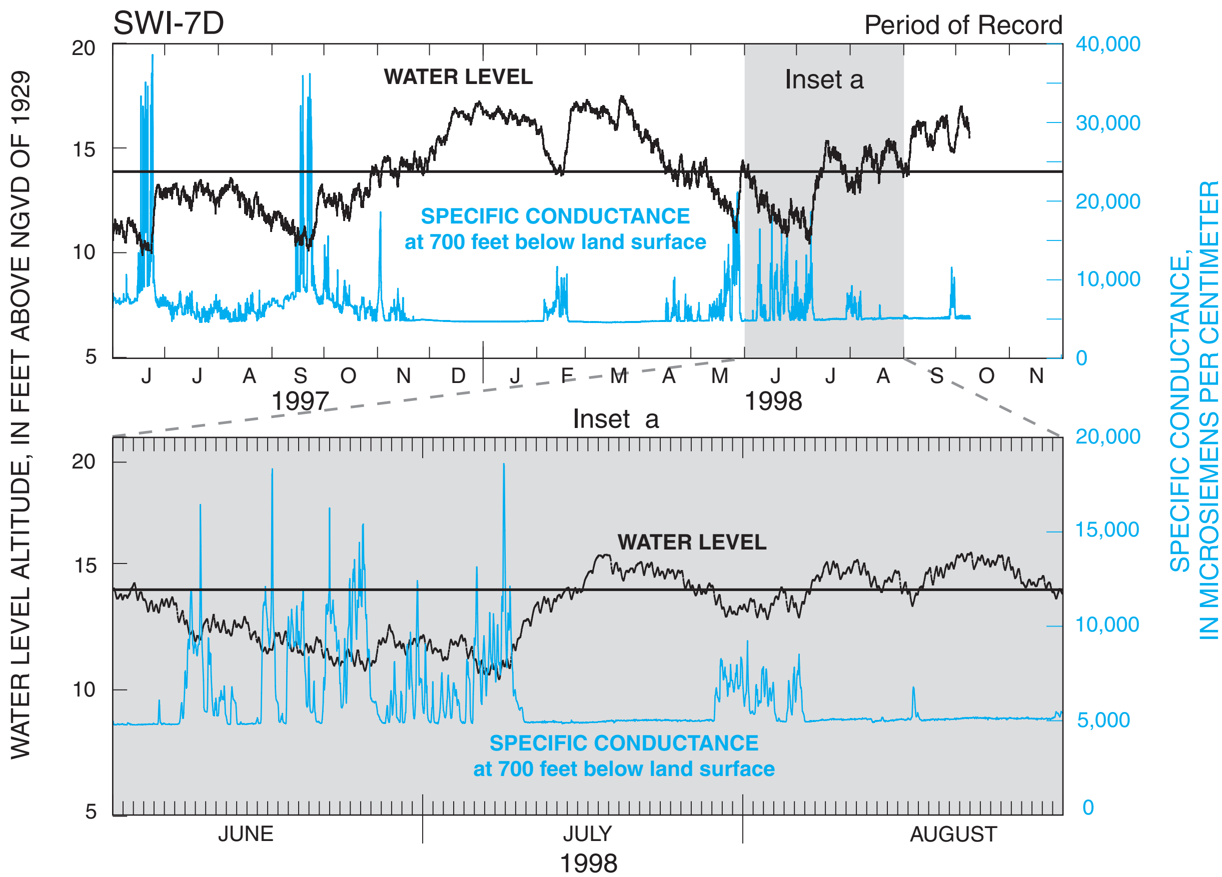


Figure 29. Water levels and specific conductance of water from fixed depths at well SWI-7D, June 1997–December 1998.

gradient between wells 2A and 3B was northeast toward 3B (fig. 32). The average head difference between wells 2A and 3B was 0.5 ft, and the maximum was 4.5 ft.

Periods of greatest pumpage generally were associated with a greater head difference between wells 2A and 3B. During periods of decreased pumpage, the head difference between wells 2A and 3B was more variable. Decreased pumpage occurred during periods of increased rainfall and water levels (fig. 32). When large head differences existed between wells 2A and 3B, which occurred at the end of September and early October 2000, the specific conductance measured at both depths in well 3B approached 800 µS/cm, indicating more water was coming from the lower flow zone (fig. 33). When water levels recovered at well 3B, neither flow zone dominated. From late October 2000 to January 2001, when pumping was low and head differences between 2A and 3B were small, substantially fresher water was present in the upper part of 3B (fig. 31 and 33). These distinct characteristics were observed only in the continuous data, and were not observed while fluid and flow logging were conducted.

Attempts to find linear correlations between the head difference between wells 2A and 3B and specific conductance at monitored depths at all three wells produced mixed results. Head difference was best correlated to specific conductance at well 3B ($R^2 = 0.68$ for the lower zone monitor and 0.54 for the upper zone monitor). Correlations between head difference and specific conductance were lower at wells 2A and 201-M than at 3B, possibly reflecting the influence of numerous permeable zones and distance from actively pumping wells. For example, well 201-M has more than 700 ft of open hole and is located west of the well field away from pumping centers. Contributions from flow zones of varying water quality may also compensate for head differences under specific pumping scenarios.

Individual permeable zones may compensate for pressure changes by contributing varying amounts of flow from specific zones with different water quality, without measurably affecting water levels. For example, data from one zone showed a time lag between observed water levels and specific conductance changes, whereas other zones experienced a change in either water level or specific conductance, but not both. Lag time between water-level changes and observed water-quality response can be explained as the time needed to allow various flow paths to equilibrate with different potentiometric conditions that induce ground-water movement. Pumping from wells open to multiple flow zones may induce water with relatively high or low specific conductance values to enter and exit along

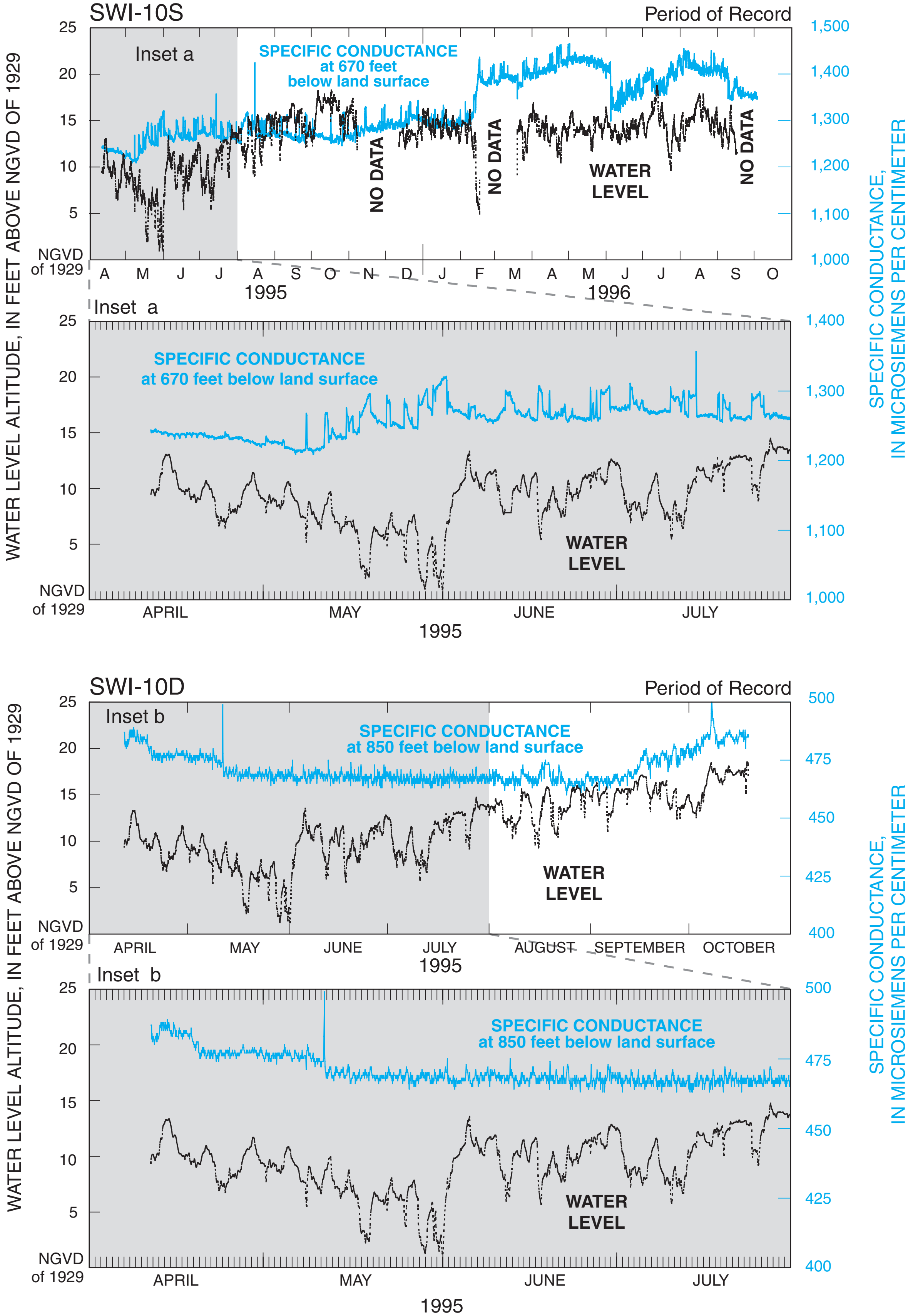


Figure 30. Water levels and specific conductance of water from fixed depths at wells SWI-10S and SWI-10D, April 1995–October 1996.

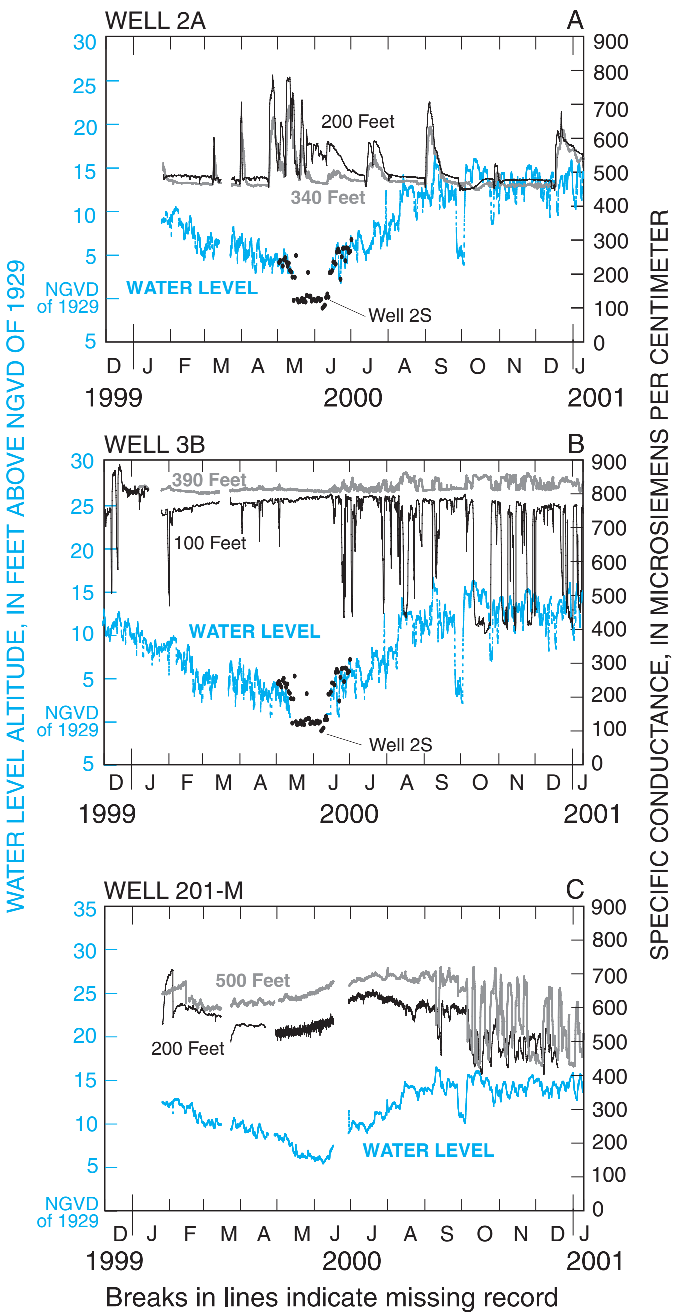


Figure 31. Water levels and specific conductance of water at selected depths at wells 2A, 3B, and 201-M at the Eldridge-Wilde well field, December 1999 –January 2001.

the permeable intervals. For example, in wells 2A and 5N, water with high specific conductance enters one permeable zone and exits along another.

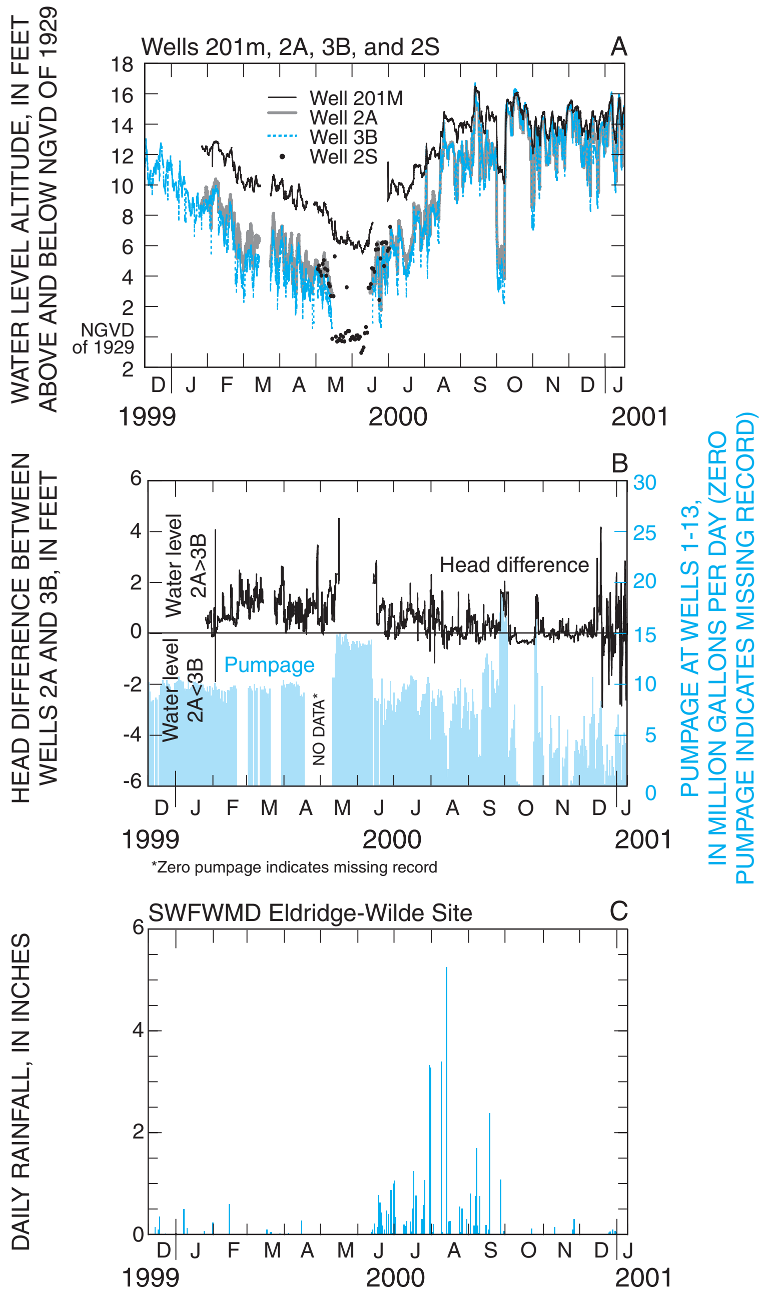
Although ground-water declines and pumpage correlated directly with some observed spatial and temporal patterns in specific conductance, there were periods of time when neither pumpage nor substantial head differences correlated with patterns observed in the specific conductance data. Because the observed relations and responses between pumping, water levels, and changes in specific conductance are complex and do not always follow a distinct pattern, it is likely that different pumping configurations induce different responses. Localized changes in ground-water movement within a heterogeneous aquifer, induced by pumping wells, may affect one well, but not another, because flow zones intersected by each well may be different.

Chloride and Specific Conductance Variability in the Avon Park Producing Zone

Within the study area, chloride concentrations and specific conductance varied over several orders of magnitude both spatially and temporally within the Avon Park producing zone. Chloride concentrations in water from wells with discrete open-hole intervals, specific conductance logs, and continuous monitoring of specific conductance at fixed depths within selected wells open to the Avon Park producing zone were used to describe ground-water movement and mixing that could explain the observed variability. Primarily, vertical variations in water-quality data within the study area are related to the location of the well and proximity to the saltwater interface. In the study area, the depth to the saltwater interface decreases towards the west (fig. 22). Additionally, continuous data from fixed depths indicate that high specific-conductance ground water moves along specific flow zones and can affect the water quality of a borehole. Although water-quality changes appear to correspond to water-level changes, the specific conductance and percentage of total flow supplied by a flow zone from a specific depth can also affect the water quality of the borehole.

The highest specific conductance values within the study area were observed in wells with open-hole intervals within the Avon Park producing zone (580-780 ft below land surface). West of the EW well field at well NLKTP (open 758-780 ft below land surface), the specific conductance was 45,900 µS/cm. Specific conductance values greater than 20,000 µS/cm were identified in wells SWI-2D, SWI-6D, and SWI-7D, located 1 to 2 mi west of the well field (fig. 2), each with open intervals 600-750 ft below NGVD of 1929. Specific conductance at well SWI-4D, approximately 0.5 mi west of the well field and open to approximately the same depth (710-775 ft below land surface), exceeded 6,000 µS/cm. Nearby at well 201-M (open hole interval from 144-684 ft below land surface), specific conductance ranged from less than 500 to more than 800 µS/cm, indicating that specific conductance values can be affected by movement of the nearby saltwater/freshwater interface. Within the well field, specific conductance values at SWI-10S (open 650-700 below land surface) exceeded 1,000 µS/cm. At the same site (SWI-10D) (open 830-900 ft), specific conductance was lower, ranging from 400 to 900 µS/cm.

Specific conductance values also fluctuated within the highly transmissive Avon Park producing zone. Specific conductance logs collected under ambient conditions at several wells with less than 200 ft of open hole in the Avon Park producing zone (wells SWI-1S, SWI-1D, SWI-10S) showed



Breaks in lines indicate missing record except for figure 32c.

Figure 32. Water levels, pumpage, and head difference at selected wells, and rainfall at the Eldridge-Wilde well field, December 1999–January 2001.

both increases and decreases in specific conductance at intervals that correspond to the fracture zone identified in the acoustic televiewer logs (fig. 8). Specific conductance changes that can vary up to several thousand microsiemens per centimeter appear to be associated with discrete borehole intervals that may correspond to fractures within the Avon Park producing zone. The specific conductance logs of well SWI-1D indicate that fluid conductance under ambient conditions ranged from about 700 to about 2,000 µS/cm on three different dates in 1994 and 1995 (fig. 34). In May 1994, specific conductance generally decreased with depth to 615 ft below NGVD of 1929, where a major decrease was observed (fig. 34). Specific conductance logs from March and August 1995, however, show a reversed trend. Similar reversals in specific conductance occurred at other sites, although to a lesser degree than those observed at SWI-1D; specific conductance profiles from wells 201-M, SWI-2S, SWI-5S and SWI-6S also indicate that specific borehole intervals are associated with water-quality changes.

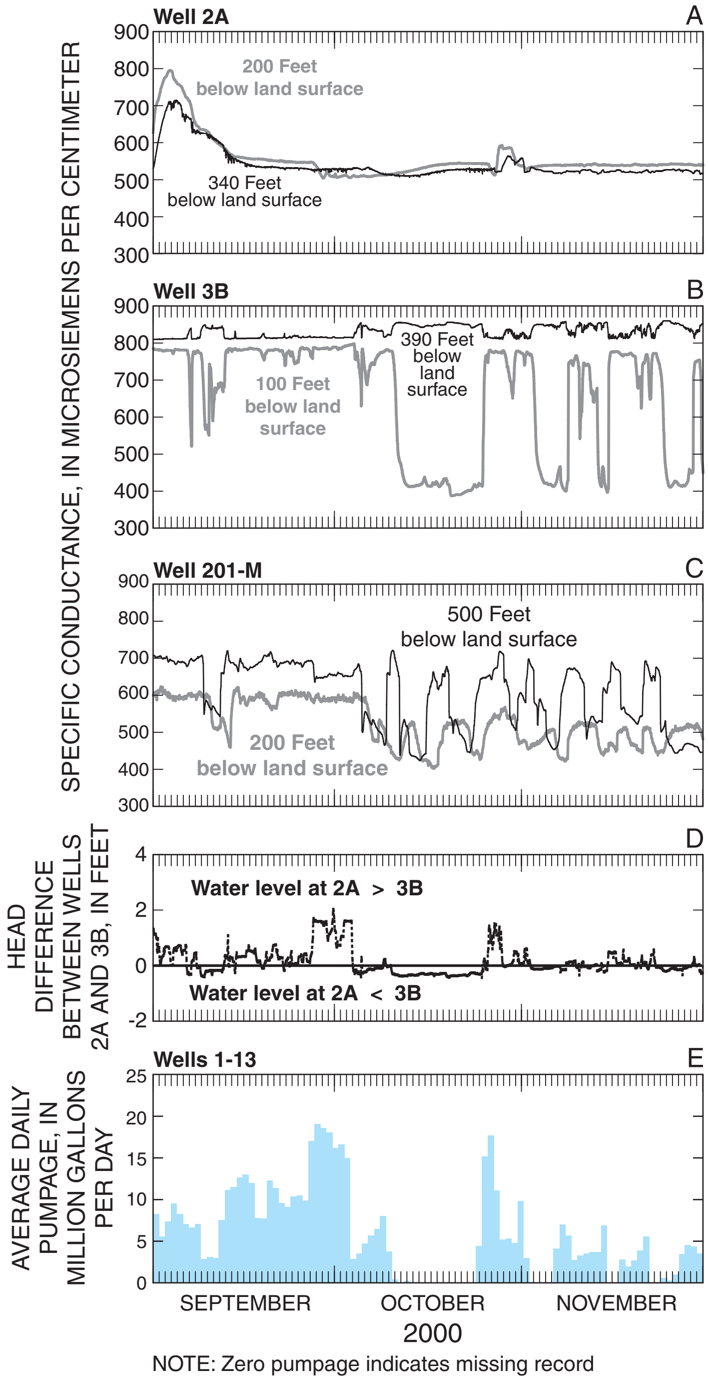


Figure 33. Relation between ground-water pumpage, head differences, and continuous specific conductance at fixed depths in ground water at wells 2A, 3B, and 201-M, September–November 2000.

The presence of fractures within the Avon Park Formation appears to affect permeability and water quality but not water-level trends. Specific capacity, water levels, and specific conductance were compared at wells SWI-10S and SWI-10D, which are located about 30 ft apart. Well SWI-10S penetrates the Avon Park producing zone, the same zone that provides water to nearby production wells. Acoustic televiewer data collected at SWI-10S indicate that numerous fractures were present at 600-650 ft below NGVD of 1929 in the monitored interval (fig. 8). The specific capacity determined for this interval was 525 gal/min/ft (Nettles and Associates, Inc.,1990). Conversely, at SWI-10D, no distinct fractures were observed in the acoustic televiewer data at 830-900 ft below top of casing. The specific capacity determined for SWI-10D at this interval

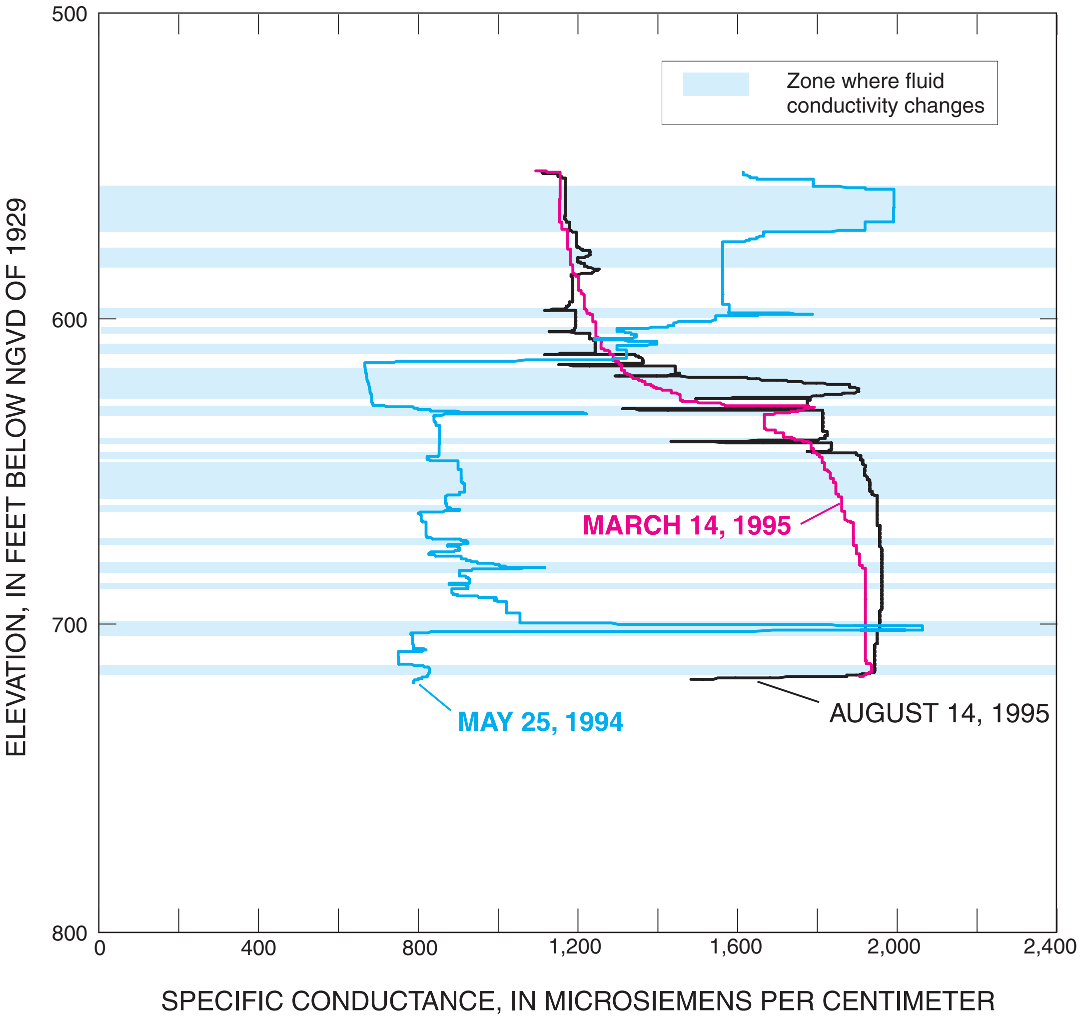


Figure 34. Selected fluid conductivity logs for well SWI-1D. Logs collected by Pinellas County, 1994-1995.

was 6 gal/min/ft, indicating the presence of a low permeability zone within the lower part of the UFA near the top of the MCU (Nettles and Associates, Inc., 1991c).

Although water-level changes at these two wells were nearly identical (fig. 30), changes in specific conductance in response to water-level changes were not. In well SWI-10S, specific conductance increased when water levels declined. In well SWI-10D, the change in specific conductance in response to water-level changes was minimal, with the exception of a few high-frequency fluctuations in water levels, like those observed at SWI-1D, which appeared to coincide with distinct sporadic increases in specific conductance. In contrast, within the high permeability zone at well SWI-10S, water-level changes were accompanied by nearly simultaneous changes in specific conductance (fig. 30).

Concurrent changes in water levels and specific conductance indicate that permeable zones within the Avon Park producing zone respond rapidly to water-level changes and appear to transmit water with high specific conductance along these permeable intervals. In some cases, a slight lag exists between the change in water level and the change in specific conductance. Pumping stresses at adjacent wells could induce ground-water movement along permeable zones intersected by the monitor wells. Both direct and lagged responses between water levels and specific conductance were observed at different periods at wells SWI-1S and SWI-10S, monitoring the Avon Park producing zone.

Ground-Water Quality and Mixing

In the study area, most ground water from the UFA is a calcium-bicarbonate-type water that has been enriched to varying degrees by mixing with seawater and calcium-sulfate-type water (Sprinkle, 1989; Maddox, 1992). Stiff diagrams plotted along an east-west geologic section from the coast to the well field show where calcium-bicarbonate water is predominant and where calcium-sulfate or sodium-chloride enrichment occurs at depth (fig. 35). Twenty-three wells within and outside of the

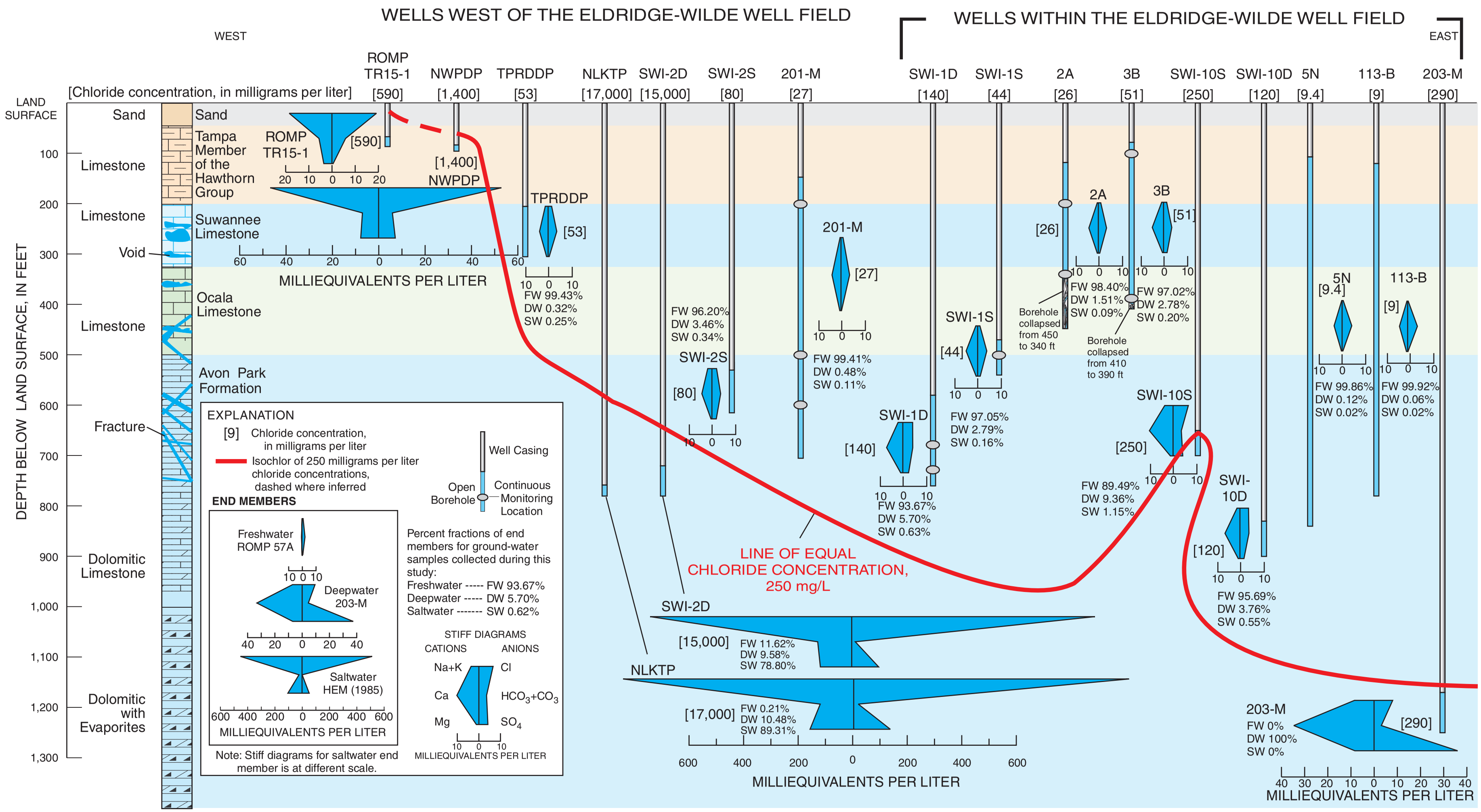


Figure 35. A generalized east-west geologic section, well construction, and water-quality characteristics of individual wells, including chloride concentrations, stiff diagrams, and percentages of end-member mixing within and west of the study area. Locations of wells shown in figs. 1 and 2.

well field were sampled during this study, including monitor wells constructed to discrete open-hole intervals and production wells with large open-hole intervals (fig. 1). Ionically enriched ground-water samples and a representative seawater composition (Hem, 1985) were used to characterize the water quality of "end-member" samples, which are defined as 100 percent calcium-bicarbonate, calcium-sulfate, and sodium-chloride type waters. Water-quality data are summarized in appendix B.

The location, length of open hole, and access to different depth zones of the UFA affect the overall composition of the water from production wells (fig. 35). Well 3B in the southwestern part of the well field is slightly deeper than the first supply wells constructed in the well field; open hole ranges from about 80 to 390 ft below land surface, penetrating the Tampa/Suwannee producing zone. Well 5N in the central part of the well field is typical of deeper well construction open to the Avon Park Formation; open hole ranges from about 107 to 863 ft below land surface. Increases in chloride concentrations have been observed in both wells over time. When chloride concentrations were consistently greater than 80 mg/L at well 3B during the 1990s, the well was removed from production. Well 5N experienced increases in chloride concentrations above 20 mg/L beginning in 1986, then decreased to background levels by 1992. Concentrations of sodium, chloride, and sulfate are higher at well 3B than at well 5N even though well 3B is shallower (390 ft) than well 5N (863 ft). Several factors could explain this difference. Well 3B is located closer to the saltwater interface (where ground water has specific conductance greater than 10,000 μS/cm and chloride concentrations are in excess of 250 mg/L), whereas well 5N is located farther inland (figs. 1, 2). Well 3B has a substantially shorter open-hole interval than well 5N, and the specific capacity at well 3B is lower (40 gal/min/ft) than that at well 5N (122 gal/min/ft). The specific conductance at well 3B is dominated by a flow zone at 350 ft below top of casing, associated with increased specific conductance (fig. 19). A major flow zone is present at a similar depth in well 5N, but the specific conductance is slightly lower and the overall higher specific capacity and length of open hole at well 5N indicate that more freshwater flow enters well 5N compared to well 3B (figs. 19, 20). Sodium, chloride, and sulfate concentrations in ground water increase as distance from the saltwater interface decreases (Sprinkle, 1989).

The chemical signature at each well represents a unique mixture of ground water depending on the depth of the well, the length of the open-hole interval, and water-quality characteristics of specific permeable zones. Analysis of a Piper diagram confirms that water from wells within the well field is a chemically variable mixture of the three water-quality types (fig. 36). Calculated mixing lines show end-member mixing between calcium-bicarbonate, calcium-sulfate, and sodium-chloride type waters (freshwater, deepwater, and saltwater, respectively). The calcium-bicarbonate water type end member is from ROMP 57A, an UFA well located east of the study area in Polk County, Florida (fig. 1). Water from this well was selected to represent typical calcium-bicarbonate water having a low ionic concentration. Chloride concentration of water from ROMP 57A is low (5.1 mg/L), and is considered unaffected by influences of deepwater or the saltwater transition (mixing) zone. The calcium-sulfate water type end member is from well 203-M, which penetrates the MCU in the eastern part of the well field (fig. 2). The chloride and sulfate concentrations in water from 203-M are 290 and 1,800 mg/L, respectively, which is typical of upper MCU water and, therefore, considered representative of a deepwater source that would most likely influence the water chemistry within the study area. The sodium-chloride water type end member used to represent seawater within the Gulf of Mexico is the standard analysis of seawater as defined by Hem (1985).

Production wells and monitoring wells open to the production zones in the well field (5N, 202-M, 113-B, 201-M, 2A, 3B, SWI-1S) plot along the mixing line between the calcium-bicarbonate and calcium-sulfate water types (fig. 36). Deep wells within the well field that are open only to the Avon Park Formation plot closer to the 203-M end member, showing the influence of deepwater mixing and enrichment of sulfate. Coastal wells and deep wells (such as SWI-2D and SWI-6D), located to the south and west of the well field, plot near to the seawater composition. Water from well SWI-7D, west of the well field, is a mixture of sodium-chloride seawater and calcium-sulfate water. Deep wells open to the Avon Park Formation within the EW well field (SWI-1S, SWI-1D, SWI-2S, SWI-10S, SWI-10D) plot more towards the middle of the Piper diagram, indicating they are mixtures of seawater, deepwater, and freshwater.

The relation between the ratio of sulfate-to-chloride and sulfate concentration in ground water can help differentiate waters influenced primarily by deepwater from those influenced by seawater (fig. 37). Both seawater and deepwater mix with freshwater in the study area. Wells to the west of the well field are dominated by seawater mixing (SWI-2D, SWI-6D, SWI-7D, NWPDP, NLKTP). Shallow wells (2A and 3B) contain a mixture of all three water types but plot closer to the deepwater mixing line, indicating that these wells are influenced by ground water from the deeper zones of the Avon Park Formation.

The effect of proximity to the saltwater/freshwater interface on ground-water quality was examined by comparing the sulfate-to-chloride ratio to sulfate concentration at three monitor wells that penetrate the entire length of the UFA (fig. 37). Samples from wells 201-M, 202-M, and 113-B represent composite water quality similar to a deep production well with a large open-hole interval, and all have relatively low specific conductance because of the large open hole. Well 201-M is south and west of the well field, and well 202-M is north and west of the well field. Well 113-B is in the central part of the well field. Wells 201-M and 202-M are closer to the estimated location of the 10,000-μS/cm specific conductance line (saltwater interface) than well 113B (fig. 2). Wells 202-M and 113-B have similar concentrations of chloride and sulfate, but well 201-M has three times the sulfate and chloride concentrations found in wells 202-M and 113-B, indicating the influences of

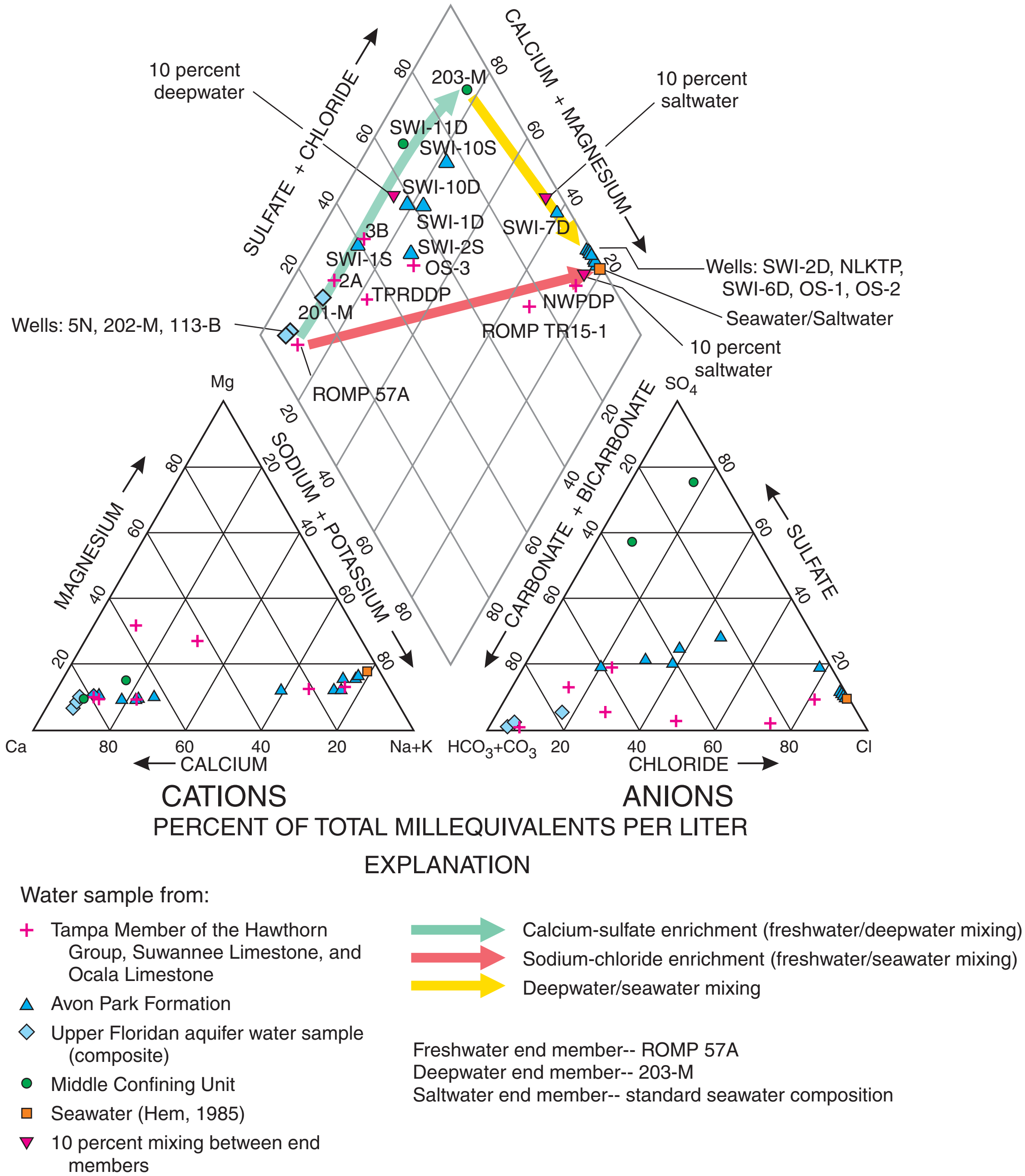


Figure 36. Ground-water mixing trends between end members and ground-water samples within the study area.

both calcium-sulfate and sodium-chloride water types associated with the high specific conductance ground water nearby (figs. 1, 37).

To quantitatively describe the amount of mixing, a three-way mixing model was used to calculate fractions of freshwater, deepwater, and saltwater. Mass-balance equations were derived using chloride and sulfate as conservative ions. Chloride was assumed to be conservative for this study, a standard assumption in water-quality calculations. Sulfate, which is less conservative, was used in the calculations to indicate mixing with deepwater that contains dissolved gypsum and other evaporite minerals. Sulfate is more reactive than chloride, and two possible reactions that could affect sulfate concentrations are: (1) sulfate reduction, which removes sulfate and produces sulfide, and (2) additional sources of sulfate other than the evaporites present in the lower part of the UFA. Sulfate reduction results in an underestimation of sulfate concentrations. The observed presence of sulfide in many of the wells indicates that sulfate reduction does occur, so the percentage of deepwater may be slightly underestimated. Sulfide concentrations, however, are low within the EW well field. The median value for sulfide as H_2S is 1 mg/L, ranging from 0.06 to 2.95, an order

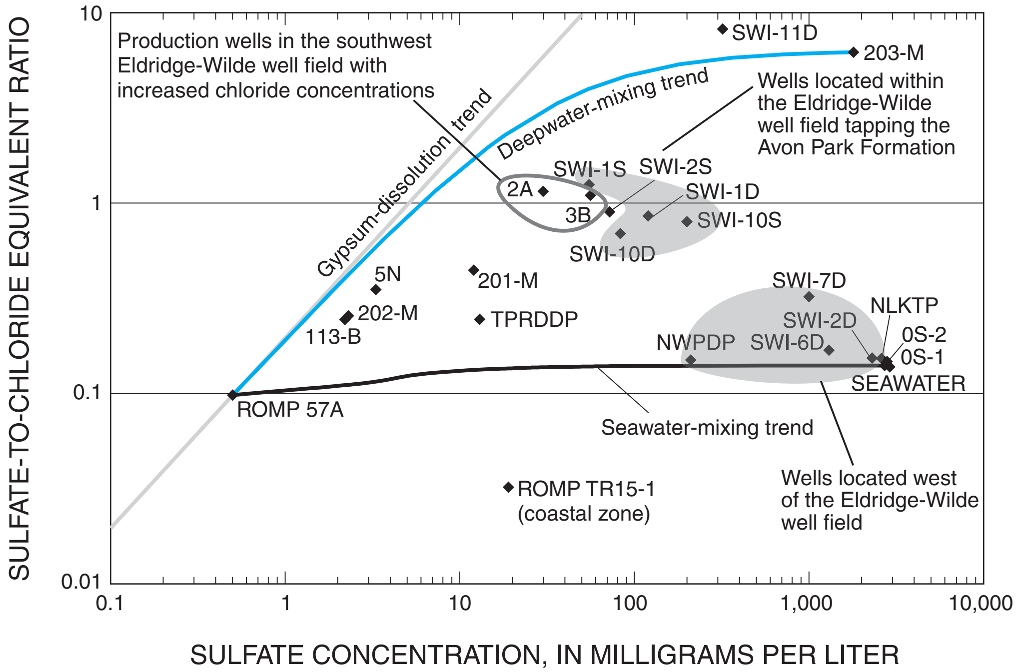


Figure 37. Relation of sulfate-to-chloride equivalent ratio to sulfate concentration in water from the Upper Floridan aquifer in and near the Eldridge-Wilde well field and end-member mixing lines. Locations of sampled wells shown in figs. 1 and 2. Well-construction and water-quality data are provided in appendixes A and B, respectively, and in fig. 35.

of magnitude lower than sulfate concentrations (John Trout, Tampa Bay Water, written commun., 2001). Sulfide can be removed by pyrite precipitation, but the amount of pyrite precipitation probably is low based on geochemical modeling in other areas of the UFA (Plummer and others 1983; Sacks, 1996; Sacks and Tihansky, 1996; Plummer and Sprinkle, 2001). Therefore, the amount of reduced sulfur probably is low compared to sulfate. Based on the mineralogy of the UFA, the presence of additional major sources of sulfate is not likely (Sprinkle, 1989).

Assuming that all ground-water samples are a mixture of the three end members, each ground-water sample contains fractions of saltwater (f_{sw}), freshwater (f_{fw}), and deepwater (f_{dw}):

$$1 = (f_{sw}) + (f_{fw}) + (f_{dw}). \qquad (1)$$

The observed chloride and sulfate concentrations, in milligrams per liter, in a ground-water sample represent a mixture of fractions based on the chloride and sulfate concentrations of the end members:

$$(f_{sw})\,([Cl^-]_{sw}) + (f_{fw})\,([Cl^-]_{fw}) + (f_{dw})\,([Cl^-]_{dw}) = [Cl^-]_{observed\ gw\ sample}, \text{ and} \qquad (2)$$

$$(f_{sw})\,([SO_4^{2-}]_{sw}) + (f_{fw})\,([SO_4^{2-}]_{fw}) + (f_{dw})\,([SO_4^{2-}]_{dw}) = [SO_4^{2-}]_{observed\ gw\ sample}. \qquad (3)$$

Percentages of freshwater, deepwater, and saltwater calculated for samples based on the mixing calculations are shown in table 3 and figure 35. A sensitivity analysis based on 5-percent variability of chloride and sulfate concentrations indicated that percentage error for calculated mixing percentages ranged from 0 to 0.16 percent. Samples from wells with large open-hole intervals were used to compare with historical trends at production wells, because these mixtures represent generalized water-quality characteristics of the entire aquifer. Samples from wells with discrete open-hole intervals were used to describe specific water-quality characteristics of distinct hydrogeologic units, and are better for describing ground-water mixing reactions occurring in the area.

Freshwater Mixing

The freshwater fractions for ground-water samples, excluding the end members, averaged about 80 percent and ranged from 0.21 to 99.92 percent (table 3). Within the well field, ground water with the greatest percentage of freshwater (greater than 95 percent) came from wells penetrating the Tampa/Suwannee producing zone and from wells with large intervals open to the entire UFA. Ground water that was 90 to 95 percent freshwater came from wells of varied depth and open-hole interval, and was mixed with 3 to 6 percent deepwater. The freshwater fraction ranged from 0.21 (NLKTP) to 89 percent (SWI-10S) for ground water with less than 90 percent

Table 3. Percentages of mixing end members calculated for selected ground-water samples within the study area using the ionic concentrations of ground water from ROMP 57A, 203-M, and modern seawater, as freshwater, deepwater, and saltwater end members, respectively.

[bls, below land surface]

Site name	Open hole (feet bls)	Percent freshwater	Percent deepwater	Percent saltwater
113-B	120-780	99.92	0.06	0.02
202-M	132-780	99.91	0.07	0.02
5N	106-863	99.86	0.12	0.02
TPRDDP	205-305	99.43	0.32	0.25
201-M	144-684	99.41	0.48	0.11
2A	113-340[a]	98.40	1.51	0.09
SWI-1S	470-540	97.05	2.79	0.16
3B	78-390[b]	97.02	2.78	0.20
SWI-2S	530-630	96.20	3.46	0.34
SWI-10D	830-900	95.69	3.76	0.55
SWI-1D	580-760	93.67	5.70	0.63
SWI-10S	650-700	89.49	9.36	1.15
SWI-11D	810-899	82.20	17.89	0.00
SWI-7D	680-740	52.37	31.82	15.81
SWI-6D	640-720	47.96	11.71	40.33
SWI-2D	720-780	11.62	9.58	78.80
NLKTP	758-780	0.21	10.48	89.31
Average		80.02	6.58	13.39
Maximum		99.92	31.82	89.31
Minimum		0.21	0.06	0.00
End members:				
EW 203-M		0	100	0
Seawater[c]		0	0	100
ROMP 57A		100	0	0

[a]Original depth 450 feet; [b]Original depth 410 feet; [c]Hem (1985).

freshwater. The deepwater and saltwater fractions of water from these two wells varied considerably. Water from well NLKTP tapping the Avon Park producing zone west of the well field and within the saltwater interface, contained the lowest freshwater fraction – approximately 10 percent deepwater and 89 percent saltwater. Other wells west of the well field tapping the Avon Park producing zone contained low freshwater fractions; wells SWI-6D and SWI-7D contained 48 and 52 percent freshwater, respectively. Deepwater and saltwater fractions from these two wells were substantially different. Water from well SWI-6D contained 40 percent saltwater and 12 percent deepwater, whereas water from well SWI-7D contained about 16 percent saltwater and 32 percent deepwater.

Deepwater Mixing

Most wells had ground water with higher sulfate concentrations than could be explained by the mixing of freshwater and saltwater, indicating deep aquifer gypsum dissolution as an additional source (Rye and others, 1981; Sacks, 1996; Sacks and Tihansky, 1996). Deepwater fractions for all wells sampled ranged from 0 to 32 percent (table 3). Wells with the lowest percentage of deepwater also had the longest open-hole intervals. Water from five wells, 5N, 113-B, 202-M, 201-M, and TPRDDP showed little to no influence of sulfate-enriched water, having deepwater fractions less than or equal to 0.5 percent (table 3, figs. 35, 36). The first four of these wells have over 500 ft of open hole and fresh flow zones may substantially dilute the deepwater component. Well TPRDDP (fig. 1), west of the well field, penetrates the Tampa/Suwannee producing zone and has only 100 ft of open hole. The deepwater fraction of this well was 0.32 percent.

The presence of increased deepwater fractions in shallow aquifer zones within the well field indicates upward migration of deepwater into shallow producing zones. Ground water from wells within the well field having less than 1 percent saltwater had deepwater fractions ranging from 2 to 6 percent (table 3). Deepwater fractions within shallow aquifer zones (less than 400 ft deep) within the well field (wells 2A and 3B) are more than four times as high as the same zone outside the well field at well TPRDDP. The deepwater enrichment occurred primarily in areas where the potentiometric surface was lowered by ground-water withdrawals.

The largest deepwater fractions (greater than 15 percent) were present at monitor wells outside the well field with less than 100 ft of open hole penetrating the Avon Park Formation (table 3). Water from well SWI-11D is from the less permeable zone of the Avon Park Formation (810-899 ft below land surface) and is a mixture of freshwater (82 percent) and deepwater (18 percent), with no saltwater component. Farther west, well SWI-7D (fig. 2), also open to the Avon Park producing zone (680-740 ft below land surface), has greater ionic concentrations and is a mixture of deepwater (32 percent), saltwater (16 percent) and freshwater (52 percent). At these concentrations, the freshwater fraction has negligible influence on water quality, and on a Piper diagram, the ionic mixture falls along a mixing line between seawater and deepwater (fig. 36). Both of these wells are located north and west of the major pumping area (figs. 1, 26).

Saltwater Mixing

The saltwater interface, as defined by specific conductance greater than 10,000 μS/cm, has been delineated about one 1 mi west of the well field in the Avon Park producing zone at 680-780 ft below land surface (figs. 1, 2, 26). The saltwater fraction ranged from 0 to 89 percent of the ground-water composition for all wells sampled (table 3). Ground-water samples with the highest percentages of saltwater came from wells that were open to less than 100 ft of aquifer in the Avon Park producing zone and were a mile or more west and southwest of the well field. The highest percentage of saltwater (89 percent) was present south and west of the EW well field at well NLKTP, which taps the Avon Park producing zone (758-780 ft below land surface). Other ground-water samples with saltwater fractions greater than 15 percent were from wells SWI-2D, SWI-6D, and SWI-7D, which also tap the Avon Park producing zone. The saltwater fractions in these wells were 79, 40, and 16 percent, respectively (table 3).

Ground water from monitoring wells in or close to the EW well field generally contained less than 1 percent saltwater. Only a few wells (SWI-1S, SWI-1D, and SWI-10S) within the well field are constructed to monitor discrete intervals within the Avon Park producing zone where higher percentages of saltwater may be present (figs. 26, 35). Below the Avon Park producing zone (well SWI-10D), ground water is a mixture of 3.8 percent deepwater, 0.6 percent saltwater, and 96 percent freshwater. Wells SWI-1S, SWI-1D, and SWI-10S penetrate the highly permeable producing zone and have deepwater fractions ranging from 3 to 9 percent and saltwater fractions ranging from 0.16 to 1.15 percent. Based on these wells, both deepwater and saltwater fractions increase with depth and towards the center of the well field.

Combined Effects of Deepwater and Saltwater Mixing

Although saltwater mixing is minimal in the well field, small percentages of saltwater can affect the potability of the ground water. For example, a mixture of 1.3 percent saltwater and 98.7 percent freshwater results in a chloride concentration of 250 mg/L (the drinking-water standard). Thus, even small amounts of saltwater mixing are important to the ground-water quality. Because of high sulfate concentrations, a larger fraction of deepwater (10-15 percent) also would render drinking water nonpotable. At the EW well field, both deepwater and saltwater mixing occur. The highest fractions of saltwater and deepwater were found within the Avon Park producing zone in areas where the potentiometric surface was the lowest.

Less than 400 ft below land surface, chloride and sulfate concentrations present in shallow wells in and near the well field are associated with deepwater and saltwater mixing. In the Tampa/Suwannee producing zone, chloride concentrations are less than 0.5 percent of the concentration in seawater. Ground-water samples from the Tampa/Suwannee producing zone west of the well field (TPRDDP), plot more closely along the seawater mixing line than ground-water samples from wells within the well field (fig. 37), indicating a dominant seawater source for the chloride concentrations outside the well field. Within the same producing zone, however, in the southwestern part of the well field (wells 2A and 3B), ground-water samples plot closer to the deepwater mixing line, with mass-balance calculations indicating that elevated chloride concentrations are from a deepwater source. Increased sulfate concentrations, especially in wells within the well field, indicate that there is a deep ground-water source of chloride and sulfate. The deepwater component within the well field is four times greater than that observed to the west within the Tampa/Suwannee producing zone, although overall chloride concentrations are similar. In wells that tap both the Tampa/Suwannee producing zone and the Ocala semiconfining unit that are located toward the center of the well field, the deepwater fraction doubles that found in wells outside the well field in the same zone.

Chloride concentrations are in part associated with mixing that occurs in the transition zone between saltwater and freshwater. The combined effects of deepwater and saltwater mixing on chloride and specific conductance for discrete sampling depths are shown in figure 38. Historical water-quality data from Pinellas County and the USGS follow two main trends. Water samples from the southwestern part of the well field within the Avon Park producing zone (shown in pink) plot parallel to the calculated chloride/specific conductance curve (Ron Miller, U.S. Geological Survey, written commun., 2000), indicating that saltwater mixing is the predominant factor affecting ground-water quality. The consistent offset above the curve is attributed to minor amounts of sulfate enrichment from deepwater mixing, which causes higher specific conductance than can be explained by increasing chloride from saltwater mixing alone. Water samples from the UFA at depths above and below the Avon Park producing zone (generally less than 550 ft or greater than 760 ft below land surface) showed some enrichment of sulfate, but relatively low (less than 100 mg/L) chloride concentrations (fig. 38). Water quality in these wells (shown in blue) is predominantly affected by deepwater mixing. Water with both high specific conductance and chloride concentrations from depths 1,100 to 1,240 ft below land surface (MCU) also are affected by deepwater mixing. Shallow wells 2A and 3B show effects of both saltwater and deepwater mixing. Deepwater mixing occurs to varying degrees throughout the ground-water system but saltwater mixing occurs predominantly within the Avon Park producing zone.

The relative permeability of hydrogeologic units and distance from deepwater and saltwater sources (relative sulfate and chloride concentrations) control where and to what extent ground-water mixing occurs. The influence of a deepwater source appears to affect most wells throughout the southwestern part of the well field (fig. 35). Sulfate concentrations increase with depth as the proximity to a deepwater source decreases. Discrete flow zones, however, and periodic increases in specific conductance in relatively shallow wells, such as wells 2A and 3B (figs. 31 and 33), indicate that deepwater may be migrating along geologic features that are associated with increased permeability. Similar relations exist within the Avon Park producing zone. Increases in chloride concentrations related to a saltwater source occur in wells that are open to the Avon Park producing zone south and west of the well field. Moderately saline water, about a mile south and west of the well field, appears to move preferentially inland along the fractured and highly permeable Avon Park producing zone. Similar preferential ground-water movement has been simulated along zones of high transmissivity in deep-well injection flow studies within the Avon Park Formation in Pinellas County (Hutchinson and

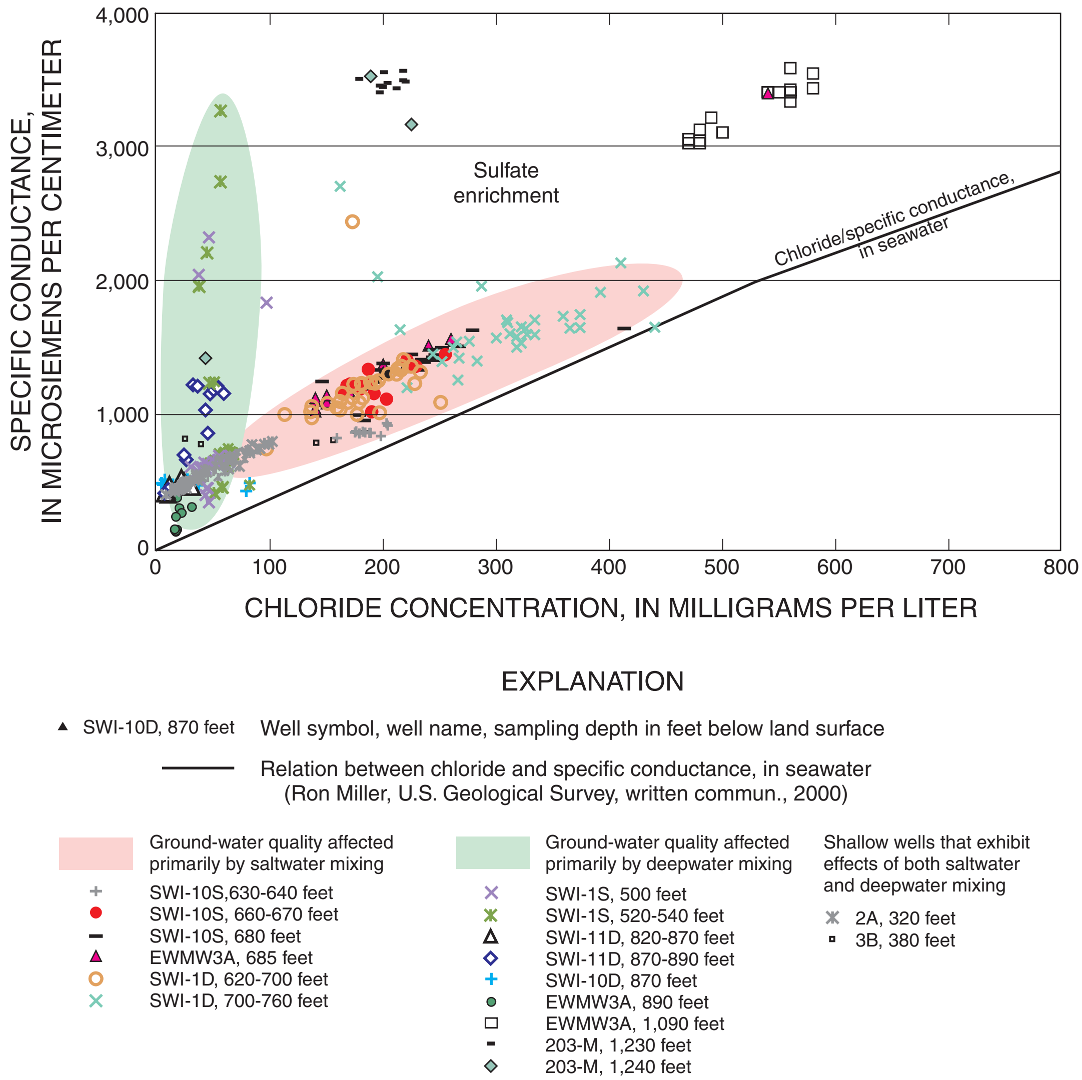


Figure 38. Relation between chloride concentration and specific conductance for ground-water samples obtained at specific depth intervals. Well locations shown in fig. 2.

others, 1993) and chloride migration has been documented to occur along fractures within the Floridan aquifer system in northeastern Florida and southeastern Georgia (Maslia and Prowell, 1990; Phelps and Spechler, 1997).

The localized existence of low chloride concentrations between the MCU and the Avon Park highly transmissive zone indicates saltwater moves inland preferentially along fractures within the same highly transmissive zone in which ground water is withdrawn for supplies. Ground water from the deepest part of the UFA (from wells penetrating depths greater than 870 ft deep) had chloride concentrations ranging from less than 100 to more than 500 mg/L, with sulfate concentrations generally greater than 200 mg/L (fig. 38). These concentrations reflect the low transmissivity of the deep zone when compared to the highly productive Avon Park producing zone above it.

Isotopic Evidence of Ground-Water Mixing

The relation between $\delta^{18}O$ and δD also can be used to identify sources of water. Isotopically light waters generally indicate recent recharge, whereas heavier signatures indicate that the waters have either been enriched by evaporative processes, are older waters that recharged under different climatic conditions, or are influenced by seawater. Within the study area, ground water with less than 90 percent freshwater (table 3) plots on the seawater mixing line, indicating that saltwater mixing is the likely source for elevated chloride concentrations in these wells (fig. 39). The $\delta^{18}O$ ratios in waters having greater than 90 percent freshwater, however, are highly variable. Comparison of $\delta^{18}O$ and δD data for fresh ground waters indicates that evaporation prior to recharge could cause the

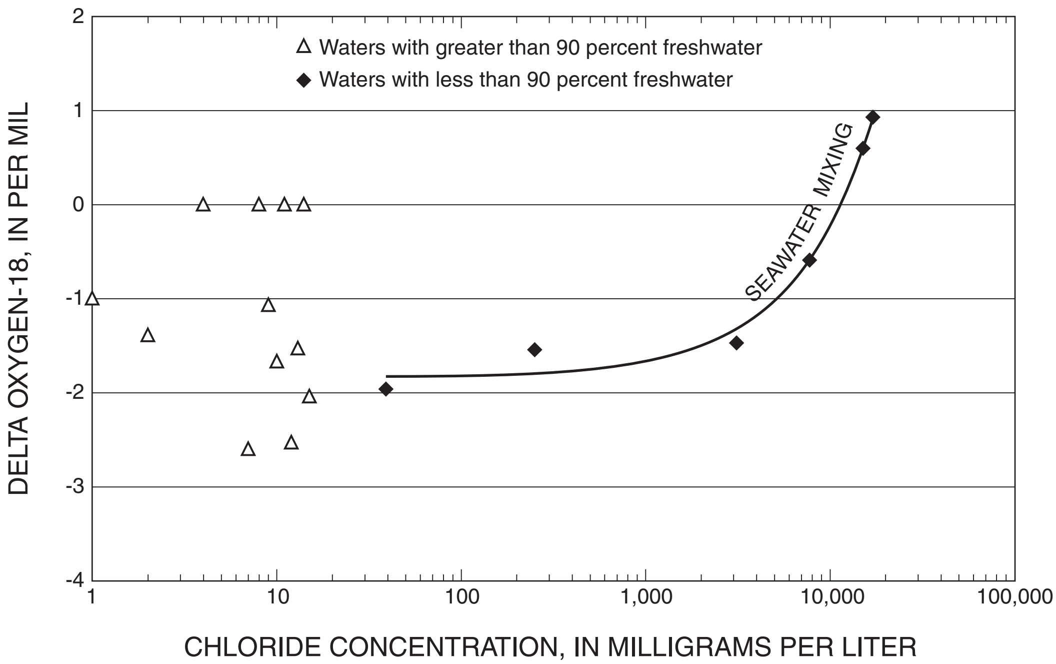


Figure 39. Relation between chloride concentration and delta oxygen-18 for selected Upper Floridan aquifer water samples.

observed isotopic enrichment of $\delta^{18}O$ and δD, rather than saltwater mixing. Ground-water recharge within the study area occurs by way of mantled sinkholes and karst features that underlie numerous shallow ponds and wetlands. As evaporative processes occur in the wetlands and ponds, recharge water entering the ground-water system has an evaporative isotopic signature. The point sources of recharge to the ground water and preferential flow paths likely contribute to poor regional mixing and could explain the variability in the observed $\delta^{18}O$ and δD ratios. In general, when chloride concentrations are less than 1,000 mg/L, $\delta^{18}O$ is not a good tracer for sources of salinity (fig. 39).

Strontium isotopes were analyzed in water from selected wells and were compared to chloride concentrations and strontium signatures for geologic units (Hess and others, 1986). Most data plotted in a range indicating Oligocene-age seawater even though the water was from wells open to the Avon Park Formation, which is Eocene age (fig. 40a). This age discrepancy may be a result of diagenetic changes that have affected the composition of strontium in the aquifer materials or a result of mixing with water having a younger strontium source, such as ground water from the Suwannee Limestone or modern seawater. Wells open to multiple flow zones receive a mixture of ground water that has been in contact with geologic formations of younger ages. The Avon Park Formation is a dolomite unit, and deep mineralized ground water likely has undergone substantial diagenetic changes. Strontium is not conservative, and multiple sources related to carbonate dissolution and precipitation reactions could alter the strontium isotope ratio in rocks such as dolomites. Sacks and Tihansky (1996) found that ground water in southwestern Florida had $^{87}Sr/^{86}Sr$ isotope ratios indicating Oligocene age, although the aquifer materials were of Eocene age. The Oligocene-age seawater signature resulted from dissolved strontium derived from Eocene-age rocks mixing with strontium derived from younger seawater that was introduced into the aquifer. The mixture of isotopically heavier modern seawater with the lighter signature of Eocene-age rocks could result in an isotopic signature indicating an Oligocene age.

The strontium isotopic signature in ground water sampled during this study ranged from Miocene to Eocene regardless of the chloride concentrations (fig. 40a). Wells with large open-hole intervals showed a greater range in strontium isotopic signatures, indicating that multiple flow zones contribute to a mixed strontium value. Deepwater is enriched in strontium from dissolution of evaporates in the Eocene-age MCU, and waters with high percentages of deepwater (greater than 10 percent) had $^{87}Sr/^{86}Sr$ ratios closest to those of Eocene age (fig. 40b). Samples from two shallow coastal wells, ROMP TR15-1 and NWPDP (fig. 40b), have $^{87}Sr/^{86}Sr$ ratios close to modern seawater, indicating that nearby seawater has interacted with the aquifer at these sites. Most wells, especially those in the southwestern part of the well field, have $^{87}Sr/^{86}Sr$ ratios that indicate mixing of both saltwater and deepwater (fig. 40).

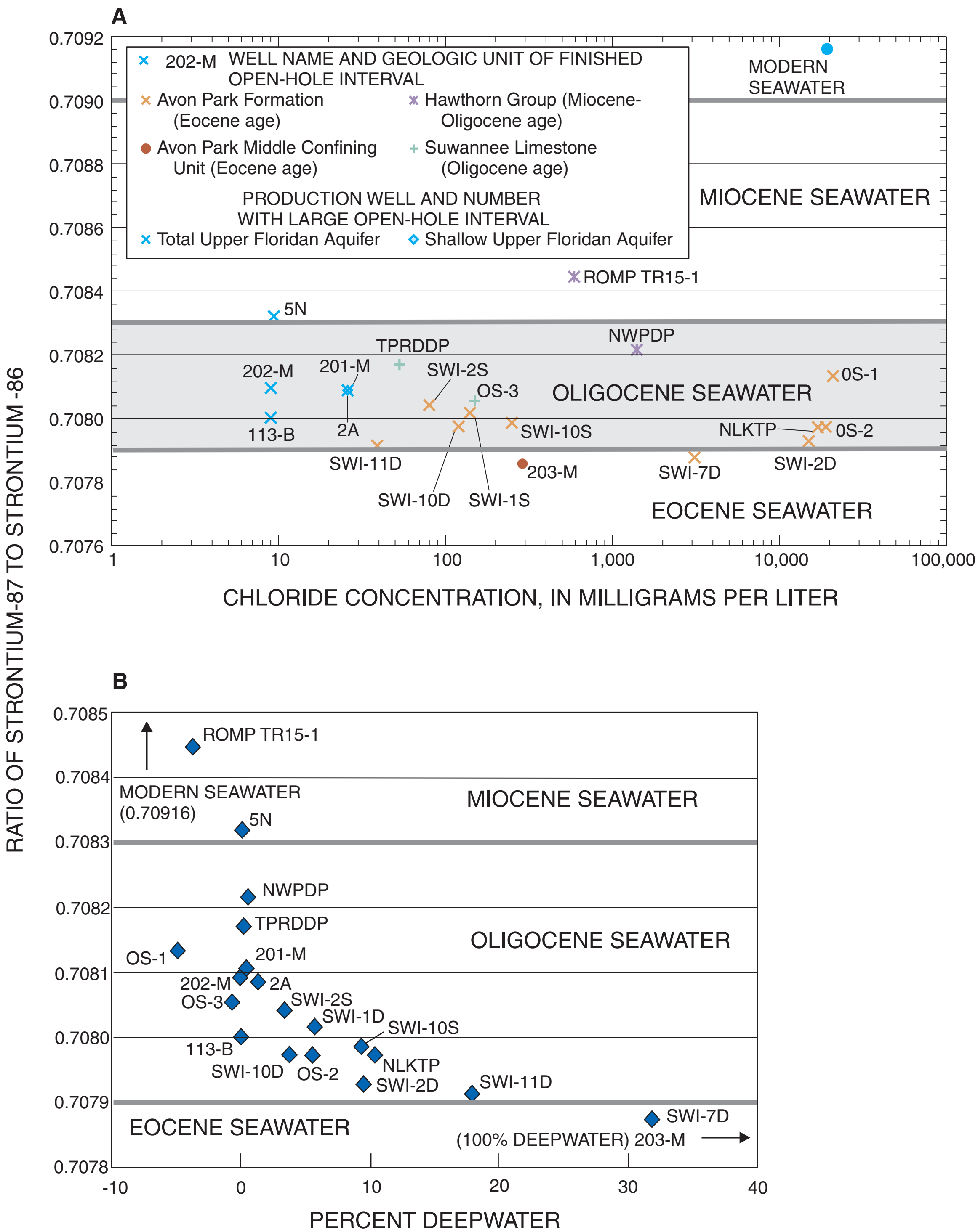


Figure 40. Relation between strontium isotope data and geologic units with (A) chloride concentrations and (B) sulfate enrichment above that from saltwater mixing. Strontium age boundaries based on Hess and others (1986).

Conceptual Model for Ground-Water Flow Patterns and Mixing

The data presented in this report were used to develop a conceptual hydrogeologic model that explains the distribution of chloride concentrations in the ground water of the study area. The distribution of hydraulic properties, permeable zones, borehole geophysical logs, and water-quality data indicate that elevated chloride concentrations within the EW well field originate from two main sources: (1) mineralized ground water from the lower parts of the UFA and (2) saltwater from the saltwater interface. The lowered potentiometric surface in the area of the EW well field creates the potential for upconing and localized lateral movement of ionically enriched waters into producing zones in the well field. Ground waters of different types are mixed and distributed throughout the well field along preferential permeable zones, fractures, and boreholes.

The depth of the 250-mg/L isochlor ranges from near land surface to 1,000 ft below land surface within the study area. Directly south and west of the well field, the 250-mg/L isochlor is at a depth of 600 to 1,000 ft, but near Lake Tarpon the depth ranges from less than 100 to more than 600 ft below land surface (figs. 35, 41). Coastal drainage systems directly west of

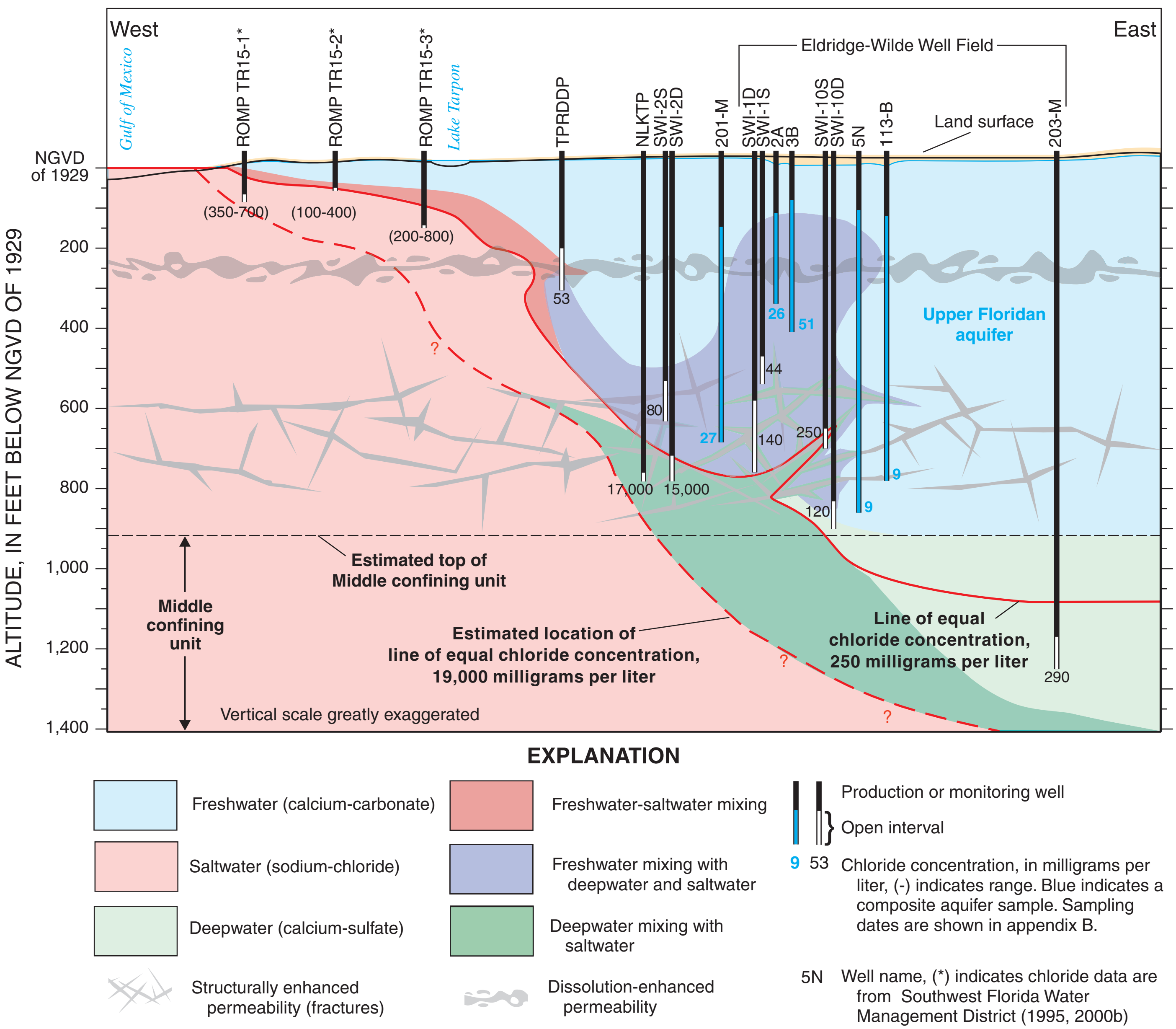


Figure 41. Schematic section of observed chloride concentrations in wells located within and west of the Eldridge-Wilde well field, incorporating the conceptual model for aquifer heterogeneity and ground-water pumping conditions.

the well field, along the Anclote River and Salt Lake Bayou, provide avenues for tidally influenced saltwater to move inland from the Tarpon Springs area. Based on data collected during this study, moderately saline ground water to the west and south appears to have migrated inland preferentially along zones of high transmissivity within the UFA. These zones were the first to exhibit increases in chloride concentrations and also have exhibited the highest chloride values.

Chloride concentrations in wells west of the well field within the freshwater/saltwater transition zone (from land surface to about 500 ft deep in the study area where freshwater and saltwater mix) range from 100 to 1,000 mg/L and are substantially lower than concentrations found within the saltwater interface (Trommer, 1993; fig. 41). Wells in the transition zone west of the EW well field that are open to the Tampa/Suwannee producing zone have shown increasing chloride concentrations with time, and wells open to the Tampa/Suwannee producing zone within the well field show a similar trend. The increasing chloride trend indicates that saltwater moves along the transmissive Tampa/Suwannee Limestones, possibly from the Salt Lake Bayou area located to the west. Wells 2A and 3B, where some of the highest chloride values for production wells were measured, are open to the upper 500 ft of the UFA, and ground water flows along distinct permeable zones within the Tampa/Suwannee Limestones. Wells 2A and 3B are near production wells 4A and 5, which have relatively high specific capacity values and are pumped at double the rate of other wells in the area. Well 4A is 210 ft deep and penetrates the upper part of the Tampa/Suwannee producing zone, which is a highly productive shallow flow zone. The permeable zones in wells 2A and 3B likely are connected to the production wells by way of permeable zones, because ground-water pumping appears to affect the quality of water in wells 2A and 3B. The influence of pumping from wells 4A and 5, which penetrate a shallow, highly transmissive part of the Tampa/Suwannee producing zone, likely induces ground-water movement along discrete zones within this part of the well field.

Ground water from well 5N shows a well-defined increase in chloride concentrations with time (type 1), indicating that the well consistently receives excess chloride from some source. The increased specific conductance at well 5N corresponds to a high flow zone within the Tampa/Suwannee producing zone. The apparent movement of water into and out of the borehole along this permeable interval indicates that this zone may be a source of water with high specific conductance (fig. 20). Well 5N receives and loses substantial amounts of ground water through the Tampa/Suwannee producing zone; an increase in chloride concentrations of more than 20 mg/L was observed in well 5N from 1987 to 1990. After 1990, however, the chloride concentrations decreased to background levels (about 10 mg/L), possibly due to reduced pumping stress on the Tampa/Suwannee producing zone during the early 1990s. Ground-water movement within the Tampa/Suwannee producing zone could be an important source of chloride.

Over time, chloride concentrations in production wells have increased in an inland (northeastern) direction (fig. 26). The most rapid increases in chloride concentrations occurred when pumping increased in the Avon Park producing zone (figs. 13, 23). Increased withdrawals from the Ocala/Avon Park and Avon Park producing zones causes preferential lateral ground-water movement along the highly transmissive producing zone between 600-750 ft deep. Below a depth of 800 ft, the Avon Park is less fractured and less transmissive. Ground-water samples obtained from depths below the Avon Park transmissive zone show chemical influence of mineralized ground water associated with the MCU, but samples have relatively low chloride concentrations, indicating that this zone is less affected by the lateral movement of saltwater because of the low transmissivity. Ground water moves laterally at a faster rate within the highly transmissive zone in the Avon Park Formation than vertically through the poorly transmissive MCU. Chloride concentrations in ground water in the southwestern part of the well field above and below the Avon Park producing zone are substantially lower than within the producing zone, but south and west of the well field specific conductance and chloride values within the Avon Park producing zone are similar to seawater concentrations. More than 40 percent of the 54 production wells active at the EW well field during this study tap the Avon Park producing zone (app. A). Nearly half of the water pumped at the well field (43 percent) is from wells with more than 500 ft of open hole penetrating the highly transmissive 600-750 ft zone.

The predevelopment pattern of westward ground-water flow has changed over time (fig. 14). Ground-water withdrawals have likely caused local reversals in the hydraulic gradient, thus increasing the potential for landward movement of saline ground water into the well field along permeable zones and fractures within the Avon Park producing zone. Although chloride concentrations equivalent to seawater do not occur within the well field, water with chloride concentrations greater than 250 mg/L moved inland 3,000 ft in the southwestern part of the well field between 1997 and 2000 (Water and Air Research, Inc., and others, 2001). The relative location of the 250-mg/L isochlor from 1992 to 2000 shows how this boundary has moved over time (fig. 26). Declines in the potentiometric surface below NGVD of 1929 can be important with respect to the location of the saltwater interface. Periods of extreme low water levels and high pumpage can further affect regional flow, thereby increasing the potential for saltwater intrusion or deepwater upconing.

The permeability differences between the Tampa/Suwannee and Avon Park producing zones and the Ocala semiconfining unit appear to create a distinct distribution of water types and their ionic concentrations within the study area (fig. 41). Rates and patterns of ground-water movement differ between aquifers dominated by primary or secondary porosity. The rates and directions of ground-water flow in a doubly porous system (system with both primary and secondary porosity) can vary substantially (Knochenmus and Robinson, 1996). Flow zones and continuous specific conductance data observed in the

Tampa/Suwannee and the Avon Park producing zones indicate that substantial secondary porosity results in well-developed conduit networks along which ground water moves preferentially and at higher velocities. In contrast, little preferential flow occurs within the Ocala semiconfining unit, but the high primary porosity and vertical hydraulic conductivities (Loizeaux, 1995) likely contribute to diffusive intergranular ground-water flow, which is relatively slow and uniform. Although both primary and secondary porosity occur within the interlayered aquifer system, the majority of measured borehole flow and water-quality changes occur along discrete secondary porosity features. Intergranular flow appears to be insignificant when compared to flow in zones with substantial secondary porosity. Although elevated chloride concentrations appear to originate from seawater at shallower depths (200-300 ft) within the Tampa/Suwannee producing zone and at deeper depths (500-750 ft) within the Avon Park/Ocala and Avon Park producing zones (fig. 36), elevated sulfate concentrations, beyond those explained by saltwater mixing, indicate that upward migration of deep mineralized ground water also contributes to increases in chloride (fig. 37). Natural upwelling has not been documented in the study area; however, localized effects of ground-water withdrawals can introduce deepwater into shallow units and create ground-water mixtures that are chemically similar to those observed in natural upwelling areas (fig. 22b,c). The lowering of ground-water levels associated with pumping from wells 4A and 5 creates the potential for upward movement of ground water to wells. Nearby pumping stresses affect wells by changing head gradients and increasing the potential for ground-water flow along permeable intervals, subsequently altering the composition of water within the borehole and causing the observed changes in specific conductance over time (figs. 31 and 33). The greatest influence of deep mineralized ground water appears to be in the southwestern part of the well field, coincident with the cone of depression and the greatest increases in historical chloride concentrations. Toward the north and central part of the well field, less evidence of the deepwater chemical signature exists (fig. 41).

Deep ground-water movement both along primary and secondary porosity features likely contributes to the observed distribution of water types throughout the study area. Mineralized ground water appears well dispersed throughout the southwestern part of the well field as a result of upward migration. Because the deepwater signature is well distributed within the southwestern part of the well field, intergranular flow of deepwater through the Ocala semiconfining unit probably occurs in response to upconing. Within the southwestern part of the well field, however, the seismic reflection data and the presence of photolinear features indicate that particular stratigraphic units may be discontinuous, and these disruptions may create more effective hydraulic connections through the semiconfining unit, thereby enhancing vertical flow.

Ground-water movement along permeable intervals, high-angle fractures, and boreholes may provide more localized avenues for upward movement of saltwater and deepwater. Once this water enters shallow flow zones within the aquifer, it can travel from one production well to another, mixing various water types within the well field. Fractures that connect water from deep mineralized zones or the saltwater interface to shallow zones can introduce high ionic concentrations into the shallow zones. Wells with high specific capacity values (open to more producing zones) or large open-hole intervals probably intersect numerous permeable intervals. Conversely, permeable intervals contributing freshwater result in an overall dilution of ionic concentrations within a well. Consequently, whether ionic concentrations are diluted or increased depends on the percentage of the total flow contribution and water-quality characteristics of each permeable interval.

Even minor contributions of water to a well from a saltwater source, when compared to similar contributions from a deepwater source, can significantly affect chloride concentrations. For example, a 1-percent solution of saltwater has a chloride concentration of approximately 190 mg/L whereas a 1-percent solution of deepwater has a chloride concentration of approximately 2.9 mg/L. Although ground water from wells tapping shallow production zones, such as wells 2A and 3B within the well field, is composed of more than 97 percent freshwater, the influence of saltwater on water quality is substantial. Chloride concentrations at wells 2A and 3B were 26 and 51 mg/L, respectively, corresponding to low relative percent contributions of saltwater (0.09 and 0.2, respectively) (table 3). The percentages of the total chloride concentrations supplied to the sample by each water type are calculated by multiplying the chloride concentration of the respective end member by the percent fraction of the end member found in that sample. For example,

$$[(0.2_{(x)} * 19{,}000 \text{ mg/L}_{(y)}] = 38 \text{ mg/L}_{(z)},$$

where

x is percent fraction of saltwater contribution to well 3B;
y is chloride concentration in saltwater end member; and
z is chloride concentration at well 3B derived from saltwater fraction.

At well 3B, 38 mg/L (74 percent) of the total 51 mg/L chloride was derived from saltwater, while 8 mg/L was from a deepwater source. Of the total chloride concentrations found in samples from wells 2A and 3B, 65 and 75 percent of the total chloride, respectively, were derived from saltwater, 16 and 17 percent, respectively, were derived from deepwater and 10 and 19 percent, respectively, were associated with the background from the freshwater fraction. Therefore, even if water within the Tampa/Suwannee producing zone has only a small fraction of seawater, most of the chloride is derived from a saltwater source.

A nearby saltwater source, containing chloride concentrations from 15,000 to 17,000 mg/L, occurs south and west of the well field near the saltwater interface (wells NLKTP, SWI-2D, SWI-6D, and SWI-7D). This saltwater source contributes to increased chloride concentrations observed in wells that tap the Avon Park producing zone between 640-780 ft deep near and within the well field. Within the Avon Park producing zone in the middle of the well field, ground water containing 250 mg/L chloride was a mixture of approximately 1 percent saltwater, 9 percent deepwater, and 90 percent freshwater (well SWI-10S). The saltwater source contributed 87 percent of the total chloride in this well, whereas only 11 percent originated from deepwater.

Ground-water movement and changes in specific conductance in the EW well field were associated with enlarged borehole conditions and fractures within the Tampa/Suwannee and the Avon Park producing zones. Ground water moves along preferred flowpaths within the permeable zones, and wells can act as vertical connections between the zones. Specific conductance and flow logs indicate that water with high specific conductance from the Avon Park producing zone can enter a well, migrate upward, and exit at shallower depths along permeable intervals within the Tampa/Suwannee producing zone. Similarly, water with high specific conductance can enter other wells from shallow permeable intervals within the Tampa/Suwannee producing zone. Within the well field, even wells that are dominantly freshwater contain measurable percentages of both deepwater and saltwater. A network of permeable intervals and fractures contributes deepwater and saltwater fractions to the relatively shallow Tampa/Suwannee producing zone.

Evidence of ground-water movement between permeable intervals within an open borehole was observed in all wells where flow and fluid logging data were collected. This complex network of flow zones, boreholes with large open-hole sections, and pumping wells is an important mechanism for introducing, transporting, and diluting chloride concentrations throughout producing zones within the EW well field (fig. 17). In an aquifer with multiple permeable intervals, there are many competing flowpaths of relatively high permeability. High chloride water can shift from one path to another as a function of the way each pumping well affects the flow in a particular permeable interval. If the pattern of drawdown changes, water with different chloride concentrations can be pulled into different permeable intervals carrying flow in different directions. Changes in relative contributions of high chloride water can create shifts in specific conductance or spikes in chloride concentrations recorded over time.

Changes in head gradients and gradient reversals produced by changes in pumping rates at individual wells in the well field complicate local ground-water flow patterns. Complexities observed in continuously recorded specific conductance, borehole-flow measurements, and water-quality data at individual wells appear to be related to nearby pumping, permeable zones intercepted by the borehole, and well location. Wells along the boundaries of the well field, farther from production wells, exhibited spikes in chloride concentrations even though increasing trends did not exist. Anomalous spikes in the chloride concentrations also have been observed in production wells in the northern part of the well field, indicating that they periodically receive a greater contribution of high conductance water from the permeable zones. Chloride concentrations along specific flow zones are dispersed by mixing with water from other flow zones, either along preferential flow paths or in production wells. The result is a heterogeneous distribution of chloride concentrations, with fluctuations in specific conductance with depth and the interlayering of high chloride waters between zones of freshwater (fig. 41).

Summary

Chloride concentrations in ground water have been increasing at the Eldridge-Wilde (EW) well field for several decades. In 1975, chloride concentrations were less than 20 mg/L in the southwestern part of the well field. By 1996, chloride concentrations had increased to more than 100 mg/L at several wells and to more than 20 mg/L in surrounding wells in the same area. Increasing trends in individual wells and the elongated northeast-southwest pattern of high chloride concentrations indicated that structural heterogeneity within the aquifer was affecting the movement of chlorides.

This study used multiple techniques to determine how and where aquifer properties are related to geologic characteristics, to identify permeable intervals and mechanisms for observed ground-water flow, and to clarify sources of observed increases in chloride concentrations. Acoustic televiewer and caliper logs provided evidence of fractures and enlarged boreholes associated with poorly lithified units and dissolution features. The logging data, combined with borehole fluid and flow logs, were used to identify permeable intervals and the types of geologic features that created them. Continuous monitoring of water levels and specific conductance and water-quality analyses provided information about ground-water flow patterns and mixing. Together, these techniques were used to help define the hydrogeologic controls on ground-water movement within the study area.

The Upper Floridan aquifer (UFA) comprises a multilayered sequence of carbonate rocks with each sequence characterized by different hydrogeologic properties. Highly transmissive zones, corresponding to well-developed secondary porosity, appear to control ground-water flow and observed changes in water quality. Highly transmissive zones are associated with the Tampa/Suwannee Limestones and the Avon Park Formation. Well-developed dissolution features and fractures within the Tampa/Suwannee Limestones and the Avon Park Formation serve as highly transmissive pathways for ground-water movement. The Ocala semiconfining unit separates the two producing zones. Although the Ocala semiconfining unit is less permeable relative to the producing zones above and below it, the unit has substantial intergranular porosity. Fractures observed in the acoustic televiewer data range from horizontal to near vertical and are associated primarily with the Avon Park producing zone; however, dolomitized sections of the Ocala/Avon Park producing zone and the Ocala semiconfining unit also may contain fractures. High angle fractures are capable of providing vertical connections between other permeable zones. Land-based seismic-reflection data indicate that dolomite units may be laterally discontinuous in the southwestern

part of the well field owing to fractures. Discontinuities in the dolomite units and fractures within the Avon Park Formation may extend into shallower stratigraphic units.

The timing of well-field expansion to the north and into deeper parts of the UFA corresponds to observed increases in chloride concentrations in wells located within the southwestern part of the well field. Ground-water withdrawals in the EW well field have lowered ground-water levels and altered ground-water flow patterns from predevelopment conditions. Changes in ground-water flow patterns have been accompanied by increases in chloride concentrations at some wells. The amount and variability of observed increases in chloride concentrations at each well are related to well location and permeable intervals intercepted by the borehole.

Flow measurements indicate that ground water moves in response to changes in the head gradients along permeable zones within the UFA. Pumping stresses can induce flow through a complex network of permeable intervals, boreholes, and fractures that can affect water quality by connecting zones of poor quality to those with better quality. Production wells open to the entire length of the UFA that intersect more than one permeable zone can convey deep mineralized ground water into shallow producing zones.

Water quality within the UFA varies depending on well location and depth interval sampled. Within the study area, water from the UFA is a calcium-bicarbonate-type freshwater that has been enriched to varying degrees by mixing with saltwater and deepwater (calcium-sulfate-type water). Both deepwater and saltwater are the likely sources for elevated chloride and sulfate concentrations within the ground water. Deepwater is present beneath the well field just above and within the MCU. The saltwater interface in the Avon Park producing zone (chloride concentrations greater than 10,000 mg/L) is approximately 1 mile west of the well field.

Wells located closest to the saltwater interface show the greatest increases in chloride concentrations over time, indicating a source of chloride to the southwest. The 250-mg/L isochlor within the Avon Park producing zone has migrated to the northeast over time. Increased chloride concentrations within the production wells are oriented northeast-southwest with well-defined increases found in wells that are within the center of the southwestern part of the well field. In this part of the well field, chloride concentrations exceed 250 mg/L in the Avon Park producing zone.

Water-quality data and mass-balance calculations were used to determine sources of chloride and mixing of waters of different origins. These data indicate that elevated chloride concentrations within the EW well field are due to mixing of both deepwater and saltwater. Nearly all wells in the southwestern part of the well field also show an influence from deepwater as it migrates into the shallow permeable units, contributing to elevated sulfate and chloride concentrations. Saltwater is an additional source of chloride. Because chloride concentrations in saltwater are greater than those associated with deepwater, even a small amount of saltwater has a large effect on chloride concentrations.

The preferential movement of saltwater along fractures within the highly transmissive Avon Park producing zone has the potential to affect water quality throughout the well field. In 2000, the 250-mg/L isochlor was located beneath the center of the southwestern part of the well field about 700 ft below land surface (well SWI-10S). Temporal fluctuations in the location of the 250-mg/L isochlor indicate that the isochlor migrates with time.

A conceptual model of ground-water movement and variability in chloride concentrations was developed from the hydrogeologic and water-quality data to describe flow paths and mixing within the study area. Most ground-water movement is through the Tampa/Suwannee and the Avon Park producing zones, which are preferential flow paths within the aquifer system. Substantial changes in ground-water quality also occur along these flow paths. Water-quality analyses for specific wells indicate mixing from different flow zones. The movement of deepwater and saltwater along these preferential flow paths and the subsequent mixing with potable ground water has resulted in increased concentrations of chloride and sulfate in these producing zones.

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Appendixes A and B

Appendix A. Well-construction, specific-capacity, and pump-capacity data for production wells at the Eldridge-Wilde well field.

[ft, feet; gal/min, gallons per minute; ft^2/d, feet squared per day. Data from Black, Crow, and Eidsness Inc. (1970); Gee and Jenson Inc. (1981a,b; 1983); and Nettles and Vandor Inc. (1985)]

Well name	Year constructed/ modified[a]	Diameter (inches)	Well depth original/ modified (ft)	Casing depth (ft)	Length open hole original/ modified (ft)	Specific capacity original/final[b] (gal/min)/ft	Specific capacity per foot saturated thickness original/final [(gal/min)/ft]/ft	Transmissivity calculated from final specific capacity[c] (ft^2/d)	Pump capacity[d]
1	1954	12	300	89	211	49	0.23	13,100	700
1S	1954	12	299	65	234	67/53	0.29/0.23	14,200	700
2	1954	12	297	80	217	94	0.43	25,100	700
4	1954	12	300	112	188	188	1.00	50,300	700
6	1954	12	300	77	223	130/169	0.58/0.76	45,200	700
4S	1955	12	285	65	220	46	0.21	12,300	700
5S	1955	12	175	124	51	58/57	1.14/1.12	15,200	700
6S	1955	12	140	76	64	65/41	1.02/0.64	11,000	700
7	1955	12	285	92	193	86/101	0.45/0.52	27,000	700
7S	1955	12	290	63	227	130/60	0.57/0.26	16,000	700
8S	1955	12	245	95	150	193	1.29	51,600	700
3S	1956	12	309	88	221	49	0.22	13,100	700
5	1956	12	210	76	134	200	1.49	53,500	700
8	1957	12	300	69	231	320/191	1.39/0.83	51,100	1,200
9	1957	12	302	75	227	221	0.97	59,100	1,200
4N	1958	12	300	103	197	200	1.02	53,500	700
5A	1958	12	295	103	192	175	0.91	46,800	700
6N	1958	12	346	96	250	93	0.37	24,900	700
4A	1960	12	210	74	136	223	1.64	59,600	1,400
5B	1960	16	300	75	225	111	0.49	29,700	1,400
11A	1961	16	300	86	214	311	1.45	83,200	1,400
12	1961	16	300	66	234	95	0.41	25,400	1,400
101	1961	16	311	149	162	600	3.70	160,400	1,400
106	1961	16	345	97	248	103	0.42	27,500	1,400
107	1961	16	308	80	228	175	0.77	46,800	1,400
104	1964	16	403	72	331	89	0.27	23,800	1,400
112	1964	16	314	62	252	259	1.03	69,200	2,100
115	1964	16	321	84	237	103	0.44/0.43	27,500	1,400
116	1964	16	400	60	340	146/122	0.43/0.36	32,600	1,400
117	1964	16	302	80	222	65	0.29	17,400	1,400
119	1964	16	407	124	283	160	0.57	42,800	1,400
142	1966	16	400	66	334	84	0.25	22,500	1,400
10A	1969	16	550	99	451	93	0.21	24,900	1,400
2A	1970	12	450/340	113	337/227	130	0.39	34,800	700
3B	1970	12	410/390	78	332/312	40	0.12	10,700	700
5N	1958 / 1980	12	340/863	107	233/756	39/122	0.17/0.16	32,600	700
13	1961 / 1981	16	320/780	72	248/708	50/362	0.20/0.51	96,800	1,400
105	1961 / 1983	16	250/658	82	168/576	59/345	0.35/0.60	92,200	1,400
103	1961 / 1985	16	310/767	85	225/682	100/319	0.44/0.47	85,300	1,400
109	1961 / 1985	16	384/770	85	299/685	27/364	0.09/0.53	97,300	700
110	1961 / 1985	16	333/776	64	269/712	51/214	0.19/0.30	57,200	700
102	1961 / 1985	16	316/774	79	237/695	171/408	0.72/0.59	109,100	1,400
113	1964 / 1985	12/16	503/647	100	403/547	65/308	0.16/0.56	82,300	1,400
114	1964 / 1985	16	407/776	58	349/718	53/339	0.15/0.47	90,600	1,400
118	1964 / 1985	16	407/775	78	329/697	31/86	0.09/0.12	23,000	1,400

Appendix A. Well-construction, specific-capacity, and pump-capacity data for production wells at the Eldridge-Wilde well field. (Continued)

[ft, feet; gal/min, gallons per minute; ft^2/d, feet squared per day. Data from Black, Crow, and Eidsness Inc. (1970); Gee and Jenson Inc. (1981a,b; 1983); and Nettles and Vandor Inc. (1985)]

Well name	Year constructed/ modified[a]	Diameter (inches)	Well depth original/ modified (ft)	Casing depth (ft)	Length open hole original/ modified (ft)	Specific capacity original/final[b] (gal/min)/ft	Specific capacity per foot saturated thickness original/final [(gal/min)/ft]/ft	Transmissivity calculated from final specific capacity[c] (ft^2/d)	Pump capacity[d]
111	1964 / 1983	16	399/780	71	328/709	78/400	0.24/0.56	106,900	1,400
139	1966 / 1981	16	560/780	63	497/717	27/264	0.05/0.37	70,600	700
136	1966 / 1982	16	430/780	60	370/720	150/328	0.41/0.46	87,700	1,400
137	1966 / 1982	16	330/780	84	246/696	97/343	0.39/0.49	91,700	1,400
140	1966 / 1982	16	440/780	66	374/714	59/121	0.16/0.17	32,400	700
138	1966 / 1985	16	400/778	58	342/720	34/363	0.10/0.50	97,100	700
141	1966 / 1985	16	510/780	63	447/717	13/155	0.03/0.22	41,400	700
134	1966 / 1986	16	275/778	84	191/694	209/507	1.09/0.73	135,600	1,400
135	1966 / 1986	16	287/778	63	224/715	140/373	0.63/0.52	99,700	1,400
131	1966 / 1985	16	460/778	83	377/695	90/490	0.24/0.17	131,000	700
120	1970 / 1986A	16	809	78	731	77/135	0.11/0.18	36,100	1,400
121	1970 / 1986A	16	770	116	654	110/207	0.17/0.32	55,300	1,400
122	1970 / 1986	16	291/780	123	168/657	231/563	1.38/0.86	150,500	1,400

[a]Indicates well was modified by acidizing.

[b]Original specific capacity determined after initial construction. Final specific capacity determined at later date or after modification or deepening.

[c]Driscoll (1986).

[d]Based on available data in 2003.

Appendix B. Well-construction and water-quality analytical data for wells sampled during this study.

[<, less than; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; °C, degrees Celsius; --, not applicable; µg/L, micrograms per liter; Sr, strontium; $^{87}Sr/^{86}Sr$, ^{87}strontium /^{86}strontium; O-18, ^{18}oxygen; E = estimated; TPA, Tampa Member, Hawthorn Group; SUW, Suwannee Limestone; OCA, Ocala Limestone; AVPK, Avon Park Formation; TPA, Tampa Member]

Site name	Open hole interval depth (feet below top of casing)	Length of open hole (feet)	Geologic unit	Sampling date	Temp-erature, (°C)	Color (platinum-cobalt)	Specific conductance, in µS/cm (field)	pH, field	Bicarb-onate, field (mg/L as HCO_3)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
NWPDP	83-96	13	TPA	11/16/1999	25.0	10	4,980	7.32	269	110	75	810
NLKTP	758-780	22	AVPK	12/7/1999	26.4	20	45,900	6.80	244	1,200	987	9,100
TPRDDP	205-305	100	SUW	11/15/1999	25.0	10	525	7.60	214	71	5.7	26
ROMP TR15-1 Dp	68-87	19	HTLS	11/16/1999	24.0	70	2,460	7.01	338	100	35	350
McKay OS-1	710-901	191	AVPK	11/10/1999	27.0	80	52,900	7.32	211	800	1,200	10,800
McKay OS-2	551-585	34	AVPK	11/10/1999	27.0	240	50,200	7.42	219	930	1,100	10,490
McKay OS-3	236-265	29	SUW	11/10/1999	25.1	20	896	7.44	260	75	28	57
2A	113-450 (caved in to 340)	227	TPA,SUW,OCA	11/19/1999	25.0	10	499	7.48	217	81	5.9	12
3B	78-410 (caved in to 390)	312	TPA,SUW,OCA	11/19/1999	25.0	10	633	7.40	219	97	6.9	17
201-M	144-684	540	TPA,SUW,OCA, AVPK	11/19/1999	24.6	10	479	7.51	220	77	5.9	11
202-M	132-780	648	TPA,SUW,OCA, AVPK	11/18/1999	23.3	10	413	7.37	251	73	4.6	6.1
203-M[a]	1170-1250	80	AVPK	11/17/1999	27.0	10	3,750	7.10	246	690	90	190
SWI-1S	470-540	70	OCA,AVPK	11/11/1999	25.5	10	614	7.50	227	97	7.5	16
SWI-1D	580-760	180	AVPK	11/11/1999	25.2	10	1,020	7.40	235	140	11	53
SWI-2S	530-630	100	AVPK	11/11/1999	26.3	20	717	7.75	212	89	8.0	40
SWI-2D	720-780	60	AVPK	11/11/1999	26.5	30	39,700	6.94	181	1,200	672	7,800
SWI-6D	640-720	80	AVPK	11/18/1999	26.0	10	23,000	7.10	222	760	362	4,200
SWI-7D	680-740	60	AVPK	11/16/1999	25.6	5	10,680	7.02	212	650	161	1,500
SWI-10S	650-700	50	AVPK	11/17/1999	25.9	10	1,470	7.40	224	200	15	73
SWI-10D	830-900	70	AVPK	11/17/1999	25.8	20	877	7.50	221	130	9.5	37
SWI-11D	810-899	89	AVPK	11/18/1999	25.2	10	1,040	7.58	236	190	13	20.0
EW-5N	106-863	757	TPA,SUW,OCA, AVPK	3/16/2000	25.3	5	430	7.20	249	75	3.2	6.1
113-B	120-780	660	TPA,SUW,OCA, AVPK	3/17/2000	25.6	5	436	7.54	260	73	5.3	6.1
ROMP 57A FLRD[b]	274-315	41	OCA	8/25/1992	25.5	--	184	7.80	105	21	7.0	3.8
Seawater[c]	n/a	--	--	--	--	--	50,000	--	--	412	1,294	10,773

Appendix B. Well-construction and water-quality analytical data for wells sampled during this study. (Continued)

[<, less than; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; °C, degrees Celsius; --, not applicable; µg/L, micrograms per liter; Sr, strontium; $^{87}Sr/^{86}Sr$, ^{87}strontium /^{86}strontium; O-18, ^{18}oxygen; E = estimated; TPA, Tampa Member, Hawthorn Group; SUW, Suwannee Limestone; OCA, Ocala Limestone; AVPK, Avon Park Formation; TPA, Tampa Member]

Site name	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Residue, (mg/L at 180 °C)	Dissolved solids, calculated, (mg/L)	Strontium, dissolved (mg/L as Sr)	Isotopes		
									$^{87}Sr/^{86}Sr$	Deuterium (per mil)	O-18 (per mil)
NWPDP	29	1,400	210	0.1	9.1	2,920	2,780	1,100	0.708215	--	--
NLKTP	260	17,000	2,600	<0.1	8.7	32,218	31,300	26,033	0.707972	9.1	0.93
TPRDDP	1.1	53	13	<0.1	12	313	287	180	0.708169	-3.2	-1.07
ROMP TR15-1 Dp	11	590	19	<0.1	11	1,380	1,280	350	0.708445	--	--
McKay OS-1	380	21,000	2,900	0.3	12	E38,107	37,200	22,979	0.708133	--	--
McKay OS-2	320	19,000	2,800	0.2	13	E35,874	34,800	27,295	0.707973	11.0	1.12
McKay OS-3	1.9	150	10	0.4	37	559	493	700	0.708055	-14.2	-3.23
2A	1.0	26	30	0.1	13	301	276	230	0.708088	--	--
3B	1.1	51	56	0.1	12	407	349	280	--	-10.5	-2.04
201-M	0.9	27	12	0.1	13	285	255	250	0.708102	-6.7	-1.67
202-M	0.8	9	2.3	<0.1	12	246	232	240	0.708095	--	--
203-M[a]	9.4	290	1,800	2.0	19	3,470	3,220	12,086	0.707857	--	--
SWI-1S	1.2	44	55	0.1	13	392	350	300	0.708090	--	--
SWI-1D	1.4	140	120	0.1	13	693	595	570	0.708017	--	--
SWI-2S	5.0	80	72	0.1	14	433	409	600	0.708042	-2.5	-1.00
SWI-2D	190	15,000	2,300	<0.1	10	E28,040	27,300	24,152	0.707928	9.1	0.60
SWI-6D	94	7,700	1,300	<0.1	9.4	15,578	14,500	15,289	--	-0.2	-0.59
SWI-7D	36	3,100	1,000	<0.1	13	7,970	6,580	10,901	0.707877	-3.6	-1.47
SWI-10S	1.6	250	200	0.1	13	974	864	970	0.707986	-5.7	-1.54
SWI-10D	1.4	120	83	0.1	13	609	503	570.0	0.707974	-6.9	-1.39
SWI-11D	1.8	39	320	0.1	14	736	715	1,400	0.707914	-6.7	-1.96
EW-5N	0.6	9.4	3.3	0.1	11	250	231	120	0.708320	-11.3	-2.53
113-B	0.8	9.0	2.2	0.1	12	250	237	300	0.708002	-6.4	-1.53
ROMP 57A FLRD[b]	1.4	5.1	0.5	0.1	13	--	104	290	--	-12.5	-2.60
Seawater[c]	399	19,344	2,712	1.3	6.4	34,500	34,500	8,000	0.709160	--	--

[a]203-M represents deepwater end member for mixing calculations.

[b]ROMP 57A FLRD represents freshwater end member for mixing calculations.

[c]Seawater, based on Hem (1985), represents saltwater end member for mixing calculations.