Influence of Geologic Setting on Ground-Water Availability in the Lawrenceville Area, Gwinnett County, Georgia

Scientific Investigations Report 2005-5136

Prepared in cooperation with the
City of Lawrenceville

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

Cover photographs:

Top left: Differential weathering in an amphibolite-biotite gneiss outcrop.

Bottom right: Steeply-dipping joints in a granite gneiss.

Notebook (4.5 inches by 7 inches) for scale.

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Gale A. Norton, Secretary

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P. Patrick Leahy, Acting Director

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8$$

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

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

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

Influence of Geologic Setting on Ground-Water Availability in the Lawrenceville Area, Gwinnett County, Georgia

By Lester J. Williams[1], Randy L. Kath[2], Thomas J. Crawford[3], and Melinda J. Chapman[4]

Abstract

Obtaining large quantities of ground water needed for municipal and industrial supply in the Piedmont and Blue Ridge physiographic provinces can be challenging because of the complex geology and the typically low primary permeability of igneous and metamorphic rocks. Areas of enhanced secondary permeability in the bedrock do occur, however, and "high-yield" wells are not uncommon, particularly where careful site-selection techniques are used prior to test drilling. The U.S. Geological Survey—in cooperation with the City of Lawrenceville, Georgia—conducted this study from 2000 to 2002 to learn more about how different geologic settings influence the availability of ground water in igneous and metamorphic bedrock with the expectation that this knowledge could be used to help identify additional water resources in the area.

In compositionally layered-rock settings, wells derive water almost exclusively from lithologically and structurally controlled water-bearing zones formed parallel to foliation and compositional layering. These high-permeability, water-bearing zones—termed *foliation-parallel parting systems*—combined with high-angle joint systems, are the primary control for the high-yield wells drilled in the Lawrenceville area; yields range from 100 to several hundred gallons per minute (gal/min). Near Lawrenceville, areas with high ground-water yield are present in sequences of amphibolite, biotite gneiss, and button schist where the structural attitude of the rocks is gently dipping, in areas characterized by abundant jointing, and in topographic settings with a continuous source of recharge along these structures.

In massive-rock settings, wells derive water mostly from joint systems, although foliation-parallel parting systems also may be important. Wells deriving water primarily from steeply-dipping joint systems typically have low yields ranging from 1 to 5 gal/min. Joint systems in massive-rock settings can be identified and characterized by using many of the methods described in this report. Geologic mapping was the primary method used to determine the distribution, variability, and relative concentrations (intensity) of joint systems. In the subsurface, joints were characterized by taking orientation measurements in the open boreholes of wells using acoustic and/or optical televiewers.

In this investigation, the only practical approach found for locating areas of high ground-water potential was first through detailed geologic mapping followed by test drilling, borehole geophysical logging, and aquifer testing. Geologic methods help characterize both large- and small-scale structures and other lithologic and stratigraphic features that influence development of increased secondary permeability in the bedrock. The rock types, discontinuities, depth of weathering, topographic position, and recharge potential—which were the principal factors assessed through detailed geologic mapping—must be evaluated carefully, in relation to one another, to assess the ground-water potential in a given area.

Introduction

Obtaining large quantities of ground water for municipal and industrial supply in the Piedmont and Blue Ridge physiographic provinces can be challenging because of the complex geology and the typically low primary permeability of igneous and metamorphic "crystalline" rocks. Areas of enhanced secondary permeability in the bedrock do occur, however; and "high-yield"[5] wells are not uncommon, particularly where careful site-selection techniques are used prior to test drilling. Most municipal and industrial supplies in the Atlanta, Georgia, region are derived from surface-water sources that are limited and may not be able to meet future water demands.

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[5] In this report, "high-yield" refers to well yields generally greater than 70 gallons per minute.

Ground water, drawn from crystalline-rock aquifers, could offer a potential source of water to supplement surface-water sources or be used as a sole-source supply for small communities and industries.

Understanding how ground water moves through crystalline-rock aquifers is crucial to the development and management of water resources in the area. Large amounts of ground water (greater than 100,000 gallons per day) may be developed from wells in areas where the underlying bedrock has been brittlely deformed and weathered, resulting in increased storage and water-transmitting capacity. Conversely, little ground water may be developed from wells in areas underlain by unfractured and unweathered bedrock. A detailed knowledge of the geology is essential to understanding the water-bearing capabilities of the bedrock and to identifying geologic settings capable of supplying the quantity and quality of water needed for various purposes.

To learn more about how various geologic settings influence the availability of water in igneous and metamorphic rocks, the U.S. Geological Survey (USGS)—in cooperation with the City of Lawrenceville, Georgia—conducted a detailed hydrogeologic study during 2000–2002, adding to and complimenting earlier work by Chapman and others (1999). This detailed hydrogeologic study focused on evaluating the distribution of rock types and both large- and small-scale structures in the bedrock—including foliation planes, compositional layering, and joints—that independently or together, influence the development of secondary bedrock permeability in various geologic settings. Chapman and others (1999) provided a general description of the study area; Williams and others (2004) described detailed subsurface lithology, yield, and fracture characteristics in the Lawrenceville area.

It was apparent at the outset of this study that variations in the character and attitude of the bedrock at the scale of hundreds or even tens of feet are not uncommon, and that such small variations could not be described for the entire area of study in a single report. Therefore, data from smaller subareas and from individual well sites in different geologic settings are described in this report.

Purpose and Scope

This report describes the influence of geologic setting on the availability of ground water in the Lawrenceville, Georgia, area. A standard suite of geophysical logs including caliper, combination[6], borehole camera, and borehole televiewer logs were collected from 32 bedrock wells situated in a variety of geologic settings. Hydraulic testing on the wells included flowmeter surveys, aquifer tests, packer tests, and water-level monitoring.

This report includes:

- information on water use, geologic setting, and hydrogeologic setting;
- a discussion of geologic factors that influence the availability of ground water;
- geologic and hydrologic data from selected wells in compositionally layered-rock and massive-rock settings, citing examples of various geologic features and characteristics that support the development of high- or low-yield conditions;
- conceptual models of ground-water availability in compositionally layered-rock and massive-rock settings and recharge pathways into bedrock;
- methods and approaches used to identify and characterize water-bearing zones in the bedrock in the different geologic settings; and
- a discussion of the potential for future ground-water development in igneous and metamorphic rocks.

Methods of Study

Prior to this study, detailed information on how geologic factors and settings influence ground-water availability in the Lawrenceville area was limited to that described by Chapman and others (1999) and Cressler and others (1983). Additional data were needed to develop a better understanding of geologic settings favoring high ground-water yield. The fieldwork for this study began during June 2000 and was carried on more-or-less continuously until January 2002. During 2000–2002, some previously mapped areas (Chapman and others, 1999) were mapped in greater detail, paying close attention to lithologic and structural features in the mapped areas. Twelve test wells were drilled during 2001 to determine subsurface lithologic and yield characteristics. All new test wells were geophysically logged to determine detailed bedrock lithology and structural characteristics, and flowmeter logs were collected to characterize the hydrologic characteristics of water-bearing zones. Aquifer tests were conducted in six of the test wells.

A geologic map was constructed to provide data on the geologic and hydrogeologic conditions. Geologic mapping was conducted primarily to define (1) the overall geometry of rock units and general structural style; (2) strike and dip of the major and minor rock units; (3) pervasive foliation, if present; and (4) the relative weathering characteristics of the different lithologies, such as weathering at contacts between rocks of contrasting character. Field-mapping data were collected by walking traverses along roads, creeks, and rivers noting features such as the lithology, strike and dip of foliation and

[6] Combination log includes: long-normal resistivity, short-normal resistivity, lateral resistivity, natural gamma, fluid temperature, fluid resistivity, single-point resistance, and spontaneous potential.

compositional layering, and structural attitude and relative degree of jointing. Field location was determined with a global positioning satellite (GPS) receiver. Geologic-mapping data were plotted on USGS 7½-minute quadrangle maps (or on maps of smaller scales) and used to construct geologic maps.

Borehole geophysical logs were collected in selected wells to delineate the structural and water-bearing properties of the bedrock in open boreholes of wells. Structural characteristics in open boreholes were determined mainly from optical and acoustic televiewer (ATV) logs. These logs are digital images of the borehole wall from which the strike and dip of planar features can be measured. Borehole camera surveys were used to inspect the open interval of a borehole and to supplement the optical televiewer and ATV logs. The strike and dip of intersecting structures was compared to surrounding foliation and compositional layering and classified as (1) "joints" for fractures that crosscut rock foliation and compositional layering, (2) "open joints" for fractures that had a visible opening intersecting the borehole wall, (3) "foliation partings" for small openings formed parallel to foliation or compositional layering, and (4) "major foliation openings" for large openings formed parallel to foliation or compositional layering (Williams and others, 2004). Irregular openings, apparently formed from weathering and dissolution, were classified into the primary weathered feature—weathered joints were included in the open joint category; and weathered foliation planes/compositional layers were included as a foliation parting or major foliation opening. Yield from individual water-bearing zones were estimated by correlating increases in yield recorded during drilling to the measured depths of the water-bearing zones.

Flowmeter logs were collected to identify discrete water-producing and water-losing zones in open boreholes of selected wells. Water-producing zones are intervals that yield measurable amounts of water to the borehole when pumped, or where water flows into the borehole during ambient conditions, such as for confined or semiconfined water-bearing zones. Water-losing zones are zones where water exits the borehole into openings or water-bearing zones of lower hydraulic head.

Packer-test data were collected from one well to delineate the hydraulic interconnection among individual high-yield, water-bearing zones. Packers were lowered into the borehole and inflated to isolate a hydraulically productive water-bearing zone. A submersible pump was then used to pump water from the isolated zone, and pressure transducers were used to monitor the drawdown in the pumped interval and in the upper and lower portions of the borehole.

Aquifer-test data were collected to provide information on the ability to sustain high yields from production wells for extended periods without lowering the water level below the water-bearing zone. Following each aquifer test, the rate of water-level recovery was monitored to determine the efficiency of recharge to the water-bearing zones that supply the well. The latter observations were used to estimate the amount of time the well could sustain a specified yield. Water levels in observation wells near the pumped wells were measured to determine the areal extent of drawdown.

Previous Studies

Chapman and others (1999) described the geology and ground-water resources of the Lawrenceville area. That report describes characteristics of major rock units and the relation of well yield to lithology, and presents borehole geophysical logs collected at several well sites. In addition, the report presents and discusses continuous water-level data collected during the study and the effect of pumping from the Rhodes Jordan Well Field. Chapman and others (1999) also present the most detailed lithologic map of the Lawrenceville area to date (2005); that lithologic map shows the distribution of major rock types and fault contacts at a scale of 1:24,000 for the about 44-square-mile (mi^2) study area. The various rock types that crop out in the area were divided into seven principal lithologic units.

Williams and others (2004) compiled lithology, fracture, and yield characteristics from 32 wells in the Lawrenceville area. That report described the methods used and the data obtained from a December 1994–October 2001 drilling and geophysical-logging program. The report presented (1) bedrock lithology and characteristics of water-bearing zones in the Lawrenceville area; (2) borehole geophysical log data, flowmeter survey data, and borehole images; (3) yield ranges of different types of water-bearing zones and yield of wells; (4) depths and nature of water-bearing zones associated with high yields; (5) fluctuations and long-term trends in ground-water levels in response to precipitation and local ground-water withdrawal; and (6) aquifer-test data showing yield of wells and the direction and magnitude of drawdown resulting from pumping high-yield wells. Data from the Williams and others (2004) report were extensively used in the compilation of this report.

Herrick and LeGrand (1949) reported on the ground-water resources of the Atlanta, Georgia, area. That report describes the occurrence of ground water in the Atlanta area, availability of water and the quantity that could be reasonably obtained, chemical quality, and the suitability of ground water for domestic, municipal, and industrial supply. The report was one of the first to indicate that the availability of ground water in the area is dependent on the geology, stating that "The occurrence of ground water in the Atlanta area is dependent on many different—though in part closely related—factors. Among these factors are rock type, structure, weathering, and topography" (Herrick and LeGrand, 1949, p. 9).

Cressler and others (1983) reported on the ground-water resources of 27 counties in the Metropolitan Atlanta area. This was the first comprehensive work to discuss geologic factors effecting ground-water availability in the igneous and metamorphic rocks of the Atlanta area. Results from that study indicated that high well yields are available only where aquifers have "localized increases in permeability," usually in association with structural and stratigraphic features such as contact zones and stress-relief fractures.

Clarke and Peck (1991) reported on the ground-water resources of the south Metropolitan Atlanta region. That study area encompassed nine counties: Coweta, Fayette, Henry, Lamar, Meriwether, Pike, Spalding, Talbot, and Upson.

Except for the extreme southern part of Talbot County, the study area lies within the Piedmont physiographic province. The report describes the ground-water supplies of the south metropolitan area and includes a list of domestic, agricultural, municipal, and industrial wells and springs; yield; hydrogeologic and topographic settings; well-construction information; and quality of water.

Several reports described the regional geology of the Atlanta area. McConnell and Abrams (1984) compiled previous geologic maps by many geologists and reported on the geology of the Atlanta area. In the Lawrenceville area, the authors used a map compiled by Atkins and Higgins (1980) in the Luxomni 1:24,000 quadrangle and a modification of the 1:24,000-scale reconnaissance map by Atkins and Morris (1982). Higgins and others (1988) published results of a study of the structure, stratigraphy, tectonostratigraphy, and evolution of the southernmost part of the Appalachian orogen. Crawford and others (1999) revised the stratigraphic nomenclature in the Atlanta, Athens, and Cartersville 30- x 60-minute quadrangles.

Prowell (1988) reported on post-Cretaceous and Cenozoic tectonism in the Atlantic coastal margin and documented the presence of reverse fault systems in the Atlantic coastal margin caused by compressive tectonic stresses in the eastern continental United States (Zoback and Zoback, 1989). The same compressive tectonism active in other areas of the Atlantic coastal margin probably is active in the Piedmont physiographic province of the southeastern United States, thus indicating the potential for post-Paleozoic brittle deformation (D.C. Prowell, U.S. Geological Survey, oral commun., 2001).

Acknowledgments

This study was conducted in cooperation with the City of Lawrenceville, Georgia. The authors gratefully acknowledge the former Mayor of Lawrenceville, Bartow Jenkins; former Director of Public Works, Don Martin; and City Clerk, Bob Baroni, for their support. The authors also thank all of the city employees who constructed roads and provided day-to-day assistance in obtaining access to test-drilling sites. Special thanks also goes to the Director of Public Works, Jim Steadman; Water Department Superintendent, Mike Bowie, and Water Treatment Plant Operator, Robert Paul, for their help in obtaining clearance for underground utilities and for coordinating the city's efforts on this cooperative water-resources study. The authors acknowledge Mike Higgins (USGS, retired) for his extensive effort in the geologic mapping used for this study. Many other people substantially contributed to the study including Joshua Lawson (Georgia Environmental Protection Division), who provided day-to-day assistance during much of the drilling and logging activities, and many others at the USGS Georgia Water Science Center in Atlanta. Finally, we thank USGS employees Caryl Wipperfurth who prepared the maps and other illustrations used in this report and Patricia Nobles who edited and prepared the final manuscript.

Description of the Study Area

The 44-mi^2 study area encompasses the City of Lawrenceville and adjacent areas in Gwinnett County (fig. 1), which is located in the Piedmont physiographic province. In Georgia, the Piedmont lies between the Valley and Ridge and Blue Ridge Provinces to the north and the Coastal Plain to the south (fig. 1). Topography in the study area consists of low hills and moderately entrenched stream valleys that range in altitude from 780 to 1,170 feet (ft). Lawrenceville is on a drainage divide that separates the Yellow River and Alcovy River Basins. To the west, the area is drained by Redland Creek, Pew Creek, and unnamed tributaries of the Yellow River; to the east, the area is drained by Shoal Creek and unnamed tributaries of the Alcovy River (fig. 1).

Wells in the area have a wide range of yield and depth (table 1), and derive water mainly from the crystalline igneous and metamorphic bedrock that underlie the entire study area. The yields of wells range from 1 to 600 gallons per minute (gal/min). Most of the bedrock wells range from 100 to 600 ft in depth. All of the production wells used by the City of Lawrenceville area are open to and derive water from water-bearing fractures in the underlying bedrock.

Water Use

In Gwinnett County, water use totaled about 90 million gallons per day (Mgal/d) during 2000 (Fanning, 2003). Of this amount, only about 0.5 Mgal/d were withdrawn from ground-water sources: 80,000 gallons per day (gal/d) of which were used for commercial purposes, 390,000 gal/d for public supply, and 10,000 gal/d for livestock. From surface-water sources, 90 Mgal/d were used for public supply and the remainder (80,000 gal/d) was used for livestock.

The City of Lawrenceville currently (2005) uses about 2.5 Mgal/d for public supply, of which about 120,000–140,000 gal/d are obtained from ground-water sources (Mike Bowie, Water Superintendent, City of Lawrenceville, oral commun., 2002, 2005). The Rhodes Jordan Well Field (fig. 1), which currently is the city's only operating municipal well field, consists of two production wells that are pumped alternately at rates of 200–250 gal/min for 10 or more hours per day. This well field was refurbished during the early 1990s and has operated nearly continuously since 1995. Historically, ground water also was produced from another well (14FF08) located on Maltbie Street (fig. 1). A replacement well for the Maltbie Street well was drilled during the late 1990s, but was never put into production because of ground-water contamination near that site. During the present study (2000–2002), the City of Lawrenceville converted six test wells into production wells. These new production wells, combined with wells at the Rhodes Jordan Well Field, are capable of producing a combined estimated yield of about 2 Mgal/d (Mike Bowie, Water Superintendent, City of Lawrenceville, oral commun., 2002).

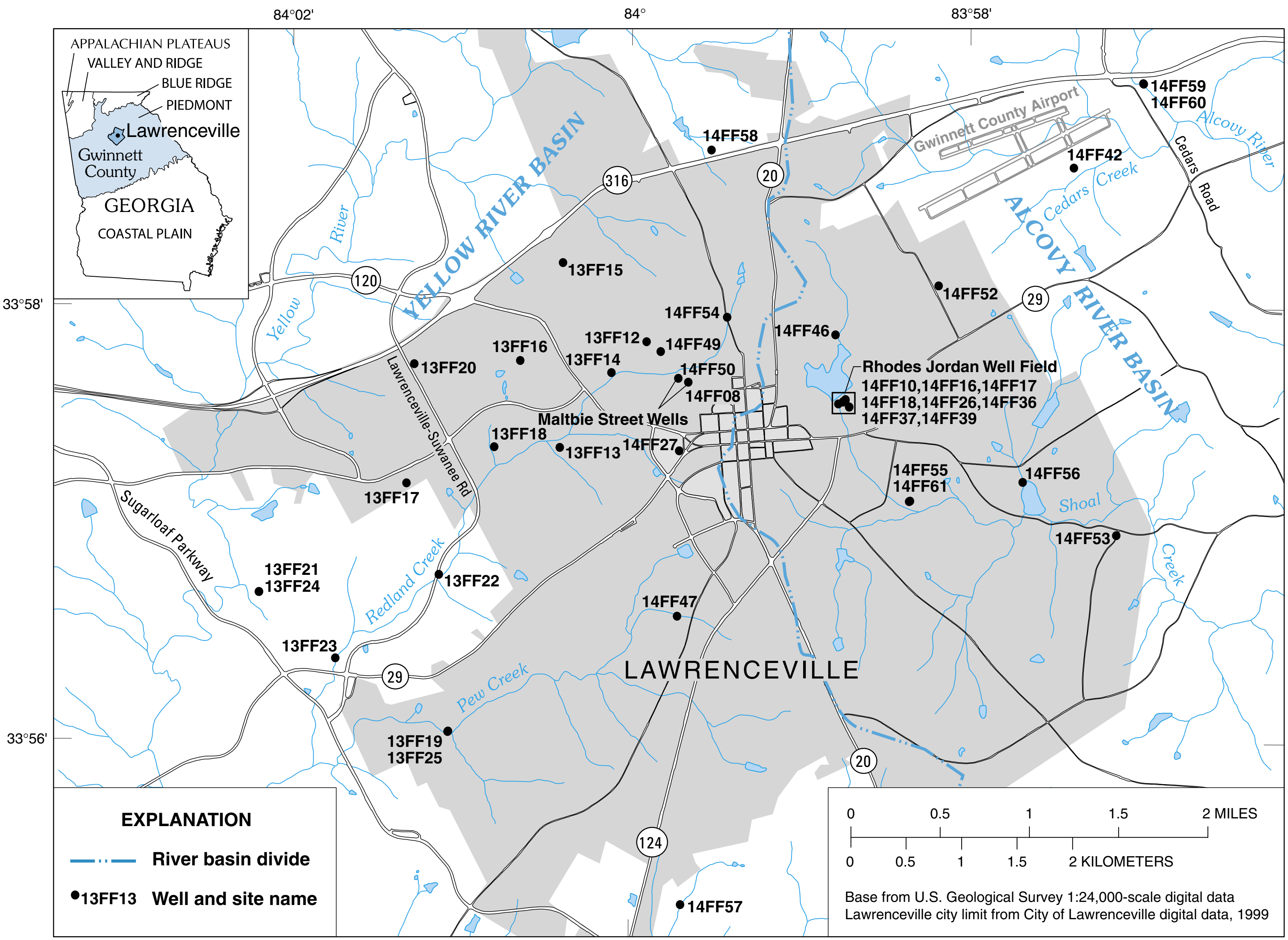


Figure 1. Physiographic provinces in Georgia, study area in Gwinnett County, and well locations in the Lawrenceville, Georgia, area.

Table 1. Location and well construction information for the Lawrenceville, Georgia, area.

[ft, foot; in., inch; gal/min, gallons per minute; °, degree; ', minute; ", second; —, data not collected; altitude, above NGVD 29.
Geologic units: a, amphibolite; bg, biotite gneiss; bs, button schist; gg, granite gneiss; qs, quartzite/schist. Casing type: PVC, polyvinyl chloride.
Source: Juan Ruiz, written commun., 2002, E&C Consulting Engineers, Inc., Lawrenceville, Georgia]

Well name	Latitude	Longitude	Land surface altitude (ft)	Top of casing altitude (ft)	Well depth (ft)	Casing depth (ft)	Casing diameter (in.) and type	Ream depth (ft)	Well yield (gal/min)	Geologic units penetrated
Bedrock wells										
13FF12	33°57'50.33"	–83°59'54.40"	1,040.0	1,040.12	265	54.0	6 – steel	—	[1]254	bg, bs, bg, a
13FF13	33°57'21.06"	–84°00'24.96"	972.3	976.13	448	19	6 – PVC	—	[1]135	a, bg, a, qs, bs, a
13FF14	33°57'41.77"	–84°00'06.77"	987.9	991.09	285	22.8	10 – steel	—	[1]140	a, bg
13FF15	33°58'12.01"	–84°00'24.10"	1,053.2	1,054.61	605	55	10 – steel	250	[1]250	bg
13FF16	33°57'44.97"	–84°00'39.10"	1,004.7	1,006.32	605	32	10 – steel	252	[1]75	a, bs, a, bg
13FF17[2]	33°57'11.05"	–84°01'19.08"	990.9	994.04	480	15	6 – PVC	—	[3]90	a
13FF18[2]	33°57'21.14"	–84°00'48.13"	953.8	955.76	550	55	8 – steel	200	[3]100 [4]150	a
13FF19[2]	33°56'02.62"	–84°01'04.11"	921.8	923.58	477	65	8 – steel	275	[3]250 [4]350–400	a
13FF20[2]	33°57'43.95"	–84°01'16.52"	990.1	992.06	455	69	6 – PVC	—	[3]35	a, bs
13FF21[2]	33°56'40.90"	–84°02'11.03"	889.4	891.5	505	40	8 – steel	277	[3]130 [4]125	bg, a
13FF22[2]	33°56'45.88"	–84°01'07.44"	929.7	932.99	600	23	6 – PVC	—	[3]100	a, bg
13FF23[2]	33°56'22.72"	–84°01'43.98"	906.2	908.04	498	30	8 – steel	270	[3]250 [4]350–400	a, bg, bs
14FF08	33°57'39.24"	–83°59'39.62"	1,019.8	1,020.89	352	28	8 – steel	—	[1]400	a, bs, bg, gg
14FF10			994.2	996.09	386	20	8 – steel	—	[1]270	a
14FF16			994.2	998.69	320	30.5	10 – steel	210	[1]471	a, bs
14FF17	33°57'33.49"	–83°58'46.47"	990.9	992.07	212	25	6 – steel	—	[3]150	a
14FF18	33°57'32.62"	–83°58'42.65"	999.3	1,001.09	180	24	6 – steel	—	[3]100	a
14FF26	33°57'33.97"	–83°58'44.76"	993.4	996.14	380	33	6 – steel	—	—	a, bg, bs, a, bg
14FF27	33°57'20.32"	–83°59'42.65"	1,048.3	1,050.7	600	59	6 – steel	—	[3]150	gg, bg, qs, a, bs
14FF39	33°57'34.12"	–83°58'44.81"	993.4	996.09	180	36	6 – steel	—	[3]150	a
14FF42	33°58'38.81"	–83°57'23.55"	1,028.2	1,029.67	599	35	8 – steel	—	[1]10.0	a, bs, bg
14FF46	33°57'52.51"	–83°58'47.58"	1,022.9	1,028.46	301	9	6 – steel	—	[3]70	a, bs, bg
14FF47	33°56'34.71"	–83°59'43.20"	1,004.2	1,006.07	300	39.5	6 – PVC	—	[3]25	bg
14FF49	33°57'47.63"	–83°59'49.41"	1,041.7	1,044.79	400	80.5	6 – PVC	—	[3]10	bg, gg
14FF50	33°57'40.32"	–83°59'43.13"	1,019.3	1,023.31	387	77.5	10 – steel	275	[1]600,[3]300	a, bs, bg, gg
14FF52	33°58'06.16"	–83°58'11.22"	1,082.3	1,083.57	630	22	6 – PVC	—	[3]40	a, bs, bg
14FF53	33°56'57.58"	–83°57'07.96"	967.7	969.43	605	29	6 – PVC	—	[3]50	bs, a, gg
14FF55[2]	33°57'06.68"	–83°58'21.28"	969.6	971.87	450	63	8 – steel	301	[3]250 [4]325	bg, a
14FF56[2]	33°57'12.09"	–83°57'41.11"	936.3	937.86	600	25	6 – PVC	—	[3]60	a, bs, bg
14FF57[2]	33°55'15.22"	–83°59'41.63"	954.1	956.47	380	35.5	6 – PVC	—	[3]3	bg
14FF58[2]	33°58'43.29"	–83°59'31.79"	1,030.2	1,031.98	550	34	6 – PVC	—	[3]1	gg
14FF59[2]	33°59'02.07"	–83°56'58.91"	952.1	954.19	470	35	8 – steel	400	[3]180 [4]350–400	a, bs, bg

Table 1. Location and well construction information for the Lawrenceville, Georgia, area.—Continued

[ft, foot; in., inch; gal/min, gallons per minute; °, degree; ', minute; ", second;—, data not collected; altitude, above NGVD 29.
Geologic units: a, amphibolite; bg, biotite gneiss; bs, button schist; gg, granite gneiss; qs, quartzite/schist. Casing type: PVC, polyvinyl chloride.
Source: Juan Ruiz, written commun., 2002, E&C Consulting Engineers, Inc., Lawrenceville, Georgia]

Well name	Latitude	Longitude	Land surface altitude (ft)	Top of casing altitude (ft)	Well depth (ft)	Casing depth (ft)	Casing diameter (in.) and type	Ream depth (ft)	Well yield (gal/min)	Geologic units penetrated
Regolith wells										
13FF24[5]	33°56'40.89"	–84°02'11.13"	889.4	891.60	16.5	11.5	2 – PVC	—	—	Regolith
13FF25[5]	33°56'02.71"	–84°01'04.00"	921.6	923.89	16.3	10.3	2 – PVC	—	—	Regolith
14FF36	33°57'34.47"	–83°58'44.12"	993.4	996.63	—	—	—	—	—	Regolith
14FF37	33°57'32.67"	–83°58'42.66"	1,000	999.98	—	—	—	—	—	Regolith
14FF60[5]	33°59'02.17"	–83°56'59.08"	952.8	955.57	9.3	4.3	2 – PVC	—	—	Regolith
14FF61[5]	33°57'06.76"	–83°58'20.93"	970.6	972.76	14	9	2 – PVC	—	—	Regolith

[1] Values for wells 13FF12, 14FF08, 14FF10, 14FF16, and 14FF50 are reported from aquifer tests conducted by well driller. Other values are the estimated yield from air-lift tests

[2] Well drilled as part of recent (2001) investigation

[3] Reported air-lift yield from 6-inch well

[4] Reported air-lift yield from 8-inch well after reaming

[5] Five feet of slotted screen used below casing

Geologic Setting

The Lawrenceville area is entirely underlain by igneous and metamorphic rocks that have undergone intense structural deformation. Because of this deformation, the geology varies greatly across short distances. The general history of structural deformation of the Piedmont region of Georgia includes thrust faulting, large-scale folding and faulting, partial melting, and syntectonic to post-tectonic intrusion of granitic bodies. Atkins and Higgins (1980), Higgins and others (1984, 1988, 1998), McConnell and Abrams (1984), and Chapman and others (1999) described the geology of the region. Crawford and others (1999) described the revision of the stratigraphic nomenclature for the geologic units.

Chapman and others (1999) divided the numerous rock types in the Lawrenceville area into seven principal lithologic units: amphibolite, biotite gneiss, button schist, granite gneiss, magnetite quartzite (not shown on map because of limited extent), quartzite/aluminous schist (quartzite/schist), and diabase dikes (fig. 2 and table 2). The principal lithologic units represent mappable rock groups correlated based on dominant rock types. Because of the great variation of lithologies, these rocks also have a wide range of lithologic, structural, and weathering characteristics (table 2).

Five of the seven principal lithologic units were penetrated by wells drilled in the study area: amphibolite, biotite gneiss, button schist, granite gneiss, and quartzite/schist. Except for the granite gneiss, each of these units is compositionally layered and consists of one to many different lithologies. The compositional layering in these units varies from finely laminated (individual layers only tenths of an inch thick) to thinly layered (typically less than 6 inches) to thickly layered (greater than 6 inches). Each of these units also can be massive (nonlaminated); in particular, there are large bodies of massive granite gneiss and biotite gneiss throughout the area.

The amphibolite consists of fine- to medium-grained, dark green to greenish-black, massive to thinly laminated, hornblende-plagioclase and plagioclase-hornblende amphibolite (table 2). This unit, interlayered with biotite gneiss, is penetrated by many high-yield wells in Lawrenceville (see the “Geologic units penetrated” column in table 1) and forms a significant water-bearing unit. Twenty-seven wells penetrate the amphibolite unit. In these wells, the amphibolite ranges from 130 ft (well 14FF56) to greater than 550 ft (well 13FF18) in thickness. The amphibolite unit generally has fine layering or thick felsic layers, augen, and folded foliation. Locally, the layering in the amphibolite is complexly folded and undulatory. Small-scale folding in the amphibolite unit was observed in many of the ATV and borehole image processing system (BIPS) images (Williams and others, 2004). Low-angle undulatory foliation also was observed in the amphibolite unit penetrated by wells at the Rhodes Jordan Well Field.

The biotite gneiss consists of medium- to coarse-grained, gray to grayish-brown, to dark gray biotite-rich gneiss (Chapman and others, 1999) and forms a significant water-bearing unit where interlayered with amphibolite (table 2). The biotite gneiss in places has a schistose texture, and locally it contains lenses and pods of hornblende-plagioclase amphibolite. Twenty-one wells penetrate the biotite gneiss unit. In these wells, the biotite gneiss unit ranges from about 50 ft (well 14FF27) to greater than 605 ft (well 13FF15) in thickness. Locally, the biotite gneiss unit is complexly folded and undulatory.

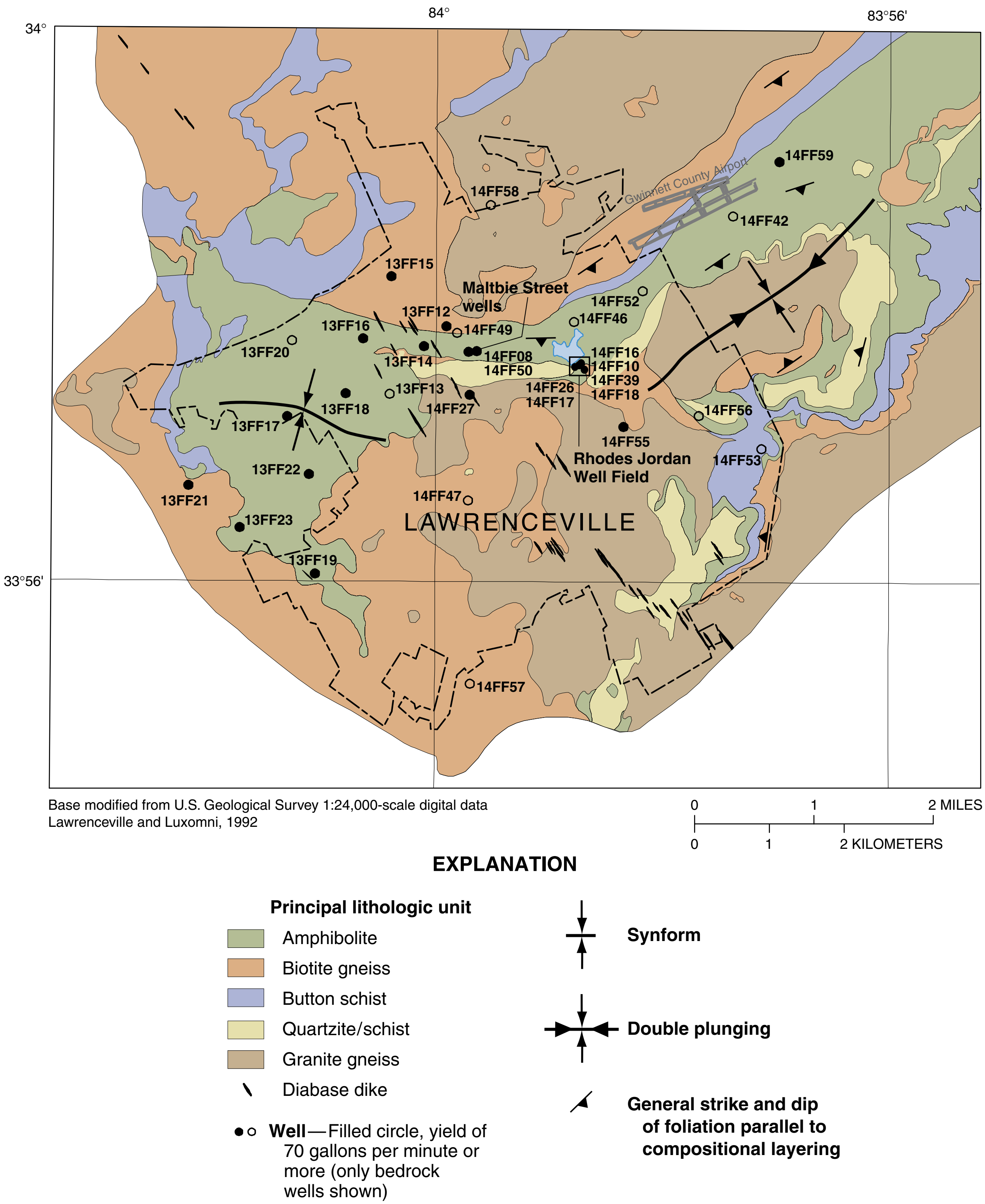


Figure 2. Distribution of principal lithologic units and location of high-yield wells, Lawrenceville, Georgia, area (modified from Chapman and others, 1999).

Table 2. Description, structural, and weathering characteristics of principal lithologic units in the Lawrenceville, Georgia, area.

Lithologic unit and description	Structural features	Weathering characteristic
Amphibolite (a) – Fine- to medium-grained, dark green to greenish-black, ocher weathering, massive to finely layered, locally laminated, locally pillowed, locally chloritic, commonly garnetiferous, locally magnetite-bearing, generally pyrite-bearing, generally epidotic, hornblende-plagioclase and plagioclase-hornblende amphibolites with minor amounts (generally less than a very small fraction of 1 percent) of fine- to medium-grained, generally amphibole-bearing, granofels.	Strong foliation, compositionally layered, locally well jointed.	The amphibolite unit weathers into a very characteristic dark red clayey soil. Well-developed differential weathering where interlayered with biotite gneiss.
Biotite gneiss (bg) – Medium- to coarse-grained, gray to grayish-brown to dark gray, commonly schistose, generally pegmatitic (biotite-muscovite-quartz-potassium-feldspar pegmatites), biotite-rich gneiss with generally rare but locally fairly common layers, lenses, and pods of hornblende-plagioclase amphibolite. Characteristically and commonly contains small pods and lenses of altered meta-ultramafic rocks.	Strong foliation, compositionally layered, locally well jointed.	The biotite gneiss weathers to a uniform, slightly micaceous, dark red saprolite and clayey dark red soil; vermiculitic mica is characteristic of soils formed from the biotite gneiss. Well-developed differential weathering where interlayered with amphibolite.
Button schist (bs) – Medium- to coarse-grained, dark gray to brownish-gray, lustrous (where fresh), (± chlorite)-garnet-biotite-muscovite-plagioclase-(± microcline)-quartz button schist with tiny black opaques. In most outcrops the schist contains large muscovite fish that weather to buttons.	Strong foliation, compositionally layered, usually not well jointed.	The button schist is resistant to weathering. Weathers into a brownish to gold saprolite with resistant muscovite buttons. Well-developed differential weathering where interlayered with biotite gneiss.
Granite gneiss (gg) – Complex of granite and granitic gneiss. Light gray to whitish-gray, medium-grained muscovite-biotite-microcline-oligoclase-quartz gneiss having well-defined gneissic layering. Most commonly is poorly foliated.	Poorly developed foliation, massive, locally well jointed.	Pavement outcrops, “whale-back” outcrops, and boulder outcrops are characteristic of the granite gneiss unit. Where deeply weathered the granite gneiss forms thin light-whitish-yellow sandy soils. In general, shallow to moderate depth of weathering.
Magnetite quartzite (mq) – Thinly layered (0.4 inch) to laminated, medium-grained, magnetite quartzite in units from about 1 to 20 feet thick. Commonly has thin (from 0.4 to 1.6 inches) quartz-magnetite layers, with magnetite crystals as much as 0.4 inch in size, but commonly about 0.04 inch. The quartz-magnetite layers alternate with quartz layers without magnetite, or quartz layers with small percentage of magnetite, from about 1.6 to 3.2 inches thick. Magnetite clumps that generally disrupt the layering are locally as large as 8 inches, but are commonly about 0.4 inch.	Strong foliation, compositionally layered, commonly well jointed.	See description for quartzite/schist unit.
Quartzite/schist (qs) – White to yellowish, sugary, to vitreous, slightly graphitic to nongraphitic quartzite with accessory muscovite, garnet and aluminosilicate minerals (kyanite, staurolite, or sillimanite), in layers from about 1 to 4 feet thick, interlayered with feldspathic quartzite and garnetiferous quartz-muscovite or muscovite-quartz schist. The aluminous schist part of the unit is commonly a tan to yellow weathering, sheared or button-textured, commonly quartzose, garnet-biotite-plagioclase-muscovite-quartz schist that generally contains kyanite or staurolite.	Strong foliation, compositionally layered, locally well jointed.	The quartzite-schist unit commonly weathers into a yellow-tan saprolite. In general, shallow to moderate depth of weathering. Characterized by differential weathering where interlayered with less-resistant rocks.
Diabase (dia) – Fine- to medium-grained, dark gray to black augite diabase, in dikes generally from 16 to 66 feet wide.	Generally massive.	The diabase weathers to a dark red clayey soil containing spheroidal boulders with fresh rock inside an armoring, ocherous rind.

The button schist consists of fine- to medium-grained, dark gray to brownish-gray garnet schist with interlayered biotite gneiss and scarce amphibolite (Chapman and others, 1999) (table 2). The button schist unit has a sheared texture, and there is evidence that this unit was derived from shearing of biotite gneiss (Higgins and others, 1998). The button schist is named for a weathering characteristic that yields mica concentrations resembling “buttons.” Sixteen wells penetrate the button schist, which ranges from 18 ft (well 13FF12) to 220 ft (well 14FF53) in thickness.

The granite gneiss consists of a light gray to white, medium-grained, muscovite-biotite-feldspar-quartz gneiss (table 2). Six wells penetrate the granite gneiss unit. In these wells, the granite gneiss ranges in thickness from 131 ft (well 14FF27) to greater than 260 ft (well 14FF49). Where penetrated, the granite gneiss is massive and is not interlayered with other rock types.

The quartzite/schist consists of quartz-rich schist, muscovite schist, and layers of quartzite. The quartzite/schist unit was penetrated by only two wells: at well 13FF13, the unit thickness is 20 ft; and at well 14FF27, the thickness is 159 ft.

Large-scale structural features in the Lawrenceville area include a northeast-southwest-trending synform occupying the central and eastern part of the study area and a smaller synform in the western part of the study area (fig. 2). Through the main part of the city, the lithologic units generally strike east-west and dip gently to the south. Although not explicitly shown in figure 2, each principal lithologic unit is bounded by thrust faults. The outcrop patterns are typical of those that result from eroded open folds. Because of gently-dipping foliation in the area (dips commonly are from 10 degrees to 20 degrees), combined with thrust faulting and the relative “thinness” of the rock units, many wells presented in this report fully penetrate one or more units.

Hydrogeologic Setting

Ground water occupies pore spaces in the regolith[7] and occupies openings, voids, and other fractures in the underlying bedrock (collectively referred to as the crystalline-rock aquifer system). This type of ground-water system, often referred to as a “fractured-rock aquifer” in literature, is not used in this report. The term *fracture*, which implies breaking or fracturing of the bedrock, is imprecise when describing the wide range of secondary openings that are formed in the underlying bedrock. The term *discontinuity* is used in this report to indicate not only fractures, such as joints or zones of fracture concentration, but also to describe openings formed parallel to foliation planes, voids, and other weathered openings in the bedrock.

In general, the aquifer system in the Lawrenceville area consists of an overlying layer of regolith, which stores a considerable amount of water, and an underlying system of bedrock discontinuities that transmit water in the subsurface (fig. 3). The greatest variation in hydrologic properties of bedrock is for compositionally layered and massive rock units, as illustrated in figure 3.

Recharge and Regolith/Bedrock Storage Capability

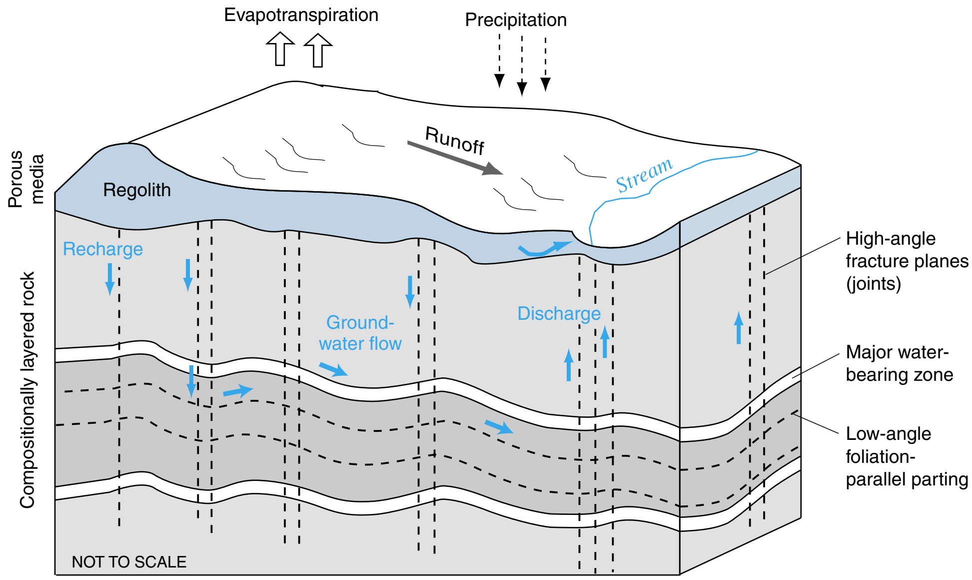
Recharge to the crystalline-rock aquifer system occurs through infiltration of precipitation at the land surface. The infiltrating water collects in the regolith and recharges the underlying bedrock aquifer (fig. 3). The bedrock aquifer consists of openings, voids, fractures, and other discontinuities that transmit water through the rock and serve to connect the bedrock system to the overlying regolith. Because regolith has a much higher storage capacity than bedrock, the regolith can be thought of as being a ground-water reservoir or “sponge” that feeds the underlying bedrock discontinuities. Joint concentrations, fractures enhanced by dissolution, and other discontinuities in bedrock, and combinations of these features, also can store a substantial quantity of water.

The storage capacity of the regolith/bedrock system is mainly influenced by differences in the weathering characteristics of various rock types. Thin saprolite (*in-place* weathered or decomposed bedrock) is developed on more resistant rock types, whereas thick saprolite is developed on less resistant rock types. The depth of casing of bedrock wells (table 1) can be used as a general indication of the depth of weathering. In the Lawrenceville area, the saprolite generally is thicker on potassium feldspar-rich rocks and thinner on quartz-rich rocks. The biotite gneiss unit is particularly susceptible to deep weathering and typically has a thick saprolite cover. Mafic rocks (such as amphibolite) typically are characterized by thin saprolite cover because of the general lack of potassium feldspar. In compositionally layered rocks, saprolite may develop between layers of more competent rock. This weathering profile is common where less chemically resistant rock (such as biotite gneiss) is interlayered with more chemically resistant rock (such as amphibolite).

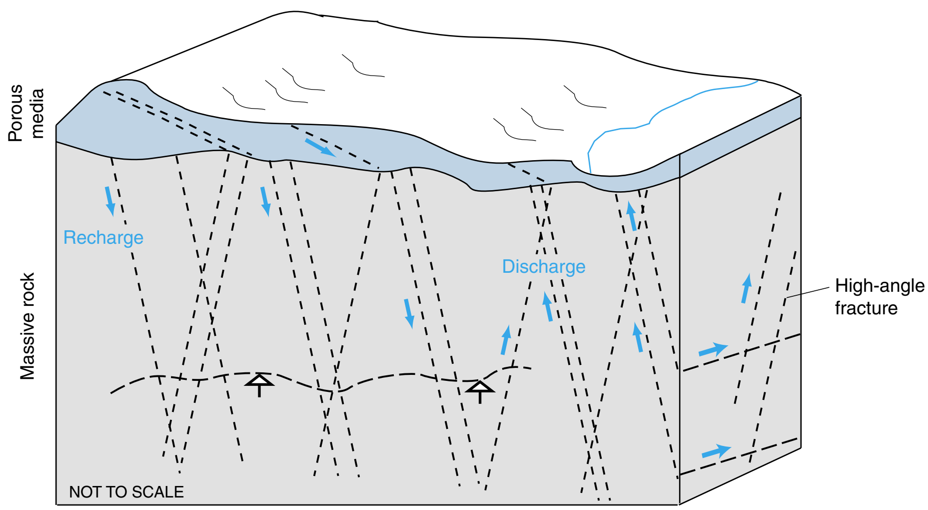
Water-Bearing Zones

Two major systems of water-bearing fractures (discontinuities) were identified using borehole imaging data correlated to individual-fracture yield (Williams and others, 2004): (1) joints, open joints, and zones of joint concentration consisting mostly of steeply-dipping, low-yield fractures; and (2) small and large openings along foliation and compositional layering, consisting of high-yield, water-bearing zones called *foliation-parallel parting systems* (fig. 3). Other water-bearing zones identified include dissolution openings along mineral infillings of joints and other irregular-shaped voids and fractures that appear to originate as joints or foliation-parallel partings/openings (Williams and others, 2004). Yield characteristics for different types of water-bearing zones in Lawrenceville are summarized in table 3.

[7] In this report, the soil, saprolite, alluvium, and weathered rock are collectively referred to as the regolith.



A. Compositionally layered rock with high-angle fractures and low-angle foliation-parallel parting. *High-angle fractures allow water to seep into the rock, serving as recharge conduits. Discharge may occur along high-angle fractures near streams or other discharge boundaries. Low-angle foliation-parallel parting connect high-angle recharging fractures.*



B. Massive rock with high-angle fractures. *Ground-water flow (solid arrows) is restricted to steeply-dipping fractures that have limited recharge potential from regolith. Subhorizontal jointing (open arrows) resulting from unloading or internal pressure release may enhance ground-water availability in massive rock.*

Figure 3. Schematic diagrams showing *(A)* compositionally layered-rock system with high-angle fractures and low-angle foliation-parallel parting, and *(B)* massive-rock system with high-angle fractures and subhorizontal jointing.

Table 3. Yield characteristics for different types of bedrock discontinuities and water-bearing zones observed in open boreholes of wells in the Lawrenceville, Georgia, area (compiled from Williams and others, 2004).

[<, less than; gal/min, gallons per minute]

Type	Description	Typical range in yield
Joint	Fracture that clearly cuts across rock foliation and does not have a significant opening or aperture; normally occurs in sets of planar fractures crossing borehole.	< 1 gal/min
Open joint	Same as a joint but has a physical opening that could be seen in the borehole wall. Zones of intense jointing and open joints common. Dissolution observed around some open joints.	1–5 gal/min
Weathered, mineral-infilled joint	Dissolution openings around mineral-infilled joints or veins.	30–35 gal/min (not common, only observed in two boreholes)
Foliation parting	Small opening formed parallel to foliation or compositional layering. These can occur singularly or in zones of weathered rock.	1–15 gal/min
Major foliation opening	Large opening formed parallel to foliation or compositional layering; often accompanied by a large increase in air-lift yield during drilling. These are sometimes associated with open joints and smaller foliation partings above or below.	10–240 gal/min (most individual openings yield between 50 and 100 gal/min)

Influence of Geologic Setting on Ground-Water Availability

The occurrence and availability of ground water in the Lawrenceville area, as well as the region as a whole, is dependent on many different but closely related geologic factors. Among these factors are *rock type*, *structure*, *weathering*, and *topography* (Herrick and LeGrand, 1949; Crawford and Kath, 2003; Crawford and Kath, 2001; and Kath and others, 2001).

Geologic Factors

One of the most important factors influencing ground-water availability in igneous and metamorphic rocks is *rock type*. This may seem to be an obvious statement but rock type often is overlooked during water-resource studies of crystalline rock areas. Rock type controls the depth and degree of weathering as well as controls the types of water-bearing discontinuities that may be formed in the bedrock. Williams and others (2004), who documented many water-bearing zones at lithologic contacts, clearly indicated the influence of rock type on well yield; thus, confirming earlier observations made by Cressler and others (1983) and Herrick and LeGrand (1949). Cressler and others (1983) reported that high well yields are found only where “localized increases in permeability” occur, usually in association with structural and stratigraphic features such as contact zones between rocks of contrasting character and within multilayered rocks. High-yield wells (greater than 70 gal/min) in the Lawrenceville area—including wells 13FF12, 13FF14–13FF19, 13FF21–13FF23, 14FF10, 14FF16–14FF18, 14FF27, 14FF39, 14FF50, 14FF55, and 14FF59 (fig. 2)—derive most of their yield from foliation openings located near or at lithologic contacts. In many of these wells, feldspathic biotite gneiss layers seem particularly susceptible to weathering and to the development of foliation partings and openings.

Another important factor with respect to ground-water availability is *geologic structure*. Geologic structure influences the distribution, nature, and yield of water-bearing zones by providing the framework (or fabric) along which weathering and possibly stress-relief[8] can occur. In this report, “structure” refers to the spatial relation of small-scale features such as foliation, joints, and folds as well as the large-scale geologic features, such as the general attitude of major rock units, faults, and larger folds. If the bedrock is massive and has no foliation, joints, or other weaknesses along which weathering can occur (i.e., no fabric), then ground-water availability will be less than if there are abundant structural features in the bedrock.

[8] Refers to the upward expansion of the rock column in response to erosional unloading causing development of sheet-like fractures (Cressler and others, 1983).

Aside from the obvious influence that rock structure (or fabric) has on the development of secondary bedrock permeability (described previously), the overall *structural attitude* of the rocks has an equally important influence with respect to ground-water availability. In the Lawrenceville area, rock units generally are flat lying or gently dipping (from 5- to 20-degree dips are common); thus, discontinuities formed along rock layering also are flat lying and more likely to intersect steeply-dipping joints (fig. 3). This low-angle or flat-lying attitude is believed to contribute to high ground-water availability in the Lawrenceville area. Foliation-parallel parting systems formed along flat-lying or gently-dipping rocks seem to have the greatest potential for high yield. Early reports, such as Herrick and LeGrand (1949), recognized the importance of structure by indicating: "Wells located in areas of gentle dip intersect more parting planes along which ground water occurs than those situated where steep dips prevail" (Herrick and LeGrand, 1949, p. 21). In discussing recharge, Herrick and LeGrand (1949, p. 21) stated "… it would seem advisable to locate a well in such a manner as to intersect water-laden schistose openings that have adequate access to influent seepage." The flat-lying attitude of lithologic units in the Lawrenceville area provides an ideal structural setting for development of potentially high-yield, foliation-parallel parting systems.

Weathering, in combination with the previous two major factors (rock type and structure), has had a particularly important influence on the hydraulic characteristics and development of water-bearing zones in the study area. The large number of dissolution openings, voids, and weathered zones observed in the open boreholes of wells in the Lawrenceville area (Williams and others, 2004) clearly shows the strong influence and importance that weathering has on widening and development of water-bearing zones in the bedrock. On a small scale, weathering has produced, or enhanced, many individual water-bearing zones that compose the ground-water flow systems; individually, these zones may be discontinuous and irregular and, therefore, would not be continuous across very large distances. The localized extent and hydrologic characteristics of these zones have an important effect on well yield; high-yield wells typically are in close proximity to low-yield wells. Across large distances and scales, zones of water-bearing systems that coalesce together may behave as larger hydrologic systems and, depending on the degree of interconnectedness, could yield substantial quantities of water to wells that tap them.

Topography, in combination with weathering, also exerts considerable influence on localized increases in permeability. Such increases in permeability typically occur where small-scale features localize drainage development in a topographic basin (Cressler and others, 1983). Combinations of small-scale features such as joints, compositional layering, foliation, and axial planes of small folds may provide weaknesses along which weathering can progress more rapidly, hence, localizing drainage development (and increased bedrock permeability) in a topographic basin.

Compositionally Layered-Rock Settings

Wells penetrating compositionally layered rocks in the Lawrenceville area derive most of their yield from locally productive, low-angle foliation-parallel parting systems. Foliation-parallel parting is distinguished from other types of water-bearing discontinuities by their development parallel (or nearly parallel) to foliation and compositional layering through the process of differential weathering (fig. 4).

All of the high-yield wells studied in the Lawrenceville area tap, and produce water from, compositionally layered-rock settings. These include the city wells at Rhodes Jordan Well Field (Chapman and others, 1999), a line of wells through the main part of the city (that are aligned parallel to the strike of compositionally layered rocks), several wells west of the city, and one well east of the Gwinnett County Airport (fig. 2). The depth and yield of the water-bearing zones vary considerably across these areas. As discussed in the following sections, these zones, which consist of a wide range of smaller foliation partings to major foliation openings and from single joints to zones of joint concentration, are strongly influenced by the geologic setting.

Example of a Productive Well (14FF59) in a Compositionally Layered-Rock Setting

One of the better examples of a productive well in a compositionally layered-rock setting is located east of the Gwinnett County Airport (fig. 5). The location of well 14FF59 was selected because this area has many of the geologic characteristics commonly associated with high-yield wells in the area, including the presence of well-developed foliation and compositional layering, jointing and other zones of brittle deformation in the rocks, and a large recharge area. Although these features individually are not uncommon in the Lawrenceville area, the combination of features suggested that a potentially high ground-water yield could be obtained from this area. Well 14FF59 was located in a position to intercept layers of amphibolite, button schist, and biotite gneiss, based on the geologic map shown in figure 5. This same sequence also was penetrated by test well 14FF42, a core hole that was used to expand the geologic database of Chapman and others (1999); this low-yield well (estimated to be 10 gal/min) was not drilled with the expectation of high yield.

Well 14FF59 is 470 ft deep and penetrates amphibolite, button schist, and biotite gneiss (fig. 6) units on the north flank of a large synform (see fig. 2). Compositional layering and foliation in outcrop and in the subsurface generally strike northeast-southwest and dip to the southeast (inclined in a down-basin direction). A comparison of the geologic map in figure 5 to the cross section shown in figure 6 indicates that the overall dip of the lithologic units is about 10 degrees.

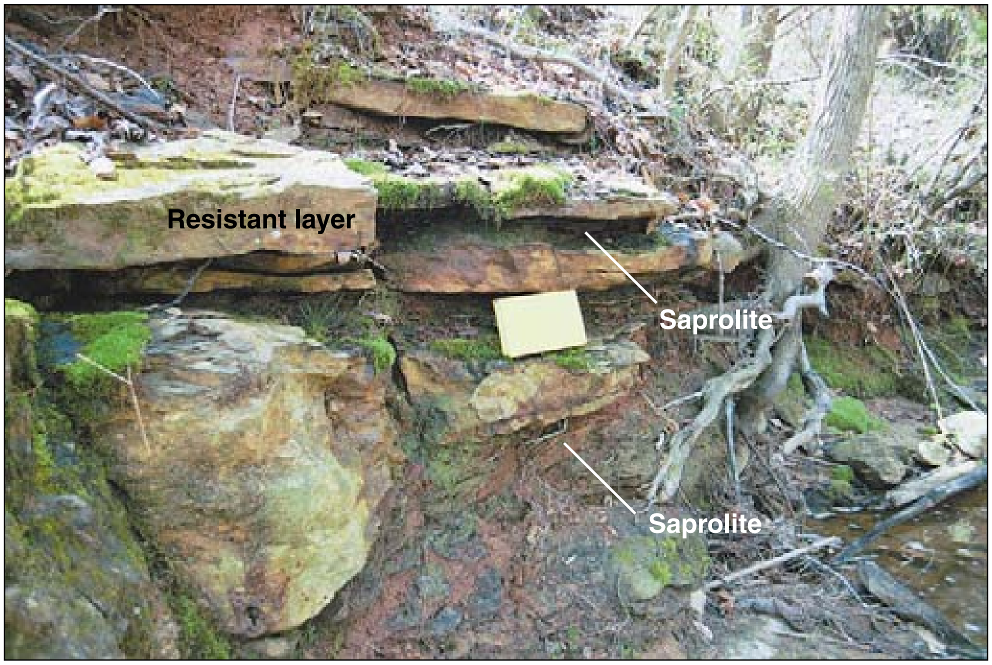


Figure 4. Differential weathering in an amphibolite/biotite gneiss outcrop. Outcrop is about 250 feet north of well 14FF59 and shows more resistant layers of amphibolite separated by saprolite derived from weathering of less resistant feldspathic biotite gneiss. The 4½- by 7-inch notebook is for scale. Photo by Lester J. Williams, USGS.

In the subsurface, the highest yielding water-bearing zones are located at the button schist contact and between rocks of contrasting character in the underlying biotite gneiss unit (fig. 5). From geophysical logs, the borehole penetrates four main water-bearing zones (figs. 6 and 7). A shallow water-bearing zone also was penetrated but later cased off behind the permanent steel casing and, therefore, is not discussed. The first three major zones—at depths of 267, 282, and 297 ft—were identified as openings formed parallel to foliation and compositional layering (fig. 8) based on the ATV log. Truncation of high-angle joints by the subhorizontal openings also was noted from the borehole camera surveys (image A in fig. 8). The fourth water-bearing zone also was identified as an opening formed parallel to foliation and compositional layering. This zone, at a depth of 348 ft, was initially identified during drilling as a “4-ft section of broken rock,” but later determined to be a discrete opening with an aperture of about 9 inches, using ATV logging. Several minor water-bearing zones also were identified; comparison of minor water-bearing zones in figure 7 to the structures in figure 8 shows that these are small foliation partings.

A flowmeter survey indicated that about 50 percent of the yield in this well is derived from the opening at 348 ft, 30 percent from 282 ft, and 10 percent each from openings at 267 and 297 ft, respectively (Williams and others, 2004). No substantial yield was derived from the minor water-bearing zones.

To test the hydraulic characteristics of the major water-bearing zones, a series of packer tests was conducted by lowering a straddle-packer assembly into the borehole, isolating the hydraulically conductive zone with inflatable rubber packers, and then pumping water from the isolated interval. Water levels were monitored above and below the straddle packer and in the pumped interval. The results of these tests indicate that ground water enters the borehole almost exclusively through foliation openings and not joint sets (Williams and others, 2004). A slight but noticeable vertical connection among individual high-yield, water-bearing zones observed in the drawdown data is attributed to high-angle joint sets. The packer tests also revealed that the high-yield foliation openings are not directly connected close to the borehole. This supports the interpretation that these openings are formed along the undulatory foliation planes and compositional layers.

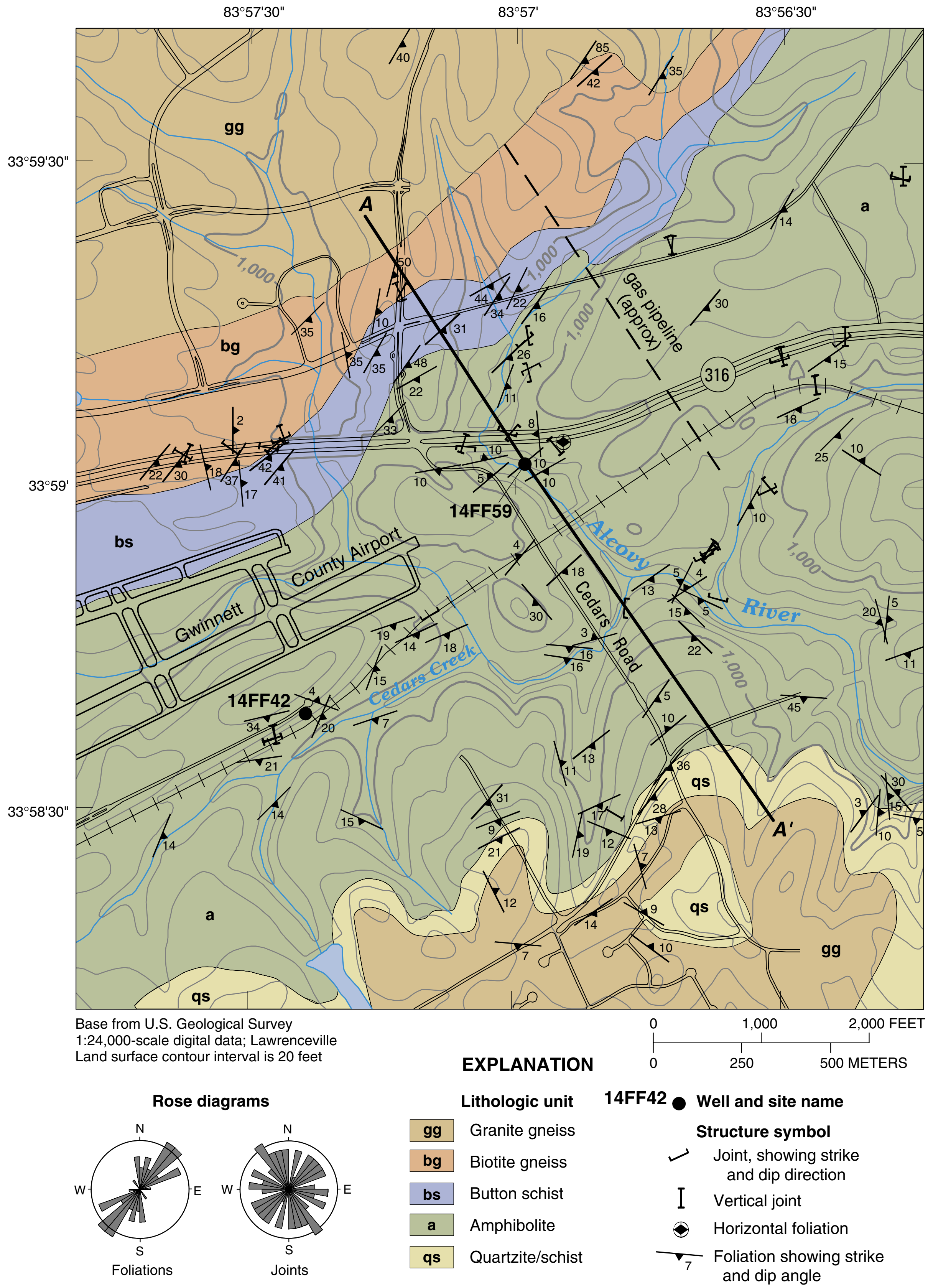


Figure 5. Geologic map, well locations, and line of section for the Gwinnett County Airport, Georgia, area (modified from Chapman and others, 1999).

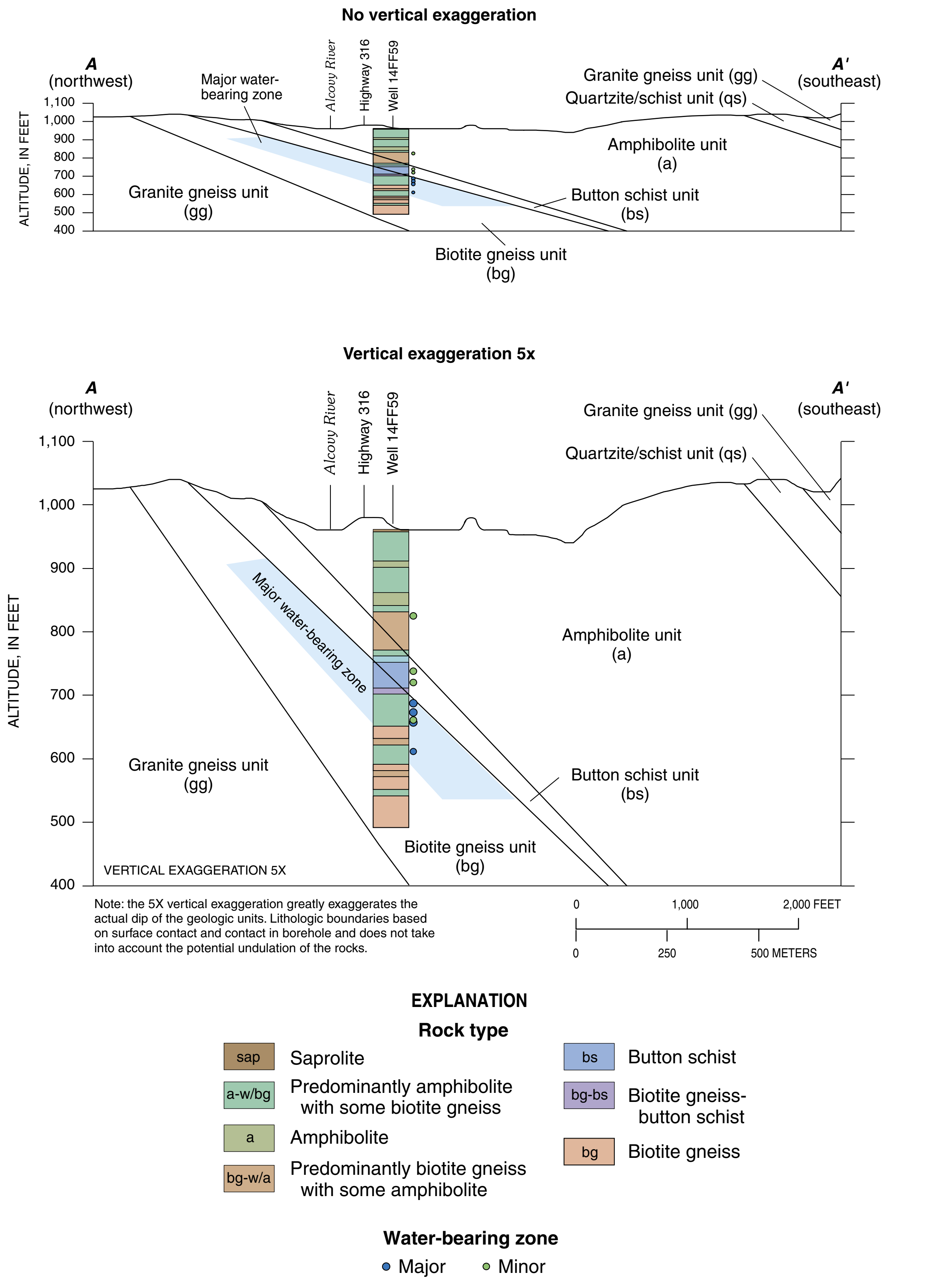


Figure 6. Hydrogeologic section A–A′ showing the southward-dipping sequence of rocks penetrated by well 14FF59 and the location of water-bearing fracture zones. Line of section shown in figure 5.

Based on geologic mapping, borehole geophysical logging, and hydraulic testing, well 14FF59 clearly derives most of its yield from productive contact zones at or below the button schist/biotite gneiss contact. Some of the key geologic features identified at well 14FF59 that are believed to enhance high ground-water yield in the area are:

- compositionally layered rock susceptible to differential weathering;
- flat or gently inclined structural features;
- well-developed foliation planes and compositional layering;
- steeply-dipping joints and zones of joint concentration;
- combination of subhorizontal (foliation and compositional layers) and vertical (steeply-dipping joints) discontinuities along which weathering can progress and form interconnected water-bearing zones;
- down-basin inclined foliation and compositional layering favoring recharge; and
- favorable position of the well at the base of a topographically large catchment area that influences recharge and flow of water needed for the development of increased permeability along bedrock discontinuities.

Examples of Other Wells in Compositionally Layered-Rock Settings

Many other wells tap productive foliation-parallel parting systems in compositionally layered-rock settings in the Lawrenceville area; hence their extent and importance with respect to water supply cannot be understated. Subsurface lithologic characteristics and water-bearing zones tapped by wells 14FF26 (Rhodes Jordan Well Field), 14FF50 (Maltbie Street well), 13FF14 (Pike Street well), and 13FF16 (Hurricane Shoals well), shown in figure 9, illustrate the extensive but discontinuous nature of foliation-parallel parting systems in the Lawrenceville area. The distance from the Rhodes Jordan Well Field at well 14FF16 to the farthest well, 13FF16, is about 10,000 ft. Lithology and water-bearing zones tapped in these wells (fig. 9), from east-to-west along strike are as follows:

- Well 14FF26 (Rhodes Jordan Well Field) penetrates large cavernous foliation openings formed in the amphibolite unit structurally down-dip from the outcrop area. Pumping at Rhodes Jordan Well Field causes a large drawdown in this well and causes drawdown in other wells located in an east-west direction parallel to the general strike of lithologic units. Sustained pumping from Rhodes Jordan Well Field is reported to average about 100 gal/min (144,000 gal/d) since 1995 (Mike Bowie, Water Superintendent, City of Lawrenceville, written commun., 2002).
- Well 14FF50 (Maltbie Street well) penetrates two separate foliation openings formed in the button schist unit down-dip from the outcrop area. Pumping from Rhodes Jordan Well Field, located about 5,000 ft away, causes about 4–5 ft of drawdown in this well (Williams and others, 2004). During an aquifer test at well 14FF50, drawdown observed in wells 13FF12, 13FF14, 14FF08, 14FF27, 14FF46, 14FF47, and 14FF49 was greater parallel to the strike of the lithologic units.
- Well 13FF14 (Pike Street well) penetrates foliation openings at the contact between the amphibolite unit and the biotite gneiss unit. The water level in this flowing well responds to pumping at the Rhodes Jordan Well Field and to pumping at other high-yield wells in the area (Williams and others, 2004).
- Well 13FF16 (Hurricane Shoals well) penetrates a single water-bearing foliation opening in the button schist unit. The depth and lithologic relation of this opening is similar to that described in well 14FF50. During an aquifer test of well 13FF16, rapid drawdown was observed in wells 14FF08 and 13FF12, indicating extensive drawdown in an east-west direction parallel to the strike of lithologic units (Williams and others, 2004).

Similar to the wells described above, test wells 13FF18, 13FF19, 13FF21, and 13FF23 drilled near Redland and Pew Creeks (fig. 1), and well 14FF55 drilled south of the Rhodes Jordan Well Field, derive water almost exclusively from major foliation openings formed at lithologic contacts (Williams and others, 2004). Hence, this indicates a very strong lithologic and structural control on this distribution of foliation-parallel parting systems in the layered rocks underlying those areas and further indicates the important geologic control on the yield of the large capacity wells near the Lawrenceville area.

Aquifer Tests of Productive Wells in Compositionally Layered-Rock Settings

To determine the ability to sustain large ground-water withdrawals for extended periods from production wells, the City of Lawrenceville conducted six aquifer tests during 2001. The following discussion summarizes the results of those tests.

Well 13FF18, located on the floodplain of Redland Creek, was drilled to a total depth of 550 ft and was cased with 55 ft of 8-inch-diameter steel casing (table 1). Three primary water-bearing zones were encountered during drilling: one at 82 ft that yielded about 63 gal/min, one at 101 ft that yielded about 83 gal/min, and one at 159 ft that yielded 4 gal/min. All three water-bearing zones were determined to be foliation openings at lithologic contacts based on geophysical logging (Williams and others, 2004). For the aquifer test, the well was pumped for 72 hours at rates ranging from 135 to 212 gal/min so that the pumping water level was kept above the uppermost water-bearing zone. The pumping rate was reduced until drawdown stabilized at a pumping rate of about 135 gal/min.

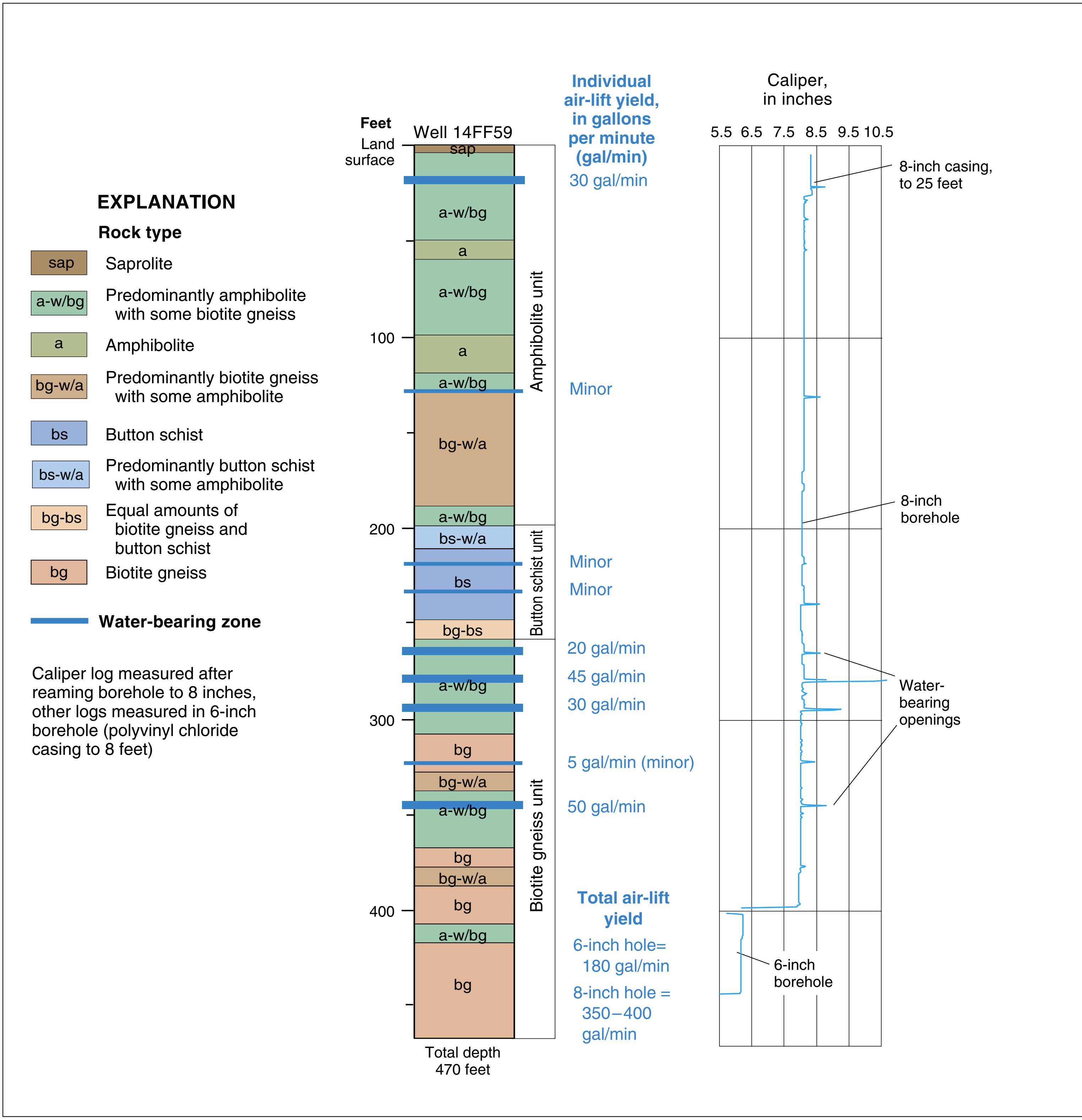
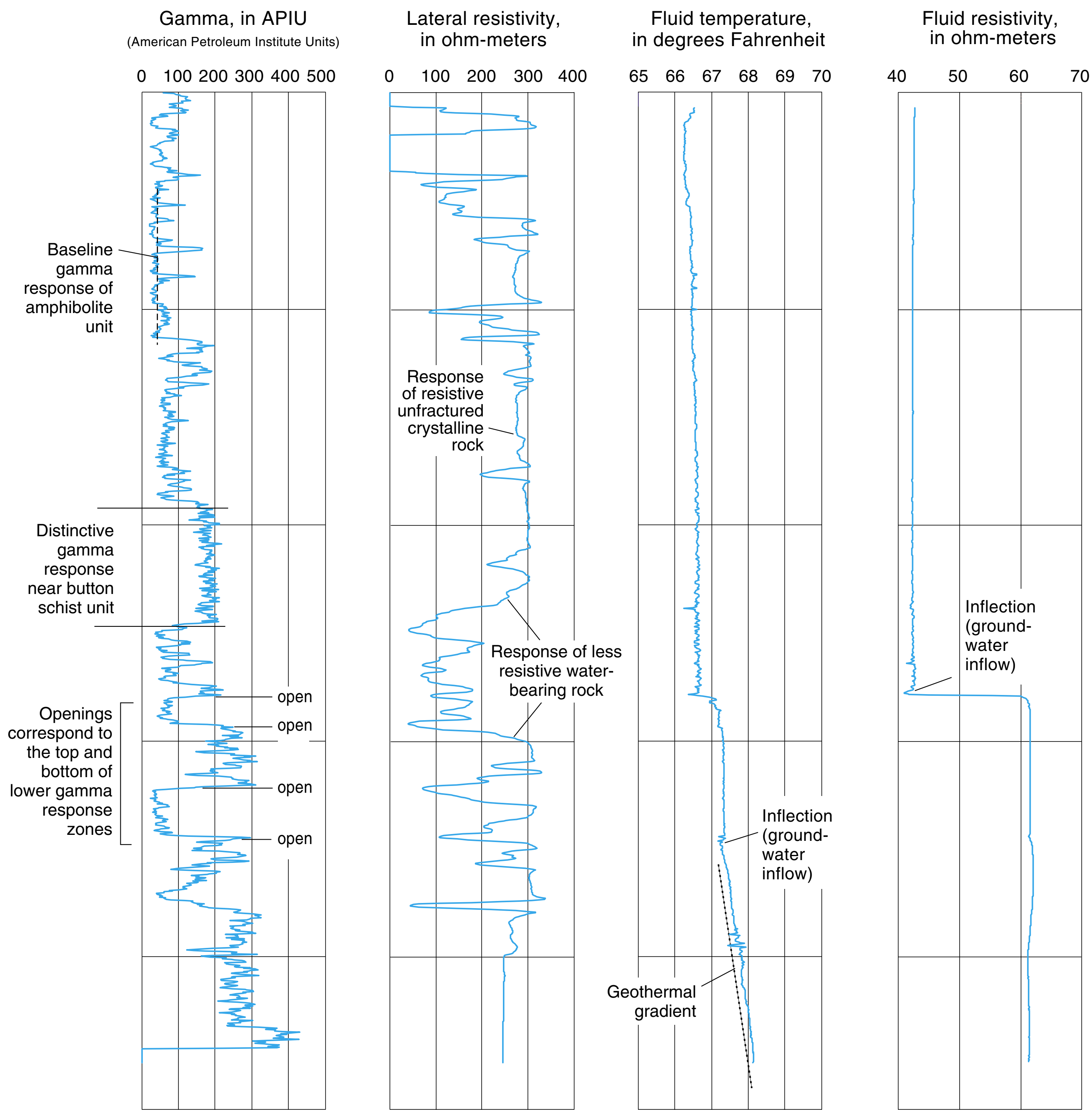
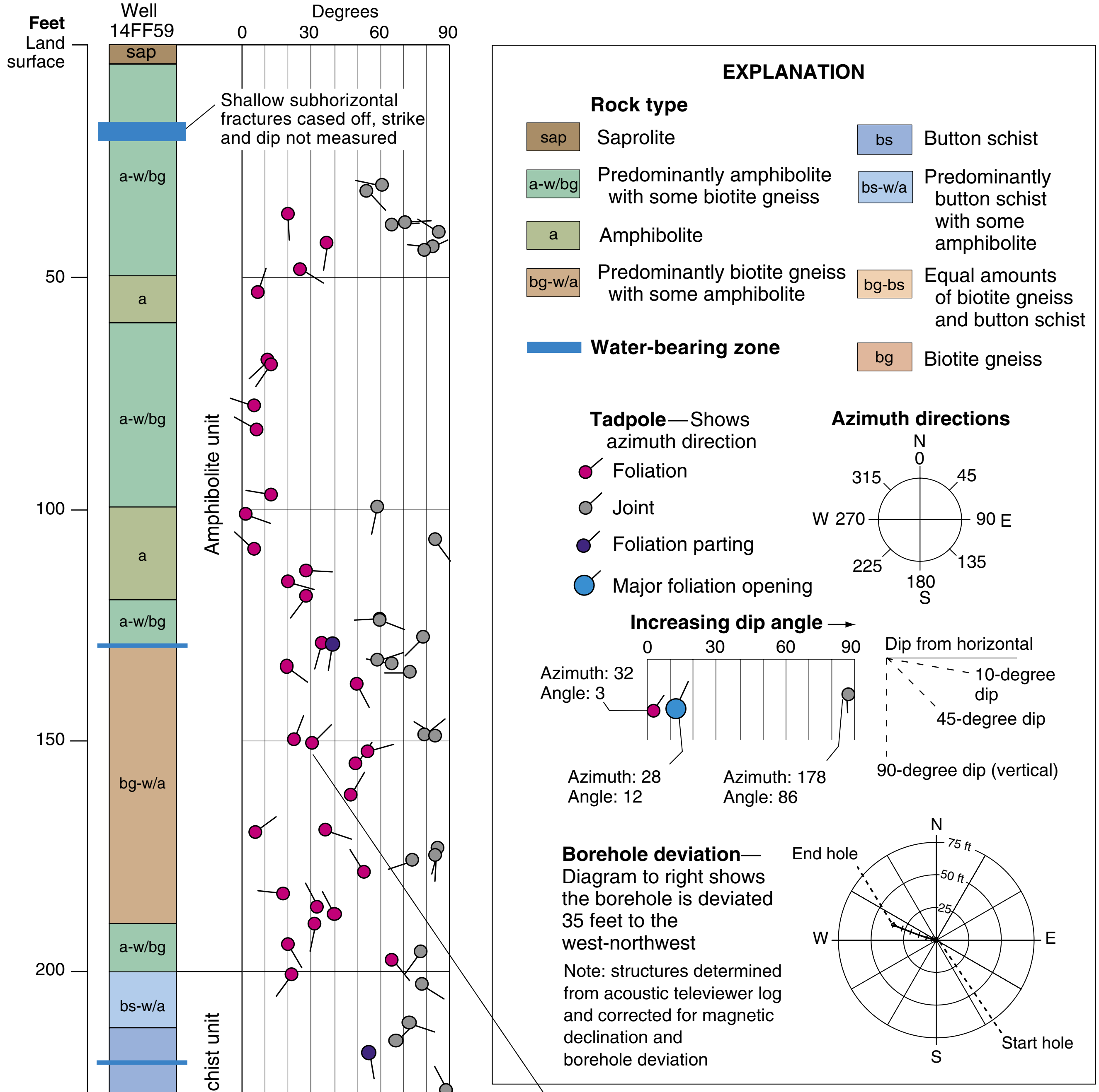


Figure 7. Subsurface lithologic characteristics and water-bearing zones tapped by well 14FF59 using borehole geophysical logs.



Gamma, in APIU
(American Petroleum Institute Units)
0 100 200 300 400 500
Lateral resistivity, in ohm-meters
0 100 200 300 400
Fluid temperature, in degrees Fahrenheit
65 66 67 68 69 70
Fluid resistivity, in ohm-meters
40 50 60 70
Baseline gamma response of amphibolite unit
Distinctive gamma response near button schist unit
Openings correspond to the top and bottom of lower gamma response zones
open
open
open
open
Response of resistive unfractured crystalline rock
Response of less resistive water-bearing rock
Inflection (ground-water inflow)
Inflection (ground-water inflow)
Geothermal gradient



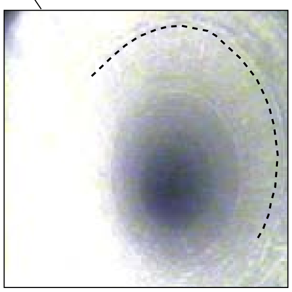
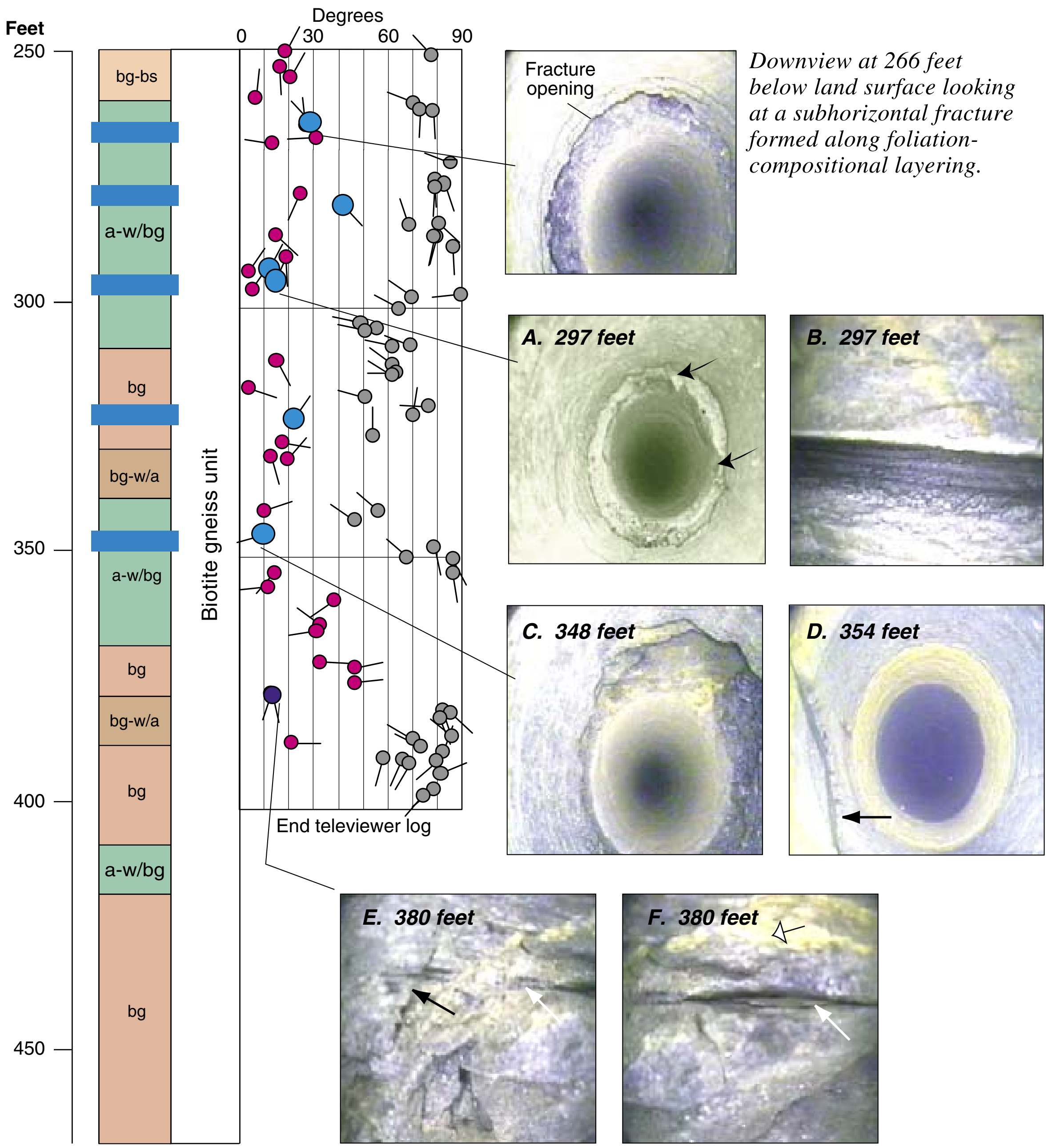

Downview at 152 feet below land surface looking at a smooth unfractured part of borehole; faint line on borehole wall (dashed line) is subhorizontal compositional layering (hole diameter is 8 inches.)

Figure 8. Structural tadpole plot and borehole camera images for well 14FF59.



*Images **A** and **B** show subhorizontal fracture at 297 feet below land surface formed parallel to compositional layering; high-angle joints (black arrows) terminate into the fracture from below; aperture is 3–4 inches. **Image C** shows the fracture formed at a contact between a darker rock above and a lighter rock below at 348 feet below land surface, **Image D** shows layering of light and dark rock and a high-angle joint face (black arrow). **Images E** and **F** show the same partially developed fracture (white arrows) along foliation-compositional layering during rotation of the downhole camera, these fractures probably are being enhanced by chemical weathering; yellowish material (open arrow) is a chemical precipitate (calicite or zeolite) formed in small openings of the rock; black arrow shows high-angle joint.*

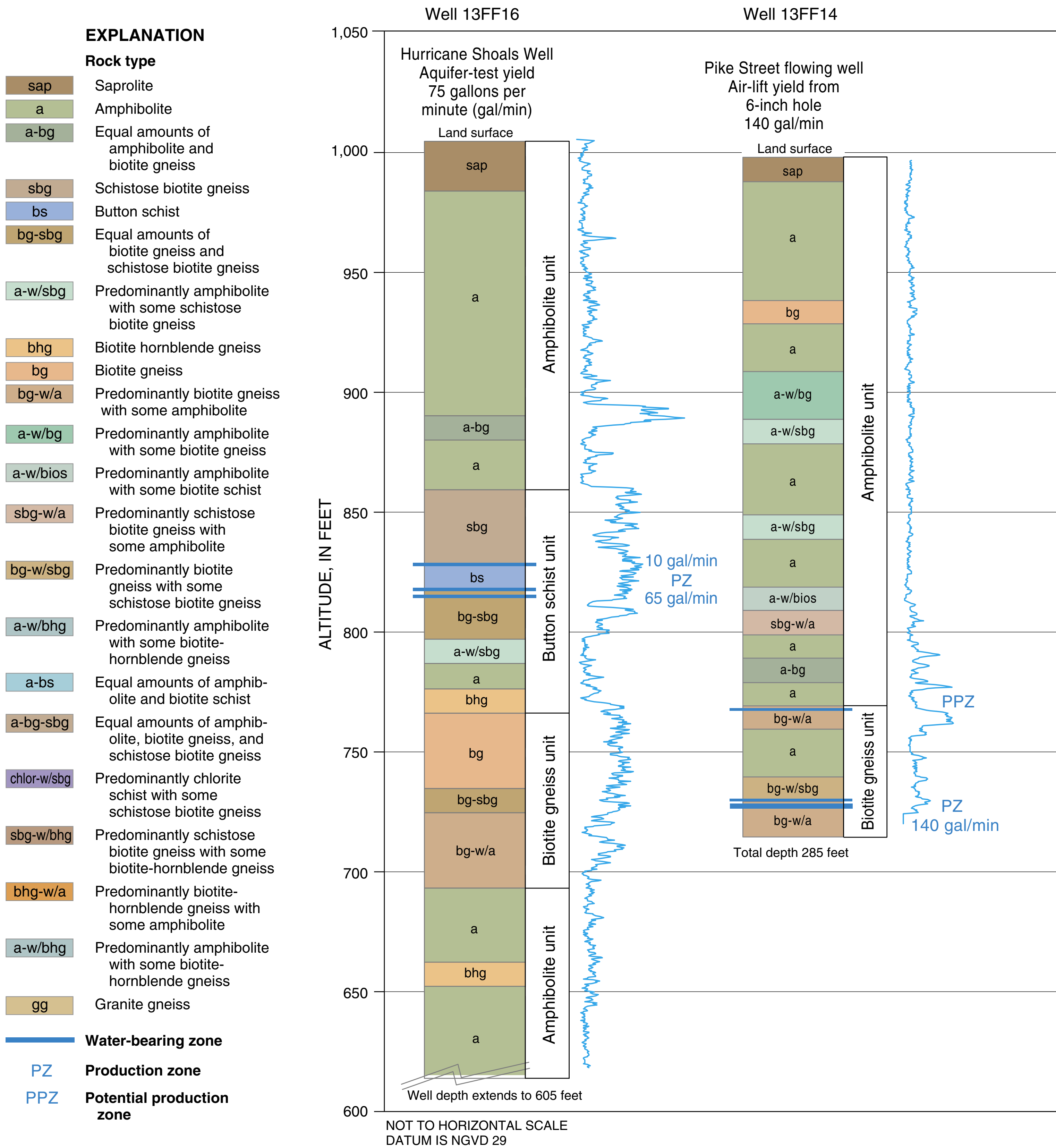
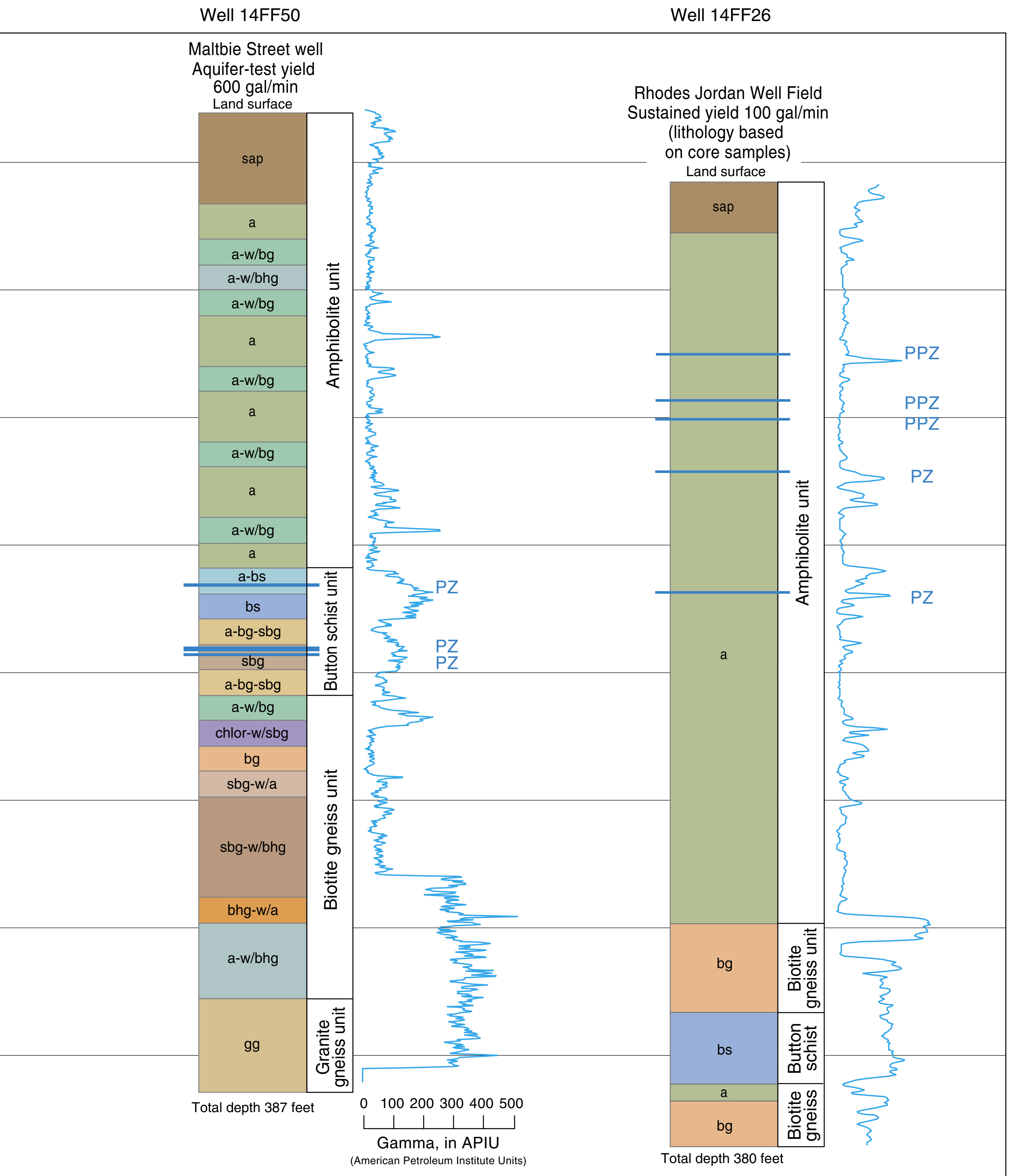


Figure 9. Subsurface lithologic characteristics and water-bearing zones tapped by wells 13FF16, 13FF14, 14FF50, and 14FF26.



Well 14FF50
Well 14FF26
Maltbie Street well
Aquifer-test yield
600 gal/min
Land surface
sap
a
a-w/bg
a-w/bhg
a-w/bg
a
a-w/bg
a
a-w/bg
a
a-w/bg
a
a-bs
bs
a-bg-sbg
sbg
a-bg-sbg
a-w/bg
chlor-w/sbg
bg
sbg-w/a
sbg-w/bhg
bhg-w/a
a-w/bhg
gg
Amphibolite unit
Button schist unit
Biotite gneiss unit
Granite gneiss unit
PZ
PZ
PZ
Total depth 387 feet
0 100 200 300 400 500
Gamma, in APIU
(American Petroleum Institute Units)
Rhodes Jordan Well Field
Sustained yield 100 gal/min
(lithology based
on core samples)
Land surface
sap
a
bg
bs
a
bg
Amphibolite unit
Biotite gneiss unit
Button schist
Biotite gneiss
PPZ
PPZ
PPZ
PZ
PZ
Total depth 380 feet

After pump shutdown, the water level recovered about 70 percent in 1 hour and fully recovered within 22 hours, indicating a fast recharge rate to the water-bearing zones supplying the well. The water level was drawn down 1.38 ft at well 13FF17 (2,800 ft away) and greater than 22.5 ft at well 13FF13 (1,950 ft away).

Well 13FF19, located on the floodplain of Pew Creek, was drilled to a total depth of 477 ft and was cased with 65 ft of 8-inch-diameter steel casing (table 1). Three primary water-bearing zones were encountered during drilling: one at 198 ft that yielded about 15 gal/min, one at 245 ft that yielded about 100 gal/min, and one at 356 ft that yielded 10 gal/min. All three water-bearing zones were determined to be foliation openings at lithologic contacts based on geophysical logging (Williams and others, 2004). For the aquifer test, the well was pumped for 46 hours at rates ranging from 223 to 300 gal/min so that the pumping water level was kept at about 185 ft, or about 95 percent of the available drawdown above the uppermost water-bearing zone. For an additional 26 hours, the well was pumped at a rate of 177 gal/min with a stabilized water level of about 152 ft. After pump shutdown, the water level recovered about 43 percent in 1 hour, but took 8 days to fully recover, indicating a slow recharge rate to the water-bearing zones supplying the well. The water level was drawn down about 1 ft at well 13FF25 (regolith well located 14 ft away) and about 1 ft at well 13FF21 (located 6,800 ft away), and was greater than 10.9 ft at well 13FF23 (located 3,900 ft away).

Well 13FF21, located on the floodplain of the Yellow River, was drilled to a total depth of 505 ft and was cased with 40 ft of 8-inch-diameter steel casing (table 1). A single water-bearing zone at a depth of 240 ft yielded about 125 gal/min. This water-bearing zone was determined to be a foliation opening at a lithologic contact based on geophysical logging (Williams and others, 2004). For the aquifer test, the well was pumped for 72 hours at rates ranging from 107 to 210 gal/min, so that the pumping water level was kept at about 194 ft, or about 80 percent of the available drawdown above the uppermost water-bearing zone. After pump shutdown, the water level recovered about 83 percent in 1 hour and was fully recovered within 39 hours, indicating a fast recharge rate to the water-bearing zones supplying the well. The water level was drawn down about 0.75 ft at well 13FF19 (located 6,800 ft away) but was not drawn down in the nearby regolith well 13FF24.

Well 13FF23, located on the floodplain of Redland Creek, was drilled to a total depth of 498 ft and was cased with 30 ft of 8-inch-diameter steel casing (table 1). Many water-bearing zones were encountered during drilling; the largest of these, at 243 ft, yielded about 150 gal/min. For the aquifer test, the well was pumped for 72 hours at rates ranging from 100 to 500 gal/min so that the pumping water level was kept at about 65 ft, or about 80 percent of the available drawdown above the uppermost water-bearing zone. After pump shutdown, the water level recovered about 25 percent in 1 hour and took 9 days to recover within 1 ft of the beginning water level, thus indicating a slow recharge rate to the water-bearing zones supplying the well. The water level was drawn down 22.37 ft at well 13FF19 (3,900 ft away) and 3.39 ft at well 13FF21 (2,900 ft away).

Well 14FF55, located along Shoal Creek south of the Rhodes Jordan Well Field, was drilled to a total depth of 450 ft and was cased with 63 ft of 8-inch-diameter steel casing (table 1). Many water-bearing zones were encountered during drilling; however, the largest were at 251 ft, with a yield of about 110 gal/min, and at 416 ft, with a yield of about 100 gal/min. These two water-bearing zones were determined to be foliation openings at lithologic contacts based on geophysical logging (Williams and others, 2004). For the aquifer test, the well was pumped for 72 hours at rates ranging from 240 to 400 gal/min so that the pumping water level was kept at about 91 ft, or about 90 percent of the available drawdown above the uppermost water-bearing zone. After pump shutdown, the water level recovered about 42 percent in 1 hour and was fully recovered within 48 hours, indicating a fast recharge rate to the water-bearing zones supplying the well. The water level was drawn down about 4 ft at regolith well 14FF61 (located 30 ft away) and about 5 ft at bedrock well 14FF16 (located 3,400 ft away).

Well 14FF59, located near the Alcovy River east of the Gwinnett County Airport, was drilled to a total depth of 470 ft and was cased with 35 ft of 8-inch-diameter steel casing (table 1). Five water-bearing zones (four major zones) were encountered between 260 and 350 ft, yielding from 5 to 50 gal/min. For the aquifer test, the well was pumped for 72 hours at four separate pumping rates (steps) ranging from 301 to 444 gal/min, with an average pumping rate of 362 gal/min. The first two steps of 444 gal/min and 398 gal/min resulted in a drawdown of 108 ft and 101 ft, respectively, or about 40 and 37 percent, respectively, of the available drawdown above the uppermost water-bearing zone. The third pumping step at 351 gal/min had a stable water level of 96 ft after pumping 22 hours, and the fourth pumping step at 301 gal/min had a stable water level of 82 ft after pumping 22 hours. After pump shutdown, the water level recovered about 88 percent within 1 hour, and was fully recovered within 7 hours, indicating a fast recharge rate to the water-bearing zones supplying the well. The water level was drawn down about 2.4 ft at well 14FF42 (located 3,100 ft away) and about 1 ft at regolith well 14FF60 (located 17 ft away).

In summary, the aquifer test results indicate the ability to sustain large ground-water withdrawals for the period of the test from the production wells. The rate of water-level recovery following pumping indicates that the water-bearing zones supplying the wells have widely varying degrees of interconnectedness with sources of recharge. The aquifer tests also confirm the production potential associated with foliation-parallel parting systems tapped by these wells.

Influence of Joint Systems

Joint systems, consisting of steeply-dipping sets of fractures, influence the availability of ground water in compositionally layered-rock settings; however, the relation between jointing in a particular area or basin to well yield was not well established in this study. Because of the importance of joint systems on ground-water availability, these systems of fractures warrant further discussion in this report. Examples of joint systems penetrated in wells 14FF59, 13FF16, 14FF56, and 13FF22 are discussed below.

The most common type of jointing in compositionally layered rocks appears to be strongly influenced by geologic structure and differing physical properties of lithologic units, as depicted on the conceptual model shown in figure 10. In these types of settings, “jointed” layers of rock are interlayered with “unjointed” or sparsely jointed layers of rock (fig. 10*A*). This type of jointing results in joints that terminate or deflect at contacts; thus, these would not necessarily extend to the land surface, as would be expected. Water probably recharges these types of joint systems laterally from the outcrop area or along contact zones, with much less influence directly from the overlying regolith (fig. 10*B* and *C*). In the Lawrenceville area, jointing tends to be more concentrated in more brittle rock units (quartzite, for example) than in ductile rock units (button schist, for example). Well 14FF59, described above, is one location where this type of jointing was observed (see fig. 8).

Other locations where structure and lithology appear to control joint development include well 13FF16, in which a jointed amphibolite overlies a poorly jointed button schist, and well 14FF56, in which poorly jointed button schist lies between jointed amphibolite and jointed biotite gneiss (fig. 11).

In well 13FF16, shown on the left side of figure 11, the overlying amphibolite is substantially more jointed than the underlying button schist. This difference is attributed to the physical properties of these two differing lithologic units. It should be noted that jointing observed in outcrops near well 13FF16 also was relatively abundant, indicating that the intensity of subsurface jointing can be correlated with jointing at the land surface at this particular well site.

In well 14FF56, shown on the right side of figure 11, the amphibolite and biotite gneiss units, which enclose button schist, are substantially more jointed than the more ductile button schist. Examination of figure 11 shows that the joints below the button schist in well 14FF56 are most abundant in a zone of foliation partings from about 340 to 420 ft; however, this interval did not produce any substantial amount of water (Williams and others, 2004). Jointing also is abundant in the intervals at about 50 and 150 ft near the major water-bearing zones.

In some wells, jointing was abundant enough to differentiate these as “zones of joint concentration.” In this report, zones of joint concentration are defined as intervals in which the bedrock is unusually well jointed and typically characterized by “open” water-bearing joints capable of producing small to moderate quantities of water. Based on their relatively common occurrence in boreholes and outcrops, zones of joint concentration probably are important hydrologic features throughout the Lawrenceville area. One zone of joint concentration was penetrated by well 13FF22, located on the floodplain of Redland Creek (fig. 1). The best-developed interval of joint concentration is from 468 to 475 ft, consisting of several open joints (fig. 12). Between these depths, joints are oriented in two main directions; one set strikes approximately east-west, and another set strikes approximately north-south, indicating an orthogonal system. Many of the joints in this zone are accompanied by dissolution openings (images D and E, fig. 12), indicating this as a hydraulically active zone. Despite the intense fracturing and dissolution in this interval, however, the yield from the zone of concentrated jointing was estimated to be only 30 gal/min; even then, some of this yield could be from a foliation parting identified in this same interval (fig. 12).

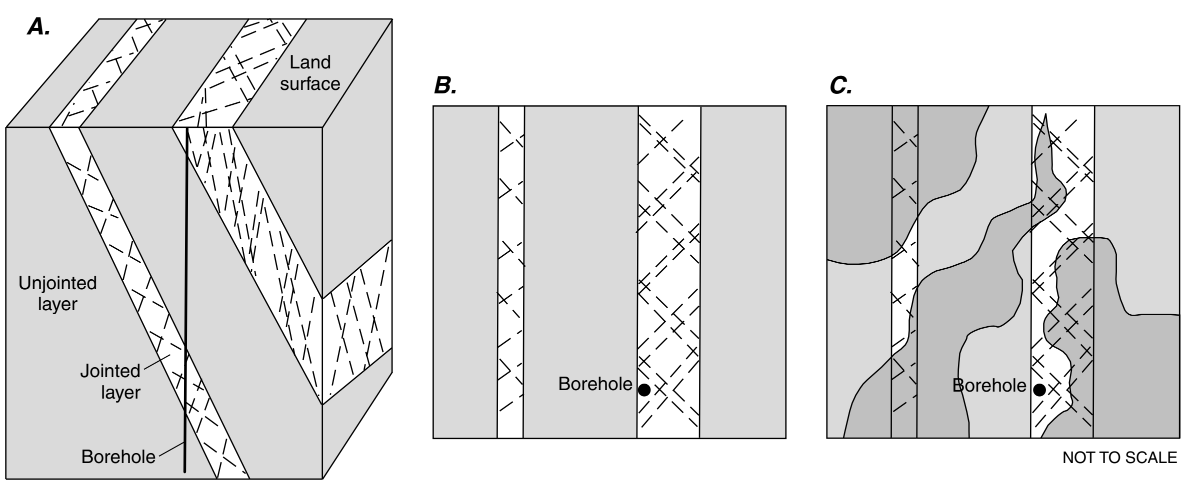


Figure 10. Schematic diagrams illustrating the *(A)* concept of jointed and unjointed layers of rock intersected by a borehole; *(B)* outcrop pattern resulting from this style of jointing; and *(C)* outcrop pattern with land cover. Differences in jointing result from differences in the physical properties of various interlayered lithologies. Joints terminate at contacts.

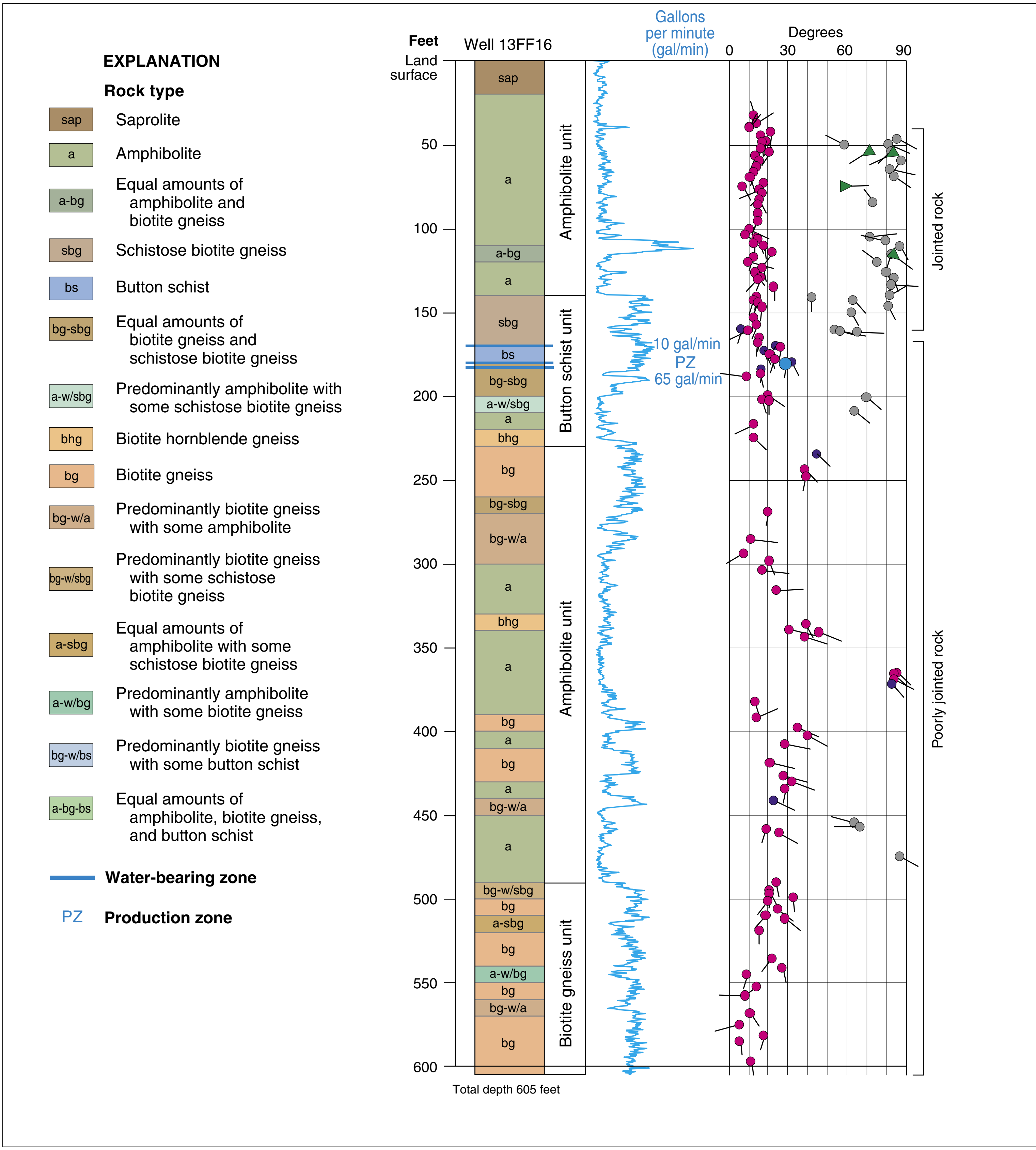
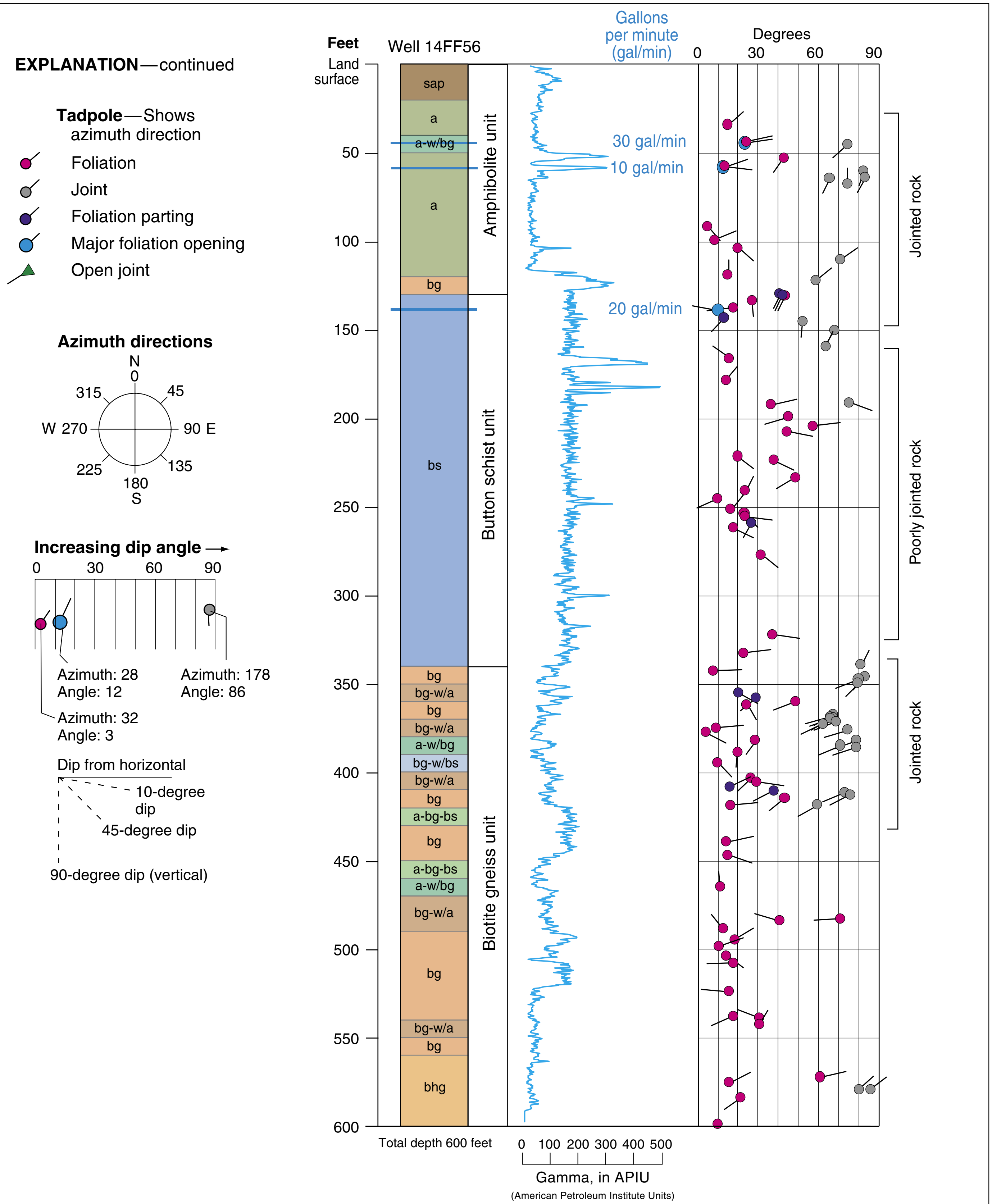


Figure 11. Subsurface lithologic characteristics and structural tadpole plots for wells 13FF16 and 14FF56 showing differences in jointing.


EXPLANATION—continued
Tadpole—Shows azimuth direction
Foliation
Joint
Foliation parting
Major foliation opening
Open joint
Azimuth directions
N 0
45
90 E
135
180 S
225
W 270
315
Increasing dip angle
0 30 60 90
Azimuth: 28
Angle: 12
Azimuth: 178
Angle: 86
Azimuth: 32
Angle: 3
Dip from horizontal
10-degree dip
45-degree dip
90-degree dip (vertical)
Feet
Land surface
Well 14FF56
Gallons per minute (gal/min)
Degrees
0 30 60 90
sap
a
a-w/bg
bg
bs
bg-w/a
a-bg-bs
bg-w/bs
bhg
Amphibolite unit
Button schist unit
Biotite gneiss unit
30 gal/min
10 gal/min
20 gal/min
Jointed rock
Poorly jointed rock
50
100
150
200
250
300
350
400
450
500
550
600
Total depth 600 feet
0 100 200 300 400 500
Gamma, in APIU
(American Petroleum Institute Units)

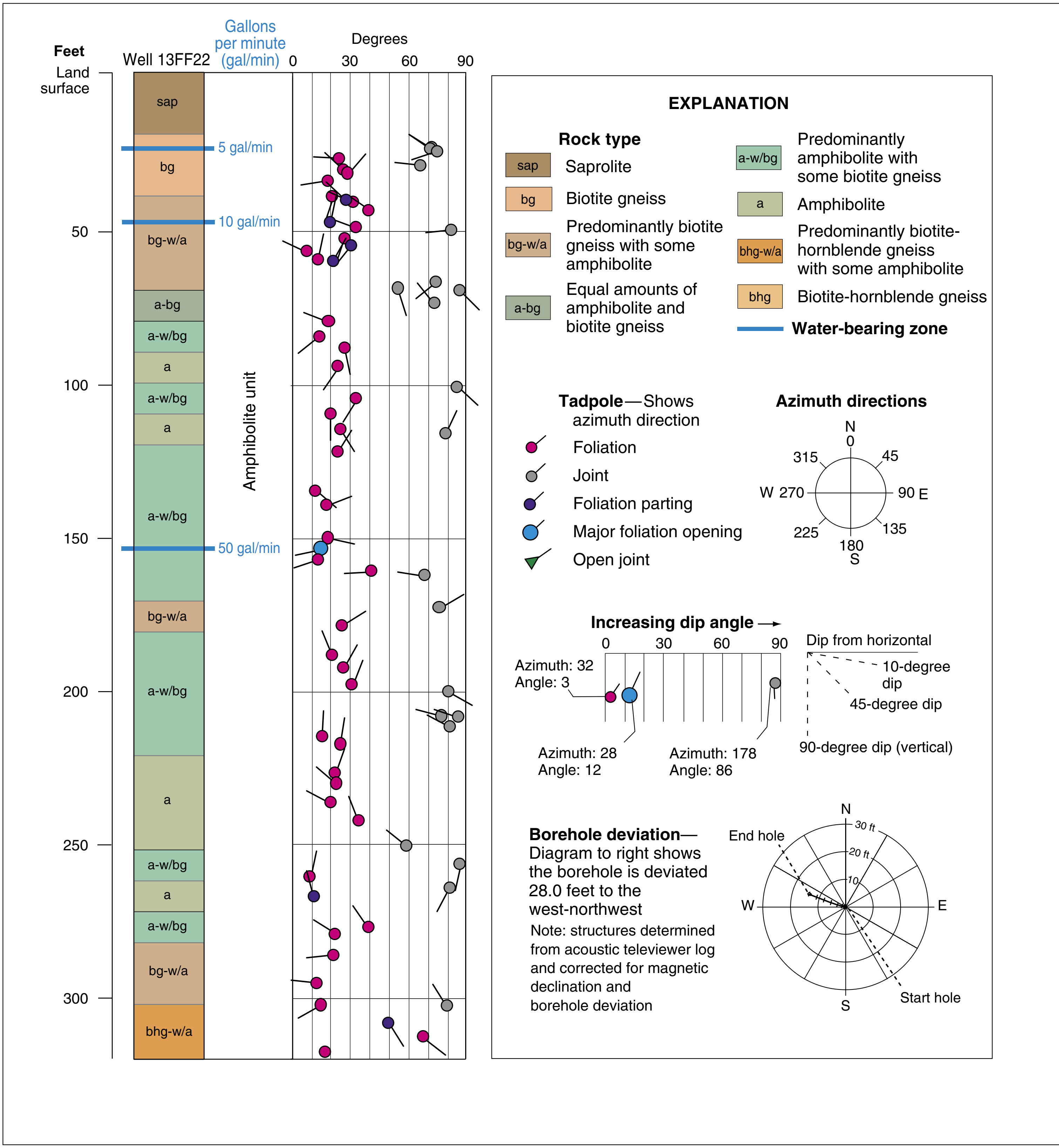
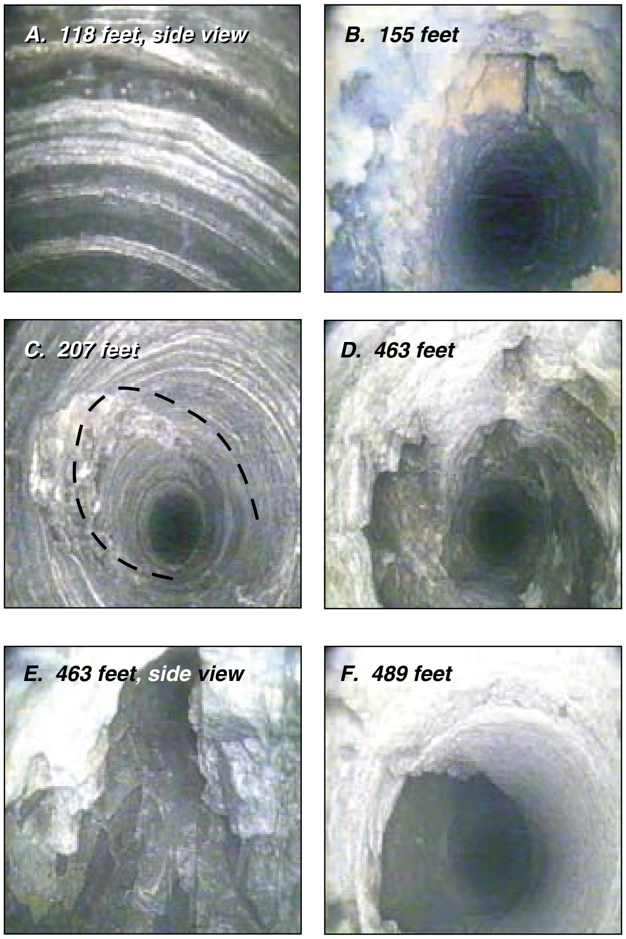
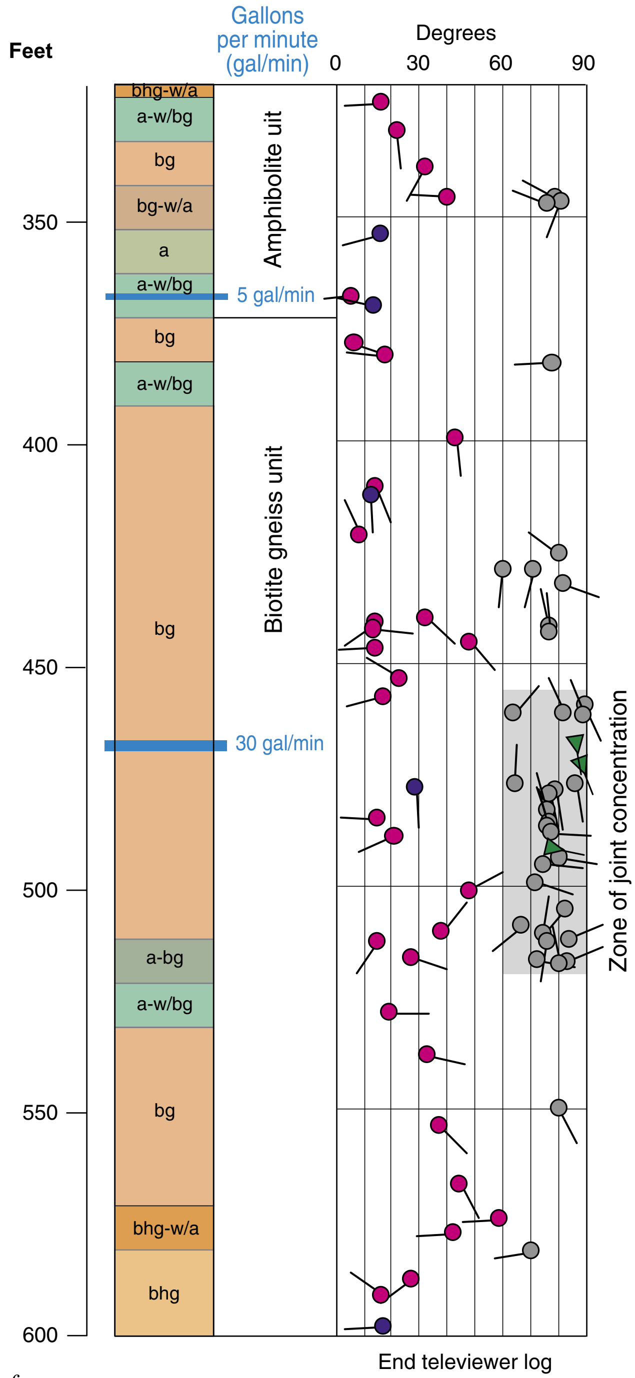


Figure 12. Structural tadpole plot and borehole camera images for well 13FF22.





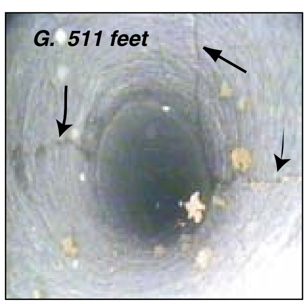


Image A *shows foliation in the rock in a side view at 118 feet below land surface.* ***Image B*** *shows a subhorizontal fracture at about 155 feet below land surface, formed parallel to compositional layering. White flocculent is probably iron bacteria.* ***Image C*** *shows a high-angle joint (dashed line) intersected by the borehole at about 207 feet below land surface.* ***Image D*** *shows a large opening probably caused by chemical solutioning along steeply-dipping joints at about 463 feet below land surface.* ***Image E*** *shows a side view into one of the large openings in Image D.* ***Image F*** *shows an open joint at about 489 feet below land surface.* ***Image G*** *shows high angle joints (black arrows) intersected by the borehole at about 511 feet below land surface.*

Conceptual Model of Ground-Water Availability

A conceptual model used to explain the system of productive water-bearing zones (foliation-parallel parting systems) in compositionally layered-rock settings was referred to as the “weathering-wedge model” by Williams (2003) (fig. 13). This model was based primarily on the observed relation between the occurrence of water-bearing zones in open boreholes of wells and the surface exposures of lithologic units. The weathering wedge is simply a zone of weathered rock along a lithologic contact or other stratigraphic feature that starts from the outcrop area and/or from steeply-dipping joint systems and extends in a down-dip direction. As a result of down-dip weathering, weaknesses eventually form in the bedrock that, in turn, separate to create physical openings in response to stress-relief and/or tectonic stresses (buckling from compressive forces, for example); although stress-relief or tectonic processes may not necessarily be needed to produce these features.

Differential weathering from the outcrop area in a down-dip direction appears to be the best model for explaining the high well yields at the Rhodes Jordan Well Field (wells 14FF10 and 14FF16), Maltbie Street (wells 14FF08 and 14FF50), and well 14FF59 (see fig. 2). Joints and joint systems also may influence the development and extent of weathering wedges in the bedrock at these sites. Open high-angle joints intersect many of the high-yield foliation partings/openings observed in boreholes, emphasizing the importance of joints in the development of foliation-parallel parting systems.

Recharge to foliation-parallel parting systems is possible, either from the regolith in the outcrop area or through discrete joint systems that allow vertical ground-water movement into the deeper bedrock (fig. 13)—the contribution from each, however, is unknown. In the outcrop area (upland setting), water stored in the regolith flows into foliation-parallel parting systems laterally and down-dip from the outcrop area possibly with steeply-dipping joints serving to further connect the system of deeper foliation-parallel partings/openings to the regolith. Once a flowpath is established, continued ground-water flow and progressive differential weathering cause further development of foliation partings and openings that comprise foliation-parallel parting systems. As a result, ground-water flow system formed along contact zones potentially could be confined or semiconfined over most of the flowpath, with discharge only through steeply-dipping joint systems (fig. 13). The occurrence of flowing wells in the Lawrenceville area seems to support this model; many of these wells flow at rates from 10 to more than 50 gal/min (Williams and others, 2004). In addition, flowmeter surveys indicate these systems are confined or semiconfined at several wells; flowmeter surveys at wells 13FF23 and 14FF55, for example, revealed confined conditions in deep water-bearing zones that cause water to flow upward through open boreholes and exit out of lower-head, shallower water-bearing fracture zones (Williams and others, 2004).

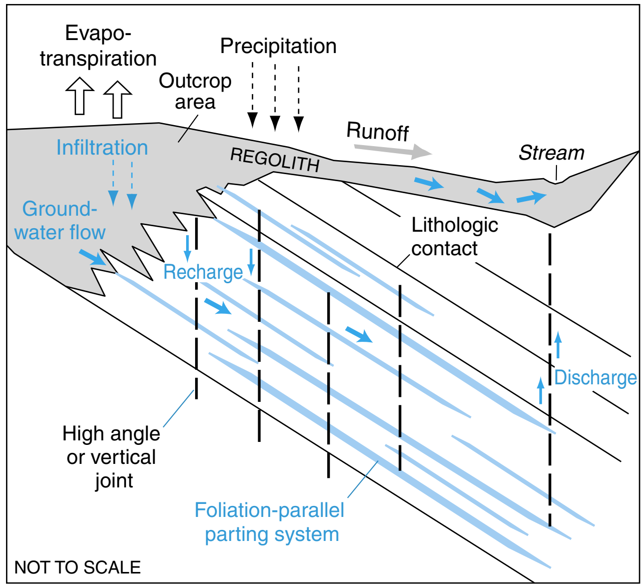


Figure 13. Weathering-wedge model showing an inclined sequence of compositionally layered rocks exposed to intense chemical and physical weathering at the outcrop. In situ weathering causes progressively deeper weathering along foliation and compositional layering and may produce down-dip productive foliation-parallel parting systems. These systems are recharged laterally from the outcrop or vertically from high-angle joint sets (from Williams, 2003).

Using this conceptual model, geologic settings favoring high ground-water yield should be those that promote weathering parallel to foliation/compositional layering in a down-dip direction from the outcrop area; specifically, along those rock sequences most susceptible to differential weathering. In the Lawrenceville area, this occurs in sequences of amphibolite, biotite gneiss, and button schist where the rocks are gently dipping, in areas characterized by abundant jointing and in topographic settings favoring a continuous source of recharge along these structures.

An important distinction is made between a “top-down” weathering profile of traditional hydrogeologic concepts to the “lateral” weathering indicated by the weathering wedge model. In the latter, the source water supplying a deep well actually may originate many hundreds or even thousands of feet away from the producing well and, therefore, would not be drawn from near the pumped well (as would be assumed). This makes determining the contributing area to a well more difficult, but not entirely impossible, and emphasizes that wellhead protection could be more involved than simply protecting the area immediately around the well.

Methods for Identifying and Characterizing Foliation-Parallel Parting Systems

Identifying high-yield water-bearing zones is important in water-resource investigations of igneous and metamorphic bedrock areas. In this study, the only practical means for identifying and characterizing foliation-parallel parting systems (and other types of water-bearing zones) was through detailed geologic mapping followed by test drilling, borehole geophysical logging, and aquifer testing. Geologic mapping was used to define rock types; the areal distribution and structural attitude of the rock units; the nature, extent, and structural attitude of discontinuities; and the weathering characteristics and topographic setting. Borehole geophysical logging was used to identify rock units in the subsurface and used to characterize the depth and nature of foliation-parallel parting systems and other water-bearing zones in the subsurface. Aquifer-test results provide a means of delineating the general extent and direction of drawdown, which could be used to infer the extent and hydrologic characteristics of foliation-parallel parting systems. Although some of these methods, such as geologic mapping, are time intensive, the likelihood of locating productive foliation-parallel parting systems or other water-bearing discontinuities is greatly enhanced by using these methods.

One of the more effective techniques used to increase the likelihood of intercepting specific structural or stratigraphic features (such as a compositionally layered-rock sequence with the potential for permeable contact zones) was a structural projection of the rock units into the subsurface (from 100 to 600 ft) using available geologic and borehole data. Although structural projections can be made in the absence of borehole data, these are more effective if the contacts are identified in the subsurface at one or more wells. Near well 14FF59, a two-point projection of the rocks between the outcrop and well 14FF42 (see fig. 5) indicated a dip of about 10 degrees, or about 176 ft per 1,000 ft (see fig. 6). This projection was accurate to within 30–40 ft of the contact penetrated in well 14FF59. Structural projections also were used with success at wells 13FF17, 13FF18, 14FF55, and 14FF56. Although using a structural projection is simple in concept, it requires that the stratigraphy and geologic structure be understood in the area of consideration.

Topography and weathering characteristics, along with lithology and structure, also can be used to identify potentially productive foliation-parallel parting systems. The relations among rock type, structure, topography, and weathering characteristics must be considered when attempting to identify these potentially productive systems. In Lawrenceville, most of the high-yield wells are located in topographic settings favoring recharge along structural and stratigraphic features. A well located structurally down-dip from potential recharge (fig. 14) is more likely to have high sustainable yield than a well positioned farther up-dip. The well located on the right in figure 14 (Well A) is ideally positioned for receiving recharge necessary to sustain the well yield. On the other hand, the well on the left in figure 14 (Well B) does not have a large recharge area to support a large sustained yield. In geologic settings where the rocks have low-angle dips, such as in the Lawrenceville area, the foliation-parallel parting systems may extend beneath topographic basin divides (fig. 15). In this situation, wells located in topographically less-favorable positions may in fact penetrate the foliation-parallel parting system with depth as illustrated by Well C in figure 15. In this case, the topographic position of the well may have less influence than the structural position and the extent of weathering along foliation and compositional layering.

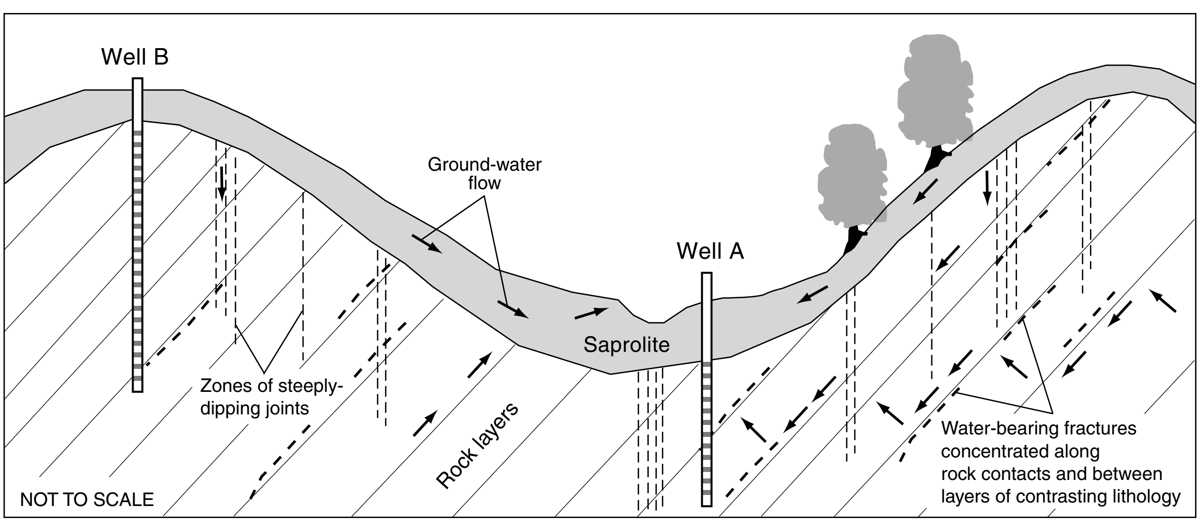


Figure 14. Relative positions of wells tapping into a moderately inclined, compositionally layered-rock system: Well A is in a topographically favorable position for intercepting influent recharge; Well B is in a topographically less favorable position (modified from McCollum, 1966).

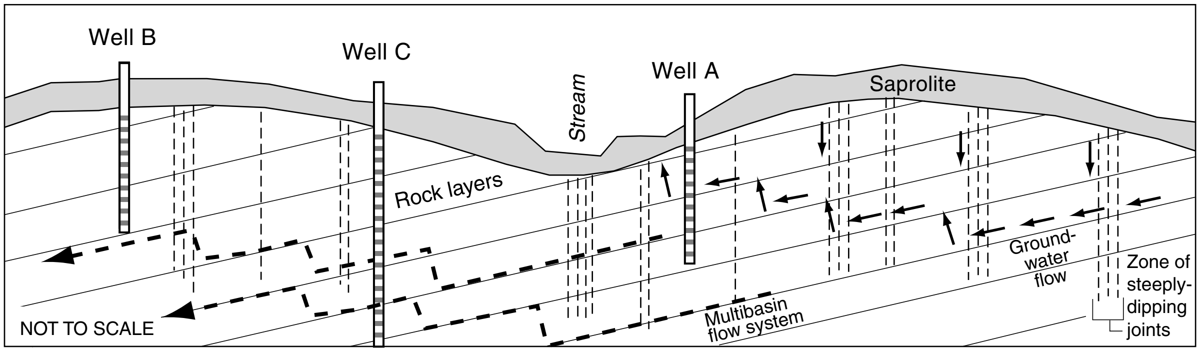


Figure 15. Relative positions of wells tapping into a gently inclined, compositionally layered-rock system: Well A is in a topographically favorable position for intercepting influent recharge; Well B is in a topographically less favorable position; and Well C is in a topographically less favorable position, but is structurally down dip and may intercept deeper multibasin flow systems (modified from McCollum, 1966).

Gaining a good understanding of the water-bearing potential of foliation-parallel parting systems requires collection and interpretation of subsurface data. In the open boreholes of wells, the only available means of identifying and characterizing foliation-parallel parting systems is through geophysical logging and borehole camera surveys. Borehole camera surveys are particularly effective in helping to identify these systems and require minimal data interpretation. In the Lawrenceville area, the characteristics of foliation-parallel parting systems include small openings along foliation planes (partings), larger openings along compositional layers, and partial openings (voids). The strike and dip of these partings/openings is similar to the strike and dip of surrounding foliation and compositional layering.

Acoustic and optical televiewer logs provide the only means available to measure the strike and dip of foliation and compositional layering in the open boreholes of wells. These data help characterize the orientation of foliation-parallel parting systems in the subsurface. Because the strike and dip of foliation and compositional layers in metamorphic rocks can vary considerably in a vertical borehole (fig. 16), these measurements may only give a general indication of structural attitude of the rocks in the subsurface. This is especially problematic where the dip of the rock units is at a low angle or undulatory. In this situation, it may not be possible to determine the regional foliation trend or the overall dip of rock units using borehole measurements. For this reason, subsurface measurements of foliation and compositional layering should be used in combination with surface measurements wherever possible.

Borehole deviation logs provide another source of data that may indicate the generalized strike and dip of the major rock units in the subsurface. Williams and others (2004) noted that boreholes in the Lawrenceville area deviate in an up-dip direction. As a result, if a borehole shows a consistent deviation direction, then this information may be useful in estimating the generalized dip of the units.

Finally, aquifer tests provided one of the more effective means of delineating the general extent and orientation of foliation-parallel parting systems. During aquifer tests, drawdown resulting from pumping generally was greater parallel to bedrock foliation and layering than perpendicular to this trend (Williams and others, 2004); hence, the drawdown observed in observation wells could be used to infer the extent and orientation of foliation-parallel parting systems. In order to use this technique, the detailed geologic structure should be mapped at the land surface and observation wells located ideally (1) structurally up-dip or down-dip and (2) along the strike of the rock units with respect to the pumped well. The open interval of the observation wells should be similar to that of the pumped well or deep enough to intercept the same water-bearing zones tapped by the production well.

Massive-Rock Settings

Wells penetrating massive rocks in the Lawrenceville area generally derive most of their yield from joint systems, which makes these systems behave much differently than that described for layered-rock settings previously.

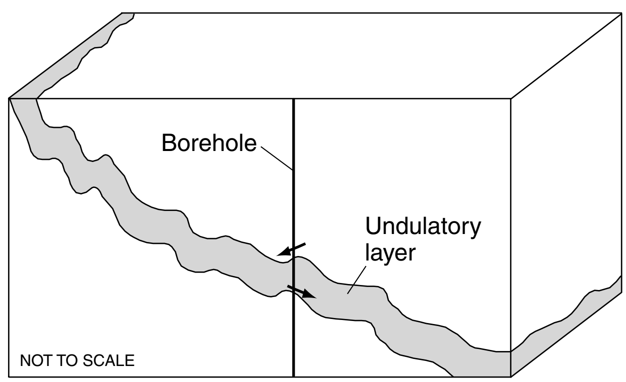


Figure 16. Schematic diagram illustrating an inclined undulatory layer intersected by a vertical borehole. Foliation and compositional layering in a borehole (arrows) can have dips that vary in direction and magnitude because of small-scale folding in the rock. Structural measurements of foliation and compositional layering in boreholes should be interpreted in conjunction with surface measurements.

Joints, as described in earlier sections, are distinguished from other types of water-bearing discontinuities by their planar character and their occurrence as sets of fractures with parallel alignment. Figure 17 shows a well-developed set of joints in granite gneiss. Because of their orientation, joints allow movement of water into the bedrock from the overlying regolith. This process not only transfers water, but also enhances physical and chemical weathering of the bedrock. As described in the following section on well 14FF58, joint systems influence both surface drainage and ground-water flow.

Although the geometry of joint systems varies substantially across the Lawrenceville area, the most common type observed in massive-rock settings is orthogonal in widely spaced sets (fig. 18). In this type of jointing, zones of jointed rock (or zones of joint concentration) are interspersed with zones of poorly jointed rock (fig. 18*A* and *B*). This type of jointing differs from that illustrated for compositionally layered-rock settings shown in figure 10.

Example of a Well (14FF58) in a Massive-Rock Setting

One of the better examples of a well deriving water from joint systems in a massive-rock setting is from well 14FF58, located east of Collins Hill Road on Georgia Hwy. 316 (fig. 19). The location for well 14FF58 was selected because it is near a contact zone between granite gneiss and biotite gneiss and because of its position near a potential zone of joint concentration along a linear stream segment (fig. 19). Although zones of joint concentration are common in the rocks of the Lawrenceville area, this specific joint concentration, in deeply weathered granite gneiss, suggested a potentially high yield might be obtained from this area. Geologic structures identified during mapping included: massive (not compositionally layered), poorly foliated rock; zones of joints; and apparent deep weathering of the bedrock. One of the key considerations in selecting this site was the potential for intercepting a zone of joint concentration.

Well 14FF58 is 550 ft deep and penetrates massive, relatively well-jointed granite gneiss (fig. 20). Based on the driller's log, water-bearing zones were encountered at a shallow depth near the bottom of casing, and at two deeper intervals; because of low yield, however, the depths of water-bearing zones were not determined at the time of drilling. From borehole video images, ATV logs, and flowmeter surveys, the borehole intersects three open water-bearing joints at depths of 35, 288, and 498 ft (fig. 20) (Williams and others, 2004).

Based on orientation measurements, the joint system penetrated by this well consists of several sets of moderately- to steeply-dipping joints (fig. 21). The strike of these joints is strongly grouped in a northwest-southeast direction, as illustrated by the rose diagram in figure 21. The distribution of joints along the borehole is uneven, resulting in well-jointed rock separated by poorly jointed rock. Joint concentrations are abundant at depths 140–160, 170–230, 280–300, 380–400, 430–500, and 520–550 ft; the apparent vertical separation of these joint concentrations is between 10 and 80 ft.

Figure 17. Steeply-dipping joints in a granitic gneiss. Outcrop is northwest of the intersection of Georgia Highways 316 and 20 north of Lawrenceville. Joints (arrows) are closely spaced. The 4½- by 7-inch notebook is for scale. Photo by Lester J. Williams, USGS.

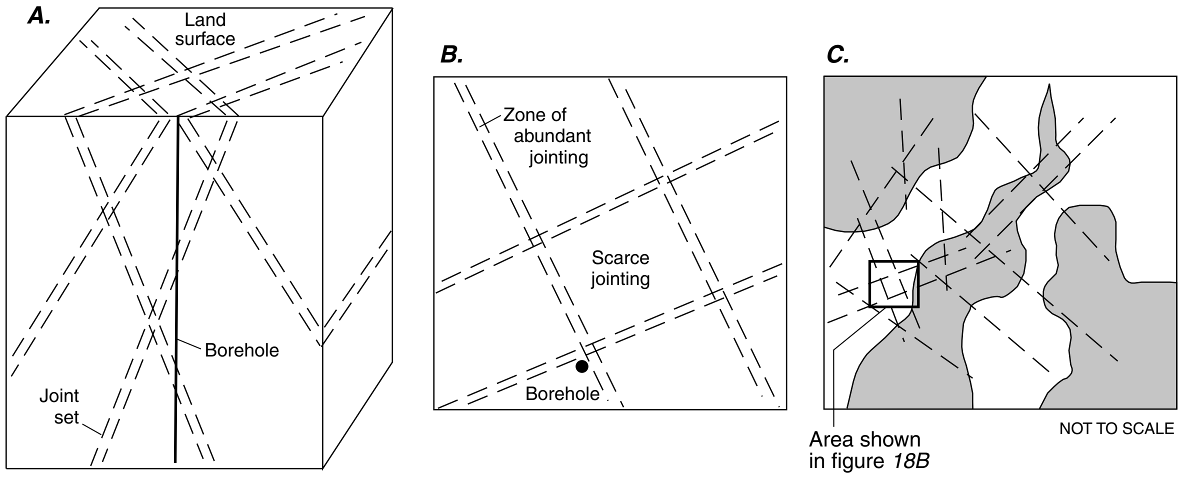


Figure 18. Schematic diagrams illustrating: *(A)* sets of orthogonal joints crossing a borehole and extending to land surface; *(B)* outcrop pattern of orthogonal joints near borehole; and *(C)* joints observed in borehole may represent only a small part of the larger joint system. Land cover (shaded) limits rock exposure at land surface.

Although this well intersects many joints and zones of joint concentration, most of these fractures are tight and do not appear to be water bearing (see borehole image C at 472 ft, fig. 21). Some of the joints have been totally annealed, whereas others have iron staining indicating some seepage of ground water through these fractures (iron-stained joints are shown in borehole camera images A, D, and F from 34, 498, and 546 ft, respectively; fig. 21). Only one joint, at a depth of 498, forms a substantial opening (borehole camera images D and E, fig. 21).

From the geologic mapping and geophysical surveys described above, some of the key geologic features identified at well 14FF58 that are believed to contribute to the low yield are:

- massive, poorly foliated rock;
- joints oriented primarily in one direction, thus greatly limiting the interconnectivity of the fracture network needed for recharge and transmission of water into the bedrock;
- absence of subhorizontal discontinuities needed to interconnect zones of steeply-dipping joints; and
- small catchment area for recharge.

Other Wells in Massive-Rock Settings

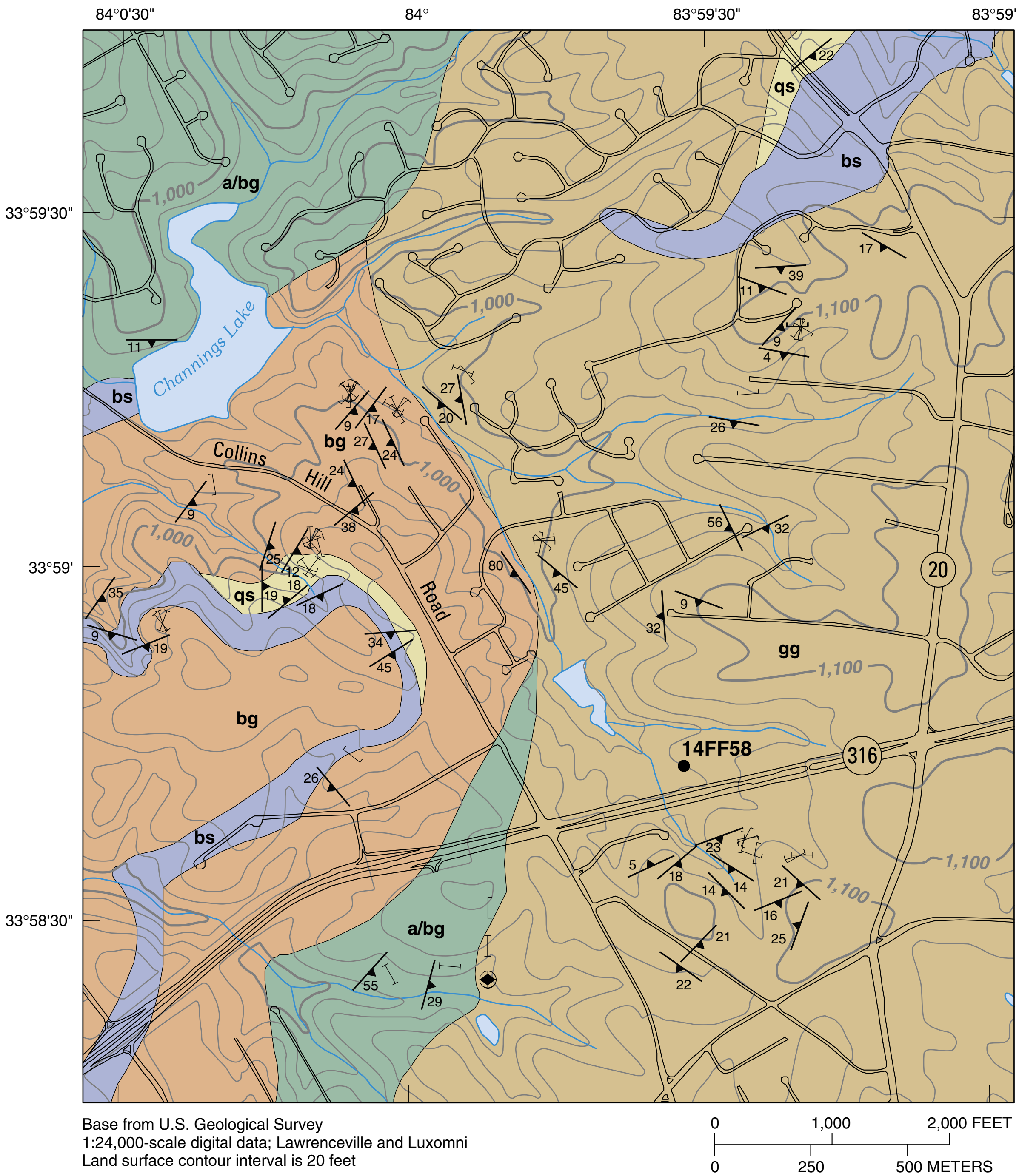
In massive-rock settings, the principal structural and water-bearing features are joint systems, although some water-bearing openings also can occur along weakly developed foliation planes. In one well (14FF47, figs. 1 and 2), the main water-bearing zones were determined to be foliation partings in combination with joints yielding about 3 gal/min (Williams and others, 2004).

Massive rocks also are penetrated at several locations beneath compositionally layered rock. In one well (14FF49, figs. 1 and 2), jointed, massive granite gneiss underlies a layered sequence of rocks. Despite the intense jointing in the massive granite gneiss, no substantial water-bearing zones were penetrated in this massive section. In fact, the only water-bearing zones identified in this well were foliation partings in the overlying sequence of compositionally layered rocks with a total yield of 10 gal/min (Williams and others, 2004).

Conceptual Model of Ground-Water Availability

In massive-rock settings, wells derive water mostly from joint systems, although openings formed parallel to foliation also may be important. The geometry of the fractures supplying wells in massive rock may differ substantially from that described for layered-rock systems. If the water is derived mostly from steeply-dipping joints, then, by the nature of the fractures, the well will be in greater hydraulic connection with the overlying regolith and, hence, may be more susceptible to shallow surface contamination near the well site. Because wells deriving water from joint systems typically only range from 1 to 5 gal/min (Williams and others, 2004; Williams, 2003), massive-rock systems do not represent an important source for the development of larger municipal supplies.

Because massive-rock settings generally lack the contrast in compositional layering and the foliation needed to produce well-developed foliation-parallel parting systems (and high ground-water yield), these systems are not an important source that could be tapped for large water supplies; however, smaller domestic supplies could be developed from these systems. Based the geometry of the water-bearing zones, the greatest availability of ground water in massive-rock settings should be from zones of joint concentration and in areas of joint intersection.



EXPLANATION

Lithologic unit

- gg — Granite gneiss
- bg — Biotite gneiss
- bs — Button schist
- a/bg — Layered amphibolite and biotite gneiss
- qs — Quartzite/schist

14FF58 ● **Test well and site name**

Structure symbol

- Joint showing strike and dip direction
- Vertical joint
- Horizontal foliation
- 16 — Foliation showing strike and dip angle

Figure 19. Geologic map and location of well in the Collins Hill Road area, Lawrenceville, Georgia (modified from Chapman and others, 1999).

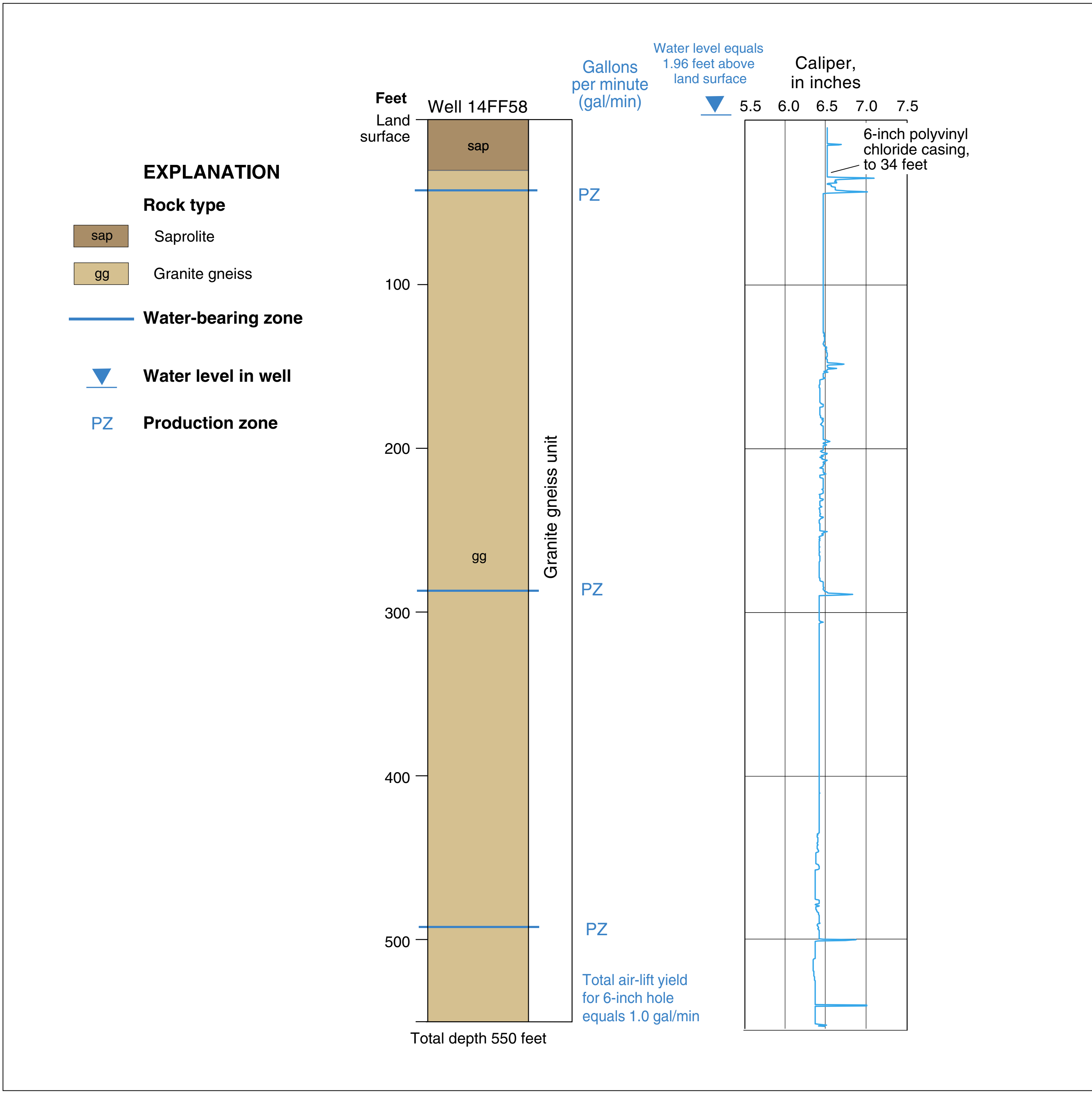
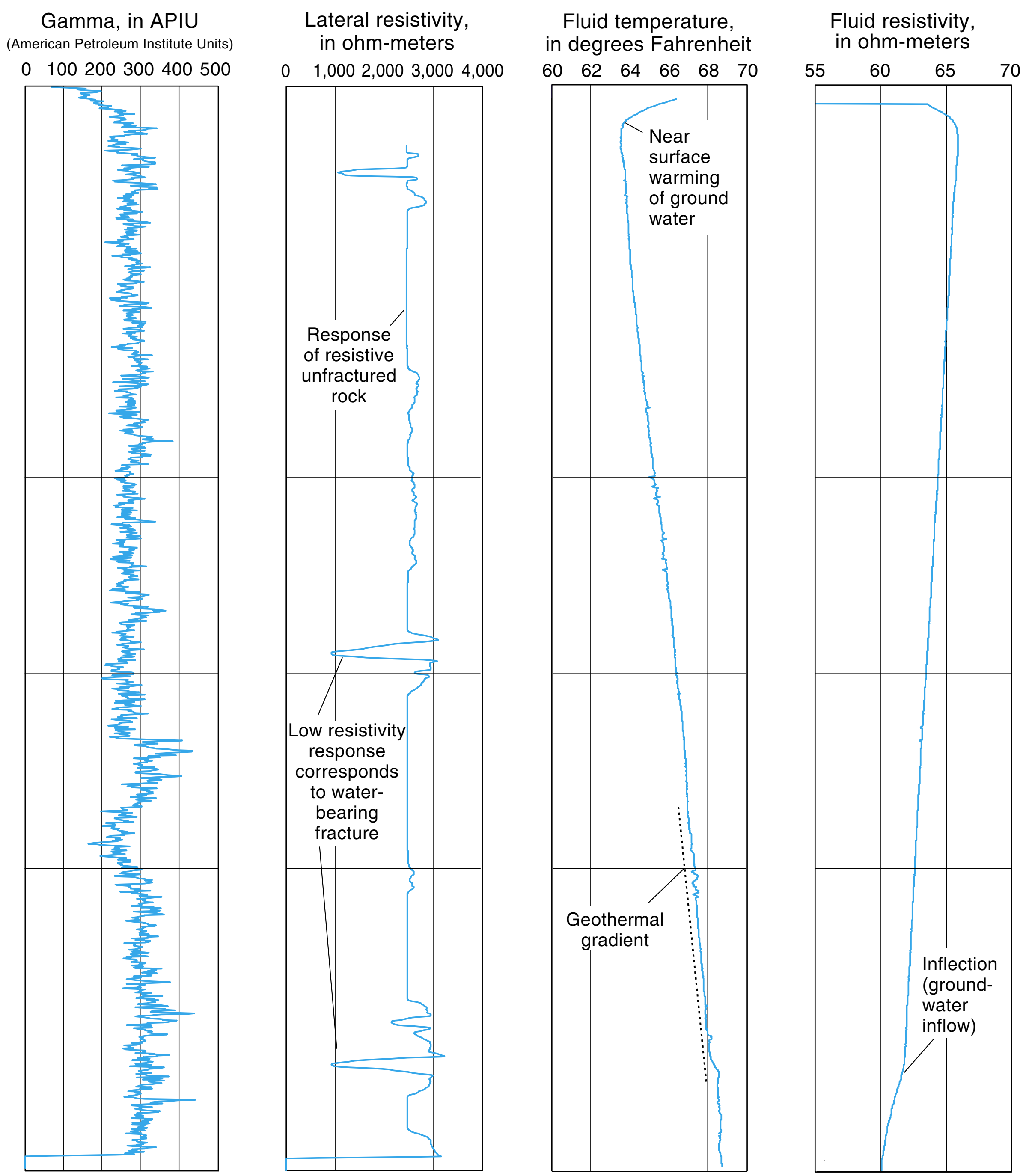


Figure 20. Subsurface lithologic characteristics and water-bearing zones tapped by well 14FF58 using borehole geophysical logs.



Gamma, in APIU
(American Petroleum Institute Units)
0 100 200 300 400 500
Lateral resistivity, in ohm-meters
0 1,000 2,000 3,000 4,000
Response of resistive unfractured rock
Low resistivity response corresponds to water-bearing fracture
Fluid temperature, in degrees Fahrenheit
60 62 64 66 68 70
Near surface warming of ground water
Geothermal gradient
Fluid resistivity, in ohm-meters
55 60 65 70
Inflection (ground-water inflow)

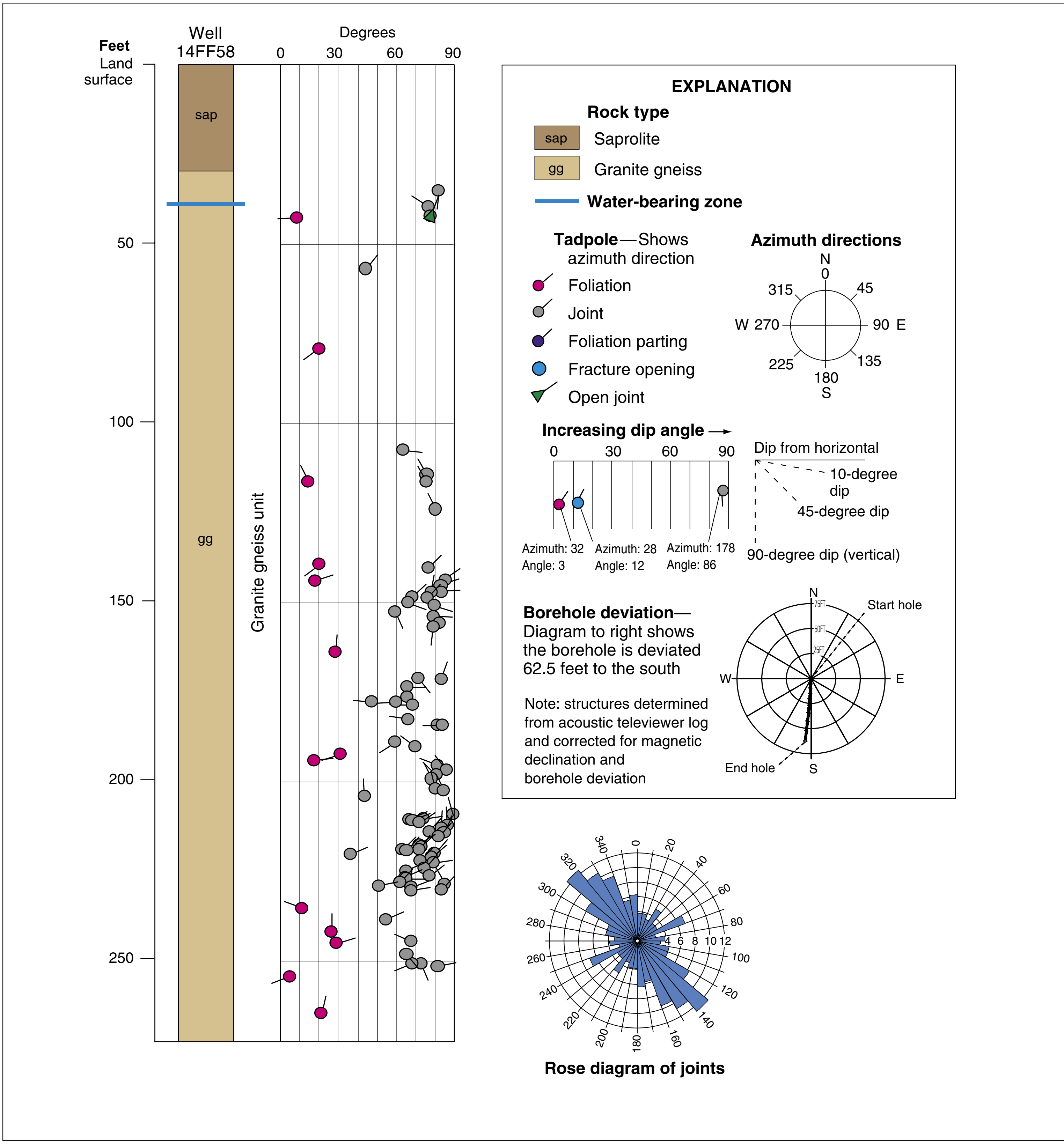
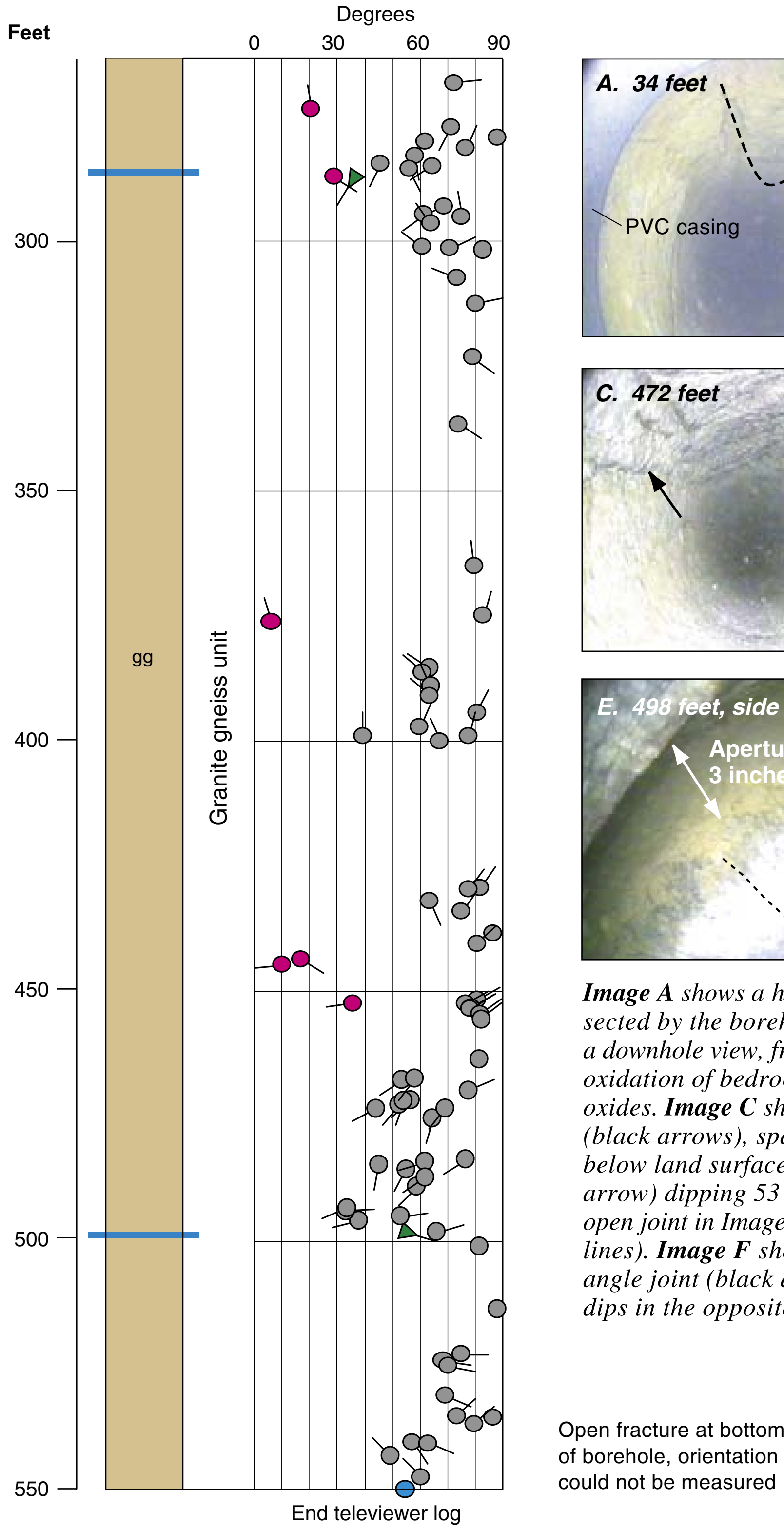


Figure 21. Structural tadpole plot and borehole camera images for well 14FF58.



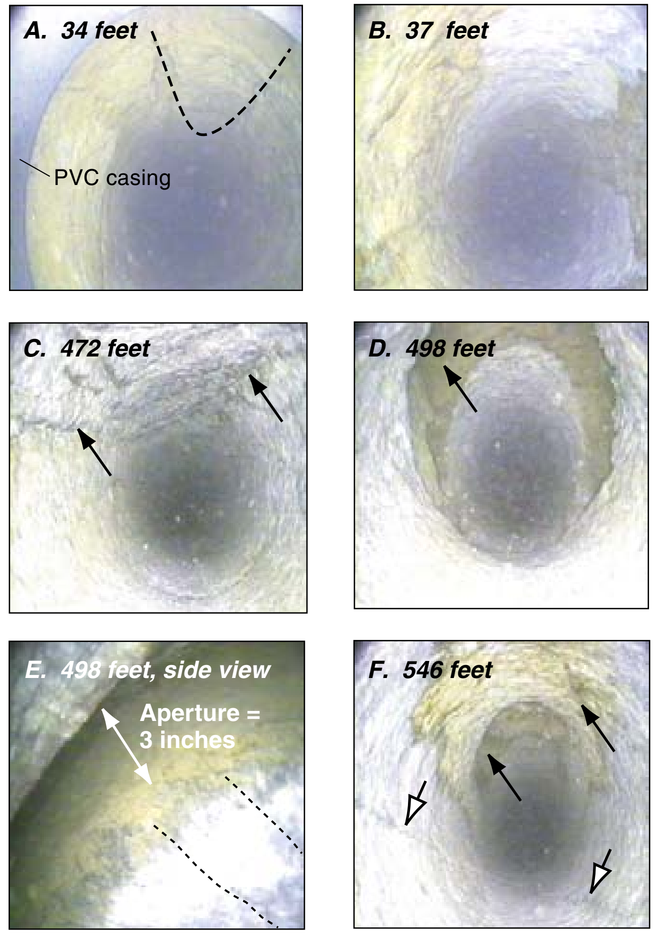


Image A *shows a high-angle fracture (dashed line) intersected by the borehole just below casing.* ***Image B*** *shows a downhole view, from 37 feet, of chemical weathering and oxidation of bedrock; darker areas are stained with iron oxides.* ***Image C*** *shows a group of closely spaced joints (black arrows), spacing is less than one inch at 472 feet below land surface.* ***Image D*** *shows an open joint (black arrow) dipping 53 degrees.* ***Image E*** *is a side view of the open joint in Image D; joint cuts across foliation (dotted lines).* ***Image F*** *shows chemical oxidation along a high-angle joint (black arrows); another joint (open arrows) dips in the opposite direction and appears to be tight.*

Methods for Identifying and Characterizing Joint Systems

Identification and characterization of joint systems may be an important component of a water-resources investigation, particularly in massive-rock settings dominated by ground-water flow in joint systems. Joint systems formed in massive-rock settings (as well as compositionally layered-rock settings) are readily identified and characterized through geologic mapping, through geophysical logging of open boreholes, and from correlations of topographic features with joint trends.

In the Lawrenceville area, geologic mapping was the primary method used to determine the distribution, variability, and relative concentrations (intensity) of joint systems. The mapping data yielded much more representative data on the distribution, variability, and intensity of joint systems in any given area than could be obtained from subsurface measurements in the boreholes of wells. Even with good exposures, however, such as in the Lawrenceville area, the best that may be expected is to develop a general understanding of the distribution, variability, and intensity of joints. Land cover can obscure and limit surface exposure of joints (fig. 18*C*) and, thus, could potentially skew any statistical evaluation attempted. Saprolite cover, bedrock exposure, and the density of data collection all factor into being able to fully characterize joint systems.

In the subsurface, joint systems were characterized by measuring the orientation of individual joints in open boreholes of wells using acoustic and/or optical televiewers. The sampling population of subsurface joints intersecting a borehole, however, likely represents only a small portion of the total joint system in the area (fig. 18). The sampling population of subsurface joints must be taken into account, and care should be used when extrapolating these data to any great distance from the borehole. In this study, the determination of joint intensity in the subsurface was probably more important than the analysis of joint orientations in boreholes.

Mapping joint systems by using topographic or photo-lineament analysis may provide additional insight into joint trends in the subsurface. Based on field mapping observations in the Lawrenceville area, however, this method probably should not be used without the added benefit of geologic mapping. Many other geologic features, such as pervasive foliation, influence the development of topographic lineaments. Topographic and photo-lineament analysis probably is most applicable to simple joint systems developed in massive rocks, such as those described for well 14FF58. Joints in massive rocks tend to extend to the land surface and may be expressed by linear and rectilinear drainage patterns.

Potential for Future Ground-Water Development

To investigate the potential for future ground-water development, 12 test wells (13FF17 through 13FF23 and 14FF55 through 14FF59) were drilled during 2001 in various geologic settings. Of these wells, six had aquifer-test yields ranging from 107 to 340 gal/min and four had reported air-lift yields ranging from 35 to 100 gal/min. Two low-yield wells (14FF57 and 14FF58) had reported air-lift yields of 1 and 3 gal/min, respectively.

Based on the results from the 2001 test-drilling program, and from this study as a whole, there appears to be a high potential for future ground-water development in the Lawrenceville area, particularly in compositionally layered-rock settings. In this report, areas with “high ground-water potential” refers to those areas where geologic and hydrologic characteristics indicate favorable conditions for large well yields generally greater than 70 gal/min. East and northeast of well 14FF59 (see fig. 2), along the strike of the amphibolite/button schist/biotite gneiss units, there should be a high potential for development of additional ground-water supplies. In that area, the biotite gneiss is deeply weathered and consists of interlayered biotite gneiss and amphibolite. Differential weathering of these adjacent lithologies enhances the ground-water potential in this sequence of rocks. A favorable area for additional wells would be several thousand feet structurally down-dip from the upper biotite gneiss contact, in order to intercept the biotite gneiss at a depth of several hundred feet. Precise drilling sites, however, would need to be located on an individual site-specific basis.

South of well 14FF59 (see figs. 1 and 2), the amphibolite is more massive but appears to be favorable for ground-water development because of the flat-lying structural attitude of the lithologic units and the presence of distinct biotite gneiss layers in the amphibolite unit. Jointing also is abundant in this area. Recent drilling by the City of Lawrenceville confirmed the ground-water potential in this area. A well drilled on the floodplain of Cedars Creek, about 1,200 ft east of Cedars Road, yields about 200 gal/min (Mike Bowie, Water Superintendent, City of Lawrenceville, oral commun., 2003).

The area directly west of Lawrenceville, along Redland and Pew Creeks (see fig. 1), probably is fully developed by the wells already drilled in that area. Additional ground-water supplies, however, may be available along Pew Creek to the southeast near Sugarloaf Parkway (see fig. 1). Compositional layering in this area is nearly flat, the rocks are deeply weathered, and structural relations favor recharge. Geologic mapping also shows abundant jointing and other brittle deformation in this area. Site-specific geologic mapping could be used to locate other areas of high ground-water potential.

Additional investigation would be useful in developing a more complete understanding of the ground-water availability and potential for ground-water development in the Lawrenceville area. The collection of aquifer-test data from new wells that are drilled in the area would provide the necessary information to correlate well yield to other types of geologic settings not addressed in this report. Borehole geophysical logging of new wells would be useful in defining and characterizing the depth and orientation of water-bearing zones and lithology in those settings. Geophysical logging data also could provide information useful for design of aquifer tests and construction of high-yield wells and may provide a better indication on the extent of “weathering-wedges” or “down-dip weathering” crucial for development of productive water-bearing zones in the bedrock. Additional observation wells and streamflow stations in outlying areas could provide data to help determine the influence of major pumping centers and provide information for developing a water budget for the aquifer. Water samples from production wells would be useful in further defining recharge processes and susceptibility to contamination. As data are collected, preliminary, and then more accurately, water budgets could provide information on the availability of ground-water resources in the Lawrenceville area.

Summary and Conclusions

Obtaining large quantities of ground water for municipal and industrial supply in the Piedmont and Blue Ridge provinces can be challenging because of the complex geology and the typically low primary permeability of igneous and metamorphic rocks. Areas of enhanced secondary permeability in the bedrock, however, do occur; and “high-yield” wells are not uncommon, particularly where careful site-selection techniques are used prior to test drilling. The U.S. Geological Survey—in cooperation with the City of Lawrenceville, Georgia—conducted this study from 2000 to 2002 to learn more about how different geologic settings influence the availability of ground water in igneous and metamorphic bedrock. Studying the geologic setting can be an effective means of identifying areas with high ground-water potential.

In compositionally layered-rock settings, wells derive water almost exclusively from lithologically and structurally controlled water-bearing zones formed parallel to foliation and compositional layering. These high-permeability, water-bearing zones—termed *foliation-parallel parting systems*—along with high-angle joint systems, are the primary control on the high-yield wells drilled in the Lawrenceville area; these wells range from about 100 to several hundred gallons per minute (gal/min). Key geologic features identified one well site in a compositionally layered-rock setting are compositionally layered rock susceptible to differential weathering; flat-lying or gently-dipping lithologic units; well-developed foliation and compositional layering along which weathering can progress; steeply-dipping joints and zones of joint concentration; a combination of subhorizontal (foliation and compositional layering) and vertical (steeply-dipping joints) discontinuities that form an interconnected system; down-basin inclined foliation and compositional layering favoring recharge from the surface; and a topographically large recharge area for infiltration and flow of water, development of secondary permeability, and for sustained yield from wells.

The “weathering-wedge model,” which refers to zones of increased permeability formed because of differential weathering, helps to explain high ground-water yield in some of the wells in the Lawrenceville area. Using this model, geologic settings with high ground-water yield should be those that promote weathering parallel to foliation/compositional layering in a down-dip direction from the outcrop area, principally along those rock sequences most susceptible to differential weathering. Near Lawrenceville, areas with high ground-water yield occur in sequences of amphibolite, biotite gneiss, and button schist where the rocks are gently dipping, in areas characterized by abundant jointing, and in topographic settings favoring a continuous source of recharge along these structures.

In this investigation, the only practical approach used for locating areas of high ground-water potential was first through detailed geologic mapping followed by test drilling, borehole geophysical logging, and aquifer testing. Geologic mapping was used to define the rock types; the areal distribution and structural attitude of the rock units; the nature, extent, and structural attitude of discontinuities; and the weathering characteristics and topographic setting. Borehole geophysical logging was used to define the rock units in the subsurface and characterize the depth and nature of the water-bearing zones. Aquifer testing provided a means of delineating the general extent and direction of drawdown during pumping, and to infer the extent and hydrologic characteristics of foliation-parallel parting systems. The likelihood of locating productive foliation-parallel parting systems was enhanced greatly by using these methods.

In massive-rock settings, wells derive water mostly from joint systems, although openings parallel to foliation also may be important. In the Lawrenceville area, wells deriving water only from joint systems typically are low yield, ranging from 1 to 5 gal/min. Key geologic features identified at one well site situated in a massive-rock setting are massive, poorly foliated rock; joints oriented primarily in only one direction (limiting the interconnectivity of the fracture network needed for recharge and transmission of water into the bedrock); absence of subhorizontal discontinuities needed for interconnection of steeply-dipping joints; and topographically small catchment that is less prone to infiltration and flow of water, and hence, development of increased secondary permeability in the bedrock. The greatest availability of ground water in massive-rock settings should be from zones of joint concentration and in areas of joint intersection.

Joint systems in massive-rock settings can be identified and characterized through geologic mapping, through geophysical logging of boreholes, and from correlation of topographic features with joint trends. Geologic mapping was the primary method used to determine the distribution, variability, and relative concentrations (intensity) of joint systems at the land surface. In the subsurface, joint systems were characterized by measuring the orientation of joints in open boreholes of wells using acoustic and/or optical televiewers. Mapping joint systems by topographic or photo-lineament analysis may provide some additional insight into joint trends in the subsurface, especially when combined with geologic mapping data.

To investigate the potential for future ground-water development, 12 test wells were drilled during 2001 in various geologic settings. Of these wells, six had aquifer-test yields ranging from 107 to 340 gal/min and four had reported air-lift yields ranging from 35 to 100 gal/min. Two low-yield wells had reported air-lift yields of 1 and 3 gal/min, respectively. Based on these results, and from the study as a whole, there appears to be considerable potential for future ground-water development in the Lawrenceville area.

In general, studying the geologic setting, primarily through geologic mapping and borehole geophysical logging, was an effective approach for locating areas with high ground-water potential. These methods help characterize both large- and small-scale structures and other lithologic/stratigraphic features that influence development of increased secondary permeability in the bedrock. The rock types, discontinuities, depth of weathering, topography, and recharge potential—which are mainly assessed through detailed geologic mapping—need to be evaluated in relation to one another to assess the ground-water potential in any given area of interest.

The methods described in this report have considerable potential for use by hydrologists, engineers, and other water-resource professionals investigating ground-water availability in areas underlain by igneous and metamorphic bedrock. Crucial to application of these methods (geologic mapping, geophysical logging) is understanding the geologic setting. With a good understanding of the geologic setting, the most suitable sites for test drilling can be selected and areas of enhanced secondary permeability can be more readily identified.

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