The Relation Between Hydrogeology and Water Quality of the Lower Floridan Aquifer in Duval County, Florida, and Implications for Monitoring Movement of Saline Water

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 96-4242

Prepared in cooperation with the

City of Jacksonville, Florida and the
St. Johns River Water Management District

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By G.G. Phelps and Rick M. Spechler

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
227 North Bronough Street, Suite 3015
Tallahassee, Florida 32301

Copies of this report can be purchased from:

U.S. Geological Survey
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Box 25286
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meters
mile (mi)	1.609	kilometer
Flow		
million gallons per day (Mgal/d)	0.04381	cubic meters per second
gallon per minute (gal/min)	0.0630	liter per second
Transmissivity		
foot squared per day (ft^2/d)	0.0929	meter squared per day
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day

Equations for temperature conversion between degrees Celsius (°C) and degrees Fahrenheit (°F):

$$°C = 5/9 \times (°F - 32)$$

$$°F = (9/5\ °C) + 32$$

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

Altitude, as used in this report, refers to distance above or below sea level.

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.

Abbreviated water-quality units

g/mL	grams per milliliter
µg/L	micrograms per liter
µS/cm at 25 °C	microsiemens per centimeter at 25 °C
mg/L	milligrams per liter

Acronyms

USGS	U.S. Geological Survey
SJRWMD	St. Johns River Water Management District
WATSTORE	Water Data Storage and Retrieval System
RASA	Regional Aquifer-System Analysis

The Relation Between Hydrogeology and Water Quality of the Lower Floridan Aquifer in Duval County, Florida, and Implications for Monitoring Movement of Saline Water

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Abstract

The hydrogeology of the Upper zone of the Lower Floridan aquifer and its relation to water quality were evaluated during a 3-year (1993-96) study. The Floridan aquifer system, a carbonate aquifer system composed of the Upper Floridan aquifer, a middle semi-confining unit, and the Lower Floridan aquifer, is the major source of water supply in northeastern Florida. The Lower Floridan aquifer is further subdivided into the Upper zone, a semi-confining unit, and the Fernandina permeable zone. As a result of increased withdrawals, heads in the aquifer system have declined and at the same time chloride concentrations have increased in the water from many wells in Duval County. A better understanding of the sources of and pathways for movement of brackish water is needed so that water managers can monitor the movement of brackish water and plan future water development.

Most of the wells in Duval County deeper than 900 feet penetrate the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer. Transmissivity estimates for these zones range from 2,000 to 194,000 feet squared per day. Permeability in the Upper zone of the Lower Floridan aquifer is primarily related to secondary porosity developed along bedding planes, joints, and fractures as a result of paleokarst processes. The Upper zone is about 300 to 500 feet thick in Duval County, based on the geophysical logs of about 40 wells ranging in depth from about 1,000 to 2,200 feet. In some areas the Upper zone has a single flow zone, but in other areas, two distinct flow zones are apparent.

Water samples collected during this study confirm the continued increase in chloride concentrations in both the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer. Most of the observed increases are in the eastern part of the county, but a pattern in the locations of wells yielding water with chloride increases is not discernible. In some areas, zones bearing brackish water are underlain by zones of fresher water, but in other areas, fresher water was not found beneath the brackish water. A single fracture or solution feature was the source of brackish water in several wells.

The most likely source of brackish water to the Upper zone of the Lower Floridan aquifer is the underlying Fernandina permeable zone, which contains freshwater in the western part of the county but saline water in the eastern part. The pathways for movement of saline water are interconnecting vertical and horizontal fracture or solution zones probably developed along paleokarst features that are not mappable from the land surface; therefore, a conventional monitor-well network probably would not provide early warning of saline-water intrusion. Continued monitoring of water-quality trends in water-supply wells, combined with collection of additional surface

and borehole geophysical data, can provide an increased understanding of the movement of brackish water in the Floridan aquifer system.

INTRODUCTION

The Floridan aquifer system is the major source of water supply in northeastern Florida. Ground-water withdrawals in Duval County have increased from about 127 million gallons per day (Mgal/d) in 1965 (Spechler, 1994) to about 152 Mgal/d in 1993 (Florence, 1996, p. 75). As a result, the altitude of the potentiometric surface of the Floridan aquifer system in northeastern Florida has gradually declined at a rate of about one-third to three-fourths foot per year (ft/yr) (Spechler, 1994, p. 2). Concomitant with the decline in the potentiometric surface have been increases in the chloride concentrations of water from numerous wells in Duval County (figs. 1 and 2), especially in the area east of the St. Johns River. A recent study (Spechler, 1994) indicates that the chloride concentration increases probably have resulted from saline water moving vertically upward from deep zones of the aquifer system along fractures, collapse features, or other structural deformities. Therefore, a better understanding is needed of the hydrogeologic and hydraulic characteristics of the lower zones of the Floridan aquifer system (in particular, the Upper zone of the Lower Floridan aquifer) and of the distribution of and mechanism for movement of saline water so that water managers can make informed decisions to meet future water supply needs in northeastern Florida. The U.S. Geological Survey (USGS), in cooperation with the city of Jacksonville and the St. Johns River Water Management District (SJRWMD), began a 3-year study in 1993 to define the areal and vertical extent of the Upper zone of the Lower Floridan aquifer underlying Duval County and to describe the fractures and solution features as they relate to water-quality variations in the Floridan aquifer system.

Purpose and Scope

This report presents a summary of the hydrogeology of the Upper zone of the Lower Floridan aquifer in Duval County, Florida, based primarily on a synthesis of geophysical logs. Selected logs are presented and interpreted in the report. Logs are available for more than 40 wells that tap the Upper zone of the Lower Floridan aquifer, including 21 wells logged during this study. In conjunction with the logging, water samples collected at the wellhead and point samples collected from various depths in the wells logged were analyzed to determine the distribution of chloride concentrations in the Upper zone of the Lower Floridan aquifer. Transmissivity values estimated from specific capacity tests of water-production wells (obtained from the files of the Jacksonville Water Production Department) are presented as indicators of the hydraulic properties of the Upper zone in Duval County. Graphs showing long-term trends in chloride concentrations for several wells are presented. The major-ion analysis of water samples collected at the wellhead and point samples collected from various depths in the 21 wells logged are presented. Chloride-concentration data for about 60 other wells in northeastern Florida are also included. Detailed descriptions of geophysical logs and water-quality data from several areas of the county where increases in chloride concentrations have been observed and from other selected areas are included in the report. The hydrogeologic and water-quality data collected during the study (1993-96) were combined to draw conclusions about effective strategies for monitoring the movement of saline water in the Floridan aquifer system in Duval County, Florida.

Method of Study

The main approach to accomplish the study objective was the analysis of geophysical logs of wells in Duval County. The logs include caliper, natural gamma, static and flowing fluid temperature and resistivity, electric, current meter (spinner), heat-pulse flow meter, and sonic televiewer (table 1).

Geophysical logs are made by traversing various geophysical tools up or down the well bore. The caliper log shows the diameter of the borehole and can show the size, but not the orientation, of fractures or solution features. Generally, when the formation penetrated is soft, the borehole is large and relatively uneven. When the formation is hard, the borehole is uniform in diameter and about the same size as the drill bit used in drilling. The natural gamma log indicates the amount of naturally occurring gamma radiation in the formations penetrated by the well. High gamma counts in Florida often are associated with clays and with phosphatic rocks or layers of peat.

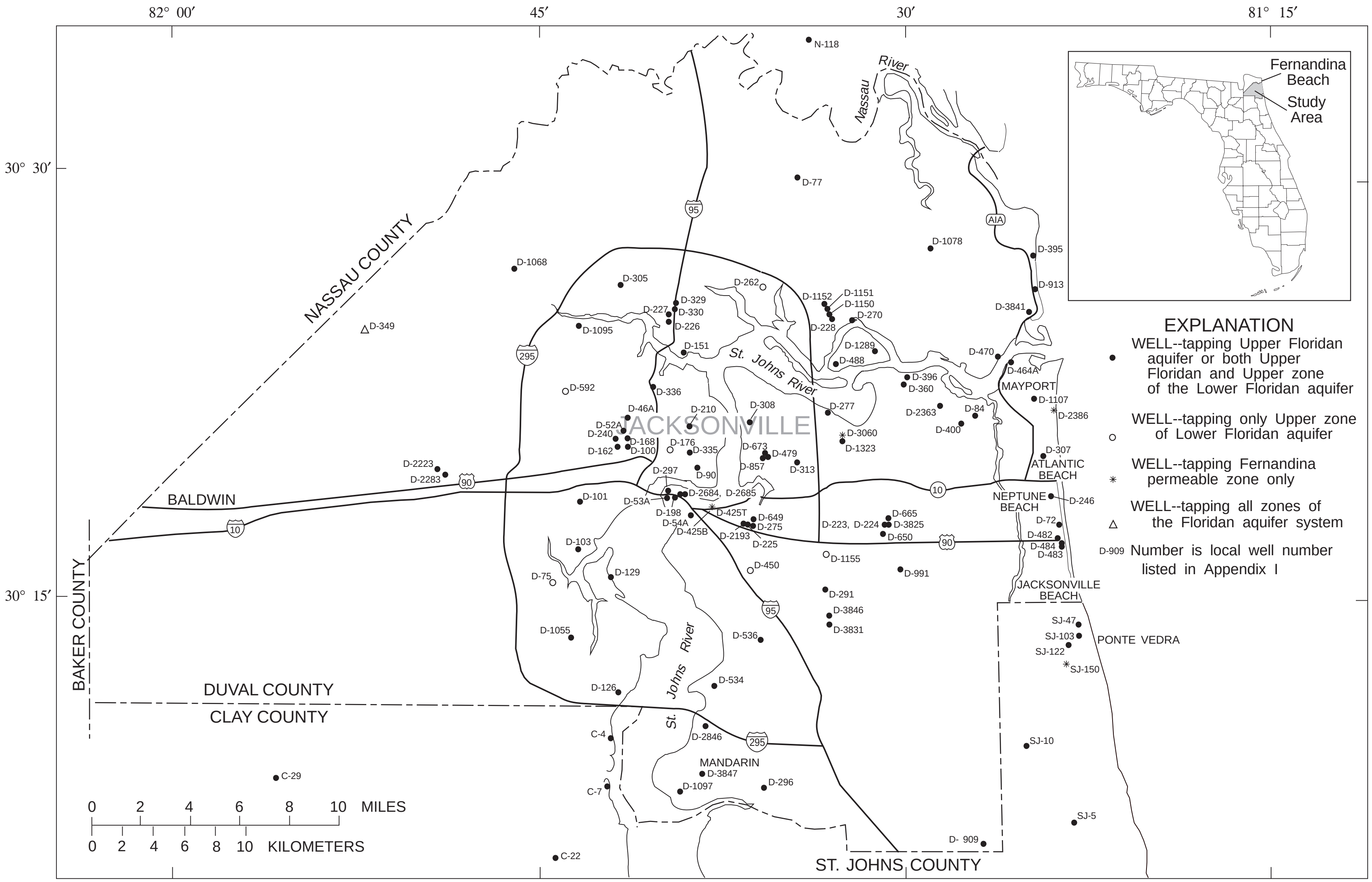

Figure 1. Selected wells in northeastern Florida.

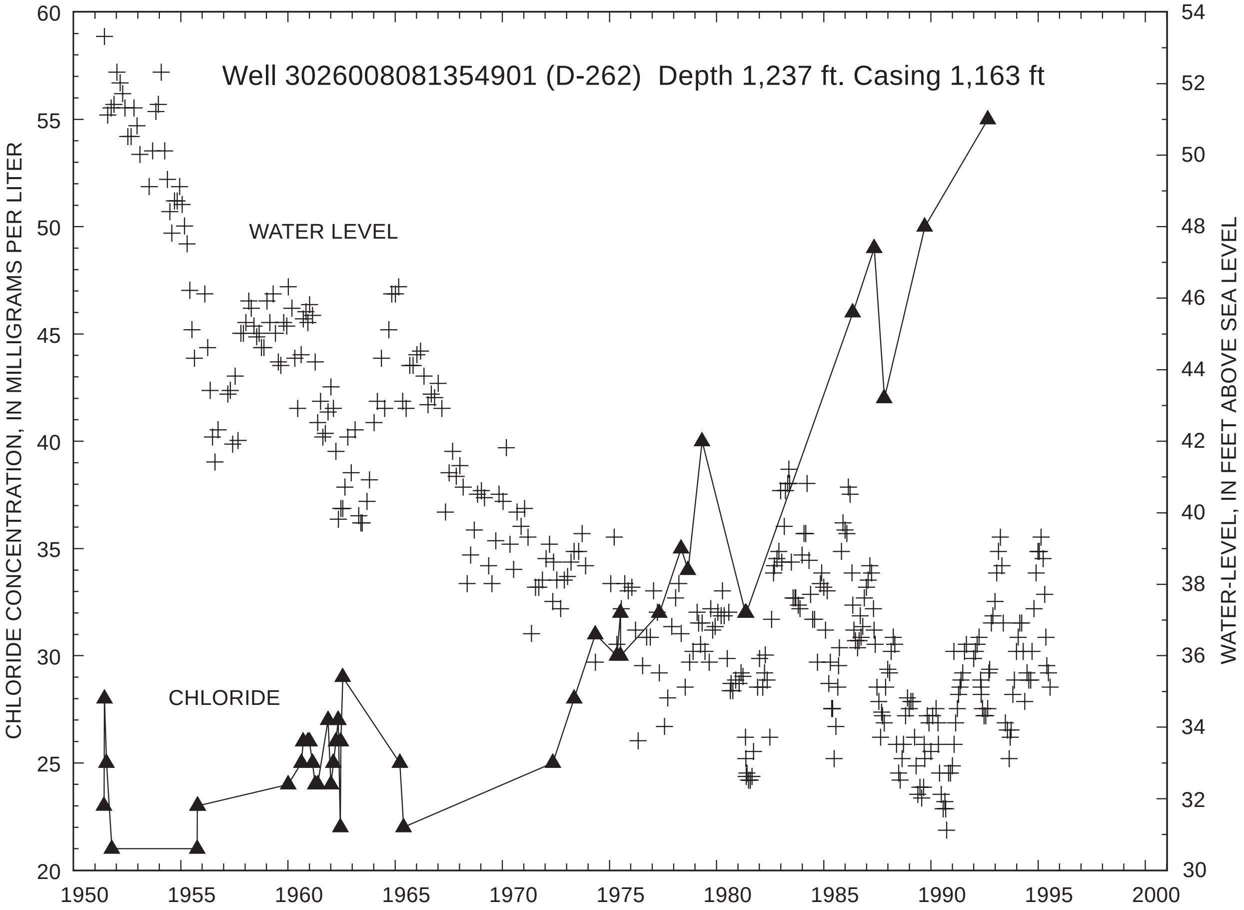

Figure 2. Water levels and chloride concentrations in water from well D-262 in Duval County, 1950-95.

Gamma radiation penetrates the well casing, so data can be collected in both the cased and open sections of the borehole. The electrical resistivity of the water is a general indicator of the concentration of dissolved ions in the water. When the resistivity of the water increases, the specific conductance (and, therefore, the concentration of dissolved ions such as chloride) decreases. The fluid resistivity logging tools generally are not calibrated absolutely, so the actual specific conductance of the water cannot be calculated. The several types of electric logs generally show the combined electrical properties of both the formation and the water in the formation; therefore, a change in either lithology or water quality can cause a variation in the electric log trace. Current meter logs are made by raising or lowering a current meter at a known rate up or down the well bore while the well is flowing or being pumped. This log indicates which intervals of the well produce water. The heat-pulse flow-meter log is run while the well is shut-in. The traveltime of a pulse of heat up or down the open borehole is measured at discrete depths to determine the magnitude and direction of intraborehole flow. The sonic televiewer creates a sonogram image of formations surrounding an open borehole. White or light-colored images are produced when the wave amplitude of sound reflected from the formation is large, indicating hard rock. Smaller amplitudes produce darker images and indicate softer rock surrounding the borehole. Black images result when no returning sound is detected and indicate voids in the formation. A compass in the sonic televiewer logging apparatus allows the orientation and dip of fractures to be determined.

Previous Investigations

The geology and hydrology of Duval County have been discussed in numerous reports. The geology of northeastern Florida was described by Puri (1957), Puri and Vernon (1964), and Miller (1986). The ground-water resources of Duval County were described by Leve (1966), Leve and Goolsby (1966), Fairchild (1972) and (1977), and Causey and Phelps

(1978). Water quality in Duval County has been described by Thompson (1982) and the intrusion of saline water into the Floridan aquifer system in northeastern Florida has been documented by Fairchild and Bentley (1977), Leve (1983), Toth (1990), and Spechler (1994). Data from test wells drilled into the Lower Floridan aquifer in northeastern Florida have been described by Brown (1980); Brown and others (1984); Brown and others (1985); and Brown and others (1986).

In addition to the interpretive reports that have been written about the hydrogeology of the Jacksonville area, a data-collection network is operated cooperatively by the USGS, the SJRWMD, and the city of Jacksonville. Water levels are recorded and water samples collected in about 30 wells. Of those wells, six are cased into the Upper zone of the Lower Floridan aquifer. The majority of the other network wells are open to both the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer. Data from the network are published annually by the USGS.

Well-Numbering System

Two well-numbering systems are used in this report. The first is a 15-digit number based on latitude and longitude, used to identify wells in the USGS National Water Data Storage and Retrieval System (WATSTORE). The first 6 digits denote the degrees, minutes, and seconds of latitude; the next 7 digits denote degrees, minutes, and seconds of longitude; and the last 2 digits denote a sequential number for a site within a 1-second grid. For example, well 302538081253101 is the first well inventoried at latitude 30°25'38" N, longitude 081°25'31" W.

The second numbering system is based on local well numbers. Local numbers have been assigned by the USGS to wells in each county in northeastern Florida as the wells were inventoried. The prefixes D, N, SJ and C denote wells in Duval, Nassau, St. Johns and Clay Counties, respectively. The sequence number denotes the order in which the well was inventoried. For example, well D-164 is the 164th well inventoried by the USGS in Duval County. Other government agencies also have local well numbering systems. For

Table 1. Geophysical logs run during this study, 1994-96

[x, log available; --, not run]

Site identification	Local no.	Natural gamma	Caliper	Temperature		Fluid resistivity		Spinner	Heat pulse	Acoustic	Resistivity/ electric	Sonic televiewer
				Static	Pump	Static	Pump					
300856081382401	D-3847	x	x	x	x	x	x	--	x	--	--	--
301210081373301	D-534	x	x	--	x	--	x	--	--	--	--	--
301335081355001	D-536	x	x	x	x	--	x	--	x	--	guard	x
301405081325601	D-3846	x	x	x	x	x	x	x	x	x	standard	--
301522081331301	D-291	x	x	x	x	x	x	x	x	x	guard	x
301704081233401	D-484	x	x	x	x	x	x	x	x	--	--	x
301716081234301	D-482	x	x	x	x	x	x	x	x	x	guard	x
301743081362301	D-225	x	x	--	x	x	x	x	--	--	--	x
301752081360501	D-649	x	x	x	--	--	x	x	x	--	--	--
301758081303901	D-665	x	x	x	--	x	x	x	x	x	standard	--
301832081422201	D-101	x	x	x	--	x	x	x	x	--	--	--
301937081471401	D-2223	x	x	x	x	x	x	x	x	--	guard	--
302003081384001	D-90	x	x	x	x	x	x	x	x	--	guard	x
302005081354501	D-857	x	x	x	x	x	x	x	x	x	guard	--
302007081353201	D-479	x	x	x	x	x	x	x	x	--	--	x
302008081242101	D-307	x	x	x	--	x	x	x	x	--	guard	x
302045081323101	D-1323	x	x	x	--	x	--	--	x	--	--	x
302058081244101	D-1107	x	x	x	x	x	x	x	x	--	guard	x
302134081284803	D-2363	x	x	x	x	x	x	x	x	--	--	--
302433081432201	D-1095	x	x	x	x	x	x	x	x	x	guard	x
302510081260201	D-3841	x	x	x	--	x	--	--	x	--	--	x

example, the city of Jacksonville Ground Water Resource Management Branch assigns local numbers beginning with a “J” and the city of Jacksonville Water Production Department assigns numbers to its water-supply wells that denote the pumping station number and sequence number. For example, well 0502 designates the number 2 well at the number 5 well field. The SJRWMD also uses local well numbers that begin with the letter D for wells in Duval County. The local well numbers used by the SJRWMD may not correspond with the local numbers used by the USGS. In this report, USGS local well numbers are given.

Acknowledgments

Well data and logistical assistance with geophysical logging were provided by: Gilbert Birdwell, Charles Stevens, and Timothy Perkins (city of Jacksonville Water Division); Gary Weise and William Essex (city of Jacksonville Ground Water Resource Management Branch); Tim N. Townsend (city of Atlantic Beach); and John L. Birch (city of Jacksonville Beach). Geophysical logging for this study was performed by Gerald Idler (USGS, Atlanta, Ga). Geophysical logs from the files of the USGS in Altamonte Springs, Fla., were digitized and plotted by Rhonda Bennett and Jennifer Piontek.

HYDROGEOLOGIC FRAMEWORK

Northeastern Florida is underlain by a thick sequence of marine sedimentary rocks that overlie a basement complex of metamorphic strata. Geologic formations and hydrogeologic units penetrated by wells in the Jacksonville area are described in figure 3. Rocks of the Cedar Keys Formation of late Paleocene age underlie all of northeastern Florida. They are overlain, in ascending order, by the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, the Ocala Limestone of late Eocene age, the Hawthorn Formation of Miocene age, and undifferentiated deposits of late Miocene to Holocene age. Geologic and geophysical data are available for numerous wells in Duval County. The locations of wells used for this study are shown in figure 1 and well data are given in Appendix I.

Series	Stratigraphic unit		Approximate thickness (ft)	Lithology	Hydrogeologic unit			Hydrologic properties
Holocene to Upper Miocene		Undifferentiated surficial deposits	20-120	Discontinuous sand, clay, shell beds, and limestone	Surficial aquifer system			Sand, shell, limestone, and coquina deposits provide local water supplies.
Miocene		Hawthorn Formation	100-500	Interbedded phosphatic sand, silt, clay, limestone, and dolomite	Intermediate confining unit			Sand, shell, and carbonate deposits provide limited local water supplies. Low permeability clays serve as the principal confining beds for the Floridan aquifer system below.
Eocene	Upper	Ocala Limestone	100-350	Massive fossiliferous chalky to granular marine limestone	Floridan aquifer system	Upper Floridan aquifer		Principal source of ground water. High permeability overall. Water from some wells shows increasing salinity.
	Middle	Avon Park Formation	700-1,100	Alternating beds of massive granular and chalky limestone, and dense dolomite		Middle semiconfining unit		Low permeability limestone and dolomite.
						Lower Floridan aquifer	Upper zone	Principal source of ground water. Water from some wells shows increasing salinity.
	Lower	Oldsmar Formation	300-500				Semi-confining unit	Low permeability limestone and dolomite.
							Fernandina permeable zone	High permeability; salinity increases with depth.
Paleocene		Cedar Keys Formation	about 500	Uppermost appearance of evaporites; dense limestone	Sub-Floridan confining unit			Low permeability; contains highly saline water.

Figure 3. Generalized geology and hydrogeology of northeastern Florida (modified from Spechler, 1994).

Surficial Aquifer System and Intermediate Confining Unit

The sediments of late Miocene to Holocene age generally consist of interbedded sand, shell, and clay with some dolomitic limestone. These sediments together make up the surficial aquifer system, which in most areas of northeastern Florida, has two water-producing zones separated by beds of lower permeability. The surficial aquifer system usually is unconfined, but may be semiconfined where overlying beds of lower permeability are sufficiently thick and continuous. The thickness of the surficial aquifer system is variable, ranging from about 20 to 120 feet (ft) in Duval County.

The Hawthorn Formation of Miocene age underlies the surficial sediments and consists of interbedded clay, silt, sand, dolomite, and limestone that contain abundant phosphate pebbles and granules and phosphatic sand. Throughout most of northeastern Florida the clays and silts of the Hawthorn Formation serve as an effective confining unit. This intermediate confining unit retards movement of water between the overlying surficial aquifer system and the underlying Floridan aquifer system. The thickness of the intermediate confining unit ranges from about 100 to about 500 ft in Duval County.

Floridan Aquifer System

The Floridan aquifer system underlies all of the Florida peninsula, as well as parts of Alabama, Georgia, and South Carolina. The aquifer system ranges in thickness from about 1,600 to 1,900 ft in the study area and includes the Ocala Limestone, the Avon Park Formation, the Oldsmar Formation, and locally, the upper part of the Cedar Keys Formation. Miller (1986) definitively described the various water-bearing zones of the Floridan aquifer system during a study of the Floridan aquifer system as part of the Regional Aquifer-System Analysis (RASA) study. The Floridan aquifer system is divided into two aquifers of relatively high permeability, referred to as the Upper Floridan and the Lower Floridan aquifers. The Lower Floridan aquifer can be subdivided into two principal water-bearing zones separated by a less permeable unit that restricts the vertical movement of water. The aquifer layers are delineated on the basis of rock permeability, not on the basis of lithology, formation, or time-stratigraphic boundaries (Miller, 1986, p. B54).

The Upper Floridan aquifer generally corresponds to the Ocala Limestone, and in some areas it also includes the upper part of the Avon Park Formation. The Upper Floridan aquifer is about 300 to 500 ft thick in Duval County. The Ocala Limestone is fossiliferous and characterized by high permeability and high effective porosity. Permeability has been enhanced by dissolution of the rock along bedding planes, joints, and fractures. The surface of the Ocala Limestone is a paleokarst plain that exhibits erosional and collapse features that developed before the deposition of the overlying Hawthorn Formation. Leve (1983, p. 251) interpreted some of the abrupt variations in the altitude of the surface of the Ocala Limestone as due to faults (fig. 4) based on the data available at that time. Using additional information collected since 1983, Spechler (1994, plate 1) compiled a more detailed map of the top of the Ocala Limestone which indicates the presence of numerous closed-contour depressions in the surface of the unit. Therefore, the observed configuration of the top of the Ocala Limestone might be the result solely of paleokarst processes, rather than of movement along faults.

The transmissivity of the Upper Floridan aquifer varies considerably throughout the study area. Transmissivity values for six wells that penetrated 500 to 550 ft of the Floridan aquifer system, corresponding to the Upper Floridan aquifer and the middle semi-confining unit, ranged from 20,000 to 50,000 feet squared per day (ft^2/d) (Franks and Phelps, 1979, p. 7). At Ft. George Island in eastern Duval County, transmissivity values of 31,000 and 49,000 ft^2/d were determined (Environmental Science and Engineering, Inc., 1985, p. 3-36) for the Upper Floridan aquifer. Brown (1984, p. 27) reported transmissivity values ranging from about 20,000 to 50,000 ft^2/d for the Upper Floridan aquifer in Nassau County and adjacent Camden County, Ga. Transmissivity values in Duval County from modeling simulations range from 50,000 to 250,000 ft^2/d (Bush and Johnston, 1988, pl. 2). Bush and Johnston noted that a contrast between field and model-derived transmissivity data was evident in the Jacksonville area, perhaps because model-derived values are averaged for 64-square mile (mi^2) area grid blocks and do not reflect local variation. They also noted (p. C19) that simulated head values in the area were relatively insensitive to transmissivity values.

The middle semi-confining unit separates the Upper and Lower Floridan aquifers and usually is composed of beds of hard, less permeable limestone

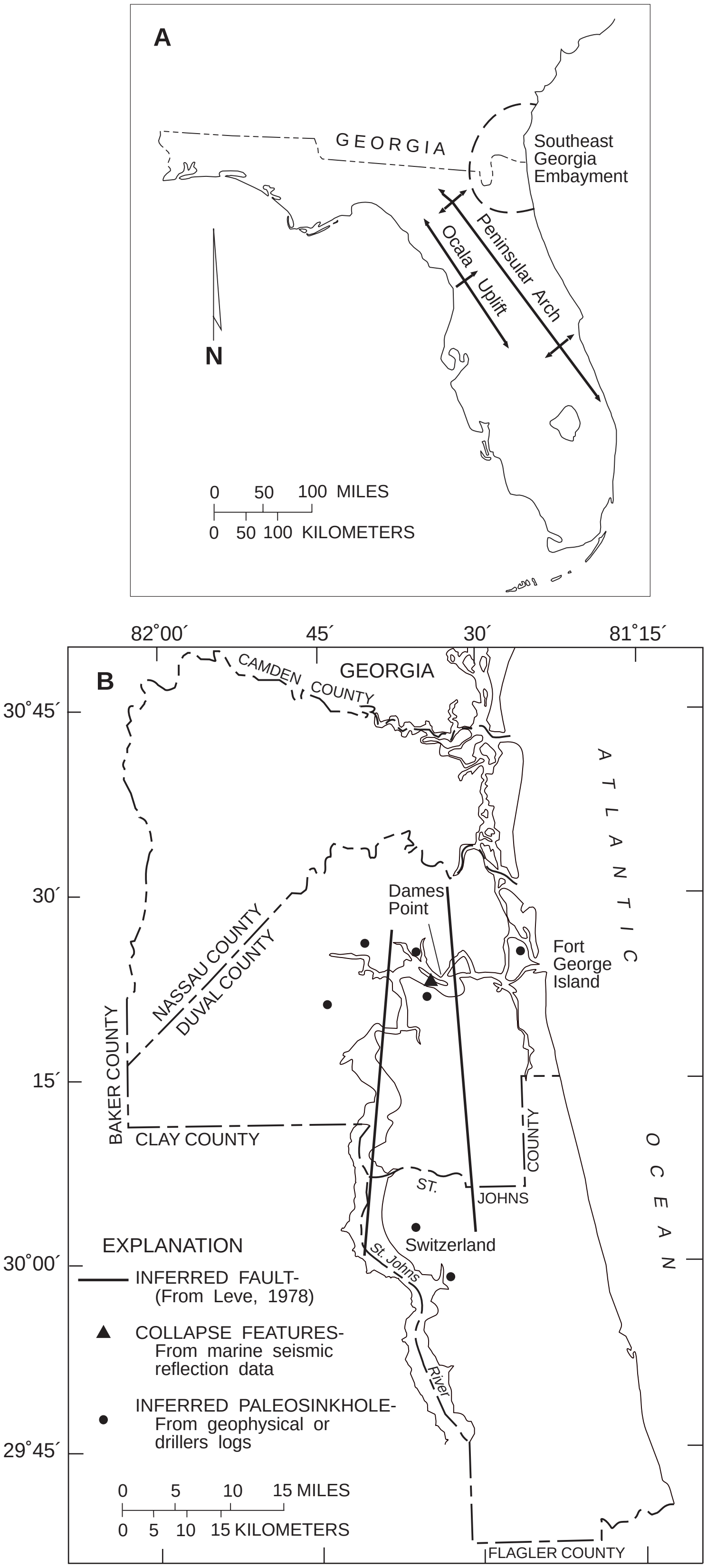

Figure 4. Major structural features in (A) northern Florida and (B) Duval and St. Johns Counties (modified from Spechler, 1994, fig. 10).

and dolomite. In Duval County, this unit generally occurs in the upper part of the Avon Park Formation, and ranges in thickness from about 100 to 200 ft (Miller, 1986, p. B57).

The Lower Floridan aquifer underlies the middle semi-confining unit. Most wells in the Jacksonville area deeper than 900 ft penetrate the Lower Floridan aquifer. The Lower Floridan aquifer contains two main water-bearing zones, the Upper zone and the Fernandina permeable zone, which are separated by a less-permeable semi-confining unit (Brown, 1984, p. 15). For convenience, in this report, the Upper zone of the Lower Floridan aquifer is called simply the Upper zone. In some parts of Duval County the Upper zone may have two subzones. The Upper zone consists of approximately the lower two-thirds of the Avon Park Formation and is composed of alternating beds of limestone and dolomite. Permeability in this zone is strongly related to secondary porosity developed along bedding planes, joints, and fractures. The hydrogeology of the Upper zone will be discussed in more detail in a later section of this report.

Miller (1986) also described but did not delineate from other permeable strata of the Lower Floridan aquifer a high-permeability, cavernous zone that occurs in the lower part of rocks of middle Eocene age. These rocks are at a depth of approximately 1,200 to 1,400 ft below sea level in Duval County. This zone is similar to the “Boulder Zone” of southeastern Florida, a highly productive zone of the Lower Floridan aquifer. The “Boulder Zone” does not represent a single cavernous horizon developed over a wide area at the same depth or in the same stratigraphic position, but rather is a fairly thick horizon of large-scale solution features representing a period when paleowater tables were at a level that permitted karstification of the carbonate rocks at or near land surface (Miller, 1986, p. B66). Furthermore, these paleokarst systems were developed, like modern cave systems, at several different levels over a vertical span that may reach several hundred feet. Borehole televiewer surveys of the "Boulder Zone" in southern Florida show that the paleokarst levels, separated by intervals of undissolved rock, commonly are connected by vertical fractures, which can be enlarged by solution into vertical "pipes" that connect the horizontal cavernous levels (Miller, 1986, p. B66). Similar to the "Boulder Zone," the middle Eocene cavernous zone is not consistently related to rock type or texture, dolomite percentage, thickness of the stratigraphic unit containing the zone, or the location of chert, anhydrite, or peat beds. The cavernous zone also shows high permeability where the middle Eocene rocks are structurally high, which supports the assumption that the zone was produced by karst activity at or near a paleowater table (Miller, 1986, p. B69). In Duval County, drillers' logs of wells show the presence of a cavernous zone in rocks of middle Eocene age. For example, in well D-665, the driller noted soft, sandy limestone and a cavity at a depth of 1,182 ft below land surface and noted that it would not be prudent to drill deeper. The vertical features associated with the middle Eocene cavernous zone provide a conduit for upward movement of saline water.

The Fernandina permeable zone is a high-permeability unit that lies at the base of the Floridan aquifer system. It was first tapped by a 2,130-ft deep test well at Fernandina Beach in 1945 (Brown, 1984, p. 39). In the Jacksonville area, the unit includes the lower Oldsmar and upper Cedar Keys Formations (Krause and Randolph, 1989, p. D23). Little is known about the extent or thickness of the Fernandina permeable zone because of the sparsity of data. Only four wells in Duval County and one test well each in Fernandina Beach and Ponte Vedra (fig. 1) penetrate the Fernandina permeable zone. In the Jacksonville area, the zone is estimated to be about 100 ft thick. No aquifer test data are available to calculate the transmissivity of the Fernandina permeable zone.

HYDROGEOLOGY OF THE UPPER ZONE OF THE LOWER FLORIDAN AQUIFER

The Upper zone consists of approximately the lower two-thirds of the Avon Park Formation and is composed of alternating beds of limestone and dolomite. Permeability in this zone is strongly related to secondary porosity developed along bedding planes, joints, and fractures. The hydrogeology of the Upper zone was evaluated using water-level and specific capacity-test data and geophysical and drillers' logs from about 40 wells. Many of the geophysical logs used in the analysis are described in detail in later sections of this report and the well locations are shown in figure 5.

Extent and Thickness

The Upper zone is present throughout northeastern Florida and southeastern Georgia. Using the sparse data available at the time, Miller (1986, pl. 31) estimated that the surface of the Upper zone dipped to the northeast and ranged in altitude from about 800 ft below sea level in extreme southwestern Duval County to about 1,200 ft below sea level in northeastern Duval County. Data from heat-pulse flow-meter logs collected during this study indicate that the top of the unit probably ranges from about 850 to 950 ft below sea level in Duval County, but these data do not indicate a dip to the northeast (fig. 6). At wells D-484 and D-307, in eastern Duval County, the apparently greater depths to the top of the Upper zone might result from the relatively high flows contributed to those wells from distinct fracture zones at depths of about 1,150 ft masking the much smaller flow contribution from the interval at a depth of about 900 ft.

In some parts of Duval County, the Upper zone has a single flow zone and a maximum thickness of about 300 ft. In wells D-225, D-1095, D-90, and D-101, one flow zone was observed. However, in other areas, less permeable strata separate two distinct flow zones in the Upper zone. At test well D-3060, flow-meter traverses indicate that the altitude of the top of the Upper zone is about 870 ft below sea level. A second highly productive zone was penetrated about 1,200 ft below sea level (Brown and others, 1985, fig. 15). Flow-meter traverses of test well D-2386 show an increase in flow to the well at about 950 ft below land surface and then a significant increase in flow between depths of about 1,150 and 1,250 ft (Brown and others, 1984, figs. 15-16). Test well D-425 also has two flow zones, one about 880 ft below sea level and the other, more productive zone about 1,080 to 1,280 ft below sea level. Two flow zones were also observed at well D-3841 at Ft. George Island. The middle semi-confining unit that overlies the Upper zone of the Lower Floridan is about 100 to 150 ft thick in Duval County. This estimate was confirmed by well logs made during this study.

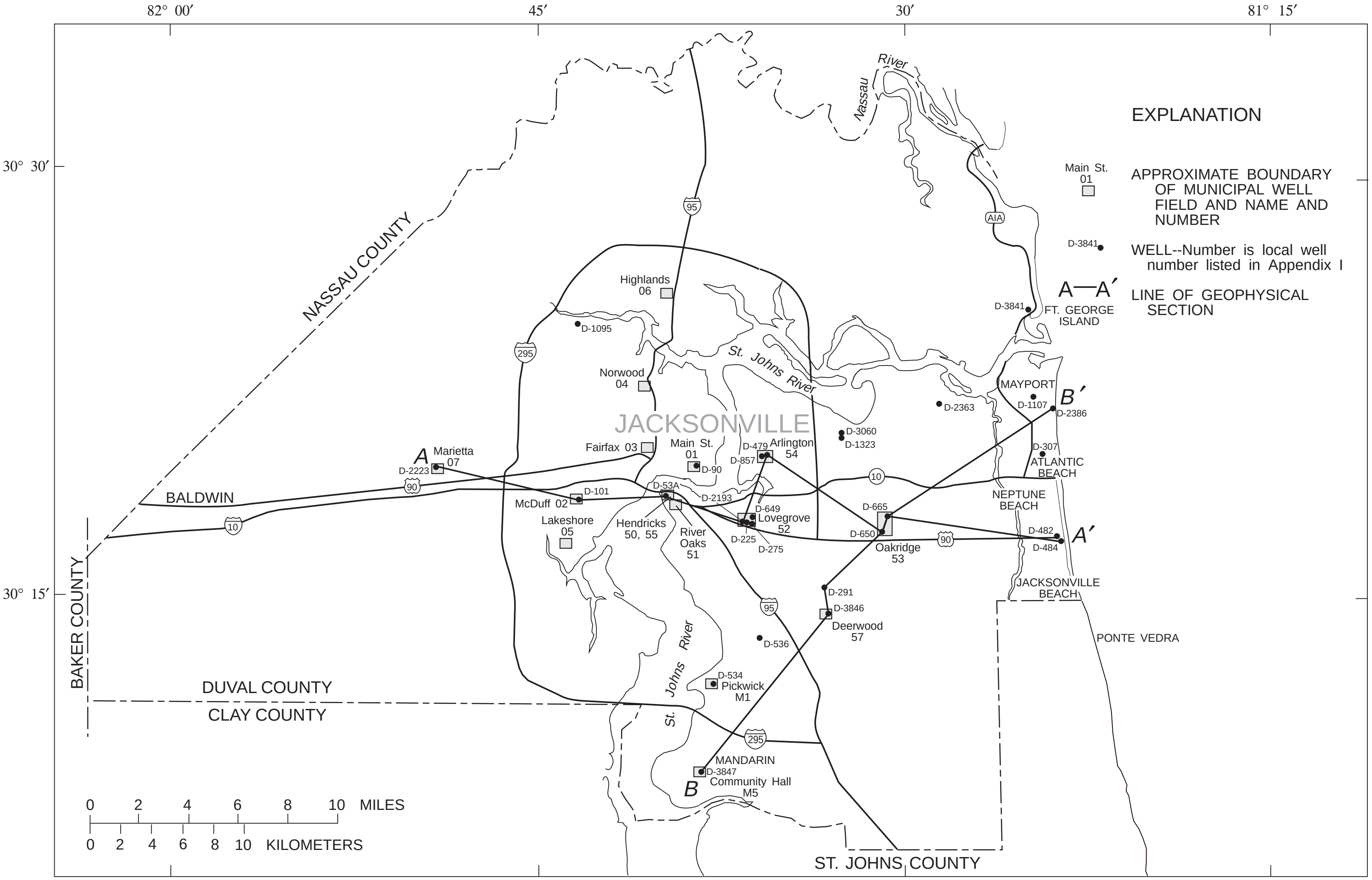

Figure 5. Wells logged during the study, other selected wells with geophysical logs, and selected municipal well fields.

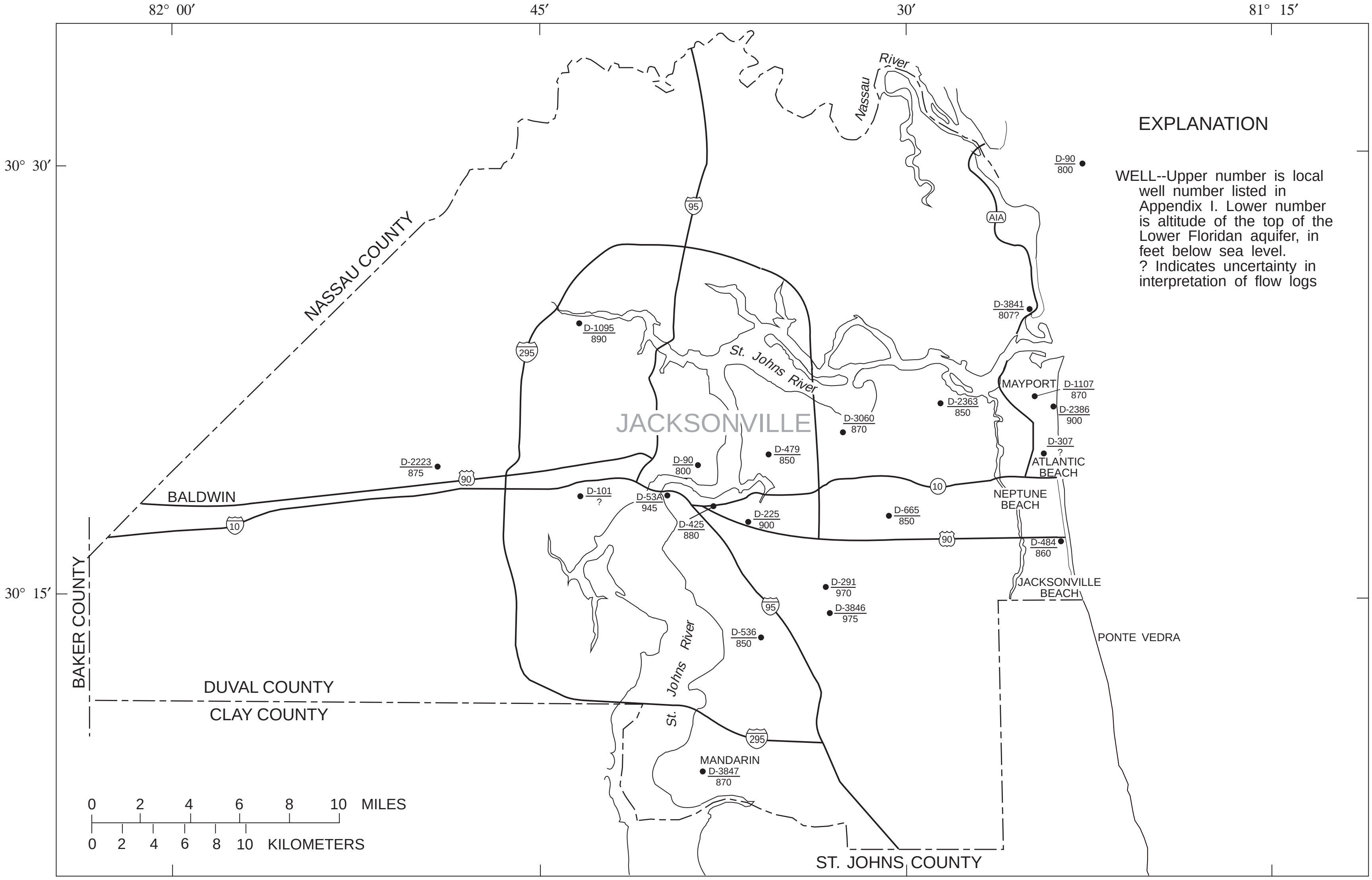

Figure 6. Estimated altitude of the top of the Upper zone of the Lower Floridan aquifer in Duval County.

Hydraulic Characteristics

The hydraulic character of the Upper zone can be described by the ways in which it contrasts with the properties of the overlying and underlying hydrogeologic units. Miller (1986) noted that the contrast in permeability between the rocks of the middle semi-confining unit in northeastern Florida relative to the rocks above and below this unit is less than that of any other confining unit mapped during the RASA study. Also, the lithology of this confining unit does not differ much from that of the permeable zones above and below it. These subtle differences can make the differentiation between the middle semi-confining unit and the underlying Upper zone somewhat subjective. Generally, the Upper zone is highly transmissive and it can be identified on flow-meter logs as an interval contributing a noticeable increase in flow to the well.

The transmissivity of the Upper zone has not been determined by aquifer tests of wells open only to that zone. Transmissivity values of 100,000 and 300,000 ft^2/d were determined for two wells that penetrated about 700 ft of the Floridan aquifer system (the Upper Floridan aquifer, the middle semi-confining unit, and the Upper zone) (Franks and Phelps, 1979, p. 7). Transmissivity values for the Upper zone derived from digital model simulations in the study area ranged from about 17,000 to 320,000 ft^2/d (R.E. Krause, USGS, written commun., 1991). Other estimates of transmissivity of the Upper zone are based on data from specific capacity tests of water-production wells in Jacksonville. Most of these wells tap both the Upper Floridan aquifer and the Upper zone, so the transmissivity values actually are estimates for both aquifers. To separate the values, flow-meter logs using packers could be run in conjunction with other geophysical logs, but such tests were beyond the scope of this study.

Transmissivity estimates derived from specific capacity are based on the work of Jacob (1946). For this study, data from step-drawdown tests performed in municipal production wells were analyzed using a computer program described in Sepulveda (1996). Estimates of transmissivity ranged from about 2,000 to about 194,000 ft^2/d (table 2). Generally, the tests with the lowest pumping rates produce the highest estimated transmissivity values, possibly because higher pumping rates induce turbulent, rather than laminar flow to the well. Also, the variation in estimated transmissivity values for some wells, such as the tests of D-53A in 1967 and in 1976, indicates another drawback to the use of specific capacity test data for estimating transmissivity: well development (or lack of development), encrustation of the open hole, or other factors related to the physical properties of the well can change the specific capacity of a well over a period of time. However, these data indicate a large range of transmissivity for both the Upper Floridan aquifer and the Upper zone.

Potentiometric Levels

One of the criteria described by Miller (1986) for differentiating between the Upper and Lower Floridan aquifers is a difference in hydraulic head between the two aquifers. Comparison of May 1994 water levels in the six Upper zone monitor wells to the potentiometric surface of the Upper Floridan aquifer in May 1994 indicates the magnitude of the head difference, as shown in the following table:

Site identification, Upper zone wells	Local no.	May 1994 water level (ft above sea level)	Estimated Upper Floridan aquifer water level (ft above sea level)
301537081441901	D-75	36.5	28
302022081393501	D-176	27.1	31
302608081354901	D-262	34.7	34
301604081361501	D-450	35.7	32
301639081330802	D-1155	34.5	30
302227081435001	D-592	39.1	35

Generally, heads are higher in the Upper zone than in the Upper Floridan aquifer, but the anomaly observed at well D-176 might be because some of the wells used to construct the map showing the potentiometric surface of the Upper Floridan aquifer (Schiffer and others, 1994) tap both the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer. Also, well D-176 is located in a well field near wells that pump from both aquifers.

Head differences between the Upper Floridan aquifer and the Lower Floridan aquifer also were observed in deep test wells in Duval County. When well D-2386 at Hanna Park was drilled, the heads in the drill stem were 13.0 ft above land surface at a depth of 600 ft; 15.5 ft at a depth of 820 ft; and 16.3 ft at a depth of 975 ft. A packer was installed in the well at a depth of 1,205 ft below land surface and heads above and below it were measured for 39 hours.

Table 2. Transmissivity values estimated from specific capacity test data

[Test data from the files of the city of Jacksonville. Q, discharge; s, drawdown; C, specific capacity; T, transmissivity; gal/min, gallon per minute; ft, feet; hr, hour; ft^2/d, feet squared per day; --, no data]

Site identification no.	Local no.	Date	Q (gal/min)	s (ft)	Time (hr)	Well depth (ft)	C=Q/s	T (ft^2/d)
301725081305002	D-650; 5304	6/02/75	2,500	15	4	1,276	167	50,000
301743081303501	D-3825; 5305	2/22/89	2,513	10	24	1,093	251	84,000
301743081303901	D-223; 5301	6/09/70	2,500	19.25	4	1,125	130	39,000
	D-223; 5301	6/09/70	4,000	34.75	0.5	1,125	115	30,000
301752081360501	D-649; 5203	6/23/75	2,000	41.2	4	1,005	48	14,000
301758081303901	D-665; 5303	7/25/75	2,000	21.08	4	1,185	95	28,000
301839081392101	D-198; 5002	4/06/71	2,500	8	4	1,297	89	30,000
301840081383901	D-2684; 5502	--	3,000	28.6	0.25	1,252	61	14,000
	D-2684; 5502	--	1,700	6.42	0.25	1,252	65	15,000
301840081393501	D-53A; 5003	11/21/67	1,892	78	0.16	1,286	18	4,200
	D-53A; 5003	11/21/67	1,200	25	0.38	1,286	23	5,800
	D-53A; 5003	11/21/67	1,400	40	0.25	1,286	21	5,000
	D-53A; 5003	3/12/76	2,210	69	0.25	1,286	24	5,800
	D-53A; 5003	3/12/76	1,200	32	0.25	1,286	21	5,200
301848081390301	D-2685; 5501	--	2,900	13.08	0.25	1,270	104	26,000
	D-2685; 5501	--	2,100	6.08	0.25	1,270	100	25,000
301930081470601	D-2283; 0703	3/31/80	2,500	15.08	4	1,250	166	50,000
301937081471401	D-2223; 0704	11/28/79	2,200	28.17	0.2	1,315	78	19,000
	D-2223; 0704	11/28/79	2,500	35	4	1,315	71	20,000
	D-2223; 0704	5/19/80	2,200	16.66	0.33	1,315	132	34,000
	D-2223; 0704	5/19/80	3,000	20	0.33	1,315	150	39,000
302005081354501	D-857; 5403	11/14/75	2,000	51	1.25	1,105	39	10,000
	D-857; 5403	11/14/75	2,500	75	1.25	1,105	33	7,000
302007081353201	D-479; 5402	3/24/73	2,000	9	0.68	1,320	222	61,000
	D-479; 5402	3/24/73	2,200	11.33	0.25	1,320	194	50,000
	D-479; 5402	3/24/73	2,400	12.75	0.25	1,320	188	48,000
	D-479; 5402	3/24/73	2,500	14.5	2	1,320	172	50,000
	D-47; 5402	3/24/73	2,600	14.75	0.25	1,320	176	45,000
	D-479; 5402	3/24/73	2,800	17.92	0.25	1,320	156	40,000
	D-479; 5402	3/24/73	3,000	28	0.25	1,320	107	27,000
302013081353801	D-673; 5404	9/03/75	2,513	4	3	814	628	194,000
302045081323101	D-1323	10/05/77	1,016	1.92	1.5	1,170	529	170,000
	D-1323	10/05/77	1,212	9.2	2.5	1,170	131	40,000
	D-1323	10/05/77	1,500	21	3	1,170	71	21,000
302107081411001	D-100; 0308	2/06/76	1,600	96	0.25	1,365	17	4,000
	D-100; 0308	2/06/76	1,000	52	0.25	1,365	19	4,500
302107081412301	D-162; 0301	8/24/71	3,000	29	4	1,309	73	21,000
302112081410001	D-168; 0302	12/01/67	1,016	98	0.25	1,320	9	2,100
302122081412201	D-240; 0303	10/12/72	3,000	47	0.16	1,362	52	12,000
	D-240; 0303	10/12/72	2,500	39	4.5	1,362	64	14,000
302127081411002	D-52A; 0304	2/20/62	1,753	35	6.5	1,356	50	15,000
302130081411802	D-46A; 0305	11/15/67	2,000	56.5	0.33	1,280	35	9,000
	D-46A; 0305	11/15/67	1,000	20	0.5	1,280	50	13,000
302514081393701	D-227; 0604	7/26/72	2,500	21	3.5	1,257	119	34,000
302527081393701	D-226; 0603	9/09/72	2,500	9	4	1,296	278	83,000
	D-226; 0603	9/09/72	3,000	16	0.25	1,296	188	47,000
302532081392501	D-330; 0601	5/23/68	2,930	14.3	0.5	1,211	95	24,000
	D-330; 0601	5/23/68	2,896	14	3.25	1,211	93	27,000
302538081392501	D-329; 0602	5/01/68	2,941	15	4.66	1,209	84	24,000
	D-329; 0602	5/01/68	2,805	13.33	0.5	1,209	85	21,000

The heads in the interval from about 429 to 1,205 ft below land surface were about 15 to 16 ft above land surface, whereas in the interval from about 1,205 to 1,378 ft below land surface, heads were about 20.5 to 21.5 ft above land surface (Brown and others, 1984, p. 5). In well D-3060 in Arlington, the head at 770 ft below land surface was about 11 ft above land surface, whereas at a depth of 1,306 ft the head was 14 ft above land surface (Brown and others, 1985, table 2). In well D-425, the head in the bottom zone (2,055 to 2,486 ft below land surface) generally is about 4 ft higher than the head in the top zone (752 to 1,895 ft below land surface)(U.S. Geological Survey, 1994, p. 77).

OVERVIEW OF WATER QUALITY

Variations in the ionic composition of water from wells tapping the Upper Floridan aquifer and both the Upper Floridan and the Upper zone in Duval County were described by Spechler (1994). Calcium bicarbonate type water predominates in most areas of the county. In a few areas, calcium magnesium sulfate type water or sodium chloride type water has been detected. Because concentrations of chloride and sulfate can be limiting factors for the use of ground water in northeastern Florida, the USGS regularly samples a network of about 30 wells in Duval County for those constituents. About half of the wells tap only the Upper Floridan aquifer, six tap only the Upper zone, and the rest tap the Upper Floridan and the Upper zone of the Lower Floridan aquifer. Four monitor wells are completed in the Fernandina permeable zone, but those wells are not sampled on a regular basis. Additionally, the city of Jacksonville regularly samples all municipal water-supply wells, many of which tap the Upper Floridan aquifer and the Upper zone, for major constituents.

Maps showing concentrations of dissolved solids, sulfate, and chloride in water from wells in northeastern Florida compiled by Spechler (1994, figs. 23, 24 and 26) indicate that saline water has continued to intrude into the aquifer. This conclusion is supported by data from the network and samples collected during this study. Chloride concentrations in water from the six Upper zone monitor wells indicate an increasing trend in some areas of Duval County but not in others (fig. 7). For example, chloride concentrations have increased in water from wells D-262, D-450, and D-1155, but not from wells D-75, D-176, and D-592. Most areas where chloride concentrations are increasing are east of the St. Johns River, but increases have not been detected in water from all of the wells east of the river. For example, wells D-53A and D-54A (fig. 1) have been pumped for more than 35 years without increases in chloride concentration. Areas

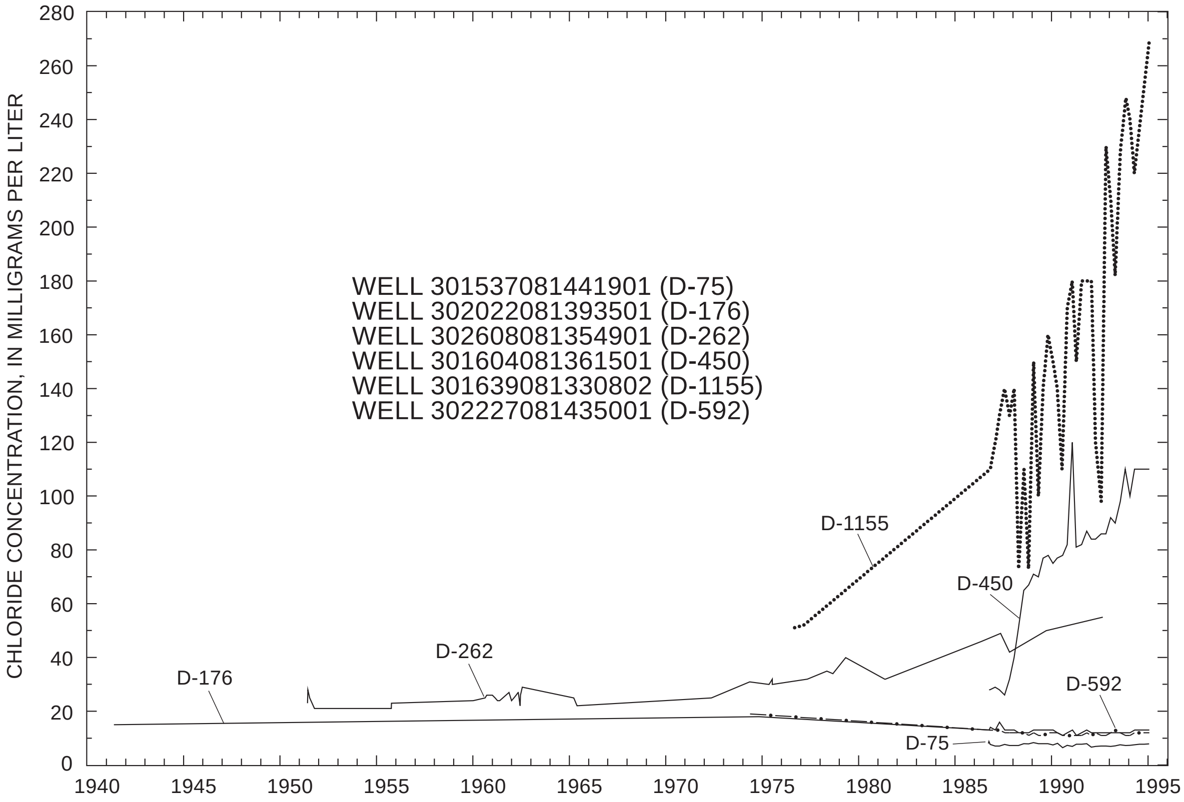

Figure 7. Chloride concentrations in water from six wells open only to the Upper zone of the Lower Floridan aquifer in Duval County, 1940-95.

where chloride concentrations are increasing apparently are not related to the locations of the inferred faults postulated by Leve (1978) (fig. 8).

The continued increase in chloride concentrations in water in some areas of Duval County was confirmed by a mass sampling of wells tapping the Floridan aquifer system. Data for 61 wells (sampled for chloride and sulfate concentration in May and September 1994 to coincide with the semi-annual mapping of the potentiometric surface of the Upper Floridan aquifer) are included in Appendix II. Many of the wells sampled tap only the Upper Floridan aquifer but others tap the Upper Floridan and the Upper zone. Of the 61 wells sampled, chloride concentration

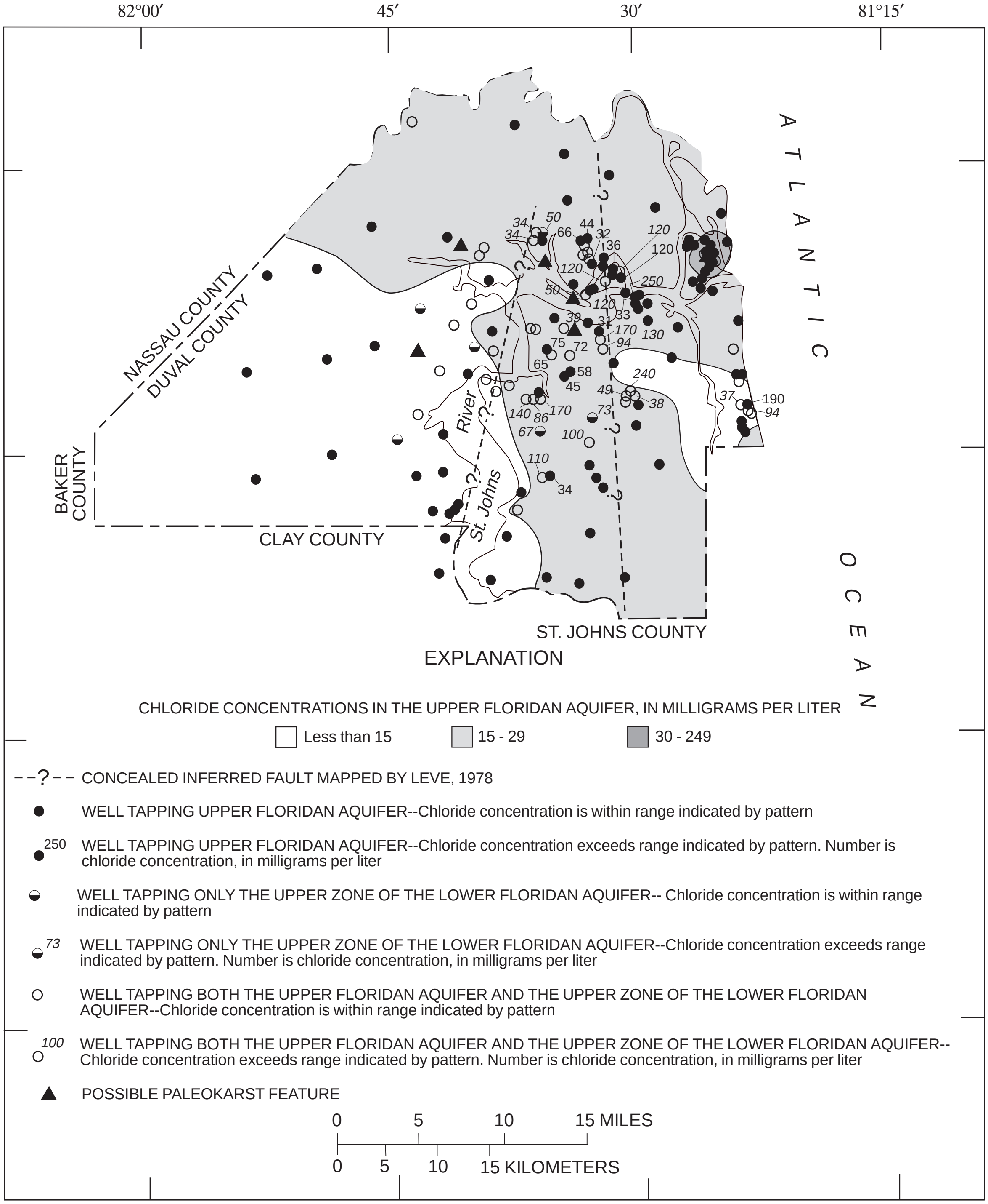

Figure 8. Chloride concentrations in water from the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer and locations of inferred faults and paleokarst features in Duval County (modified from Spechler, 1994, figs. 10 and 26).

Table 3. Chemical constituents of water samples from wells logged during this study, 1994-96

[All constituents are dissolved and given in milligram per liter, except strontium (micrograms per liter) and specific conductance (microsiemens per centimeter at 25 °C). ft, feet; w, wellhead; --, no data]

Site identification no.	Date	Sampling depth (ft)	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Silica	Strontium	Specific conductance	Alkalinity	Dissolved Solids
300856081382401	10-12-94	1,180	44	22	78	2.3	9.6	100	18	4,200	450	104	271
D-3847	10-12-94	w	47	23	82	2.2	9.8	110	17	4,000	455	98	281
	10-28-94	1,040	45	23	75	2.2	9.6	110	17	4,100	450	101	280
	10-28-94	1,220	44	23	7.7	2.2	9.4	100	17	4,200	450	103	270
301210081373301	10-25-94	w	79	39	15	2.8	32	220	21	6,000	760	121	488
D-534	10-25-94	718	76	38	15	2.7	32	220	20	6,000	760	122	484
	10-25-94	905	96	44	17	2.8	44	280	21	6,800	875	124	587
301335081355001	02-21-96	w	130	57	63	3.1	220	300	23	8,000	1,470	128	916
D-536	02-21-96	1,059	130	56	56	3.3	200	330	23	7,800	1,430	125	914
	02-21-96	1,095	130	52	27	3.0	94	350	23	7,000	1,150	123	816
301405081325601	03-14-94	w	75	30	13	2.3	17	170	24	4,400	634	140	437
D-3846	03-14-94	1,110	73	31	12	2.4	18	180	23	4,300	654	136	450
301522081331301	10-17-94	w	82	34	34	2.2	99	150	24	3,600	840	138	514
D-291	10-17-94	1,230	92	37	41	2.2	130	160	24	3,900	1,100	138	588
301704081233401	02-14-95	1,140	97	44	81	2.6	220	150	28	2,400	1,250	146	752
D-484	02-14-95	w	98	44	80	2.6	220	150	28	2,400	1,250	148	742
301716081234301	02-15-95	w	68	33	27	2.2	58	140	26	2,300	680	147	456
D-482	02-15-95	1,120	70	33	29	2.2	63	140	27	2,400	729	145	492
301743081362301	03-14-94	w	100	40	78	2.6	210	150	25	3,900	1,220	141	762
D-225	03-14-94	1,240	100	40	78	2.6	210	150	25	3,600	1,200	144	767
301752081360501	10-12-94	w	76	28	17	1.8	32	160	24	3,500	700	137	--
D-469	10-12-94	940	77	28	19	1.9	40	160	24	3,500	710	139	--
301758081303901	03-14-94	w	170	73	280	4.0	690	220	25	5,700	2,710	138	1,800
D-665	03-14-94	1,070	170	75	250	4.0	680	220	25	5,700	2,730	137	1,790
301832081422201 D-101	03-14-94	w	64	25	9.0	2.1	9.9	140	20	3,500	528	121	348
301937081471401	10-21-94	w	--	--	--	--	12	150	--	--	566	--	--
D-2223	03-14-94	880	68	24	--	1.8	11	150	21	3,200	559	128	380
	10-21-94	1,190	--	--	--	--	12	160	--	--	569	--	--
302003081384001	10-14-94	1,270	71	29	11	1.9	15	160	24	3,400	609	140	--
D-90	10-14-94	w	54	23	13	1.5	18	74	26	1,600	494	159	--
302005081354501	10-31-94	w	80	30	25	1.8	83	130	24	3,000	720	140	461
D-857	10-31-94	1,060	95	36	33	1.9	130	130	26	3,100	740	139	539
302007081353201	11-07-95	w	87	33	32	1.9	110	120	24	2,500	870	144	497
D-479	11-07-95	1,336	86	33	32	1.9	110	120	25	2,500	864	143	479
302008081242101	02-16-95	w	74	36	47	2.1	110	120	26	2,600	756	144	502
D-307	02-21-95	1,160	74	36	47	2.3	110	120	25	2,500	876	145	526
	02-21-95	1,230	62	30	15	1.8	26	120	26	2,600	756	144	502
302045081323101 D-1323	02-24-95	w	100	42	90	2.2	250	150	26	2,600	1,350	146	784
302058081244101	02-23-95	653	65	32	12	1.8	18	150	24	2,100	600	135	408
D-1107	02-23-95	923	65	28	12	1.6	17	130	25	2,200	550	145	374
	02-23-95	w	66	32	12	1.8	18	140	24	2,200	600	140	398
302134081284803	10-19-94	w	63	25	12	1.5	17	110	26	2,100	549	151	346
D-2363	10-19-94	1,000	64	25	12	1.5	17	110	26	2,000	550	151	349
	10-19-94	1,040	60	24	12	1.5	18	100	28	1,800	538	150	336
302433081432201	10-27-94	w	57	20	11	1.3	13	86	21	1,400	480	142	296
D-1095	10-27-94	940	57	20	11	1.3	13	88	21	1,400	500	142	298
	10-27-94	1,200	57	20	11	1.3	13	86	21	1,300	480	141	296
302510081260201	02-28-95	w	56	25	11	1.5	17	93	26	1,400	520	151	338
D-3841	02-28-95	1,300	--	--	--	--	20	100	--	--	530	--	--

increases were observed in ten wells, compared to data collected by Spechler (1994, fig. 26) in the early 1990's. The wells in which the chloride concentrations increased were: D-536, D-450, D-1155, D-275, D-224, D-225, D-313, D-479, D-673, and D-913. All of these wells are in the eastern part of Duval County, but neither the chloride concentrations nor the rate of increase in chloride concentrations follows a discernible pattern. In addition to the mass sampling for chloride and sulfate, samples from the logged wells were analyzed for major ions and strontium (table 3).

Water-quality data for the Fernandina permeable zone are sparse. Water samples collected in 1990 had chloride concentrations ranging from 80 milligrams per liter (mg/L) at well D-425B to 18,000 mg/L at well SJ-150 at Ponte Vedra (fig. 1). There is speculation that the consistently low chloride concentrations in D-425B could be because packers that separate the Upper zone from the Fernandina permeable zone are leaking, allowing freshwater from the Upper zone to mix with water from the Fernandina permeable zone. Another explanation could be that all of the water sampled comes from a very productive interval at a depth of about 2,000 ft below land surface, and deeper intervals, in which chloride concentrations increase abruptly, contribute little water to the well. Chloride concentrations in water samples from wells D-2386 and D-3060 were about 6,000 mg/L in 1990.

The mechanism of saline water intrusion into the Upper Floridan aquifer, described in detail in Spechler (1994), most likely is not lateral intrusion of seawater from the ocean or simple regional upconing of saline water from deeper zones in the aquifer. Instead, the upward movement is through structural features in the area. Such features include paleokarst features of both relatively small, local extent and larger, regional extent. The presence of both vertical and horizontal fractures or joints and solution features developed along the planes of those fractures or joints also strongly influence the movement of the saline water (fig. 9). In some areas the alternating layers of brackish and fresher water also could be caused by interfingering of freshwater and seawater resulting from cyclic changes in the altitude of sea level during the geologic past.

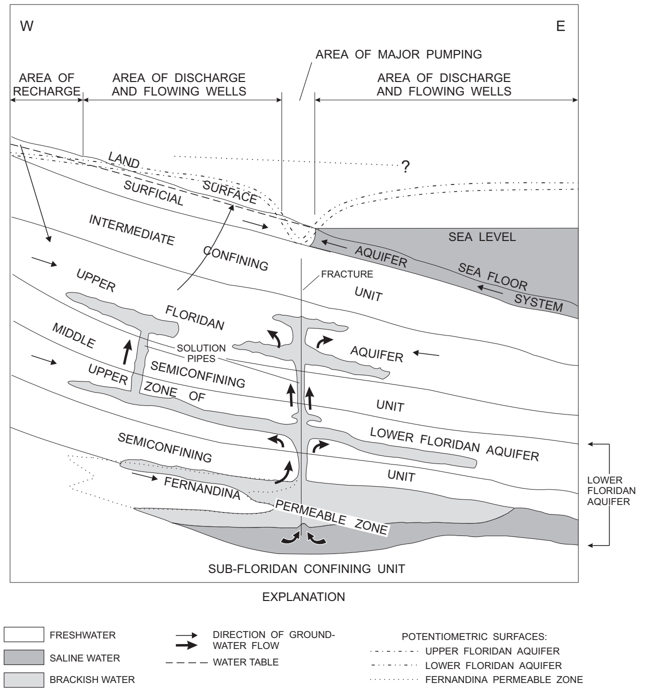

Figure 9. Simplified section of the Floridan aquifer system (modified from Spechler, 1994, fig. 37).

RELATION BETWEEN HYDROGEOLOGY AND WATER QUALITY IN SELECTED AREAS

The data from geophysical logging and analysis of water samples collected during the logging (table 3) were compiled to determine the relation between the distribution of saline water and the hydrogeology of the aquifer. Generally, higher chloride concentrations are observed in eastern Duval County, perhaps because the Fernandina permeable zone contains saline water in the eastern part of the county and freshwater in the western part. However, some areas of heavy pumping, such as the River Oaks and Hendricks municipal well fields (fig. 5) are east of the river and show no signs of water-quality deterioration. The original well field for the city of Jacksonville is located downtown, just west of the river. In the Main Street and Fairfax well fields, wells ranging in depth from 1,200 to 1,300 ft have been pumped for more than 40 years but water from the wells shows no increase in chloride concentrations. Following are detailed discussions of several problem areas and comparisons of those areas to areas where no chloride problems have been detected.

Lovegrove

Chloride concentrations in water from three of the four wells at the Lovegrove well field, in eastern Jacksonville, began to increase almost from the time the wells were drilled (figs. 10-11). Well D-275 is rarely used because of persistent chloride concentrations of about 200 to 250 mg/L. Water from well D-225 is sampled

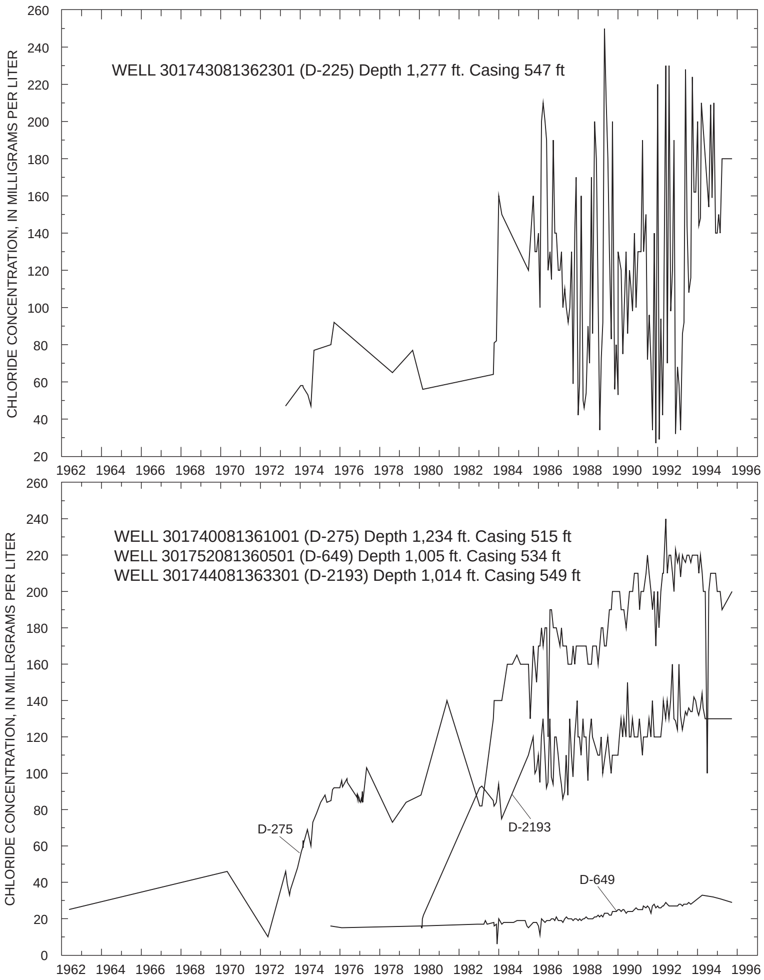

Figure 10. Chloride concentrations in water from wells in the Lovegrove well field, 1962-96.

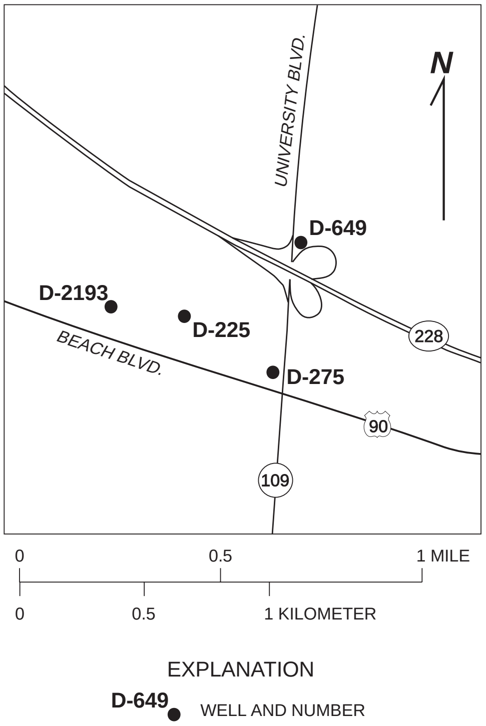

Figure 11. The Lovegrove well field.

monthly; the chloride concentration in the water samples from this well fluctuates from about 60 to 200 mg/L. The well is pumped only during peak demand periods. Existing geophysical logs for wells D-275 and D-2193 were analyzed along with logs collected during this study for wells D-225 and D-649.

Well D-225 is the deepest of the four wells at the Lovegrove well field. The fluid resistivity log for this well (fig. 12) indicates that water with higher chloride concentrations is entering the well between about 1,225 and 1,245 ft below land surface. Below a depth of about 1,270 ft the fluid resistivity increases, although little flow is contributed below that depth. The sonic televiewer log of well D-225 (fig. 13) shows that the interval (1,225 to 1,245 ft) contributing saltier water is hard rock riddled with voids, which are apparent on the caliper log of the well. Above this interval, the fluid resistivity log shows that the quality of water is nearly uniform throughout the borehole. The chemical analysis of samples collected at a depth of 1,240 ft and at the wellhead were nearly identical (table 3), indicating that the interval from the bottom of the casing to 1,240 ft contributes little flow to the well relative to the contribution from below 1,240 ft. Two or three fractures or solution features at 1,275 to 1,277 ft apparently contribute freshwater.

Logs for well D-275 (about 1,234 ft deep) show that the saltiest water is entering the well at the bottom of the well, about the same depth at which saltier water enters well D-225 (fig. 12). A sonic televiewer log is not available for well D-275. Because well D-275 is shallower than well D-225, the well is not deep enough to penetrate the fresher water-bearing flow zone at the 1,275-ft depth so the water from well D-275 has a higher chloride concentration.

Wells D-649 and D-2193 are shallower, (1,005 and 1,014 ft, respectively), although D-2193 was originally drilled to a depth of 1,301 ft. In 1987, the logged depth was 1,014 ft, apparently because the well had partially backfilled. The fluid resistivity log of D-649 (fig. 14) indicates that water with higher chloride concentration enters the well at a depth of about 940 to 955 ft. The temperature log for static (non-flowing) conditions (not shown) indicates that the water below 940 ft is warmer than water above that depth. The water sample collected at a depth of 940 ft (table 3)

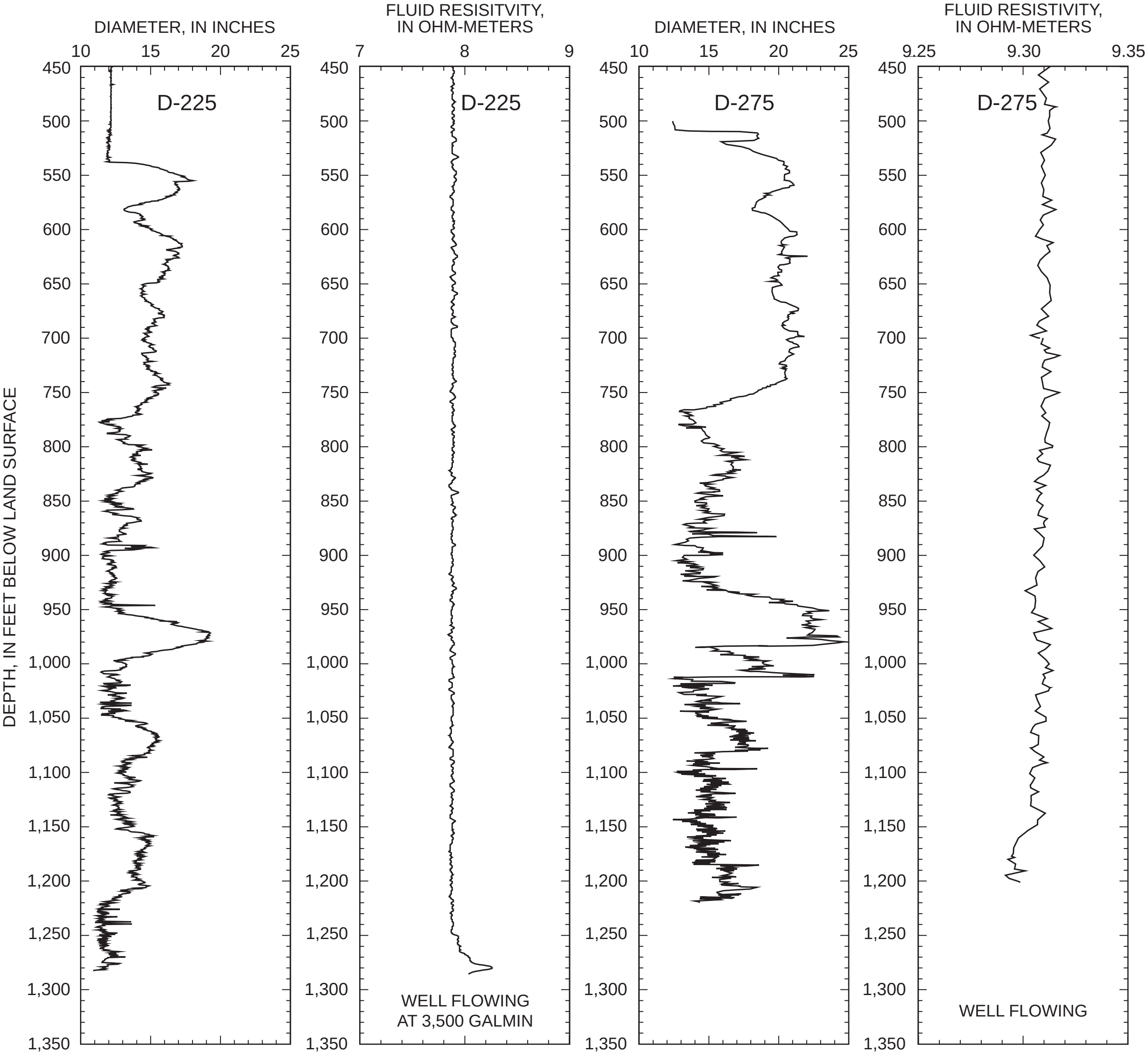

Figure 12. Geophysical logs of wells D-225 and D-275 at the Lovegrove well field.

had a slightly higher chloride concentration (40 mg/L) than the sample collected at the wellhead (32 mg/L), probably indicating the influence of the fresher water at the bottom of the well, as well as inflow from fresher flow zones above 940 ft. The heat-pulse flowmeter log for well D-649 indicates that under static conditions, water enters the well between depths of 920 and 1,005 ft. From about 820 to 920 ft the formations penetrated are less permeable and water flows up the borehole. From a depth of about 670 ft to the bottom of the casing, water flows out of the borehole into the surrounding formations. This indicates that the formations are permeable but the artesian pressure in them is lower than in the deeper strata.

Logs for well D-2193 (fig. 14) indicate that warmer, saltier water enters the borehole from a fracture or void at a depth of about 970 ft below land surface. The fluid resistivity log indicates that water in the well becomes somewhat fresher below that depth. The chloride concentration of a water sample collected at the wellhead at the time of logging was 140 mg/L. Wellhead chloride concentration in 1995 was about 130 mg/L.

Geophysical logs from the Lovegrove wells indicate that simple, areally extensive upconing of saline water from deeper zones of the Floridan aquifer system probably is not the cause of increased chloride concentrations in the wells. Instead, alternating flow

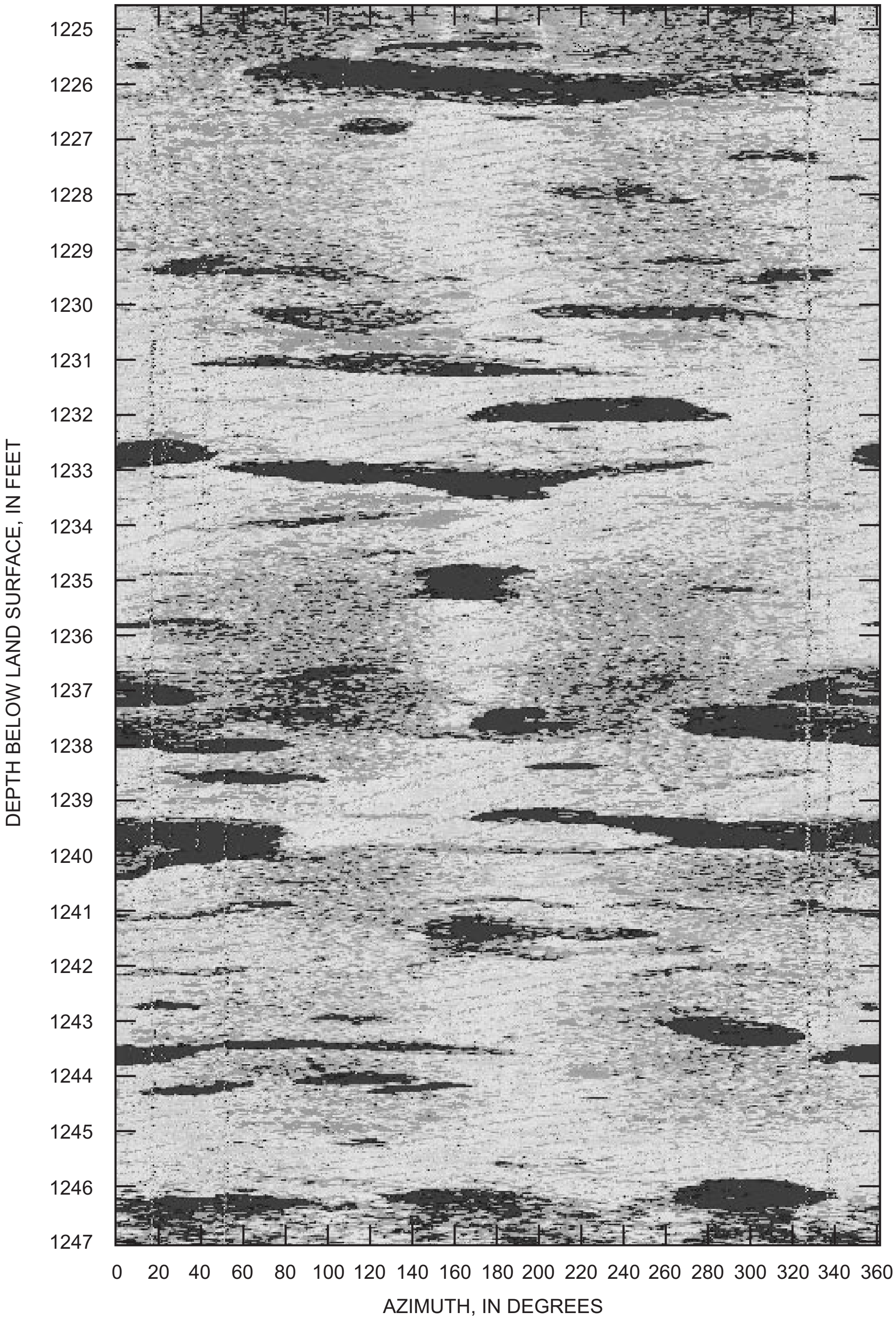

Figure 13. Sonic televiewer log of well D-225 at the Lovegrove well field.

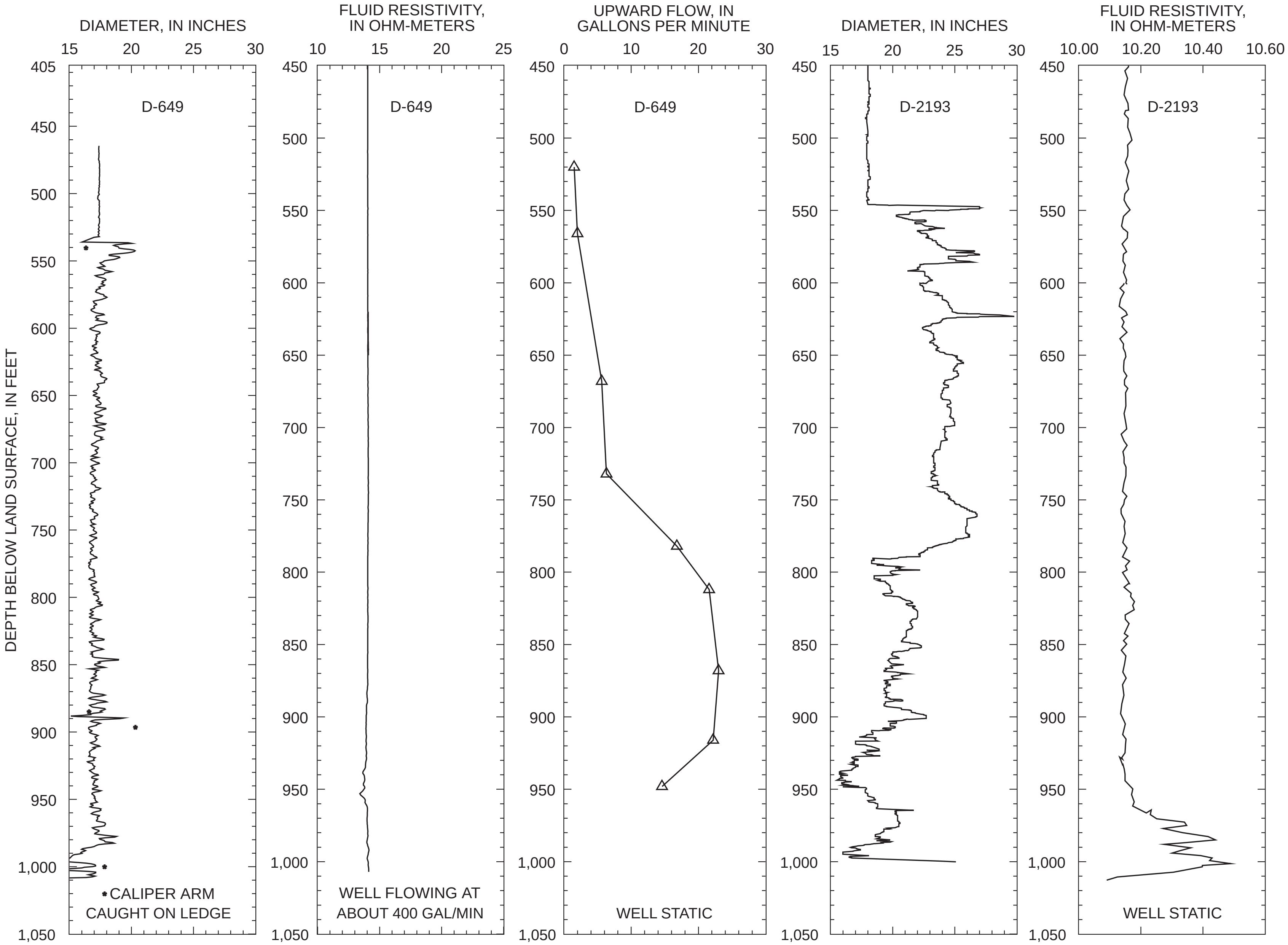

Figure 14. Geophysical logs of wells D-2193 and D-649 at the Lovegrove well field.

zones of higher and lower chloride concentrations apparently exist in the middle semi-confining unit and the Lower Floridan aquifer. The effects of fractures or solution voids are significant in influencing the development of the flow zones. The two shallower wells in the well field (D-649 and D-2193) yield water with lower chloride concentrations because they do not penetrate the zone from about 1,225 to 1,245 ft below land surface that contributes higher chloride water to wells D-225 and D-275. Well D-275 yields water with a higher chloride concentration than the deeper well D-225 because well D-275 does not penetrate the fresher water-bearing zone at a depth of about 1,275 ft.

The variation of chloride concentrations in water samples from D-225 is more difficult to explain. To study these fluctuations, a probe was installed at the wellhead in D-225 to record hourly values of specific conductance (which can be related to chloride concentration). For the same time period, the pump start and stop times for all the Lovegrove wells were recorded. The specific conductance of water from well D-225 apparently is more closely related to whether or not the other wells are pumping than to whether or not D-225 is pumping (fig. 15). This might be because the pressure in the shallower strata is reduced when the shallower wells are pumping, reducing the flow contributions from those strata and allowing the saltier water from the 1,225- to 1,245-ft zone to dominate.

Oakridge

An increase in chloride concentrations in water from several wells also has been a problem at the Oakridge well field (figs. 5 and 16). One of the five wells, D-665, was removed from service because the chloride concentration in water at the wellhead had increased (690 mg/L in 1994). Chloride concentrations have increased in all five wells since the 1970's (fig. 17). Although data for well D-223 are not shown in figure 17, the chloride concentration in water from that well was 24 mg/L when sampled by the USGS in 1978 and ranged from 74 to 142 mg/L when sampled by the city of Jacksonville in 1995 (Donald Thompson, Jacksonville Department of Public Utilities, written commun., 1996). The chloride concentration has also increased in well D-1155 (fig. 7), a monitor well open only to the Upper zone and located about 2.5 miles (mi) southwest of the Oakridge well field, although the chloride concentration in water from that well is much less than the concentration in water from well D-665.

Geophysical logs of well D-650 made in 1978 and logs of well D-665 collected during this study were analyzed to improve the understanding of the increasing chloride concentrations. The static fluid resistivity log from well D-650 (fig. 18) was used because a log had not been made under flowing conditions. The static fluid resistivity log indicates that water with high chloride concentrations probably is entering the well at a depth of about 950 to 1,000 ft below land surface. Below 1,000 ft the water freshens again, although the fresher water is made more salty by flow from a zone of warmer, slightly more salty water at 1,120 ft below land surface. Below about 1,120 ft there is no change in water temperature (log not shown in fig. 18), indicating little or no flow from those zones.

In contrast to the alternating zones of fresher and more brackish water in well D-650, brackish water underlies the fresher water in well D-665. A single fracture or solution feature at a depth of about 1,080 ft contributes much of the flow to the well and dilutes the brackish water underlying that flow zone. In well D-650, the entire interval between 1,000 and 1,180 ft contributes freshwater; therefore, the source of water with elevated chloride concentrations to the two wells apparently is not the same. The difference between the chloride concentrations in water from well D-665 and in water from the monitor well D-1155, which is open from 1,080 to 1,170 ft below land surface, also indicates that the increased chloride concentrations in water from well D-665 are not caused by a simple process of regional upconing of saline water from deeper in the aquifer. Notes from the drilling log of well D-665 indicated a cavity filled with soft, sandy limestone was penetrated at a depth of 1,182 ft, at which point drilling was stopped and the well filled in to its present depth, 1,120 ft. This cavity may be indicative of the presence of a relatively large collapse feature.

Higher transmissivity values might be expected in wells that intersect fracture systems connected to deeper, saline water-bearing zones than in wells that do not have such a connection. However, comparison of the hydraulic properties of the wells at the Oakridge well field is inconclusive:

Well no.	Depth (ft)	Transmissivity (ft^2/d)	Chloride (mg/L)
D-3825	1,097	84,000	160
D-665	1,120	28,000	690
D-223	1,125	39,000	110
D-224	1,179	--	140
D-650	1,267	50,000	59

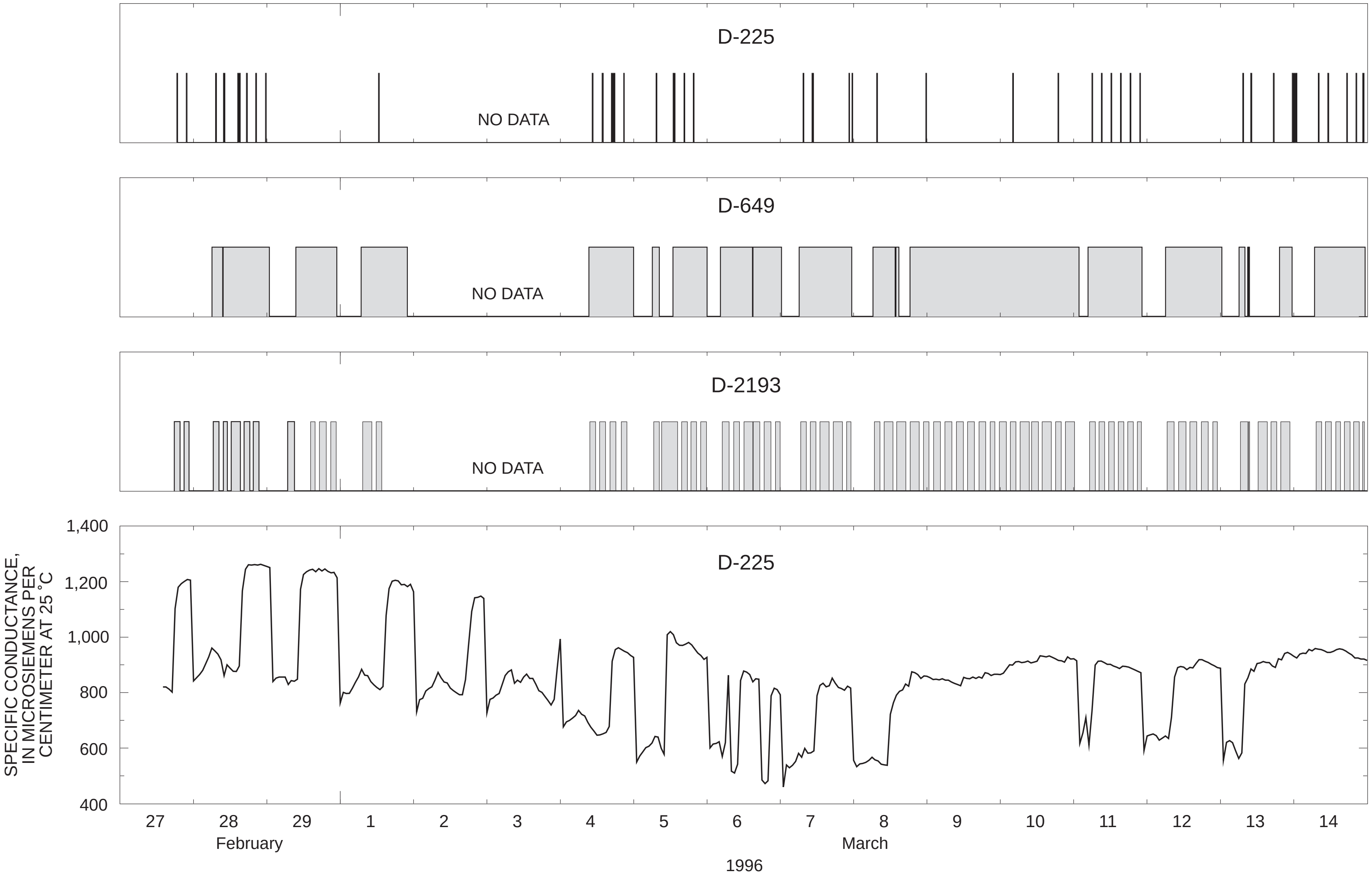

Figure 15. Specific conductance of water from well D-225 and pump running times for the Lovegrove well field.

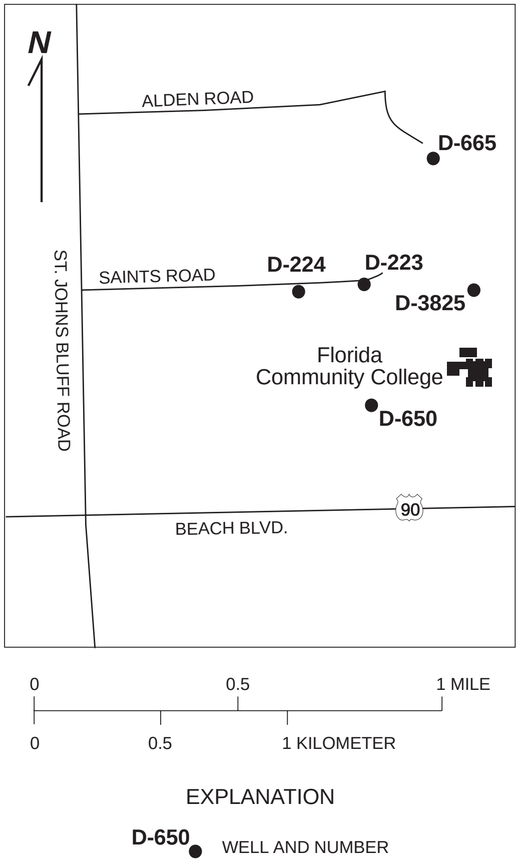

Figure 16. The Oakridge well field.

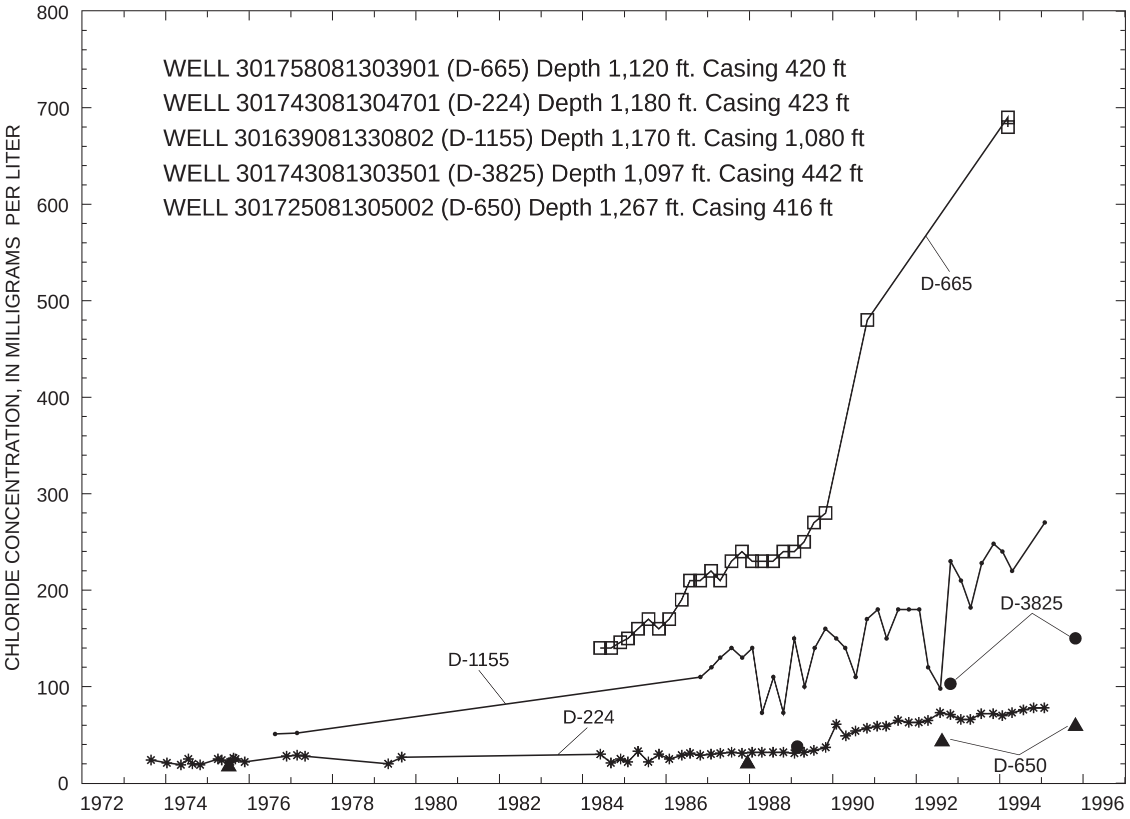

Figure 17. Chloride concentrations in water from wells in the Oakridge well-field area, 1973-96.

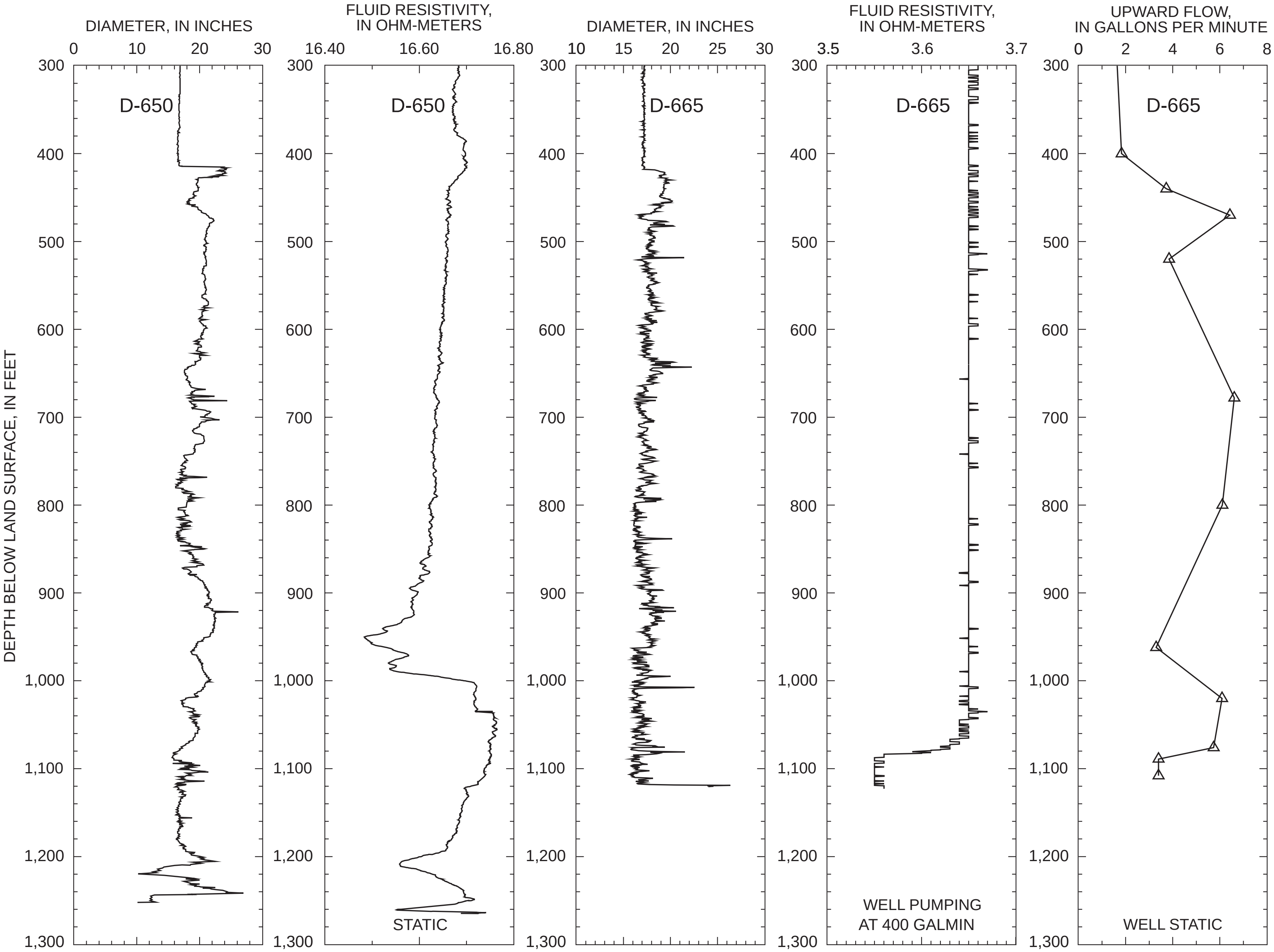

Figure 18. Geophysical logs of wells D-650 and D-665 at the Oakridge well field.

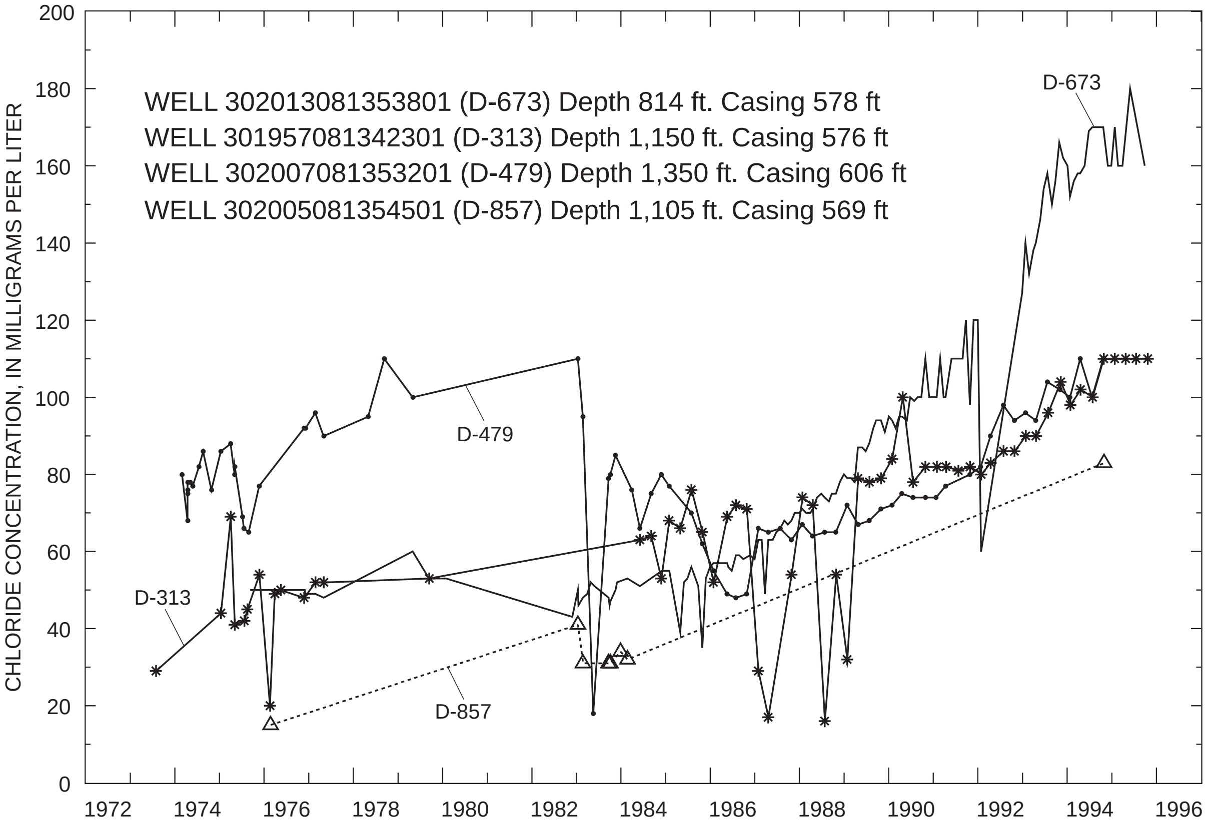

Figure 19. Chloride concentrations in water from wells in the Arlington area, 1973-96.

The shallowest well has the highest estimated transmissivity and the second highest chloride concentration. The deepest well has the lowest chloride concentration partly because it penetrates a deeper zone of relatively fresher water. This is similar to the condition at Lovegrove. The well with the highest chloride concentration, D-665, has the lowest estimated transmissivity; however, the transmissivity estimates from specific capacity tests are dependent on the physical characteristics of each individual well and the estimates could be affected by such factors as encrustation of the well or, as in the case of well D-665, leaks in the casing.

Arlington

Chloride concentrations also have increased in water from wells in the Arlington area of Jacksonville, including the wells at the city of Jacksonville's Arlington well field (figs. 19 and 20). Two of the four wells at the well field were logged during this study (fig. 21). Water from well D-857 has a chloride concentration at the wellhead of about 80 mg/L and a sample from 1,060 ft had a chloride concentration of

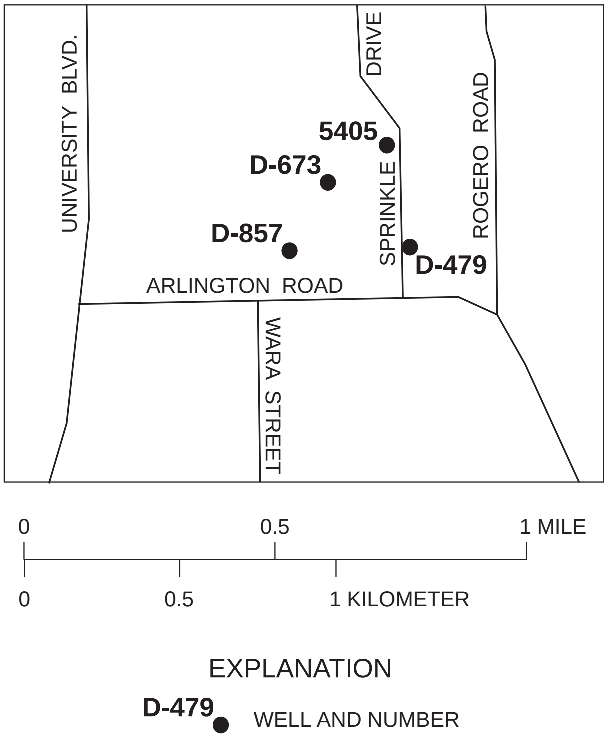

Figure 20. The Arlington well field.

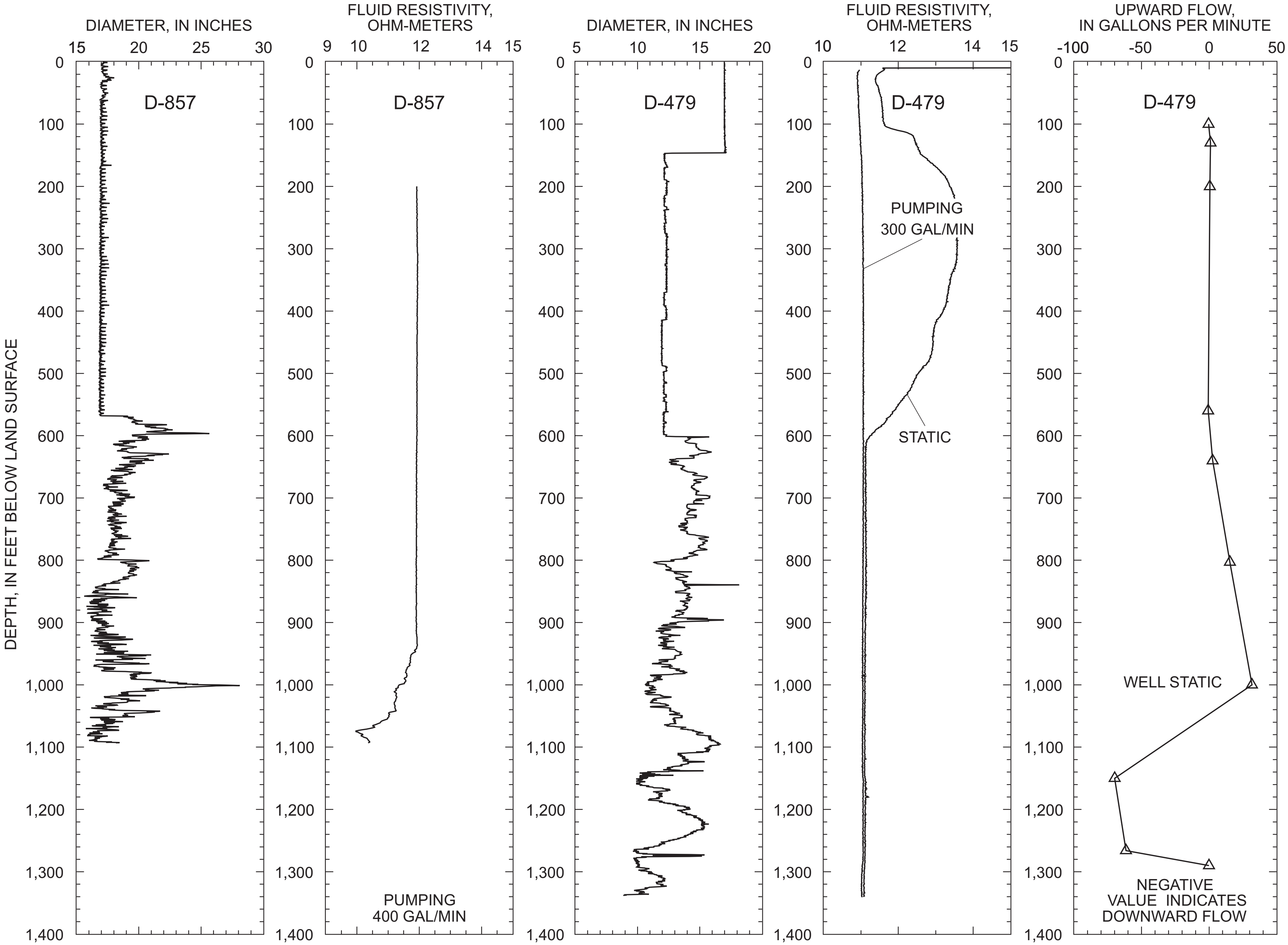

Figure 21. Geophysical logs of wells D-479 and D-857 at the arlington well field.

130 mg/L. The fluid resistivity log (fig. 21) shows that the most brackish water enters the well at 1,070 ft, although this zone contributes little flow to the well at a pumping rate of 400 gallon per minute (gal/min). The temperature log (not shown) indicates that most of the flow to the well comes from the interval of about 920 to 940 ft.

The other well logged at the Arlington well field was D-479. The fluid resistivity log for pumping conditions (fig. 21) shows no change throughout the borehole, indicating uniform water quality all the way up the well. The temperature log (not shown) indicates that little water probably is produced below a depth of about 1,280 ft. Variations in the static fluid resistivity log inside the casing are indicative of leaks in the casing. The sonic televiewer log shows solution features at depths of 971 to 972 ft, 985 to 986 ft, and 1,000 ft, with a major zone of solutioning at 1,150 to 1,160 ft (fig. 22). The heat-pulse flowmeter log of the well indicates downward flow at depths of 1,150 ft and 1,266 ft. It is unusual to measure downward flow in northeastern Florida because deeper zones in the aquifer usually have higher pressure than the overlying zones. The most likely explanation for the observed downward flow is that the solution zone at 1,150 ft is a highly productive zone that was being pumped by another well at the time the log was made. Two privately owned public supply wells, both 1,150 ft deep, are located about 0.9 mi east of the Arlington well field and are the closest wells deep enough to pump from the 1,150 ft zone.

Two test wells have also been drilled in Arlington, about 2.5 mi east of the Arlington well field. The shallower of the two wells, D-1323, has uniform water quality throughout its depth, based on the fluid resistivity log (fig. 23). The wellhead chloride concentration was 250 mg/L. The quality of the sonic televiewer images for this well is not as clear as for some of the other wells, but the images from the bottom of the well, 1,150 to 1,154 ft, could be

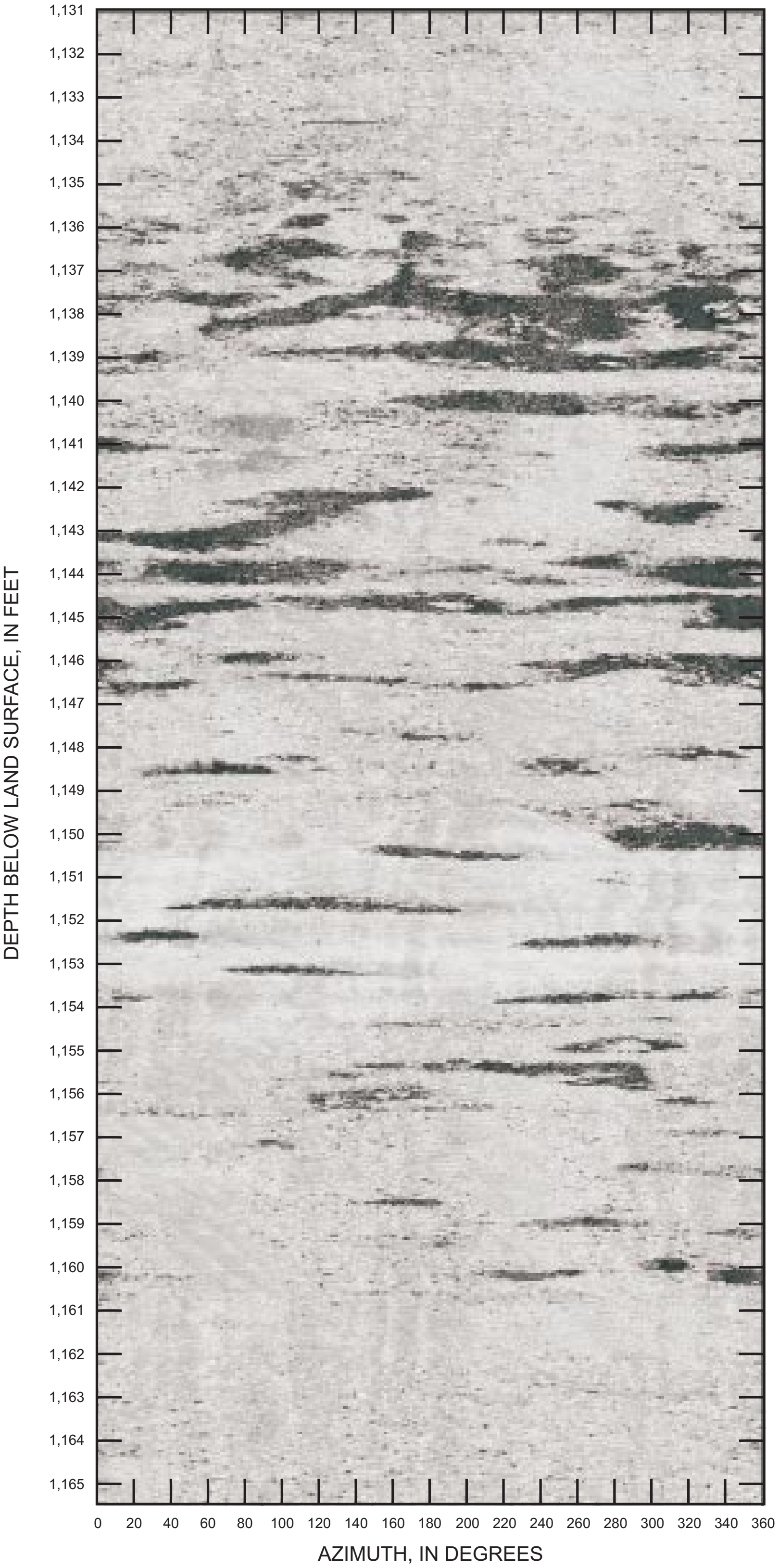

Figure 22. Sonic televiewer log of well D-479 at the Arlington well field.

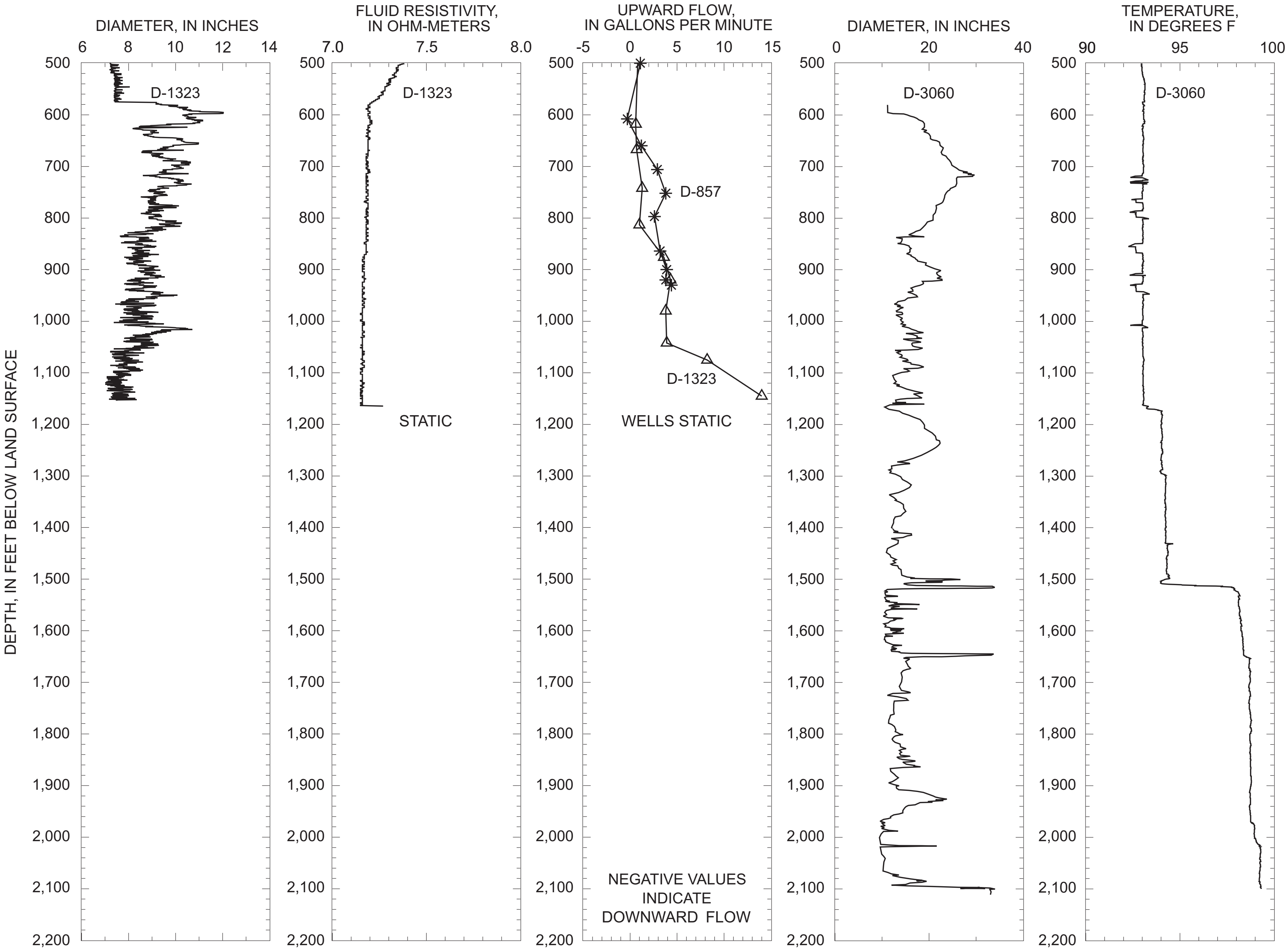

Figure 23. Geophysical logs of two test wells in the Arlington area.

solution features. Solution features are also probably at 1,066 to 1,072 ft and 1,107 to 1,110 ft. The heat-pulse flow-meter log shows that, under static conditions, water is flowing into the well bore below 1,145 ft, then flowing out into the formation between 1,030 and 1,140 ft. More water flows out from about 876 to 813 ft, indicating that the formation is very permeable.

The other test well, D-3060, is 2,112 ft deep and was drilled in 1982-83 (Brown and others, 1985). Geophysical logs were made at the time well D-3060 was drilled (fig. 23). Because the well is now cased to monitor the Fernandina permeable zone, additional logs, such as the sonic televiewer or heat-pulse flow-meter, cannot be made. When the well was drilled, drill stem chloride data averaged about 140 mg/L for depths from 700 to 1,270 ft (Brown and others, 1985, table 3). The rocks in the interval from about 1,141 to 1,151 ft were described as dolomitic limestone with recrystallized cement and moldic porosity, which could correlate with the zone of solutioning observed at a similar depth in well D-479. A zone of much fresher water, which had an average chloride concentration of abut 25 to 50 mg/L, was penetrated from 1,306 to 1,616 ft. The rocks in this interval generally had low porosity, except for two relatively small flow zones. Below a depth of about 1,640 ft, chloride concentrations increased to about 600 to 700 mg/L and very little flow was contributed to the well from that interval. The well penetrated the Fernandina permeable zone at about 2,070 ft, at which depth the drill stem chloride concentration increased to about 3,000 to 5,000 mg/L. The most recent (May 1990) water sample from a depth of 2,100 ft in the monitor well had a chloride concentration of 6,100 mg/L. No recent data for the 1,300- to 1,600-ft zone are available; however, if vertical fractures or collapse features are present in the rocks below a depth of 1,300 ft, they could provide avenues for upward movement of saline water from the deeper zones of the aquifer.

Jacksonville Beach and Atlantic Beach

Several wells in the Jacksonville Beach and Atlantic Beach areas also were logged to investigate the cause of increased chloride concentrations some of the wells (fig. 24). Logs of wells D-307, D-482, and D-484 were compared with those of well D-2386, a test well at Kathryn Abbey Hanna Park near Mayport (locations shown in fig. 5). In wells D-307, D-482, and D-484, water with higher chloride concentration enters each well through a single, highly productive fracture or solution zone near the bottom of the well (figs. 25-26). In well D-307, the flow zone is at a depth of about 1,180 ft below land surface; in well D-482, it is from about 1,120 to 1,140 ft, and in well D-484, from about 1,140 to 1,150 ft below land surface. The sonic televiewer log of well D-484 (fig. 27) shows several well-defined voids that probably are solution features. In all three wells, fresher water is present below the zone of saltier water, but the fresher zone produces little water. Most of the water produced by these wells comes from the zone of fracturing or solution. In each well, the chloride concentrations of water samples from the wellheads and from the solution zones were nearly identical: about 60 mg/L in well D-482, 220 mg/L in well D-484, and 18 mg/L in well D-1107 (table 3).

During the heat-pulse flow-meter logging of well D-484, flow in the well bore was upward throughout most of the well, but at a depth of 1,153 ft, both upward and downward flows of about 1 gal/min were measured. Downward flow was also observed at a depth of 1,187 ft. Later comparison of pumping records for well D-482 showed that well D-482 was being pumped during the time the heat-pulse flow-meter log of well D-484 was being run, except for about 10 minutes, which corresponds to the time interval when upward flow was observed at about 1,153 ft in well D-484. Pumping from the highly productive solution zone at about the 1,150 ft depth apparently almost immediately affects nearby wells tapping the same zone. This is the same effect observed in the wells in the Arlington well field. No such effect was observed in well D-307, probably because no nearby wells also tap the solution zone. In all three wells, most of the flow from the solution zone flows out into the formation between depths of about 550 and 650 ft and the bottom of the casing under shut-in conditions because pressure in the deeper zones generally is higher than the upper zones, except when the effects of pumping from nearby wells reduces pressure in the pumped zone. Well D-1107 is shallower than the other wells logged in the beach area and does not penetrate a zone of brackish water. The heat-pulse flow-meter log for the well (fig. 26) is similar to that fro well D-307, although the change from a tight to a permeable formation between 650 to 660 ft in well D-1107 is much more definitive than the change between 650 to 730 ft in well D-307.

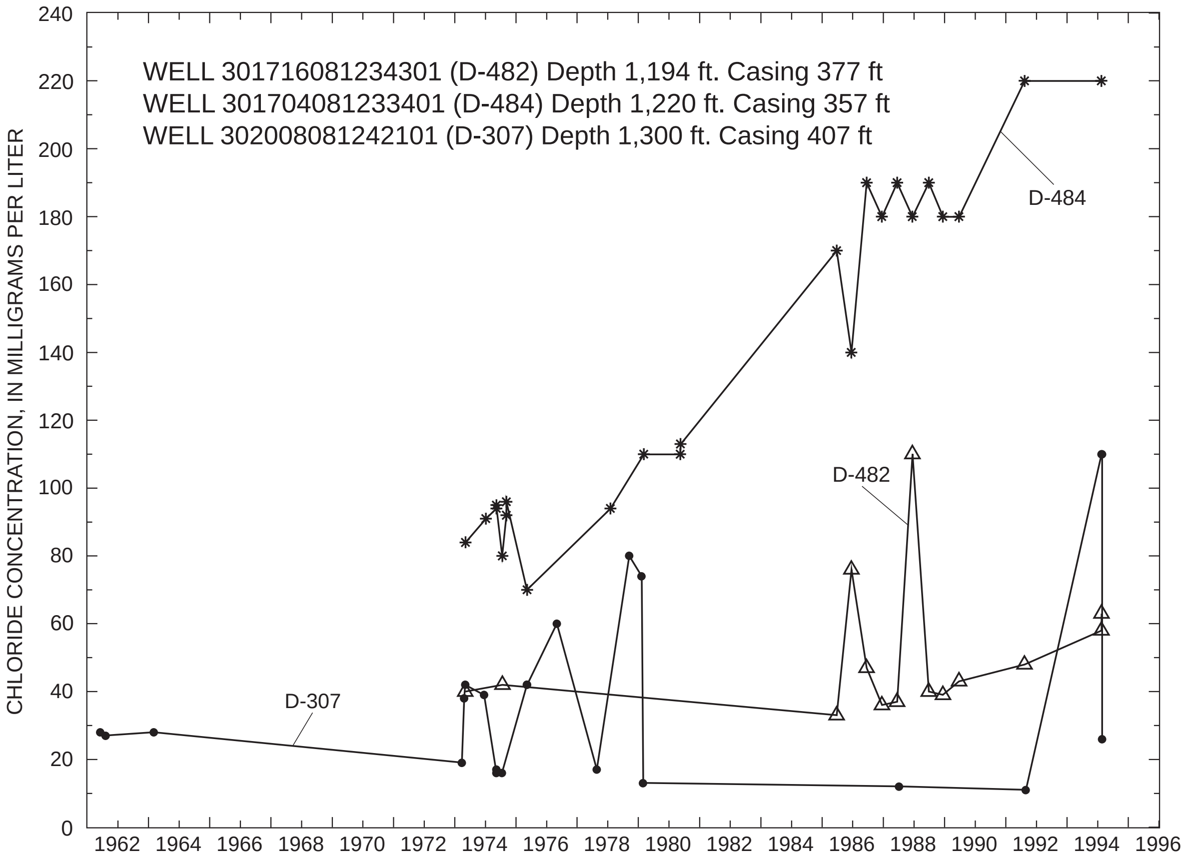

Figure 24. Chloride concentrations in water from wells at Jacksonville Beach and Atlantic Beach, 1962-96.

Data collected during the drilling of a deep test well at Hanna Park (D-2386) in 1980-81 provide additional information about the vertical distribution of chloride concentration in the Jacksonville Beach area and about the hydraulic characteristics of the Lower Floridan aquifer in that area. Drill stem chloride concentrations were about 10 mg/L until a depth of 1,184 ft, then increased to about 60 mg/L from 1,194 to 1,309 ft. From 1,309 ft to 1,906 ft chloride concentrations decreased to about 30 to 35 mg/L, then increased to about 600 mg/L at 1,926 ft. The fluid resistivity log for the interval 400 to 1,400 ft (made at the time the well was drilled) shows a gradually decreasing trend from the top to the bottom of the interval (fig. 26). This indicates increasing fluid conductivity, and usually, chloride concentration. Flowmeter logs of the well indicated an increase in flow to the well of about 700 gal/min at 1,190 ft, roughly corresponding to a flow zone of fresher water, as indicated by the fluid resistivity log. The water from this zone dilutes the more brackish water from below. This zone could also correspond to the productive solution zone encountered in wells D-482, D-484, and D-307. Well D-2386 penetrated the Fernandina permeable zone at a depth of about 2,000 ft. The chloride concentration at that depth was about 3,000 mg/L in 1981. In 1990, a sample from the bottom zone of the monitor well had a chloride concentration of 5,800 mg/L.

Another test well, D-3841 on Ft. George Island (location shown in fig. 5), also was logged. In that well, two solution features that are well-defined on both the caliper (fig. 28) and sonic televiewer (fig. 29) logs at depths from 1,228 to 1,234 ft are contributing fresher water to the well. Below that depth the chloride concentration of the water increases. The heat-pulse flow-meter log shows the presence of a very productive zone from about 820 to 900 ft below land surface which is contributing most of the flow to the well. The water from that zone is cooler and fresher than the water above and below it. The chloride concentration of water at the wellhead was 17 mg/L (table 3), but a sample from the zone with lower fluid resistivity near the bottom of the well could not be obtained.

Also logged was well D-2363, about 5.5 mi southwest of well D-3841 (location shown in fig. 5). In that well, a slight but measurable increase in the resistivity of the water (indicating a probable decrease in chloride concentration) corresponded with a fracture at a depth of 1,030 ft (fig. 28). The heat-pulse flow-meter log indicates that much of the flow to the well enters below a depth of 1,000 ft. Water leaves

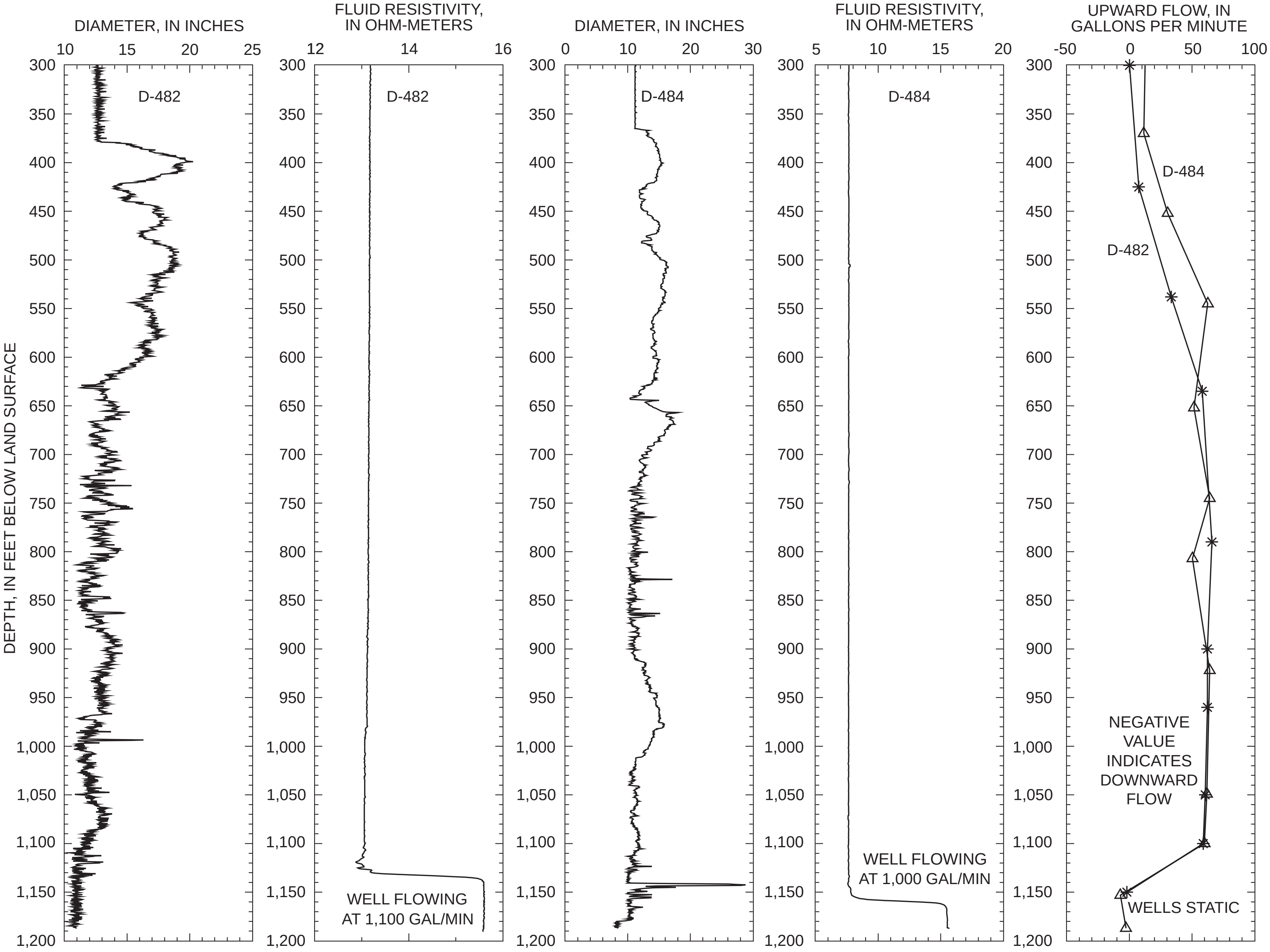

Figure 25. Geophysical logs of wells D-482 and D-484 at Jacksonville Beach.

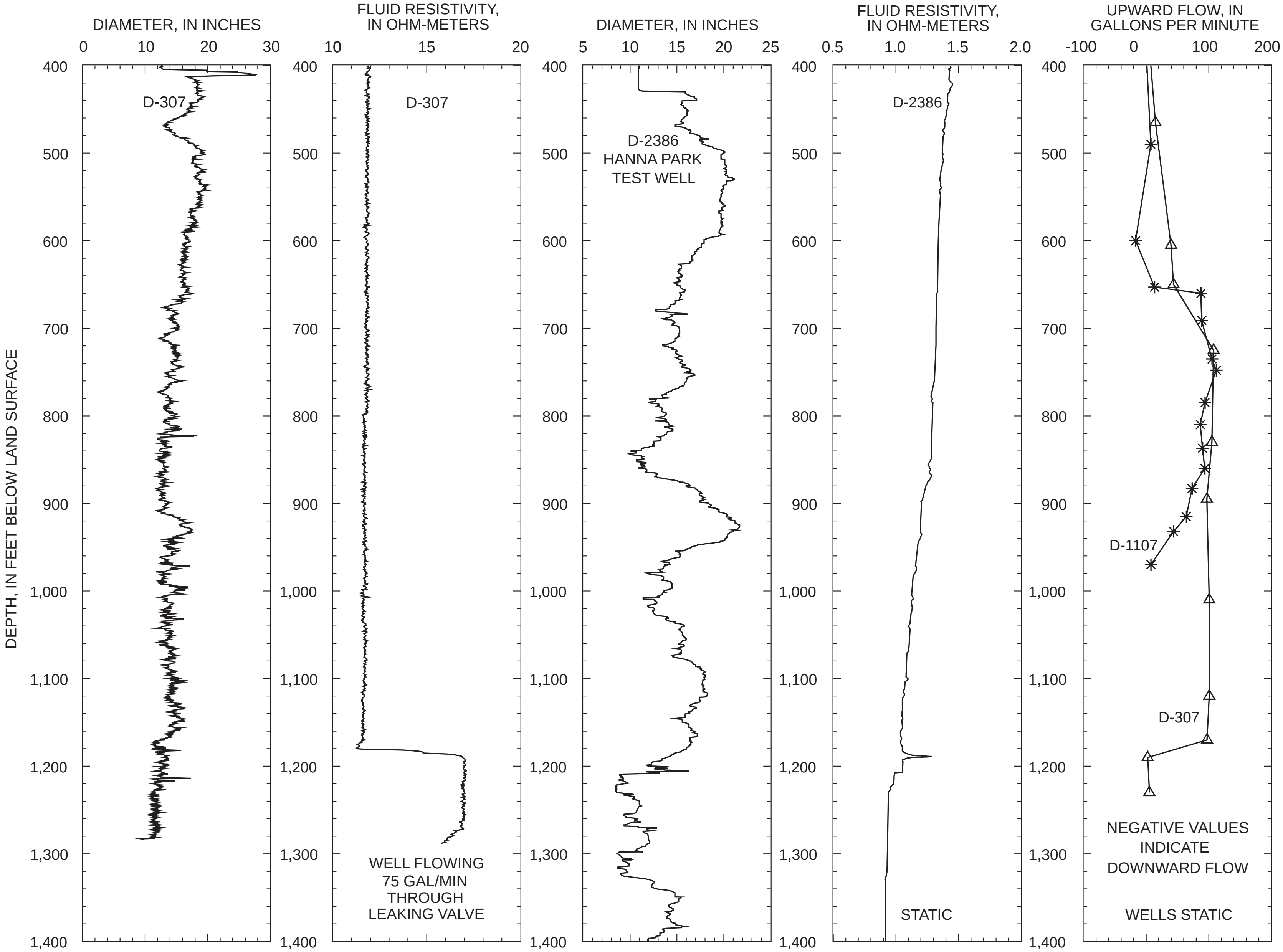

Figure 26. Geophysical logs of well D-307, D-2386, and D-1107 near Jacksonville Beach.

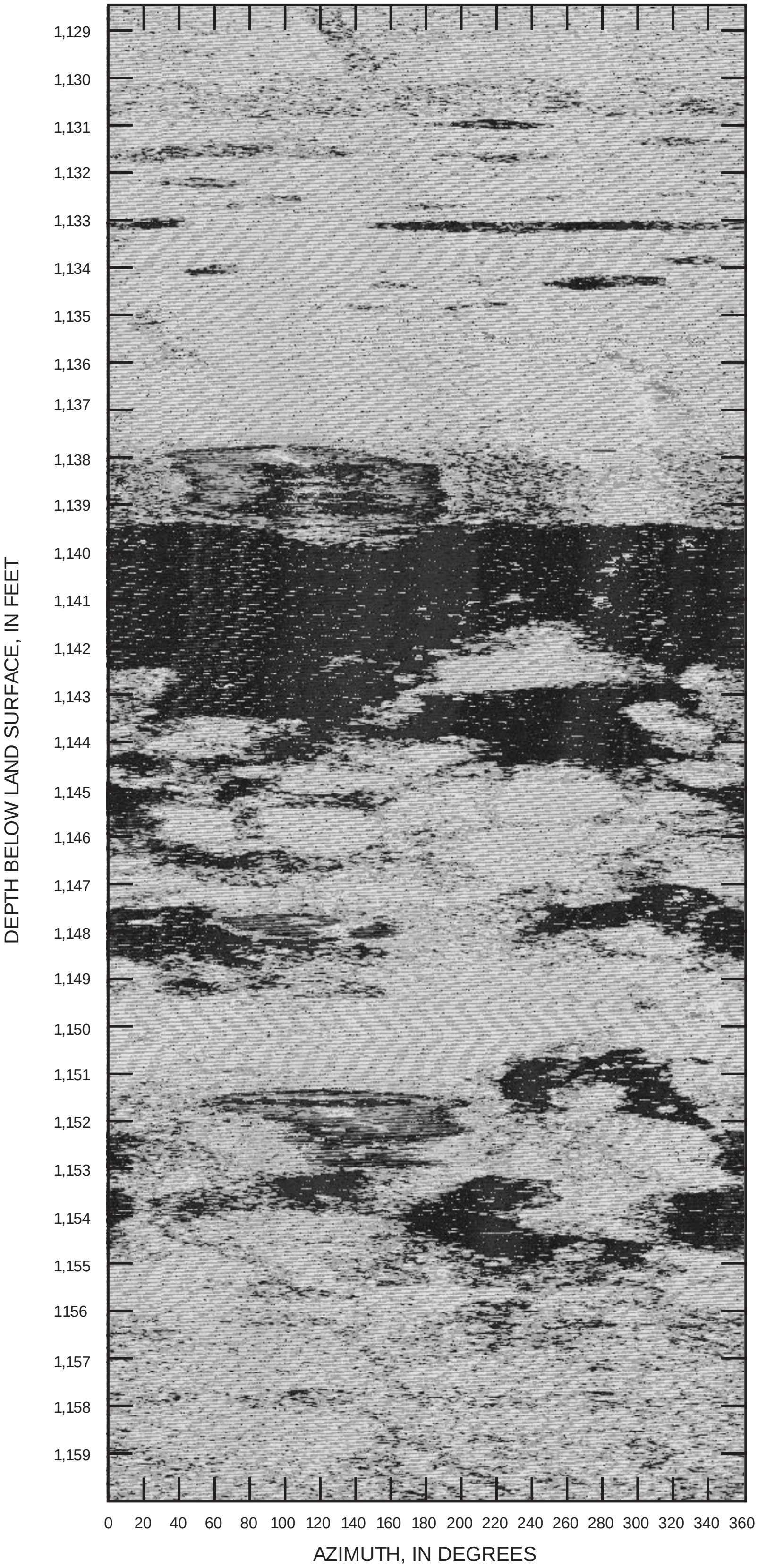

Figure 27. Sonic televiewer log of well D-484 at Jacksonville Beach.

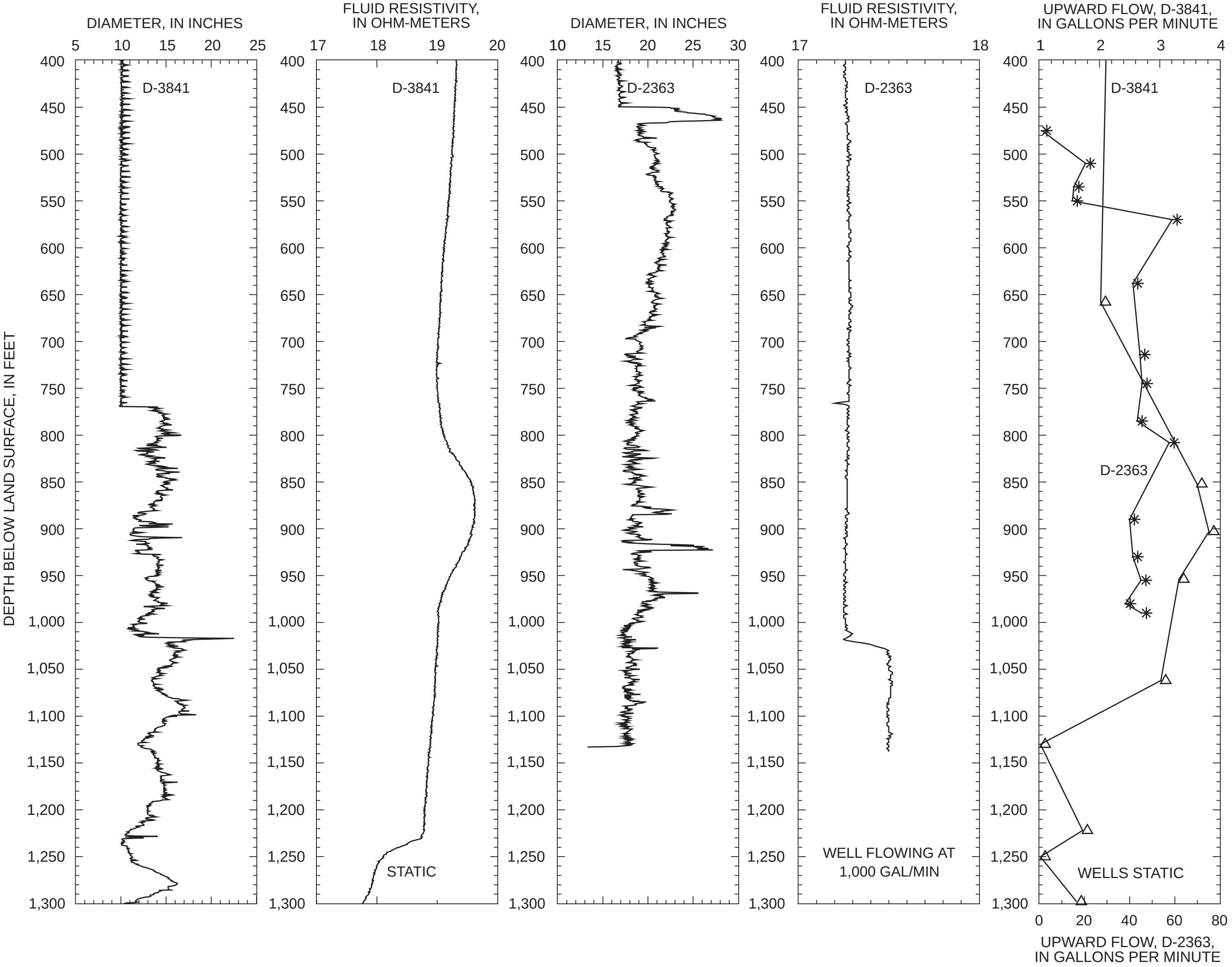

Figure 28. Geophysical logs of well D-3841 at Ft. George Island and well D-2363 in eastern Duval County.

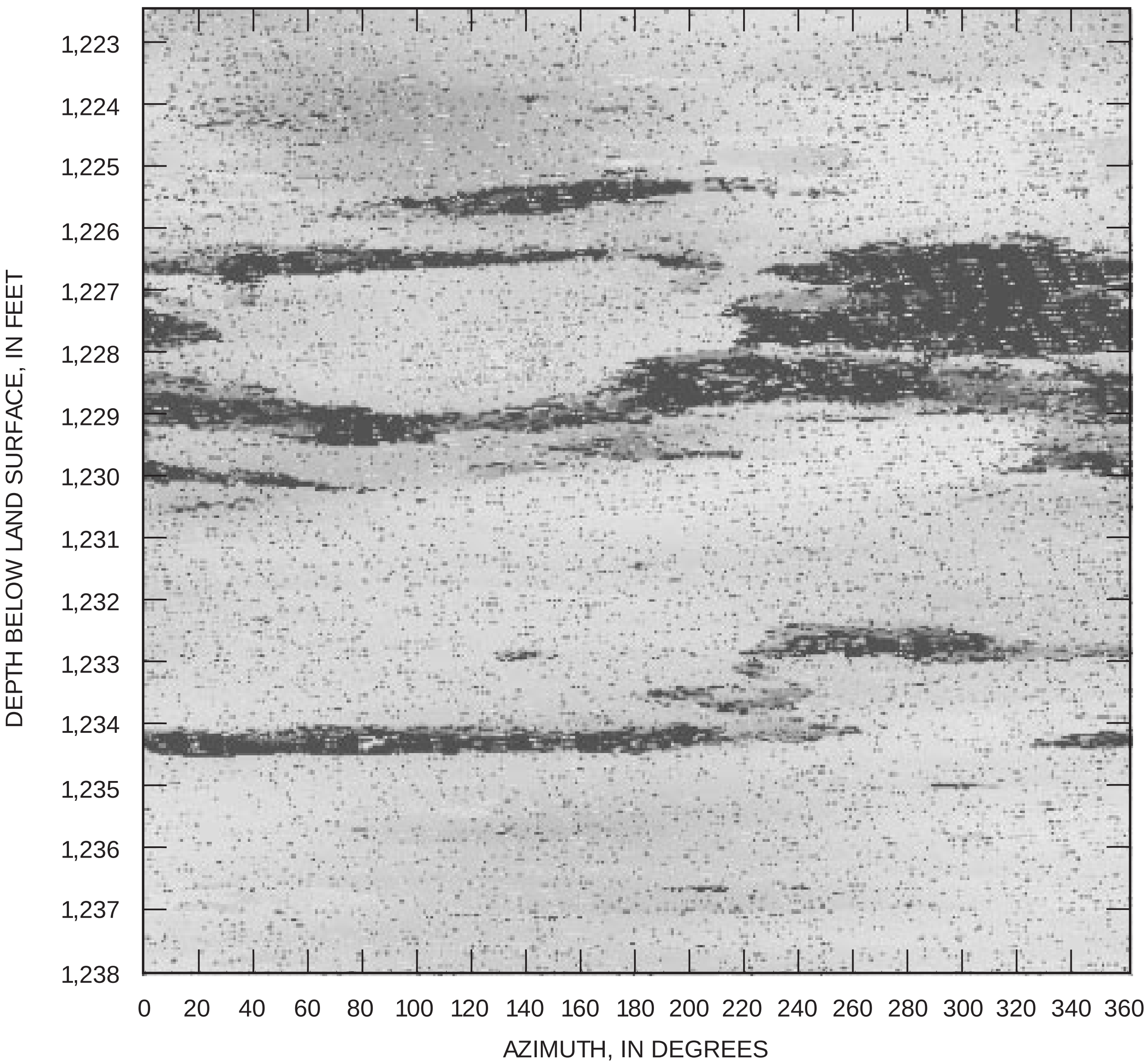

Figure 29. Sonic televiewer log of well D-3841 at Ft. George Island.

the well into a permeable zone between about 550 and 620 ft. Under shut-in conditions, most of the water flowing up the borehole flows out into a highly transmissive zone just below the bottom of the casing. Well D-2363 does not intercept a zone containing higher chloride water, probably because it is shallower than some of the other wells logged. The chloride concentrations of water from the wellhead and from depths of 1,000 and 1,040 ft were about the same (table 3). The difference between these concentrations (7 mg/L and 18 mg/L, respectively) is not considered significant. The sample from 1,040 ft had slightly lower dissolved sulfate and dissolved strontium concentrations, which could be related to a decrease of sulfate minerals such as celesite in the aquifer matrix.

Southeastern Jacksonville

The geophysical logs of several wells in the southeastern part of Jacksonville are indicative of the variations in hydrogeologic conditions in the area. The wells logged included D-291, D-534, D-536, D-3846, and D-3847 (locations shown in fig. 5). Well D-291 has been unused for about 20 years. Wells D-534 and D-536 are public supply wells; D-3846 and D-3847 are public supply wells drilled in 1994 which were logged during drilling.

Well D-291 yields water with a chloride concentration of 99 mg/L at the wellhead. A sample from a depth of 1,230 ft had a chloride concentration of 130 mg/L. The fluid resistivity log of the well (fig. 30)

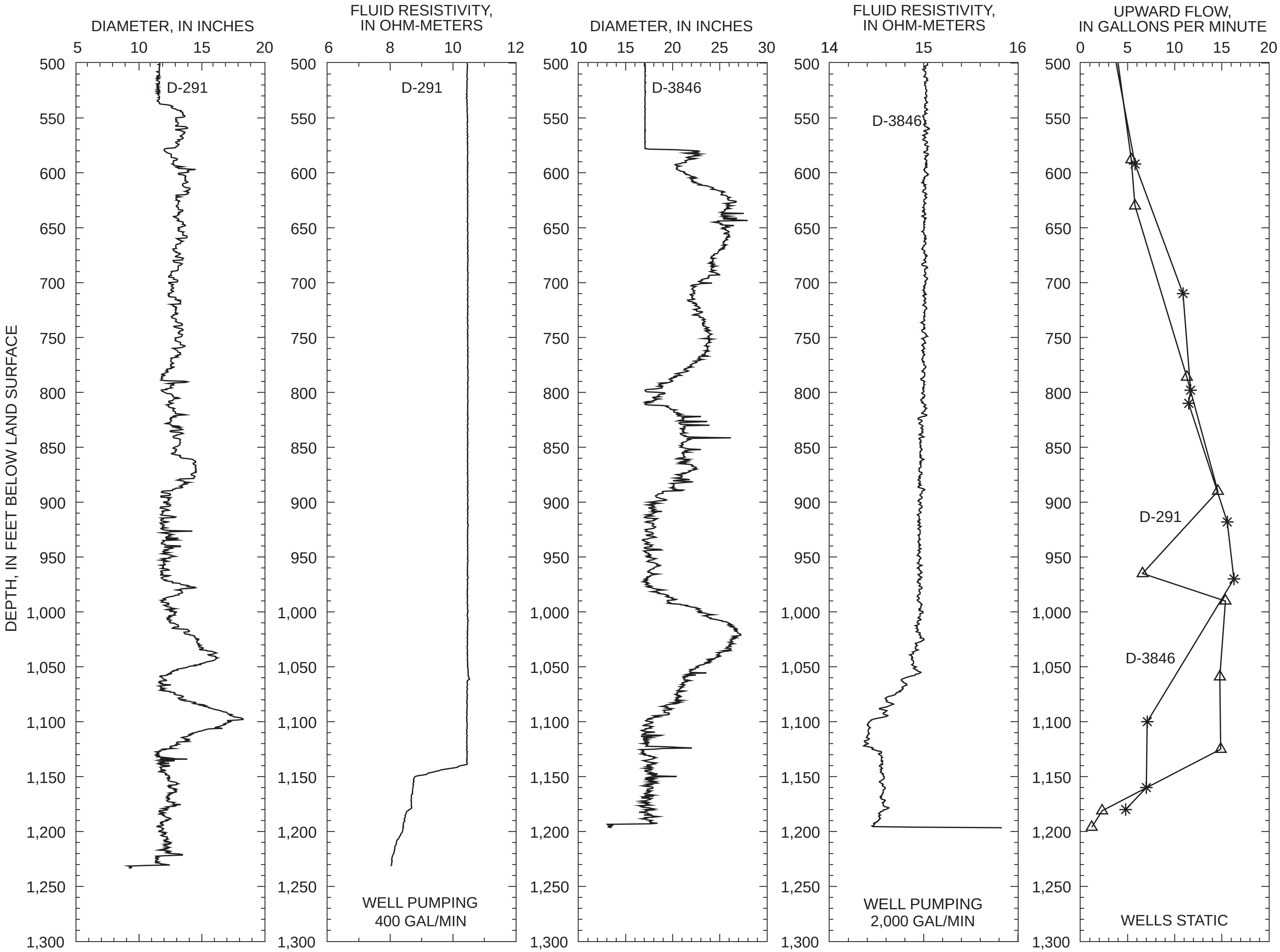

Figure 30. Geophysical logs of wells D-291 and D-3846 in southeastern Jacksonville.

indicates that a major change in water quality from fresh to saltier takes place from about 1,140 to 1,150 ft below land surface. Another, more subtle, change takes place at 1,180 ft. The caliper log shows the presence of fractures or solution features from about 1,130 to 1,140 ft, just above the water-quality change. The solution zone, which contains fresher water, contributes most of the flow to the well at the pumping rate tested. The sonic televiewer log shows some solution features at 967 to 969 ft but these are not reflected on the caliper log. The sonic televiewer also indicates a zone of solutioning at 1,127 to 1,128 ft and fracturing at 1,134 to 1,138 ft. The temperature log shows that cooler, fresher water is entering the well bore at about 1,138 ft. Below that depth the water is warmer and more brackish. The sonic televiewer log (fig. 31) also shows a feature from about 1,060 to 1,069 ft that could be a vertical fracture or solution feature. This depth corresponds to a flow zone of slightly cooler and slightly fresher water, based on the fluid resistivity and temperature logs. A focused electric (guard) log was also run on well D-291. The guard log indicates the presence of relatively thin, highly resistive zones at 1,060 and 1,130 ft. These zones of high resistivity could correspond to a thin, very tight dolomitic zone of low porosity.

The heat-pulse flow-meter log for well D-291 shows that under static conditions, water is flowing into the well between 1,181 and 1,125 ft. Flow in the well bore is gradually lost to the permeable formation above 890 ft; therefore, most of the water produced by the well probably is coming from the zone at about 1,140 ft below land surface, just above the zone with more brackish water. No fresher water-bearing zone below the saltier zone was penetrated in this well.

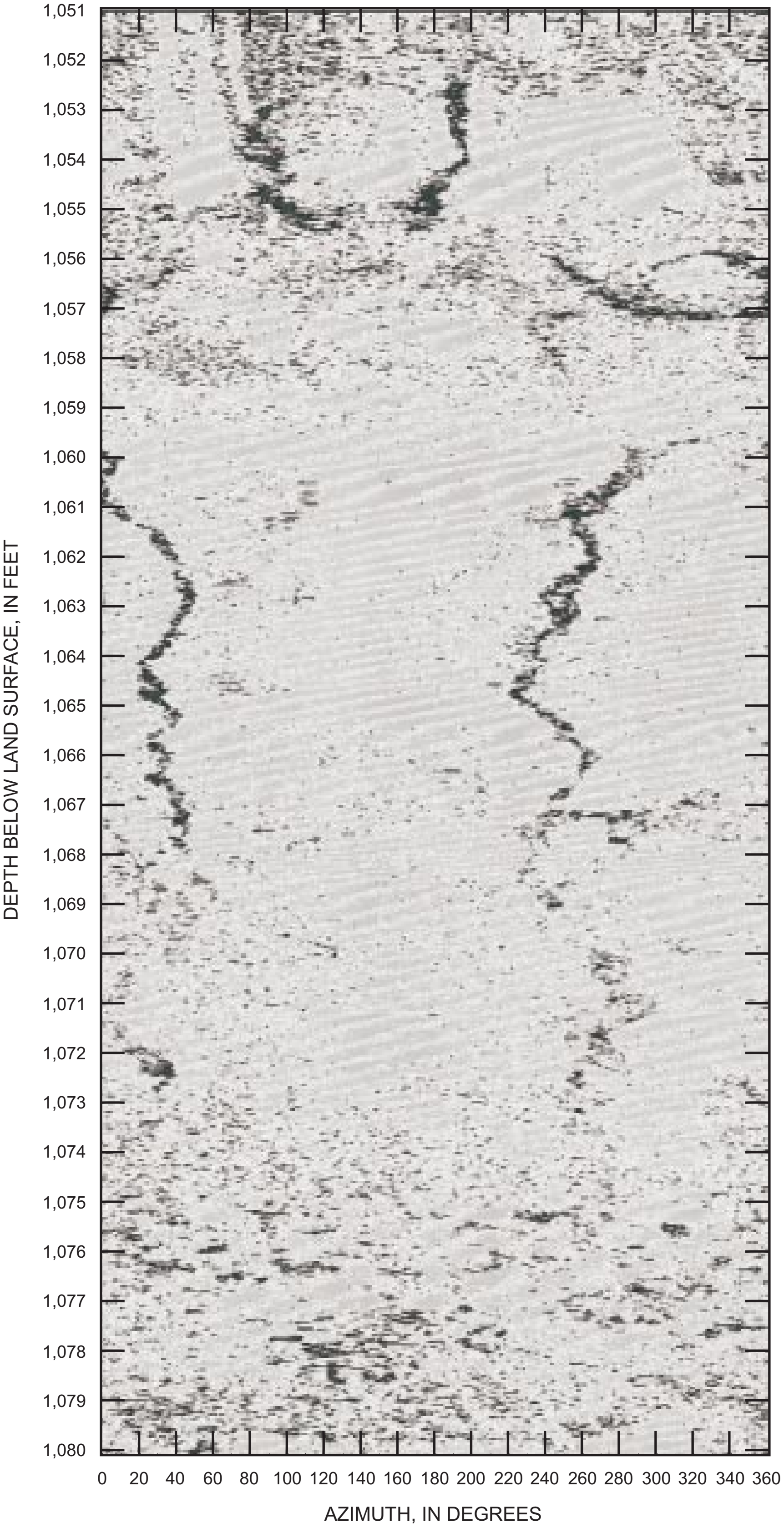

Figure 31. Sonic televiewer log of well D-291.

One of the recently drilled public supply wells logged was D-3846, which produced water with a chloride concentration of 17 mg/L and a sulfate concentration of 170 mg/L at the wellhead. At a depth of 1,110 ft the chloride concentration was 18 mg/L and the sulfate concentration was 180 mg/L (table 3). The fluid resistivity log (fig. 30) shows a zone of relatively higher chloride concentration at about 1,110 to 1,130 ft. A zone of fresher water was penetrated at the bottom of the well. The heat-pulse flow-meter log shows that some flow enters the well below 1,160 ft, but from about 1,160 to 1,100 ft, little water enters the well bore. Most of the flow to the well enters between depths of about 970 to 1,100 ft below land surface. Under shut-in conditions, most of the water in the well bore flows out into the soft, cavernous formation just below the bottom of the casing.

Well D-534 was reported to be 1,000 ft deep, but because the well bore is very rough and contains many ledges and constrictions, it could not be logged past a depth of 923 ft. The chloride concentration of water at the wellhead is 32 mg/L and a sample from 905 ft had a chloride concentration of 44 mg/L.

Well D-536 had perhaps the most complex combination of flow zones of all the wells logged during this study. The caliper log (fig. 32) shows a zone of several fractures or solution zones from about 1,040 to 1,060 ft below land surface. The fracture at 1,042 ft produces water that is slightly cooler and fresher. The feature at 1,050 ft produces warmer water with higher chloride concentration. This fracture also probably produces most of the flow to the well. The zone at 1,060 ft contains fresher, warmer water, although it probably contributes little flow to the well. The sonic televiewer log of the zone from 1,040 to1,060 ft is shown in figure 33. The feature at 1,042 ft probably is a fracture. The feature at 1,049 ft could be a solution feature and the one at 1,050 ft could be a fracture. At 1,060 ft the feature probably was caused by solution processes. Near the bottom of the well the water gets more brackish again but little flow is produced below a depth of about 1,077 ft. The wellhead chloride concentration is 220 mg/L and the sulfate concentration is 300 mg/L. At a depth of 1,059 ft the chloride concentration is 200 mg/L and the sulfate is 330 mg/L. At 1,095 ft the chloride concentration is 94 mg/L and the sulfate is 350 mg/L. This well has the hottest water temperature measured in any well in northeastern Florida; the temperature at the bottom of the well is 32.5 ^{o}C (about 91^{o}F). The water from this well also had the highest dissolved strontium concentration (8,000 micrograms per liter (μg/L)) measured in Duval County. The alternating fresher and saltier flow zones penetrated by this well could be the result of a vertical sequence of paleokarst features with different sources of water. The geophysical logs show the depth of fractures or solution zones but not the orientation in the borehole of such features; therefore, the features bearing the differing water types might intersect the borehole from different directions.

A comparison of the logs of wells D-536 and D-3847 (fig. 32) indicates obvious differences in the hydrogeology at the two well locations. The caliper log of well D-3847 indicates that the formations apparently are more uniform than those penetrated by well D-536. D-3847 has only one major zone where the strata are soft and cavernous (just below the bottom of the casing), although another thinner zone was penetrated at a depth of about 600 ft. The water quality changes little from top to bottom. Samples were collected at the wellhead, 1,040 ft, 1,180 ft, and 1,220 ft (table 3). All had chloride concentrations of about 9 mg/L and sulfate concentrations of about 100 mg/L. The fluid resistivity log, which was set to a very sensitive scale, shows minor fluctuations in water quality. The slightly fresher zone at 1,080 ft corresponds to an increase in water temperature, as does the slight decrease in fluid resistivity at 1,180 ft, indicating that those intervals contribute flow to the well. These intervals may contain fractures or solution zones that are not as apparent in a large-diameter well as in a smaller diameter well. The heat pulse flowmeter log indicates that most of the flow to the well is produced from about 1,104 to 965 ft below land surface. Under shut-in conditions, nearly all of the water flows out into the cavernous zone just below the bottom of the casing.

Other Areas

No obvious geographic patterns of water-quality deterioration could be discerned based on the wells logged in Duval County. The areas of poorer (more mineralized) water quality also do not coincide with the traces of the inferred faults (fig. 8). Water-quality deterioration (increased mineralization) might be associated with some of the mapped paleokarst features, but in other areas no such features have been detected. Generally, water with higher chloride concentrations apparently is produced from well-defined fracture or solution zones in individual wells; however, the absence

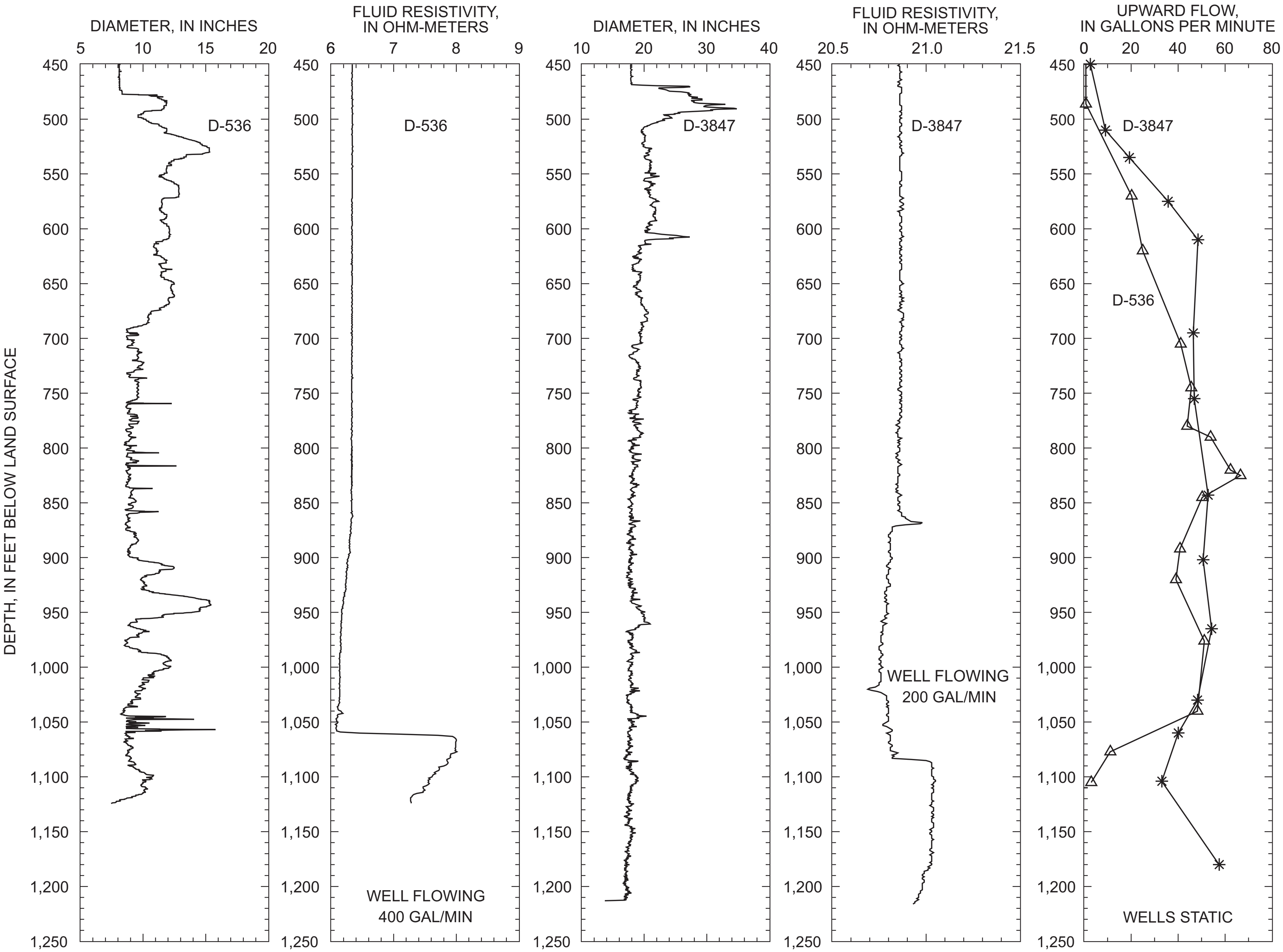

Figure 32. Geophysical logs of wells D-536 and D-3847 in southeastern Jacksonville.

of well-defined fractures or solution zones in a well may not preclude future deterioration of water quality. Some of the recently drilled wells that did not penetrate zones of fractures or solution features have not been pumped for long periods, so it may be premature to conclude that chloride concentrations in water from the wells will not increase with time. No chloride concentration increases have been detected in some deep wells in Duval County that have been pumped for long periods of time. Several such wells were logged during this study and existing logs of other wells also were evaluated to make comparisons with wells in which water quality has deteriorated. These wells include D-53A, D-90, D-101, D-1095, and D-2223 (locations shown in fig. 5).

Well D-53A was drilled to a depth of 1,037 ft in 1939 and was deepened to 1,286 ft in 1959 to improve the yield of the well. Transmissivity, estimated from specific capacity of the well, is about 5,500 ft^2/d (table 2). The caliper log shows a large fracture or solution feature at a depth of about 1,220 ft (fig. 34). The electric log also shows a highly resistive horizon at that depth that could be a fluid-filled fracture. Flow logs indicate that about 25 percent of the flow to the well comes from that interval, so the feature likely is a productive fracture or solution zone. Chloride concentrations in the well in 1994 ranged from 15 to 24 mg/L and no increases with time have been observed.

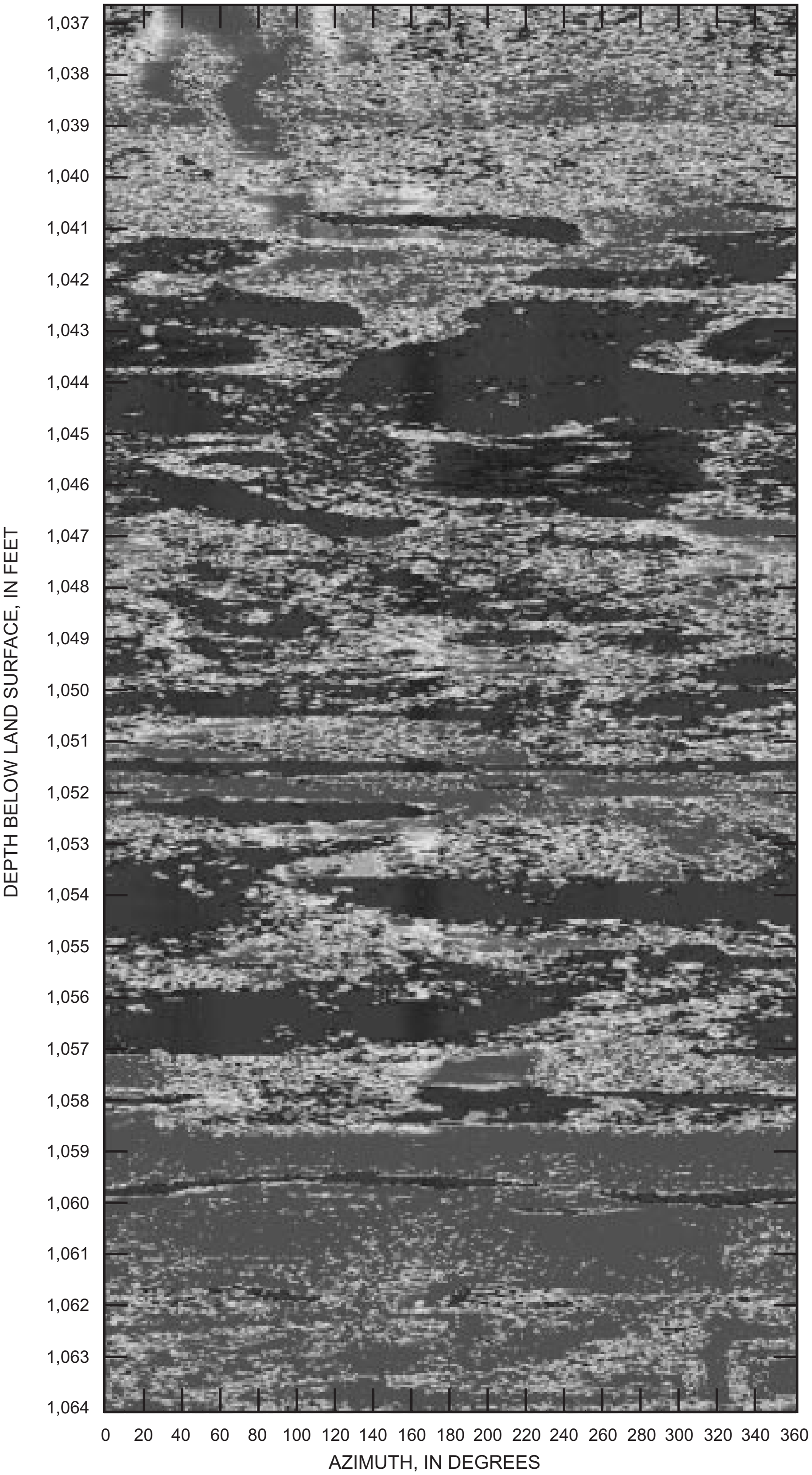

Figure 33. Sonic televiewer log of well D-536.

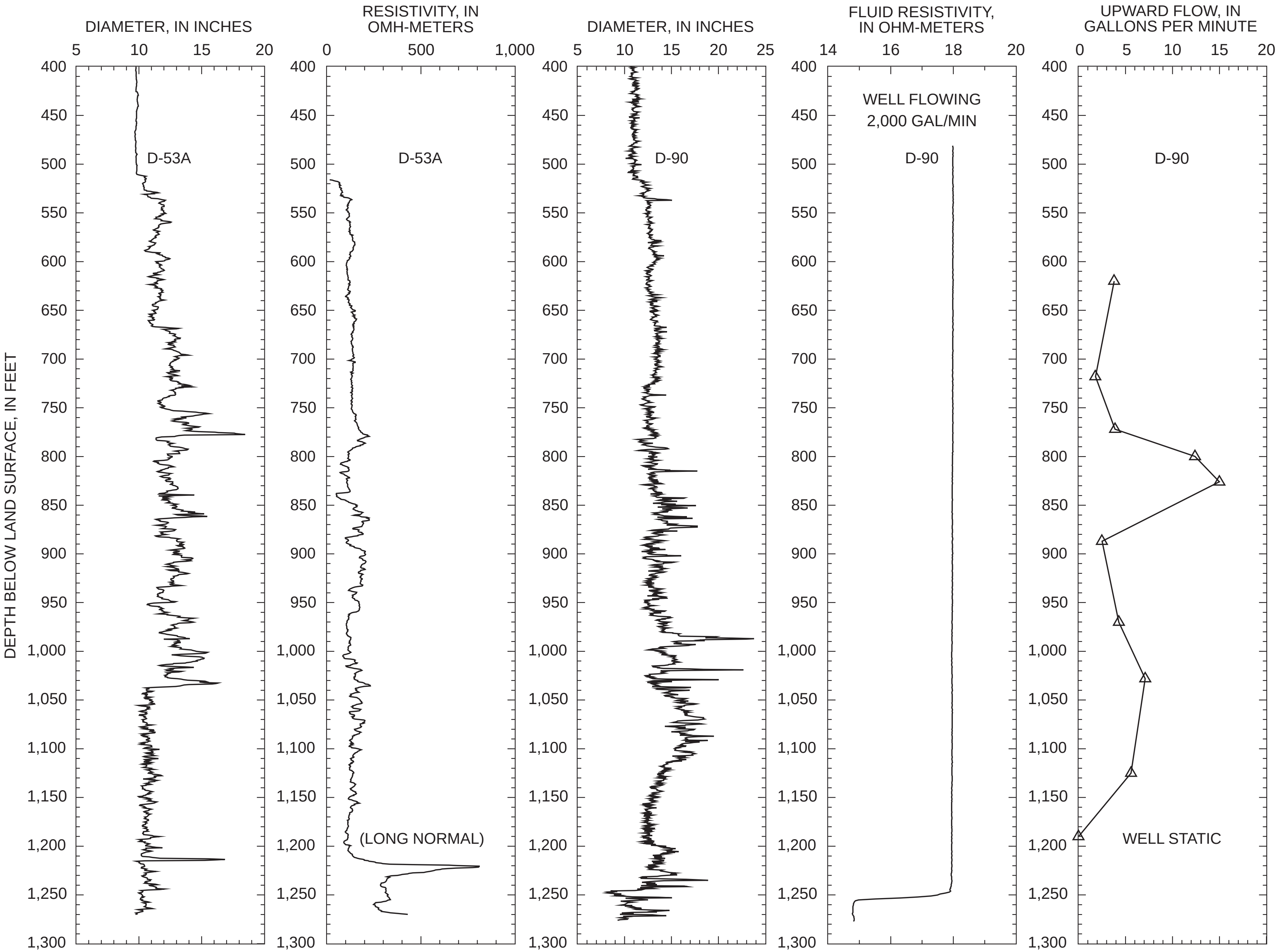

Figure 34. Geophysical logs of wells D-53A and D-90 in Jacksonville.

Another area where no increases in chloride concentrations have been observed despite long-term pumping is in downtown Jacksonville at the Main Street well field. Well D-90 was logged and sampled during this study. The wellhead chloride concentration was 18 mg/L and the sulfate concentration was 74 mg/L. A sample from a depth of 1,270 ft had a chloride concentration of 15 mg/L and a sulfate concentration of 160 mg/L. The fluid resistivity log (fig. 34) shows a change in water quality at 1,250 ft. The temperature log under flowing conditions shows that zone contains cooler water, then the water gets warmer below that depth. The decrease in the resistivity of the water at 1,250 ft could be caused by an increase in sulfate rather than in chloride concentration. The higher strontium concentration in water from 1,250 ft as well as the higher sulfate concentration probably reflects a difference in the mineralogy of the aquifer matrix. The sonic televiewer log (figs. 35-56) indicates solution features at 998 ft, 1,016 ft, 1,232 ft, and 1,250 ft, all of which also are apparent on the caliper log. The heat-pulse flow-meter log indicates no intraborehole flow at 1,190 ft, so under shut-in conditions, the solution features at 1,250 ft and 1,232 ft apparently do not contribute flow. Flow is gained between 1,190 and 1,028 ft, then lost to permeable

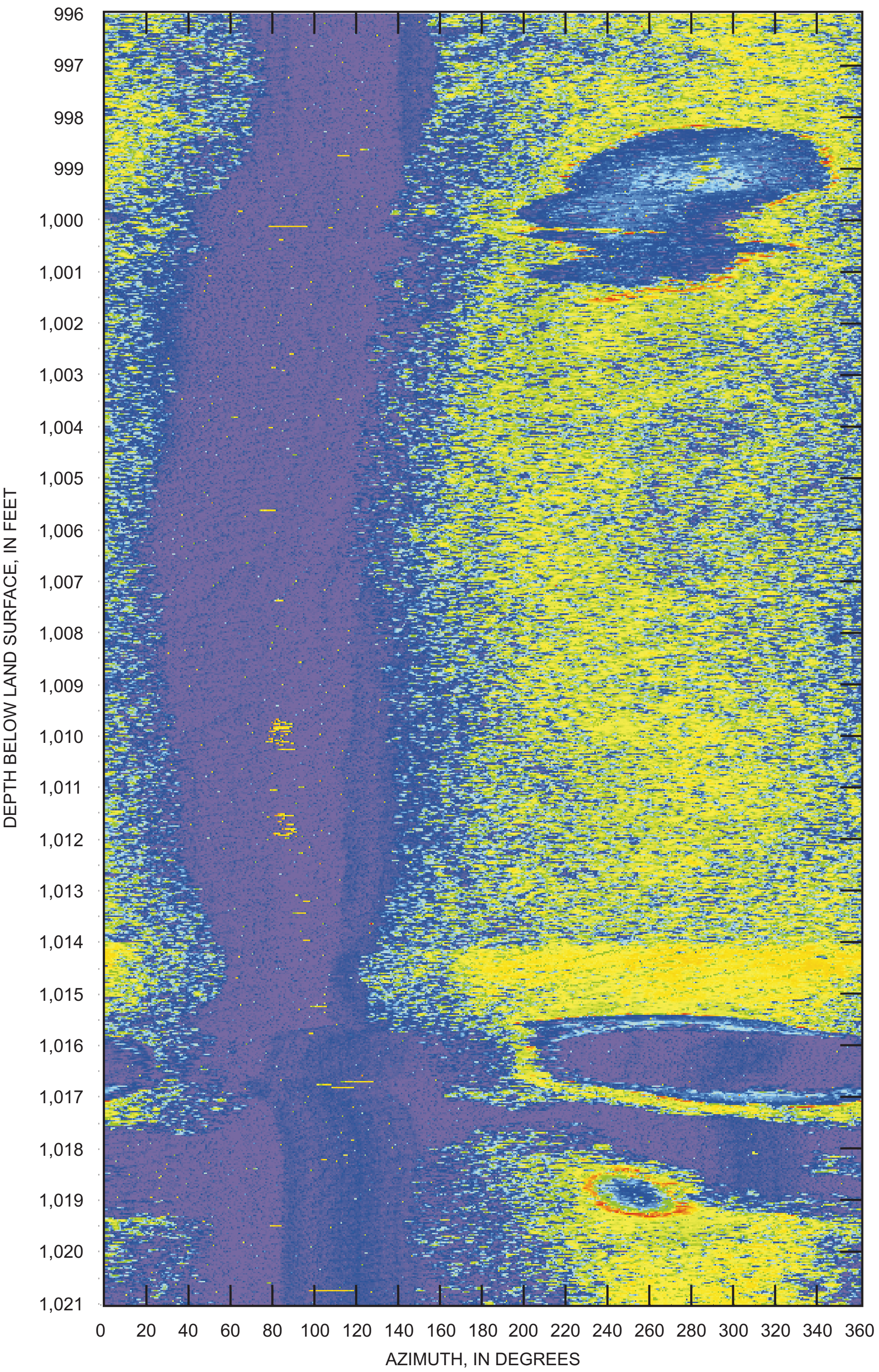

Figure 35. Sonic televiewer log of well D-90 at the Main Street well field (at depth interval 996 to 1,021 feet.

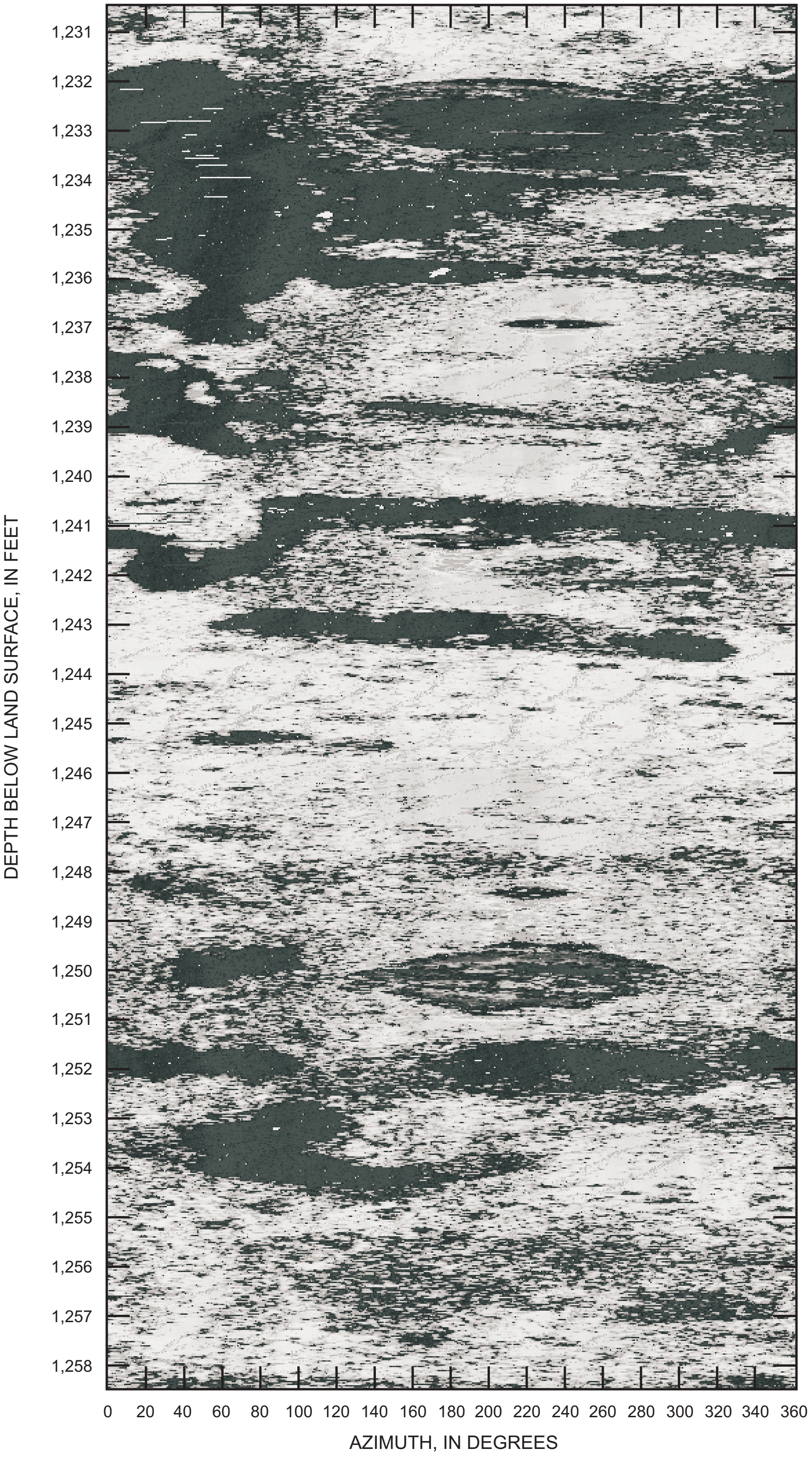

Figure 36. Sonic televiewer log of well D-90 at the Main Street well field (at depth interval 1,231 to 1,258 feet).

formations between 900 and 1,000 ft. Most of the flow to the well comes from below 1,000 ft and the remainder from the interval 850 to 1,000 ft.

Another well logged was D-101 at the McDuff well field (location shown in fig. 5). The caliper log (fig.37) shows fracture or solution zones at depths of about 940 ft, 1,100 ft, and 1,245 ft. The chloride concentration of a water sample from the wellhead was 9.9 mg/L and the sulfate concentration was 140 m/L (table 3). The fluid resistivity log showed only a slight change in water quality with depth (fig. 37), so no samples were collected from other depths in the well. The heat-pulse flow-meter log shows that under shut-in conditions, most of the flow enters the well below 1,210 ft, although there is also a slight increase in flow between 970 and 1,070 ft. Intra-borehole flow is lost into permeable zones from 600 to 800 ft below land surface.

Well D-1095 (location shown in Fig. 5) also showed no change in water quality throughout the borehole (fig. 37). The wellhead sample and water samples from depths of 940 ft and 1,200 ft all had chloride concentrations of 13 mg/L and sulfate concentrations between 86 and 88 mg/L (table 3). Most of the water enters the well near the bottom. Under static conditions, water flows into the formation in the interval from about 820 to 880 ft and in the large-diameter zone at a depth of about 960 to 980 ft. Below about 980 ft there is a slight freshening of the water. The quality of the sonic televiewer log record for this well is poor. A possible solution feature was noted at a depth of 1,196 ft but the feature was not apparent on the caliper log (fig. 38). The sonic log also shows many alternating layers of hard and soft rock. A possible vertical fracture or solution feature similar to the one in well D-291 was observed at 793 to 795 ft, but it was not apparent on the caliper log.

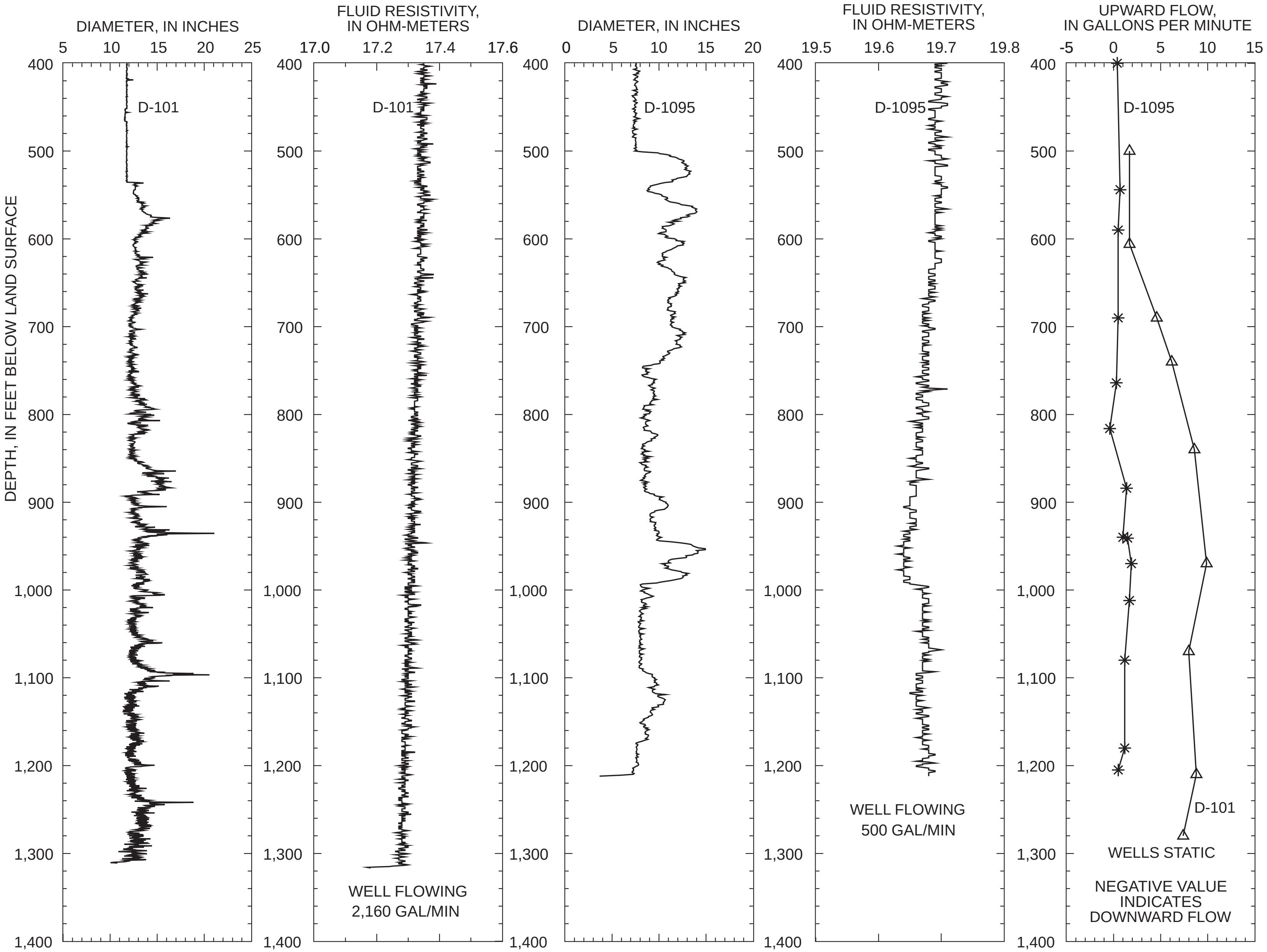

Figure 37. Geophysical logs of wells D-101 and D-1095 in Jacksonville.

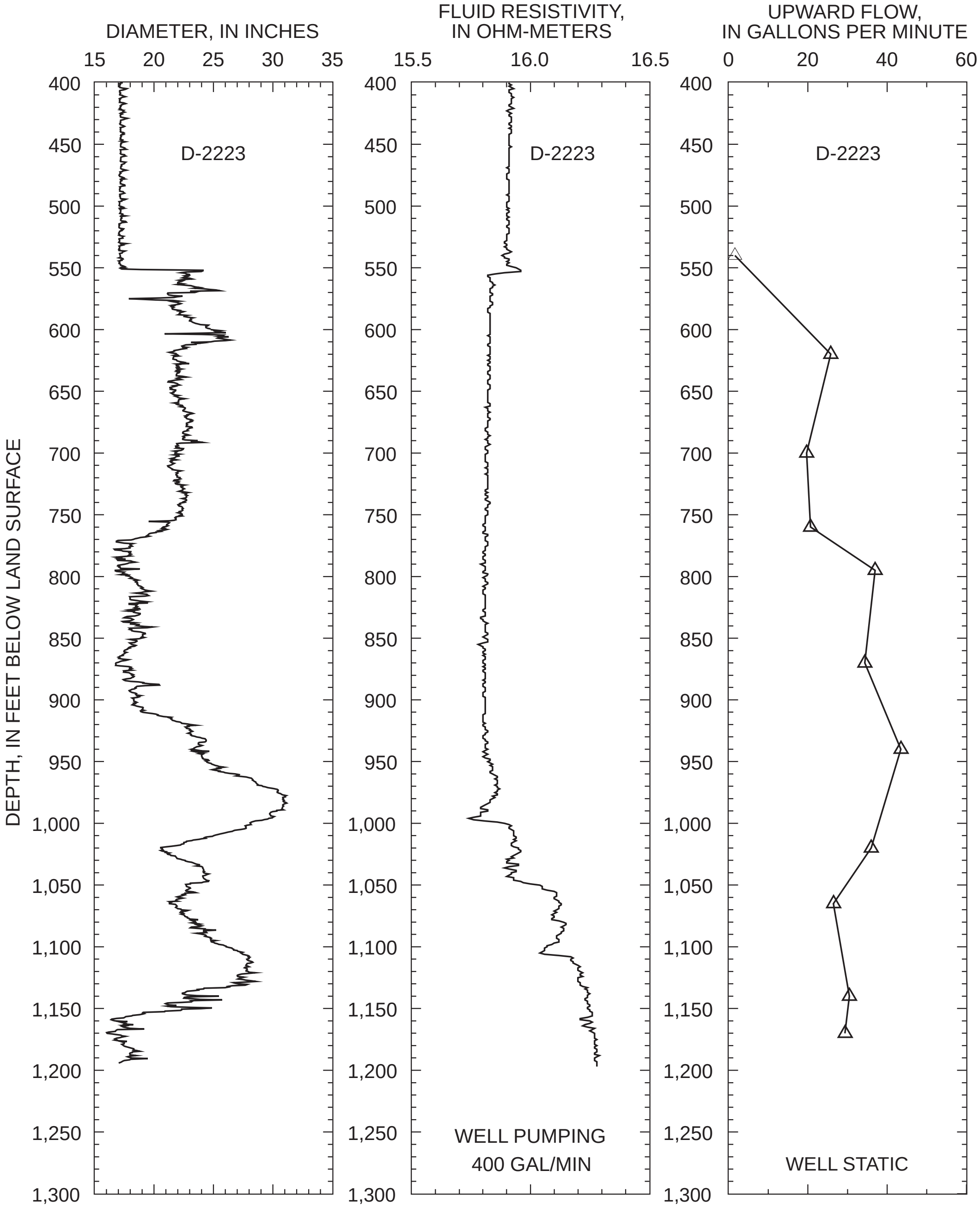

Figure 38. Geophysical logs of well D-2223 in western Duval County.

Well D-2223 also produces water of good quality (fresh) throughout its depth. The wellhead sample had a chloride concentration of 12 mg/L and a sulfate concentration of 150 mg/L and a sample from 1,190 ft had a chloride concentration of 12 mg/L and a sulfate concentration of 160 mg/L. Most of the flow to this well probably comes from depths greater than 1,000 ft. The fluid resistivity log shows several different flow zones below that depth (fig. 38). Transmissivity estimates for the well range from about 20,000 to 39,000 ft^2/d (table 2). The caliper log shows fracture or solution zones at depths of 1,140 ft, 1,144 ft, and 1,150 ft but they apparently do not produce water with different quality than the overlying strata. The two depth ranges in which the well diameter is large (950 to 1,020 ft and 1,060 to 1,140 ft) probably penetrate thick beds of relatively soft rock, in contrast to the thinner beds of alternating soft and hard rock penetrated by most wells at similar depths in other areas of the county.

IMPLICATIONS FOR MONITORING SALINE-WATER MOVEMENT

A synthesis of the data collected during this study indicates the complexity of the hydrogeology of the Floridan aquifer system in northeastern Florida. Geophysical sections across Duval County, compiled from the geophysical logs, do not show definitive correlations of the various flow zones (figs. 39-40). The strongest areal correlation was a zone of fracturing or solutioning penetrated in wells D-101, D-53A, D-225, and D-479 at an altitude of about 1,215 to 1,222 ft below sea level (fig. 39). In wells D-101 and D-53A, the zone contains fresh water, but in wells D-225 and D-479, it contains brackish water. The fracture zone at 1,160 ft below sea level in well D-650 and the one at 1,132 to 1,142 ft in well D-484 also might correlate. Wells D-3847, D-3846, and D-291 penetrated a fracture zone at altitudes of about 1,060 to 1,085 ft below sea level (fig. 40). The fracture zone in well D-665 at 1,040 ft below sea level might correlate with that zone also. The difficulty of areal correlation also is illustrated by the comparison of wells D-650 and D-665 (fig. 40). The wells are not far apart (about 3,700 ft), but the zone that is the source of brackish water to well D-665 contains fresh water in well D-650. A comparison of flow zones in the wells logged is also shown in table 4.

The most likely source of saline water to the Upper zone is the Fernandina permeable zone and the likely pathways are interconnecting vertical and horizontal fracture or solution zones probably developed along paleokarst features (fig. 9). Regional upconing of saline water from the Fernandina permeable zone and lateral movement of seawater from the Atlantic Ocean probably are not occurring in northeastern Florida. Relict sea water with high chloride concentrations can be present in the Lower Floridan aquifer in some areas, but such water is likely to be encountered in low-permeability strata, not in productive flow zones. Some of the wells penetrated zones that contain freshwater, but apparently have relatively low permeability.

The design of a conventional monitor-well network is based on the assumption that the location of the contaminant and the most likely pathways it can take are known with some degree of confidence. If lateral intrusion from the sea were the source of the saline water, then monitor wells located between the source and the well fields might provide an early warning of saline water intrusion. Similarly, if the primary cause of increased chloride concentrations in northeastern Florida were simple regional upconing of saline water through a porous aquifer medium, then a network of wells deeper than the water-supply wells and distributed across the area expected to be influenced by the upconing might provide sufficient warning of trends in increasing chloride concentrations. However, because the pathways for movement of saline water in northeastern Florida are controlled by buried paleokarst features that have, to date, not been mappable from land surface, a conventional monitor-well network would be of little value in providing warning of saline water intrusion. The proximity of a monitoring well to a production well does not ensure the reliability of that well as an early-warning system for water-quality deterioration because of the discrete nature of the flow system. No monitoring well design can be completely satisfactory in such a situation.

Monitoring and analysis of water quality from the water-supply wells will provide useful data for predicting trends in water-quality changes; however, due to the large number of wells, blanket sampling of all wells for all major ions at the same frequency might be an inefficient allocation of the resources available for the monitor-well network. In areas where water-quality problems exist, such as at Lovegrove, additional analysis of hourly specific conductance along with pump running time for all wells in the well field could help explain the cyclic fluctuations in specific conductance (and chloride concentration) in well D-225 and provide operational strategies. Monthly sampling for chloride and sulfate concentrations (coupled with annual analysis of major ions to provide verification of ion balances for the monthly samples) would be useful for wells in areas where some increases in chloride concentrations have been observed. In areas where no increases in chloride concentrations have taken place, quarterly sampling for chloride and sulfate, along with annual or biennial analysis for all major ions probably would be sufficient. Also, semi-annual sampling of the existing Upper zone monitor wells and annual sampling of the Fernandina permeable zone monitor wells would provide information about water-quality trends in those zones. Additional studies that might provide an increased understanding of the sources and pathways of the saline water include the use of seismic methods to locate buried paleokarst features (combined with additional borehole geophysical logging) and the use of geochemical analyses such as ionic ratios (for example, chloride-to-bromide or strontium-to-calcium) or isotopic ratios (such as strontium) and geochemical modeling to determine whether the water with higher chloride concentrations in different areas might come from the same source water.

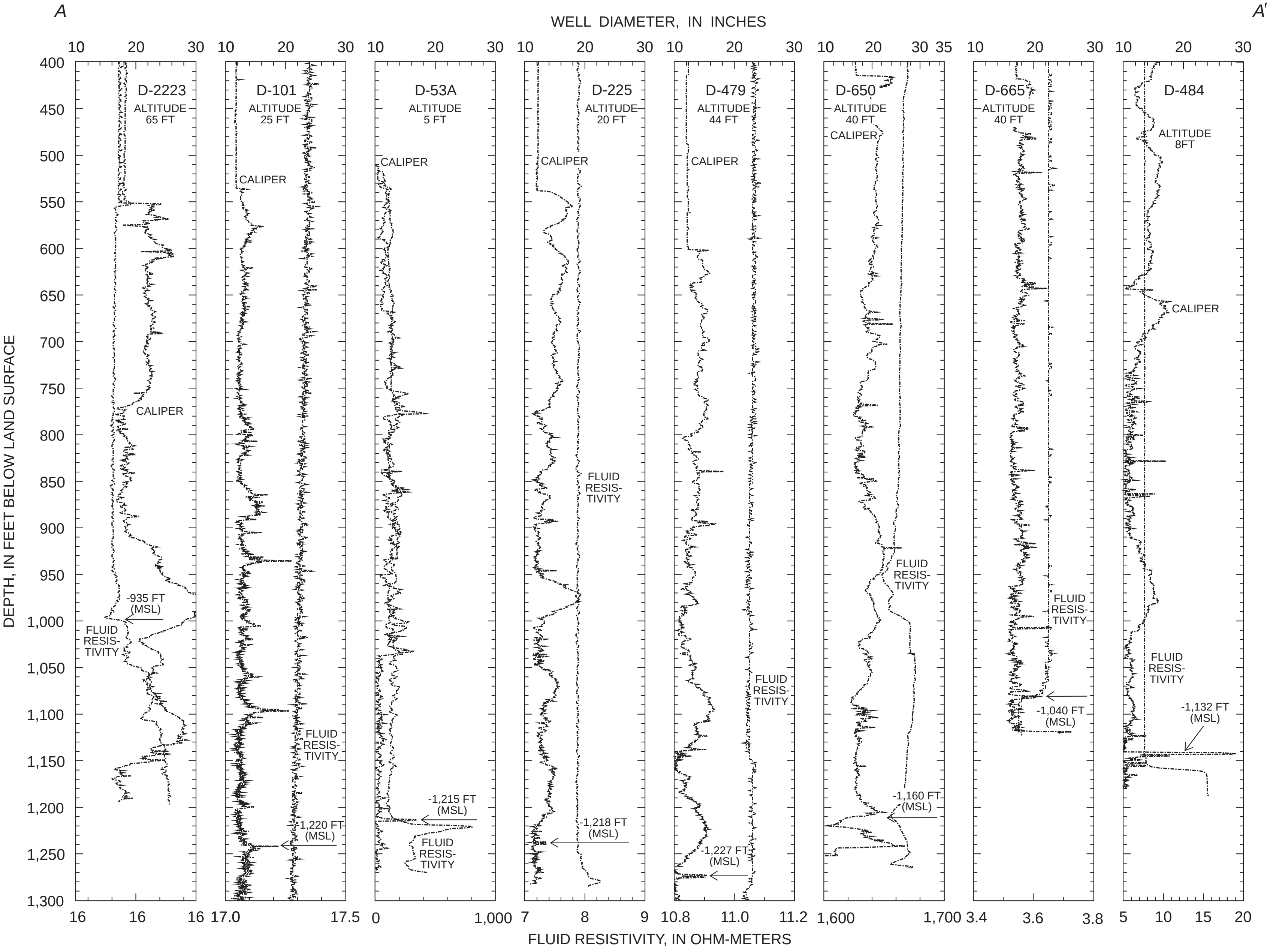

Figure 39. Geophysical section A-A′ (line of section shown in fig. 5).

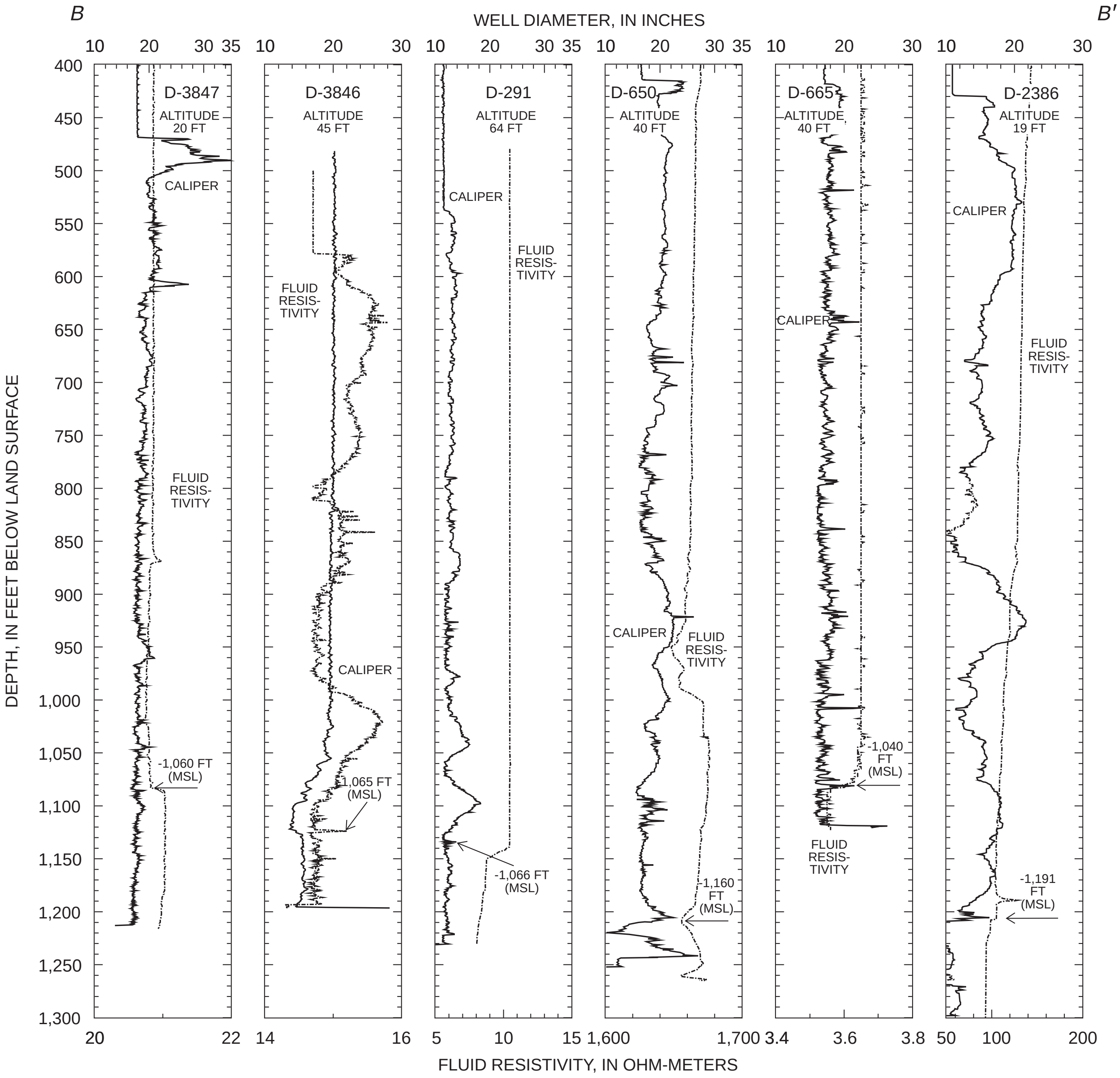

Figure 40. Geophysical section *B-B′* (line of section shown in fig. 5).

Table 4. Comparison of fracture or solution flow zones in wells in Duval County

[Altitude is in feet below sea level; na, not applicable; nd, not determined]

Site identification no.	Local no.	Altitude of fracture or solution flow zone(s)	Water type	Fresher water underlying brackish?	Altitude of fresher water
300856081382401	D-3847	1,000 1,065	fresh fresh	no	no
301335081355001	D-536	1,032 1,040 1,050	fresh brackish fresh	yes	1,050
301405081325601	D-3846	1,075	fresh	yes	1,085
301522081331301	D-291	1,066	fresh	no	
301704081233401	D-484	1,132	brackish	no	na
301716081234301	D-482	1,109	brackish	no	na
301725081305002	D-650	885 1,160	brackish brackish	yes	960-1,150
301740081361001	D-275	nd	brackish	no	na
301743081362301	D-225	1,218 1,260	brackish fresh	yes	1,260
301744081363301	D-2193	950	brackish	yes	960-bottom
301752081360501	D-649	930	brackish	yes	940-bottom
301758081303901	D-665	1,040	fresh	no	na
301832081422201	D-101	915 1,075 1,220	fresh fresh fresh	na	na
301840081393501	D-53A	1,215	fresh	na	na
301937081471401	D-2223	935	brackish	yes	955-bottom
302003081384001	D-90	1,004	fresh	no	na
302005081354501	D-857	903- 1,013	brackish	no	na
302007081353201	D-479	1,106 1,222	fresh brackish	no	na
302008081242101	D-307	1,171	brackish	no	na
302045081323101	D-1323	1,110	brackish	no	na
302058081244101	D-1107	none	fresh	no	na
302134081284803	D-2363	1,010	fresh	no	na
302159081235601	D-2386	1,171	fresh	no	na
302433081432201	D-1095	none	na	na	na
302510081260201	D-3841	1,214	fresh	no	na

SUMMARY AND CONCLUSIONS

In northeastern Florida, the Floridan aquifer system consists of the Upper Floridan aquifer, a middle semi-confining unit, and the Lower Floridan aquifer. The Lower Floridan aquifer can be further subdivided into the Upper zone, a middle semi-confining unit, and the Fernandina permeable zone. The layers of the aquifer system are delineated based on rock permeability and the resulting head differences, rather than lithology, formation, or time-stratigraphic boundaries. Heads generally are higher in deeper zones of the aquifer system than in shallower zones, except where lowered by pumping.

The Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer are the major sources of water supply in northeastern Florida. As a result of increased withdrawals, heads in the aquifer system have declined. At the same time, chloride concentrations have increased in water from many wells in Duval County.

Most wells in the Jacksonville area deeper than 900 ft penetrate the Upper zone of the Lower Floridan aquifer, which is composed of alternating beds of limestone and dolomite. Permeability in this zone is strongly related to secondary porosity developed along bedding planes, joints, and fractures because of the presence of paleokarst systems, developed at different levels by repeated episodes of active dissolution of the rock matrix. The thickness of the Upper zone ranges from about 300 to 500 feet in Duval County, based on flow logs of the wells. In some parts of the county, the Upper zone has a single flow zone, but in other areas, less permeable strata separate two distinct flow zones in the Upper zone. Transmissivity of the Upper zone is difficult to estimate because most wells penetrate the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer. Transmissivity estimates for these wells, based on specific capacity data, range from about 2,000 to 194,000 feet squared per day.

Water-quality changes in the Floridan aquifer system in Duval County are monitored by regular sampling of a network of about 30 wells. Concentrations of both chloride and sulfate can be limiting factors for the use of ground water in Duval County. Data from the monitor-well network indicate that chloride concentrations have increased in some areas of Duval County. Most of the observed increases are in the eastern part of the county, but a pattern in the locations of wells yielding water with chloride increases is not discernible. Water samples collected from about 60 wells during this study also confirm the continued increase in chloride concentrations in both the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer.

Water samples from the wellheads and from selected depths in the 21 wells logged during the study provided detailed information about the relation of water quality to hydrogeology in selected areas of Duval County. In some wells, zones bearing brackish water were underlain by zones containing fresher water; however, in other wells, fresher water was not found beneath the brackish water. In some wells, the water was fresh throughout the depth of the well. A single fracture or solution feature was the source of the brackish water in several wells, such as D-665 at the Oakridge well field and D-484 at Jacksonville Beach. In well D-225 at the Lovegrove well field, brackish water is contributed to the well by an interval of hard rock riddled with solution features. Another, deeper solution zone contributes fresher water. Chloride concentrations in water at the wellhead apparently are more closely related to whether or not nearby shallower wells are pumping than to pumping from well D-225.

Geophysical sections across Duval County, compiled from geophysical logs, do not indicate definitive correlations between flow zones. In four wells (D-101, D-53A, D-225, and D-479) a zone of fractures or solution features was penetrated at an altitude of about 1,215 to 1,222 ft below sea level. In wells D-101 and D-53A the zone contains freshwater, but in wells D-225 and D-479 it contains brackish water. Data from the study indicate that the most likely source of brackish water to the Upper zone of the Lower Floridan aquifer is the Fernandina permeable zone, which contains saline water in eastern Duval County and freshwater in the western part of the county. However, the mechanism of saline-water movement is not areal upconing but movement through interconnecting vertical and horizontal fracture or solution zones probably developed along paleokarst features.

A conventional monitor-well network would be of little value in providing early warning of saline water intrusion because the pathways for movement of the saline water are controlled by features that are difficult to map from the land surface. Continued sampling of the water-supply wells, including intensive monitoring of selected wells in which chloride concentration increases have been detected, would provide indications of trends in deteriorating water quality (increased mineralization). Water samples from the wells tapping the Upper zone and the Fernandina permeable zone would provide information about water-quality trends in those zones. The use of surface geophysical methods, combined with borehole geophysical logging, could increase knowledge of the locations of buried paleokarst features that act as pathways for saline-water movement. Additional geochemical analyses and modeling could help to determine whether saline water in the Upper Floridan aquifer and the Upper zone of the Lower Floridan aquifer in different areas of the county is from a common source or from several different sources.

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APPENDIXES

Appendix I. Records of selected wells in northeastern Florida

[ft, feet; S, sampled; L, logged; SP, specific capacity test available; --, none or not available; U, Upper Floridan aquifer well; L, Upper zone of Lower Floridan aquifer well; B, well tapping both the Upper Floridan and the Upper zone of the Lower Floridan aquifer; F, Fernandina permeable zone well. Locations shown in figure 1]

Site identification no.	Local no.	Other local no.	Depth (ft)	Casing (ft)	Land surface altitude (ft)	Type of data	Aquifer
300604081441501	C-22	--	500	440	14	S	U
300622081284701	D-909	--	--	--	20	S	--
300758081230501	SJ-5	--	350	--	4.53	S	U
300812081390801	D-1097	J-1130	560	440	15	S	U
300820081354001	D-296	--	487	--	20	S	U
300834081421301	C-7	--	550	--	5	S	U
300856081382401	D-3847	M504	1,220	470	20	S,L	B
301018081415101	C-4	--	530	--	12	S	U
301032081380401	D-2846	--	640	485	15	S	U
301037081243901	SJ-10	--	405	348	11	S	U
301132081225801	SJ-150	--	2,035	1,980	5	S	F
301144081413801	D-126	J-190	403	252	16	S	U
301210081373301	D-534	M10, J-601	920	448	25	S,L	U
301249081225801	SJ-122	--	441	335	12	S	U
301304081222701	SJ-103	--	857	385	5	S	U
301335081355001	D-536	J-603	1,140	372	10	S	B
301339081433401	D-1055	J-1109	588	492	10	S	U
301405081325601	D-3846	5702	1,198	578	45	S,L	B
301411081224201	SJ-47	--	600	--	15	S	U
301522081331301	D-291	J-356	1,237	537	64	S,L	B
301537081441901	D-75	J-139	1,290	970	10	S	L
301551081415701	D-129	J-193	600	470	9	S	U
301604081361501	D-450	J-517	1,300	1100	22	S	L
301607081301001	D-991	J-1001	885	404	40	S	U
301639081330802	D-1155	J-1285	1,170	1,080	50	S	L
301648081431801	D-103	J-167	1,330	535	15	S	B
301704081233401	D-484	J-551	1,220	357	8	S,L	B
301714081233301	D-72	J-136	850	350	8	S	U
301716081234301	D-482	J-549	1,194	377	11	S,L	B
301725081305002	D-650	5304, J-26	1,276	461	40	SP	B
301740081361001	D-275	5201, J-340	1,230	515	20	S	B
301743081303501	D-3825	5305,J-5847	1,093	440	40	SP	B
301743081303901	D-223	5301,J-290	1,125	420	40	SP	B
301743081304701	D-224	5302,J-291	1,180	423	40	S	B
301743081362301	D-225	5202, J-292	1,277	547	20	S, L	B
301744081363301	D-2193	5204, J-2381	1,014	549	20	S	B
301752081360501	D-649	5203, J-27	1,005	534	20	S, L,SP	B
301758081303901	D-665	5303, J-801	1,185	417	40	S,L,SP	B
301801081384302	D-54A	5104,J-118	1,350	504	20	S	B
301817081374901	D-425T	--	1,895	752	20	S	B
301817081374902	D-425B	--	2,486	2,055	20	S	F
301832081422201	D-101	0205, J-165	1,320	536	25	S,L	B
301839081392101	D-198	5002,J-262	1,297	552	10	SP	B
301840081383901	D-2684	5502, J-2959	1,252	537	10	SP	B
301840081393501	D-53A	5003, J-117	1,286	--	5	SP	B
301846081240201	D-246	J-313	1,210	388	10	S	B
301848081390301	D-2685	J-2960	1,270	527	15	SP	B
301902081394601	D-297	J-362	760	510	20	S	U
301930081470601	D-2283	0703, J-2256	1,250	--	--	SP	B
301937081471401	D-2223	0704, J-2257	1,200	553	65	S,L,SP	B
301957081342301	D-313	J-378	1,150	576	30	S	B

Appendix I. Records of selected wells in northeastern Florida (Continued)

[ft, feet; S, sampled; L, logged; SP, specific capacity test available; --, none or not available; U, Upper Floridan aquifer well; L, Upper zone of Lower Floridan aquifer well; B, well tapping both the Upper Floridan and the Upper zone of the Lower Floridan aquifer; F, Fernandina permeable zone well. Locations shown in figure 1]

Site identification no.	Local no.	Other local no.	Depth (ft)	Casing (ft)	Land surface altitude (ft)	Type of data	Aquifer
302003081384001	D-90	0106, J-154	1,280	510	12	S,L	B
302005081354501	D-857	5403, J-64	1,104	569	46.75	S,L, SP	B
302007081353201	D-479	5402, J-546	1,350	606	44	S,L, SP	B
302008081242101	D-307	J-372	1,300	407	9	S,L	B
302013081353801	D-673	5404, J-790	814	578	45	S,SP	U
302015081384501	D-335	J-400	1,290	531	21	S	B
302018081353401	--	J-5845, 5405	1,117	613	45	--	L
302022081393501	D-176	J-240	1,270	800	3	S	L
302045081323101	D-1323	J-1297	1,170	580	40	S,L,SP	B
302052081323201	D-3060	--	2,112	2,050	28.44	S,L	F
302058081244101	D-1107	J-1075	1,011	395	10	S,L	B
302107081411001	D-100	0308, J-164	1,365	--	25	SP	B
302107081412301	D-162	0301, J-226	1,309	--	23	SP	B
302112081384701	D-210	J-276	750	535	21	S	U
302112081410001	D-168	0302, J-232	1,320	--	26	SP	B
302122081274001	D-400	J-467	490	--	10	S	U
302122081412201	D-240	0303, J-307	1,362	--	24	SP	B
302127081411002	D-52A	0304, J-116	1,356	--	26	SP	B
302130081411802	D-46A	0305, J-110	1,280	530	30	S,SP	B
302134081284803	D-2363	9A02, J-2380	1,216	454	20	S,L	B
302137081240001	D-84	J-148	575	--	9.10	S	U
302142081330701	D-277	J-342	610	522	10	S	U
302159081235601	D-2386	--	2,026	1,892	19	S,L	F
302227081435001	D-592	J-658	1,330	1,150	10	S	L
302236081401501	D-336	J-401	1,300	520	21	S	B
302243081300401	D-360	J-425	665	462	45	S	U
302300081295101	D-396	J-463	700	--	20	S	U
302317081330401	D-488	J-555	755	560	9	S	U
302339081254702	D-464A	J-531	1,000	427	7	S	B
302345081261301	D-470	J-537	--	--	6	S	U
302351081390201	D-151	J-215	700	560	6	S	U
302416081522602	D-349	J-414	2,230	440	86	--	B
302433081432201	D-1095	--	1,250	500	10	S,L	B
302502081321001	D-270	J-335	--	--	5	S	U
302502081330701	D-228	J-295	850	--	10	S	U
302505081331001	D-1150	J-1139	1,100	520	10	S	B
302510081260201	D-3841	J-4003	1,311	771	13	S,L	B
302511081331201	D-1151	J-1140	1,100	520	10	S	B
302514081393701	D-227	0604, J-294	1,257	570	15	S,SP	B
302519081331501	D-1152	J-1141	1,100	520	10	S	B
302527081393701	D-226	0603, J-293	1,296	--	20	SP	B
302532081392501	D-330	0601, J-395	1,211	--	23	SP	B
302538081392501	D-329	0602, J-394	1,210	545	20	S,SP	B
302557081253101	D-913	J-1048	556	435	20	S	U
302608081354901	D-262	--	1,237	1,163	16	S	L
302616081413901	D-305	J-370	700	601	28	S	U
302647081460201	D-1068	J-1127	560	486	20	S	U
302724081244801	D-395	J-462	--	--	8	S	U
302738081290001	D-1078	J-1106	--	--	10	S	U
303015081343301	D-77	J-141	706	--	15	S	U
303417081342201	N-118	--	800	--	10	S	U

Appendix II Chloride concentrations in water from additional wells sampled during this study and data from previous sampling

[ft, feet; mg/L, milligrams per liter; --, no data or not sampled]

Site identification no.	Local no.	Depth (ft)	Casing (ft)	Date	Chloride (mg/L)	Date	Chloride (mg/L)
300604081441501	C-22	500	440	05/24/88	4.8	05/18/94	5.1
300622081284701	D-909	--	--	10/29/90	20	04/22/94	20
300758081230501	SJ-0005	350	--	05/23/88	16	05/17/94	17
300812081390801	D-1097	560	440	05/24/88	6.8	05/19/94	7.6
300820081354001	D-0296	487	--	05/24/88	17	05/19/94	18
300834081421301	C-7	550	--	05/24/88	7	05/18/94	6.8
301018081415101	C-4	530	--	05/24/88	6.1	05/18/94	7
301032081380401	D-2846	640	485	05/24/88	9	05/19/94	11
301037081243901	SJ-10	405	348	05/24/88	17	05/20/94	17
301132081225801	SJ-150	2,035	1,980	04/25/90	18,000	--	--
301144081413801	D-0126	403	252	05/24/88	7.4	05/18/94	8.7
301249081225801	SJ-0122	441	335	05/23/88	24	05/17/94	25
301304081222701	SJ-0103	857	385	05/22/89	28	05/20/94	28
301335081355001	D-0536	1,140	372	05/24/88	110	05/20/94	192
301339081433401	D-1055	588	492	05/24/88	7	05/17/94	6.8
301411081224201	SJ-0047	600	--	05/23/88	140	--	--
301537081441901	D-0075	1,290	970	04/18/88	7.2	04/22/94	7.5
301551081415701	D-0129	600	470	05/25/88	9	05/17/94	9.4
301604081361501	D-0450	1,300	1100	04/18/88	51	04/21/94	106
301607081301001	D-0991	885	404	05/26/88	16	05/18/94	15
301639081330802	D-1155	1,170	1,080	01/26/88	140	04/20/94	224
301648081431801	D-0103	1,330	535	01/26/88	9.4	04/21/94	9.9
301714081233301	D-0072	850	350	--	--	05/16/94	31
301740081361001	D-0275	1,230	515	05/25/88	170	05/23/94	200
301743081304701	D-0224	1,180	423	04/19/88	32	04/18/94	73
301743081362301	D-0225	1,277	547	05/25/88	54	03/14/94	210
301744081363301	D-2193	1,300	549	05/25/88	120	05/23/94	130
301752081360501	D-0649	1,000	534	05/25/88	21	03/29/94	33
301801081384302	D-0054A	1,350	504	04/18/88	13	04/18/94	13
301817081374902	D-425B	2,486	2,055	04/20/90	80	--	--
301846081240201	D-0246	1,210	388	05/23/88	28	05/16/94	26
301902081394601	D-0297	760	510	05/23/88	12	05/18/94	12
301957081342301	D-0313	1,150	576	04/19/88	72	04/21/94	102
302007081353201	D-0479	1,350	606	04/18/88	64	04/18/94	110
302013081353801	D-0673	814	578	05/24/88	74	05/23/94	160
302015081384501	D-0335	1,290	531	04/18/88	16	04/21/94	16
302022081393501	D-0176	1,270	800	04/18/88	12	04/22/94	13
302052081323201	D-3060	2,112	2,050	05/08/90	6,100	--	--
302112081384701	D-0210	750	535	05/23/88	17	05/18/94	16
302122081274001	D-0400	490	--	05/23/88	18	05/19/94	18
302130081411802	D-0046A	1,280	530	04/18/88	9.2	04/20/94	14
302137081240001	D-0084	575	--	05/23/88	15	05/16/94	15
302142081330701	D-0277	610	522	--	--	05/19/94	17
302159081235601	D-2386	2,026	1,892	04/23/90	5,800	--	--
302227081435001	D-0592	1,330	1,150	04/18/88	12	04/21/94	12
302236081401501	D-0336	1,300	520	04/18/88	9.2	04/21/94	14
302243081300401	D-0360	665	462	04/20/88	250	04/21/94	272
302300081295101	D-0396	700	--	05/23/88	17	05/19/94	17
302317081330401	D-0488	755	560	05/25/88	23	05/19/94	29
302339081254702	D-464A	1,000	427	04/21/88	17	05/16/94	15

Appendix II Chloride concentrations in water from additional wells sampled during this study and data from previous sampling (Continued)

[ft, feet; mg/L, milligrams per liter; --, no data or not sampled]

Site identification no.	Local no.	Depth (ft)	Casing (ft)	Date	Chloride (mg/L)	Date	Chloride (mg/L)
302345081261301	D-0470	--	--	09/19/88	18	05/16/94	19
302351081390201	D-0151	700	560	05/25/88	14	05/18/94	15
302502081321001	D-0270	--	--	05/25/88	19	05/19/94	20
302502081330701	D-0228	850	--	04/20/88	25	04/20/94	27
302505081331001	D-1150	1,100	520	04/20/88	32	04/19/95	34
302511081331201	D-1151	1,100	520	04/20/88	20	04/20/94	20
302514081393701	D-0227	1,300	570	05/25/88	18	05/17/94	20
302519081331501	D-1152	1,100	520	04/20/88	23	04/20/94	23
302538081392501	D-0329	1,210	545	04/18/88	20	04/20/94	20
302557081253101	D-0913	--	--	04/19/90	310	04/20/94	365
302616081413901	D-0305	700	601	05/25/88	18	05/19/94	19
302647081460201	D-1068	560	486	05/25/88	22	05/19/94	23
302724081244801	D-0395	--	--	05/23/88	20	05/16/94	25
302738081290001	D-1078	--	--	05/25/88	22	05/17/94	22
303015081343301	D-0077	706	--	--	--	05/17/94	24
303417081342201	N-118	800	--	05/24/88	24	05/17/94	23
304001081280301	N-117	2,102	2,000	04/27/90	12,000	--	--

Phelps, G.G., and Spechler, R.M.—The Relation Between Hydrogeology and Water Quality of the Lower Floridan Aquifer in Duval County, Florida, and Implications for Monitoring Movement of Saline Water—U.S. Geological Survey WRIR Report 96-4242

U.S. Department of the Interior
U.S. Geological Survey
227 N. Bronough St., Suite 3015
Tallahassee, Florida 32301

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