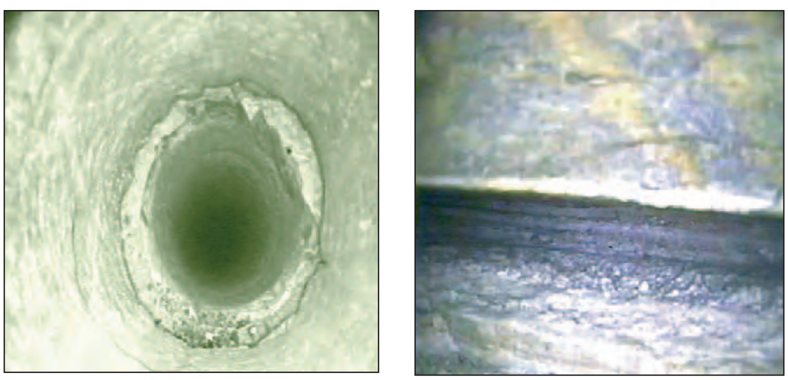
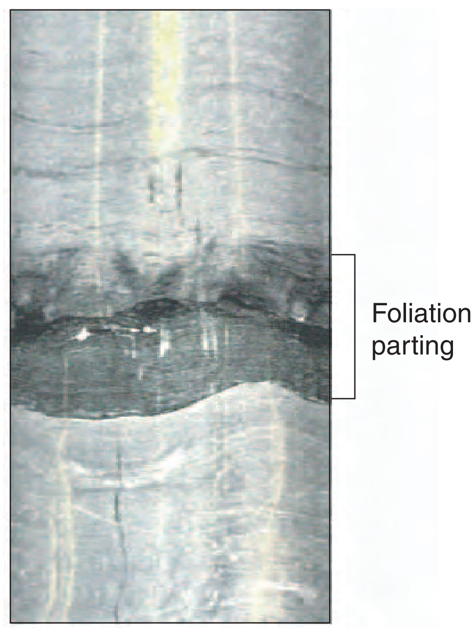
Prepared in cooperation with the
City of Lawrenceville

Methods and Hydrogeologic Data from Test Drilling and Geophysical Logging Surveys in the Lawrenceville, Georgia, Area



Borehole-camera images showing
down-hole view (left) and side view (right)



Optical televiewer image

Open-File Report 2004-1366

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

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By Lester J. Williams, Phillip N. Albertson, Donna D. Tucker, and Jaime A. Painter

In cooperation with the City of Lawrenceville, Georgia

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

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Suggested citation: Williams, L.J., P.N. Albertson, D.D. Tucker, and J.A. Painter, 2004, Methods and hydrogeologic data from test drilling and geophysical logging survey in the Lawrenceville, Georgia, area: U.S. Geological Survey, Open-File Report 2004-1366, p. 38.

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Conversion Factors and Datum

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

$$°F = (1.8 \times °C) + 32$$

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 *North American 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.

Methods and Hydrogeologic Data from Test Drilling and Geophysical Logging Surveys in the Lawrenceville, Georgia, Area

By Lester J. Williams, Phillip N. Albertson, Donna D. Tucker, and Jaime A. Painter

Abstract

Thirty-two wells, ranging in depth from 180 to 630 feet, were used to study the bedrock lithology, fracture, and water-yielding characteristics in the Lawrenceville, Georgia, area. These data were compiled to determine what geologic structures, if any, contribute to the development of increased permeability and high ground-water yield in the area. Methods used in this study include test-well drilling, geophysical logging and borehole-camera surveys, flowmeter surveys, aquifer testing, packer testing, and water-level monitoring.

Water-bearing fractures identified in open boreholes of wells include: joints, open joints, and zones of joint concentration; foliation partings and major foliation openings along foliation and layering of the rock; dissolution openings along mineral infillings; and irregular voids and fractures. Most of the joints observed in the boreholes appeared as tight hairline fractures and typically were not significant water-bearing zones. Moderate to small amounts of water—from 1 to 5 gallons per minute (gal/min)—are produced from open, steeply-dipping joints and zones of joint concentration. Foliation partings and major foliation openings, which form "foliation parallel-parting systems" in the area, yielded large quantities of water to open boreholes. Foliation partings typically yielded from 1 to 15 gal/min, with a maximum value of about 63 gal/min. In some boreholes, groups of foliation partings form significant water-bearing zones yielding as much as 50 gal/min. Major foliation openings yield substantially more water than the smaller foliation partings, with a typical range from 50 to 100 gal/min. Major foliation openings are the primary water-producing features responsible for high-yield wells in the area. In a few wells, dissolution openings along mineral infilled joints or veins had yields as much as 35 gal/min, indicating the potential importance of dissolution features in the bedrock.

Flowmeter surveys, aquifer tests, packer tests, and water-level monitoring provided additional hydrologic information on water-bearing fractures in the study area. These data were used to help confirm the depth and yield contribution from various types of water-bearing fractures, indicate the hydraulic characteristics of these fractures, and show the hydraulic response of the aquifer system to pumping.

Collectively, the data from this study indicate that foliation parallel-parting systems, consisting of discontinuous zones of foliation partings and major foliation openings, strongly influence the yields of wells in the Lawrenceville area. Wells tapping these systems are capable of sustaining large ground-water withdrawals for extended periods of time, as indicated from the continuous operation of the Rhodes Jordan Wellfield since 1995. Open-hole water levels, flowmeter surveys, and preferential drawdown parallel to foliation and compositional layering all indicate a general hydraulic confinement of foliation parallel-parting systems, and indicate a strong lithologic and structural control on the development of these water-bearing fracture systems.

Foliation parallel-parting systems are easily identified in boreholes using geophysical methods described in this report. The yield potential of foliation parallel-parting systems within an individual topographic basin or several topographic basins can be large, depending on the areal extent of the water-bearing zones and the interconnectivity of these zones with sources of recharge.

Introduction

There is a great need to assess the ground-water resources of the crystalline-bedrock aquifer in the Piedmont and Blue Ridge physiographic provinces of Georgia (fig. 1). Ground water in this region could be used to supply water to small communities or supplement the larger surface-water systems in times of drought, for emergency supplies, or as a long-term continuous source to increase the capacity of these systems to meet future supply demands. In any given area, however, little information generally is available to assess the potential of developing a water supply from these complex aquifer systems. Despite this lack of information, large ground-water supplies[1] have been developed in many parts of the region (Carter and Herrick, 1951; Cressler and others, 1983; Herrick and LeGrand, 1949; Radtke and others, 1986; Thomson and others, 1956).

[1]Large ground-water supplies typically have been defined in the literature as 25 gallons per minute (gal/min) or greater. In this report, 75 gal/min or greater generally is used to indicate a large supply.

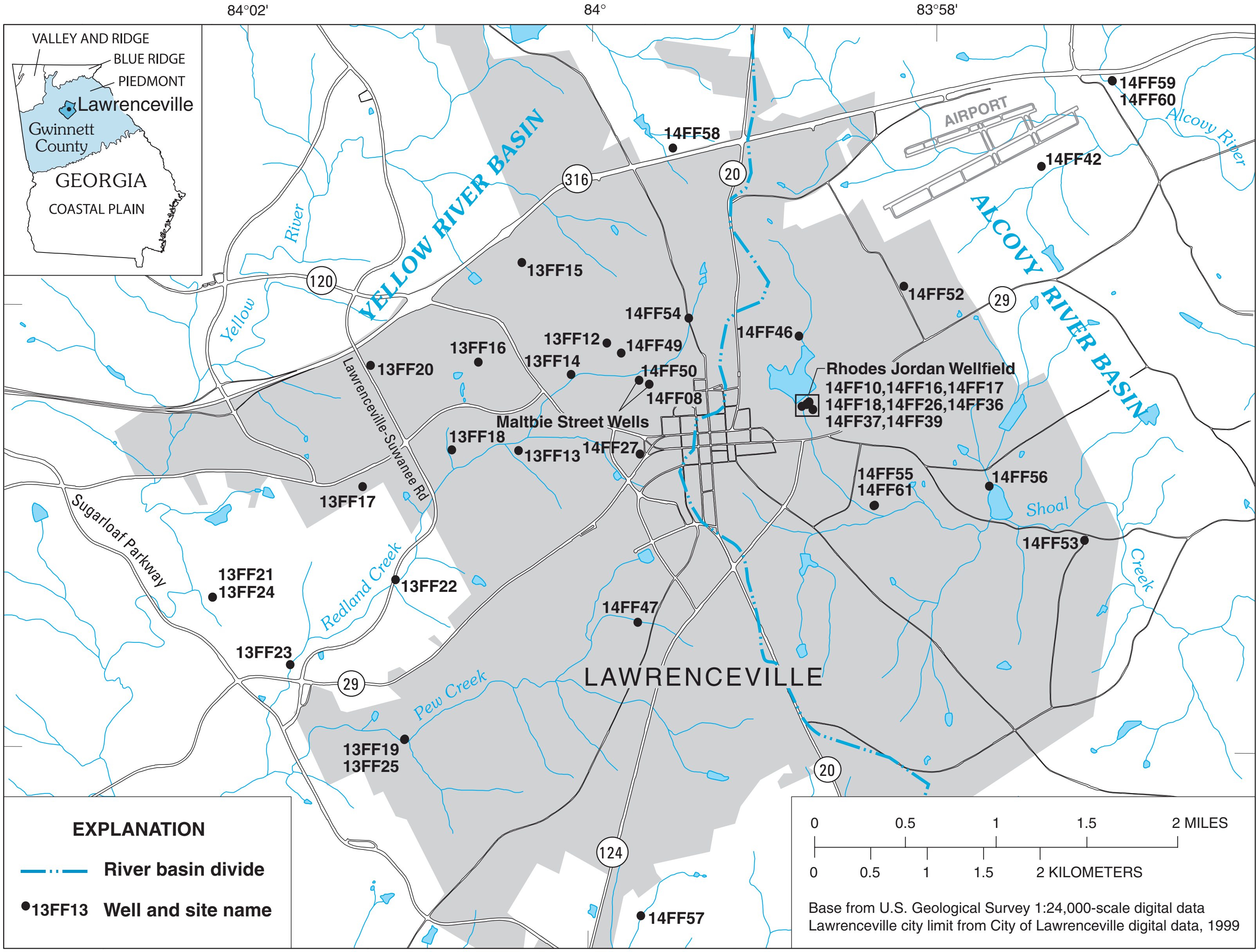

Figure 1. Location of study area in Gwinnett County and well locations in Lawrenceville, Georgia.

The U.S. Geological Survey (USGS), in cooperation with the City of Lawrenceville, began collecting lithology, fracture[2], yield, and water-level data from bedrock wells during December 1994 to investigate the geology and ground-water resources of the Lawrenceville area. Major objectives of the Lawrenceville study were to: (1) evaluate the regional hydrogeologic setting, (2) delineate and characterize subsurface discontinuities and fractures that control aquifer permeability, and (3) monitor the response of the bedrock ground-water system to local ground-water pumping. To accomplish these objectives, the USGS completed local- and site-specific studies between 1995 and 2002. The local studies entailed compiling detailed hydrogeologic information on private and publicly owned wells in the vicinity of Lawrenceville and preparing a 1:24,000 geologic map of the study area (Chapman and others, 1999). The site-specific studies included a test-well drilling program and collection of geophysical logging data needed to characterize the distribution of lithology and fractures in the subsurface. Detailed subsurface lithology, fracture, and yield data—which are a focus of this report—were compiled to determine what geologic structures, if any, contribute to the development of increased permeability and high ground-water yield[3] in the area.

Purpose and Scope

This report describes the methods used and data resulting from test drilling and geophysical logging surveys conducted between December 1994 and October 2001. Included in this report are:

- methods of collecting and analyzing data;
- fracture data showing the depth, nature, and yield of different types of water-bearing fractures;
- aquifer-test data showing the yield of wells and the direction and magnitude of drawdown;
- packer-test data showing the hydraulic response among high-yield fractures; and
- water-level data showing fluctuations in ground-water levels in response to seasonal variations in precipitation and from local ground-water withdrawals.

The test-drilling program included field observations during drilling, lithologic sampling, and descriptions of rock samples. Geophysical logging and borehole-imaging techniques were used extensively to characterize lithology and fractures in open-bedrock wells. The scope of this report includes lithologic and borehole geophysical logs from 32 wells, flowmeter surveys from 12 wells, aquifer-test data from 9 wells (total of 10 tests), packer-test data from 1 well, and continuous water-level data from 26 wells. Images of subsurface fractures and other structures are included to document the types of bedrock fractures and small-scale structural features common in the study area.

Description of the Study Area

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

Water Use

In Gwinnett County, water use totaled about 90.5 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. Of the 0.5 Mgal/d withdrawn from ground-water sources, 80,000 gallons per day (gal/d) were used for commercial purposes, 390,000 gal/d for public supply, and 10,000 gal/d for livestock. From the surface-water sources, only 80,000 gal/d were used for livestock and the remainder (90 Mgal/d) was used for public supply.

Lawrenceville currently (2003) uses about 2.5 Mgal/d for public supply, of which about 120,000 to 140,000 gal/d is obtained from ground-water sources (Mike Bowie, City of Lawrenceville, oral. commun., 2002). The Rhodes Jordan Wellfield (fig. 1) currently (2003) is the only operating active wellfield in the Lawrenceville area, and has two production wells that are alternately pumped at rates of 200–250 gallons per minute (gal/min) for 10 or more hours per day. The wellfield was refurbished in the early 1990s and has been in continuous operation since 1995. Historically, ground water also was withdrawn from another well site located on Maltbie Street (fig. 1). A replacement well for the Maltbie Street well was drilled in the late 1990s but was never put into production because of local ground-water contamination near that site. More recently, six of the test wells drilled for this study were converted into production wells by the City of Lawrenceville. These new production wells, combined with wells at the Rhodes Jordan Wellfield, are capable of producing a combined estimated yield of approximately 2 Mgal/d (Mike Bowie, City of Lawrenceville, oral commun., 2002).

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[2]In this report, "fractures" refer to openings along foliation planes, joints, and brittle fractures related to faulting.

[3]In this report, "high ground-water yield" refers to areas where wells have a reported yield of 70 gal/min or greater. Cressler and others (1983) defined "high-yield" as 25 gal/min or greater.

Geologic Setting

The geologic setting of the Lawrenceville area varies substantially from location to location, primarily because of the complex structural deformation of the bedrock. The general history of structural deformation includes thrust faulting, large-scale folding and faulting, partial melting of preexisting rocks forming migmatites, and syntectonic to post-tectonic intrusion of granitic bodies. Atkins and Higgins (1980), Higgins and others (1984, 1988, 1998), McConnell and Abrams (1984), and by 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 in the study area.

Chapman and others (1999) divide the various rock types in the Lawrenceville area into seven principal lithologic units: amphibolite, biotite gneiss, button schist, granite gneiss, magnetite quartzite, quartzite/aluminous schist (quartzite/schist), and diabase dikes (fig. 2, table 1). The principal lithologic units represent mappable rock groups correlated based on dominant rock types. Differences in weathering and fracturing in the principal lithologic units produce a wide variation in the hydrologic properties of these units.

The principal lithologic units penetrated in wells drilled in the study area include amphibolite, biotite gneiss, button schist, granite gneiss and quartzite/schist (fig. 2). For the most part, all of these units, excluding the granite gneiss, are compositionally layered, consisting of several to many rock types in each unit. The compositional layering varies from finely laminated (individual layers only tenths of inches thick) to thinly layered (typically less than 6 inches) and, in fewer instances, thickly layered (typically greater than 6 inches). All of these units also may be massive; in particular, large bodies of massive granite gneiss and biotite gneiss crop out throughout the area.

The amphibolite consists of fine- to medium-grained, dark-green to greenish-black, massive to finely laminated, hornblende-plagioclase and plagioclase-hornblende amphibolite (Chapman and others, 1999). This unit, interlayered with biotite gneiss, is penetrated by many high-yield wells in Lawrenceville and forms a significant water-bearing unit.

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 it is interlayered with amphibolite. This unit generally is schistose in texture and locally contains lenses and pods of hornblende-plagioclase amphibolite.

The button schist consists of medium- to coarse-grained, dark-gray to brownish-gray garnet schist with interlayered biotite gneiss and scarce amphibolite (Chapman and others, 1999). This unit generally has a sheared texture, and there is evidence that the button schist was derived from shearing of biotite gneiss (Higgins and others, 1998). The button schist is named for its weathering characteristic that yields mica concentrations that resemble "buttons." The button schist generally is not considered a significant water-bearing unit in the Lawrenceville area; however, several high-yield wells derive water from this unit.

The granite gneiss consists of a light gray to white, medium-grained, muscovite-biotite-feldspar-quartz gneiss. This unit generally is a poor water-bearing unit in the area.

The quartzite/schist consists of quartz-rich schist, muscovite schist, and layers of resistant quartzite. The quartzite/schist is penetrated by only two wells. No large water-bearing zones were identified in the quartzite/schist at these two wells.

Diabase and magnetite quartzite are not penetrated by any wells used in this study and are not discussed further.

Large-scale structural features in the Lawrenceville area include a northeast-southwest trending, doubly-plunging synform in the central and eastern part of the study area, and an east-west-trending 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. Each principal lithologic unit shown in figure 2 is bounded by thrust faults; the outcrop patterns are typical of those that result from eroded open folds.

Hydrogeologic Setting

Ground water fills joints, fractures, and other secondary openings in bedrock and pore spaces in the overlying mantle of soil, saprolite, alluvium, and weathered rock. In this report, the soil, saprolite, alluvium, and weathered rock are collectively referred to as regolith.

Ground-water recharge to the regolith and underlying bedrock is mainly through infiltration of precipitation at the land surface. The infiltrating water collects in the regolith and recharges the bedrock fracture system underlying it. Because regolith has a much higher storage capacity than bedrock, the regolith can be conceptualized as a ground-water reservoir or "sponge" that feeds the underlying bedrock. Joints, weathered zones, dissolution openings, and zones of brittle faults in bedrock and combinations of these features also can store a substantial quantity of water.

The storage capacity and depth of weathering of the regolith/bedrock fracture system is influenced largely by differences in the weathering character of various rock types. These variations in weathering are most apparent from geologic field mapping; rocks more resistant to weathering were observed to form pavement rock outcrops in streams and some hilltops; whereas, rocks less resistant to weathering were observed to form thick saprolite. The depth of casing of bedrock wells (table 2) also is a general indication of the depth of weathering. In the Lawrenceville area, saprolite generally is thicker on feldspar-rich rocks and thinner on quartz-rich rocks. The biotite gneiss unit (Chapman and others, 1999) is particularly susceptible to deep weathering and typically forms a thick saprolite above the bedrock. Mafic rocks (such as amphibolite), because of the general lack of feldspar, typically are characterized by thin saprolite development. In layered rocks, saprolite forms between layers of otherwise hard bedrock. In the Lawrenceville area, this occurs where chemically less resistant rock (such as biotite gneiss) is compositionally layered with more resistant rock (such as amphibolite).

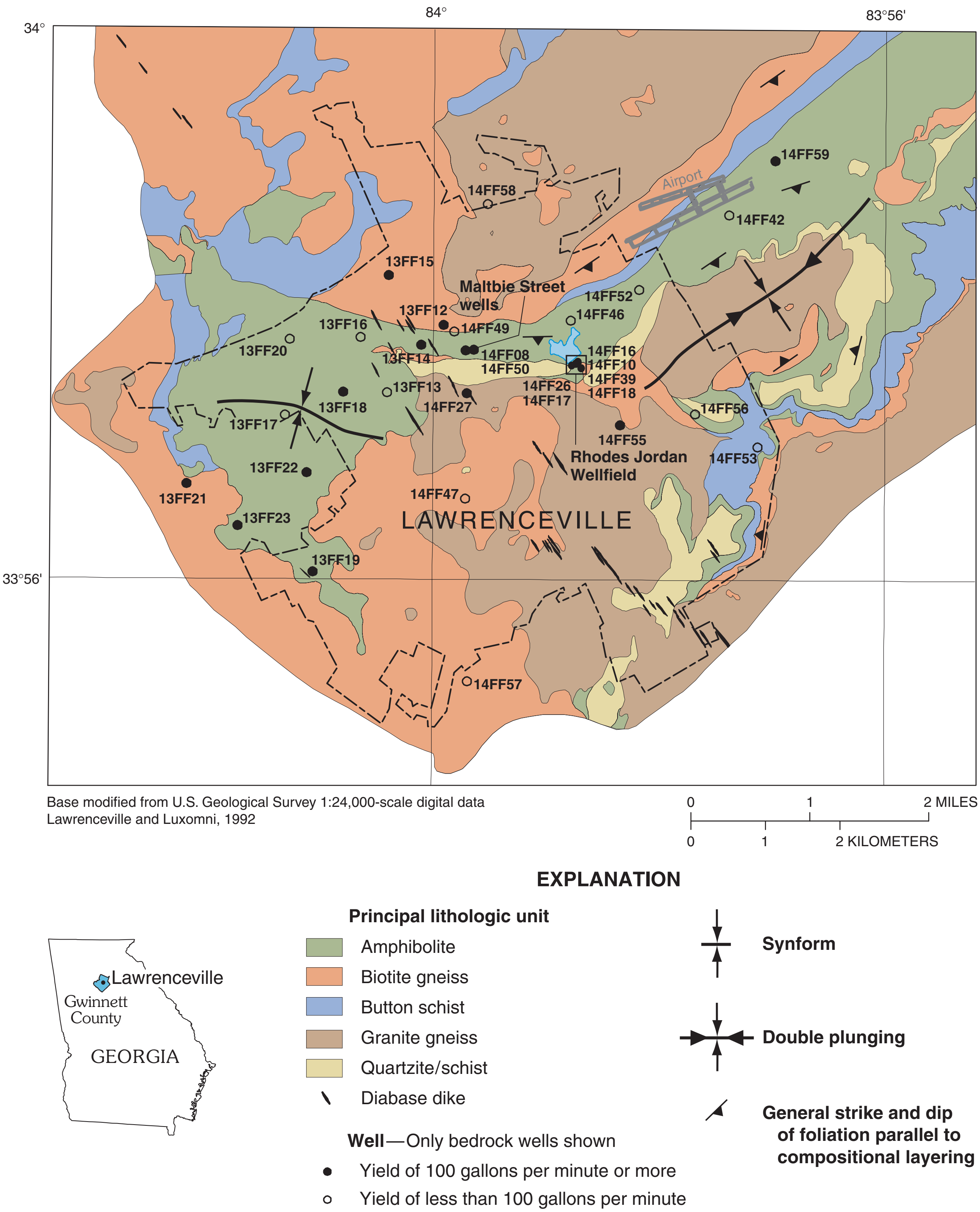


Figure 2. Distribution of principal lithologic units and bedrock well locations, Lawrenceville, Georgia (modified from Chapman and others, 1999). See table 1 for description of principal lithologic units.

Table 1. Description of principal lithologic units in the Lawrenceville, Georgia, area (from Chapman and others, 1999).

Amphibolite unit (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. The final weathering product of the amphibolite is a very characteristic dark red clayey soil.
Biotite Gneiss unit (bg) – Gray to grayish-brown to dark gray, medium- to coarse-grained, 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. 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.
Button Schist unit (bs) – Dark gray to brownish-gray, medium- to coarse-grained, 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. The button schist is resistant to weathering.
Diabase (dia) – Fine- to medium-grained, dark gray to black augite diabase, in dikes generally 16 to 66 feet wide. The diabase weathers to a dark red clayey soil containing speheroidal boulders with fresh rock inside an armoring, ocherous rind.
Granite Gneiss unit (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. Pavement outcrops, “whale-back” outcrops, and boulder outcrops are characteristic of this granite gneiss. Where deeply weathered, the gneiss forms thin light whitish-yellow sandy soils.
Magnetite quartzite (mq) – Thinly layered (0.4 inch) to laminated, medium-grained, magnetite quartzite in units 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 a 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.
Quartzite/Schist unit (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.

Well-Naming System

In this report, wells are named using a system based on USGS 7½-minute topographic quadrangle maps. Each topographic map in Georgia has been assigned a number and letter designation beginning at the southwestern corner of the State. Numbers increase eastward through 39; letters advance northward through “Z,” then double-letter designations “AA” through “PP” are used. The letters “I,” “O,” “II,” and “OO” are not used. Wells inventoried in each quadrangle are named sequentially beginning with “1.” Thus, the 55th well inventoried in the Lawrenceville 7.5 minute quadrangle (designated 14FF) in Gwinnett County is designated as well 14FF55.

Supplemental Data on CD–ROM

Supplemental data on this CD–ROM include detailed lithology, fracture, yield, and water-level data collected at various wells in the study area. These data are presented in a nonproprietary Geographic Information System (GIS) database file format that includes geographic and tabular data. A copy of ArcExplorer®, a free GIS data viewer developed by Environmental Systems Research Institute, is included on this CD–ROM for use with the GIS database and allows a user to view the data spatially and query the data of interest. In addition, much of the data are linked to a hypertext markup language (HTML) document to allow a user to access and view the data tables through text and Adobe® Portable Document Format (PDF) files. A description of the GIS data and figures contained on this CD–ROM is provided in the section “Organization and Presentation of Hydrogeologic Data.”

Acknowledgments

The authors gratefully acknowledge former Mayor Bartow Jenkins, former Director of Public Works Don Martin, City Clerk Bob Baroni, and the Lawrenceville City Council for their support during the cooperative water-resource investigations. We thank Lawrenceville Water Department Superintendent Jim Steadman, and Water Plant Operators Mike Bowie and Robert Paul for their valuable assistance in constructing roads, obtaining digging permits, and their continued day-to-day support during this study. Many USGS employees were involved with data collection during this study. We are especially grateful to Melinda Chapman, who made large contributions to the study from 1995 to 2000. Other USGS employees who contributed substantially to the study include Adrian Addison, Dianna Crilley, Joshua Lawson, Chris Leeth, Kristen McSwain Bukowski, Michael Peck, and Todd Tharpe. We also are very grateful to Thomas J. Crawford, Professor Emeritus of Geology, and Randy L. Kath, Associate Professor of Geology at the Department of Geological Sciences, State University of West Georgia, whose concepts and knowledge were extremely valuable in developing a better understanding of geology and the hydrogeology of the area; each spent numerous days working either directly or indirectly with the authors. Finally, we thank Caryl Wipperfurth who prepared the report figures and spent many hours compiling and editing data included on the CD–ROM, Steve Craigg who provided technical and editorial reviews, and Patricia Nobles who carefully edited and prepared the final manuscript for publication.

Table 2. Location and well construction information for the Lawrenceville, Georgia, area.

[ft, foot; in., inch; gal/min, gallons per minute; —, data not collected. Geologic units: a, amphibolite; bg, biotite gneiss; bs, button schist; gg, granite gneiss; qs, quartzite/schist. Casing type: stl, steel; PVC, polyvinyl chloride. Source: Coordinates and altitudes, E&C Consulting Engineers, Inc.]

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	265.0	54.0	6–stl	—	[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–stl	—	[1]140	a, bg
13FF15	33°58'12.01"	-84°00'24.10"	1,053.2	1,054.61	605	55	10–stl	250	[1]250	bg
13FF16	33°57'44.97"	-84°00'39.10"	1,004.7	1,006.32	605	32	10–stl	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–stl	200	[3]100 [4]150	a
13FF19[2]	33°56'02.62"	-84°01'04.11"	921.8	923.58	477	65	8–stl	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–stl	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–stl	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–stl	—	[1]400	a, bs, bg, gg
14FF10	Not available	Not available	994.2	996.09	386	20	8–stl	—	[1]270	a
14FF16	Not available	Not available	994.2	998.69	320	30.5	10–stl	210	[1]471	a, bs
14FF17	33°57'33.49"	-83°58'46.47"	990.9	992.07	212	25	6–stl	—	[3]150	a
14FF18	33°57'32.62"	-83°58'42.65"	999.3	1,001.09	180	24	6–stl	—	[3]100	a
14FF26	33°57'33.97"	-83°58'44.76"	993.4	996.14	380	33	6–stl	—	—	a, bg, bs, a, bg
14FF27	33°57'20.32"	-83°59'42.65"	1,048.3	1,050.7	600	59	6–stl	—	[3]150	gg, bg, qs, a, bs
14FF39	33°57'34.12"	-83°58'44.81"	993.4	996.09	180	36	6–stl	—	[3]150	a
14FF42	33°58'38.81"	-83°57'23.55"	1,028.2	1,029.67	599.0	35	8–stl	—	[1]10.0 [5]0.1	a, bs, bg
14FF46	33°57'52.51"	-83°58'47.58"	1,022.9	1,028.46	301	9	6–stl	—	[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–stl	275	[1]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–stl	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–stl	400	[3]180 [4]350–400	a, bs, bg

Table 2. Location and well construction information for the Lawrenceville. Georgia, area. —Continued

[ft, foot; in., inch; gal/min, gallons per minute; —, data not collected. Geologic units: a, amphibolite; bg, biotite gneiss; bs, button schist; gg, granite gneiss; qs, quartzite/schist. Casing type: stl, steel; PVC, polyvinyl chloride. Source: Coordinates and altitudes, E&C Consulting Engineers, Inc.]

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, and 14FF16 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

Methods of Data Collection and Analysis

A variety of methods were used to collect and analyze data during this study. These methods consisted of indirect and direct measurement of various hydrologic and geologic properties by test-well drilling, geophysical logging and borehole-camera surveys, flowmeter surveys, aquifer testing, packer testing, and water-level monitoring.

Test-Well Drilling

Test-well drilling was used to obtain detailed subsurface information about rock types, fracture zone(s), rock fabrics, and hydrologic characteristics of water-bearing zones. Many of the wells were drilled using air-percussion rotary methods and constructed as open-hole wells. Two existing wells, 14FF10 and 14FF08, reportedly were drilled using the cable-tool method. A list of wells, locations, and construction details is provided in table 2. Well locations are shown in figures 1 and 2.

Air-Percussion Rotary Drilling and Well Construction

Air-percussion rotary drilling was used for constructing test wells during the study. This drilling technique, which uses a down-hole air hammer, is the most suitable drilling method in crystalline-rock formations and also is rapid and inexpensive. The method uses air as a circulating medium to cool the air hammer, bring drill cuttings to the surface, and maintain borehole integrity. When drilling, the cuttings are removed from the borehole using high-pressure air. The air that is circulated also cools the drill bit as it circulates from inside the drill rod and out and around the bit. Water is added to the air stream when the borehole does not produce sufficient amounts of water to carry rock cuttings to land surface.

Test wells were constructed by (1) advancing an 8- to 12-inch-diameter borehole through unconsolidated soil, saprolite and the upper portion of bedrock; (2) grouting a polyvinyl chloride (PVC) surface casing to seal off the upper zones; and (3) drilling a 6-inch-diameter borehole into the underlying bedrock. When discussing fractures, yield, or other physical features within the open portion of the test well (below the surface casing) the term *borehole* is used hereafter. The term *well* is used to describe the performance characteristics of water- bearing zones intersecting the entire length of the test well.

Field observations made at the time of drilling included the depth, drilling rate, size of cuttings, changes in lithology, and color of the drilling fluid. The rate of ground-water production from the test well also was monitored to determine the depths of water-bearing fractures.

Lithologic Sampling and Determination of Rock Type

Rock cuttings collected during drilling were used to determine subsurface lithology and estimate the approximate depth of lithologic contacts. Samples were collected in a wire-mesh basket placed below the rotary table where water and cuttings were returned to the land surface. The wire-mesh basket was emptied every 10 ft that the hole was drilled, and the samples were washed, cleaned, and dried on a preparation board. Rock cuttings were then examined with a hand lens to determine approximate mineral and rock-type percentages.

If the sample contained more than 50 percent of a specific rock constituent, then the dominant component was listed first, followed by the minor component (separated by the "**w/**" code, which is short for "with"). For example, if a sample contained between 60 and 80 percent amphibolite with the remainder being biotite gneiss, the interval would be identified with the code: **a-w/bg**. Likewise, a sample with predominantly biotite gneiss and lesser amounts of amphibolite would be identified with the code **bg-w/a**. Samples with approximate equal amounts of different rock types were separated with a dash, with the rock types not listed in any specific order of predominance. A sample with equal amounts of amphibolite, biotite gneiss, and button schist, for example, would be assigned the code **a-bg-bs**. Samples with more than one minor rock type component were identified following the dominant rock code and the "**w/.**" For example, a sample with predominantly amphibolite with some biotite-hornblende gneiss and biotite gneiss would have the code **a-w/bhg-bg**.

Using the lithologic unit definitions of Chapman and others (1999), the rock types were grouped into one of the seven principal lithologic units (table 1). In general, this grouping was based on the dominant rock type identified in the rock-cutting samples. If the dominant rock type was amphibolite, for example, with layers and lenses of other rock types, it would be assigned to the amphibolite unit. Some weight also was given to the gamma log response; a distinctive gamma response in some wells was associated with a specific rock unit, such as the button schist unit, to define contacts. Most lithologic contacts, however, were defined based on rock-cutting samples from the wells.

Determining the precise depth of lithologic contacts was complicated by cuttings sloughed off from shallower portions of the test well and by having a 10-ft-long sampling interval. In the absence of any definitive contact data, such as a distinct color change of the return water, the depths of contacts were located at the end of the 10-ft-long sampling interval. Two wells (14FF26 and 14FF42) were cored, which is the most precise method of defining the depths of lithologic contacts.

Some wells did not have any rock cuttings from which to produce lithologic logs. For these wells, geophysical logs were used to correlate to the lithology observed in nearby wells. Lithologic contacts in wells 14FF10, 14FF16, 14FF17, and 14FF18 (all located in the Rhodes Jordan Wellfield) were based on the corehole at well 14FF26 and correlated using geophysical logs. Similarly, the depths of lithologic contacts in 14FF08 and 13FF12 were estimated by correlating to nearby well 14FF50.

Well Development and Short-Term Yield

Drilled, open-hole test wells do not require extensive cleaning or development to prepare them for permanent use. The test wells were developed at the end of drilling to clean the open portion of the boreholes of drill cuttings and debris and to provide a driller's estimate of short-term yield (the short-term yield is estimated by the well driller at the end of the drilling and/or development process and is the reported discharge rate that can be sustained from the well during a relatively short period of time). After drilling to total depth in each well, the driller continued to air lift and discharge water entering the well until the return water was relatively clear and did not contain appreciable sand or rock fragments. This development process was completed quickly for low-yielding wells but took considerable time (3 hours or more) for high-yield wells.

Following well development the driller estimated the short-term yield. For most test wells, the water being discharged from the well was conveyed along a ditch into a 55-gallon drum or a calibrated container for measurement. The rate at which water was air lifted out of the well was carefully monitored to determine the maximum discharge that could be sustained (i.e., short-term yield). Well drillers routinely measure short-term yield, and these measurements are considered reliable indicators of yield compared to short-term aquifer tests (Paillet and Duncanson, 1994).

In some test wells, the drilling rig was "drowned out" before reaching the target drilling depth. Air-percussion rotary drilling rigs are drowned out when ground water enters the well faster than the drilling rig can air lift the water out of the well—typically the result of a bottom-hole fracture. Hence, in drowned-out wells, the reported yield at the time of drowning typically is less than the actual yield.

Geophysical Logging and Borehole-Camera Surveys

Wells in the Lawrenceville area were logged using various geophysical tools and inspected with a submersible borehole camera to aid in characterizing the lithology and identifying water-bearing zones. Geophysical logs were collected in water-filled 6- to 10-inch-diameter open boreholes. Table 3 lists the logging tools used, types of measurements made, and uses of these data. A typical suite of logs from each well consisted of a caliper log, natural-gamma log, resistivity logs (short normal, long normal, and lateral), fluid resistivity and temperature logs, and borehole televiewer image logs. Electromagnetic-conductivity logs also were collected in 21 wells but were not used to characterize lithology or identify water-bearing zones. Data from the electromagnetic-conductivity logs, however, are included on this CD–ROM. The types of logs collected in each well are summarized in table 4.

Caliper Logging

Caliper logs were used to measure hole diameter and identify open fractures, voids, and other distinct openings in the bedrock. The caliper has three spring-mounted arms that measure the average diameter of the borehole and, hence, is used to identify zones of borehole enlargement typically associated with bedrock fractures. Borehole enlargements also occur in zones of weaker or more friable rock and, therefore, were examined visually using a borehole televiewer and a borehole camera to verify the character of the fracture. Hairline[4] "tight" joints generally could not be distinguished using caliper logs.

[4]In this report the term *hairline* is used to describe joints with little to no aperture or physical opening.

Table 3. Description of borehole geophysical tools used in the Lawrenceville, Georgia, area.

Geophysical tools	Measures	Uses
Caliper	Borehole diameter	Identify breakouts and potential fractures
Multiparameter log	Natural gamma, 64-inch normal resistivity, 16-inch normal resistivity, lateral resistivity, spontaneous potential, fluid resistivity, fluid temperature	Identify lithology, water-bearing zones, changes in water chemistry and temperature
Borehole acoustic televiewer	Oriented image of borehole wall, borehole deviation	Calculate orientation of subsurface features, calculate borehole deviation
Electromagnetic flowmeter	Fluid movement in borehole	Identify zones of inflow and outflow from the borehole during static or pumping conditions
Heat Pulse Flowmeter	Low-velocity fluid movement	Identify flow directions in static or low-flow pumping conditions
Borehole Image Processing System (manufactured by RaaX Company Ltd.)	High-resolution oriented optical images of borehole wall	Calculate orientation of subsurface features

Natural-Gamma Logging

Natural-gamma logs were used to help characterize rock types in wells. Chapman and others (1999) noted a characteristic lower baseline response (from 0 to 292 American Petroleum Institute units [API units]) for the amphibolite unit compared to the button schist and biotite gneiss (from 200 to 400 API units).

Resistivity Logging

Resistivity logs were used to detect potential water-bearing fracture zones in the bedrock. Resistivity is a measure of the bedrock formation's electrical resistance (expressed in square ohmmeters per meter [ohm/m]). Water-bearing fracture zones in highly resistive igneous and metamorphic rocks commonly are associated with a zone of decreased resistivity. Resistivities of igneous and metamorphic rocks penetrated by wells in this study area ranged from 1,000 to 4,000 ohm/m for unfractured rock, and from 100 to 500 ohm/m for fractured rock having water-bearing zones. Three types of resistivity logs were collected: (1) 16-inch normal (measures the formation resistivity within a roughly 3-ft spherical zone around the borehole), (2) 64-inch normal (measures the formation resistivity within a 10-ft spherical zone or less), and (3) lateral (measures the resistivity of a small volume of bedrock material in the formation without involving the material nearest to the borehole). Both 16- and 64-inch normal resistivity logs are sensitive to variations in borehole diameter. Because of the similar response of these logs, only the lateral log is shown in figures in this report.

Fluid-Temperature and Fluid-Resistivity Logging

Fluid-temperature and fluid-resistivity logs were used to detect changes in water temperature and water chemistry. Changes in fluid temperature and resistivity usually indicate inflow or outflow of water from the borehole; and, hence, inflections on fluid temperature and resistivity logs can be used to help identify water-bearing zones. The fluid temperature and resistivity logs typically are used in combination with other logs to verify a water-bearing zone at the inflection point.

Borehole-Televiewer Imaging

Two types of borehole-televiewer imaging techniques were used during the study: acoustic televiewer (ATV) and optical televiewer using the Borehole Image Processing System (BIPS). The ATV uses sound waves to collect a magnetically oriented (to magnetic north) image of the borehole wall. Features such as simple fractures, voids, foliation, and layering can be identified in the acoustic image. Unlike the ATV, which uses sound waves, the BIPS tool records an optical image of the borehole wall. The BIPS log has a substantially higher resolution and allows for more subtle features to be identified. The BIPS log was used in the same manner as the ATV log.

Borehole-Camera Surveys

A borehole camera was used to visually inspect and document joints, fractures and other structures intersecting the borehole wall. A Geovision™ high-resolution camera was used to collect the video images in most of the open boreholes of wells. Because the Geovision™ camera has a fixed head, a survey first was made with the camera head pointed downward and a second survey with the camera head horizontal. The downward survey provided the best view of steeply-dipping[5] fractures and large open fractures intersecting the borehole wall. The horizontal survey allowed viewing of small-scale rock fabric, open fractures, and other small voids and openings.

[5]In this report, "steeply dipping" refers to angles typically greater than 70 degrees from horizontal.

Table 4. Geophysical logs collected in the Lawrenceville, Georgia, area.

[EM, electromagnetic; BIPS, Borehole Image Processing System; —, data not collected]

Well name	Caliper	Combi-nation[1]	Acoustic televiewer[2]	EM flowmeter	Heat pulse flowmeter	BIPS[2]	Gamma EM induction	Borehole camera	Long normal	Short normal	Spontaneous potential	Fluid resistivity	Fluid temperature	Focused resistivity	Gamma
13FF12	x	x	x	—	—	x	x	x	—	—	—	—	—	—	—
13FF13	x	x	x	—	—	x	x	x	—	—	—	—	—	—	—
13FF14	x	x	x	—	—	x	x	x	—	—	—	—	—	—	—
13FF15	x	x	x	—	—	x	—	x	—	—	—	—	—	—	—
13FF16	x	x	x	—	—	x	—	x	—	—	—	—	—	—	—
13FF17	x	x	x	x	x	—	x	x	—	—	—	—	—	—	—
13FF18	x	x	x	x	—	—	x	x	—	—	—	—	—	—	—
13FF19	x	x	x	x	x	—	x	x	—	—	—	—	—	—	—
13FF20	x	x	x	x	—	—	x	x	—	—	—	—	—	—	—
13FF21	x	x	x	x	x	—	x	x	—	—	—	—	—	—	—
13FF22	x	x	x	x	x	—	x	x	—	—	—	—	—	—	—
13FF23	x	x	x	x	—	—	x	x	—	—	—	—	—	—	—
14FF08	x	—	—	—	—	[3]x	—	x	—	—	—	x	x	x	x
14FF10	x	x	—	—	—	—	—	x	—	—	—	—	—	—	—
14FF16	x	—	x	—	—	—	—	x	x	x	x	x	x	x	x
14FF17	x	—	x	—	—	x	—	x	x	x	x	x	x	x	x
14FF18	x	x	x	—	—	x	x	x	x	x	x	x	x	x	x
14FF26	x	x	x	—	—	[3]x	x	x	x	x	x	x	x	x	x
14FF27	x	—	x	—	—	x	—	x	x	x	x	—	x	x	x
14FF39	x	x	x	—	—	x	—	x	x	x	x	x	x	x	x
14FF42	x	—	x	—	—	x	—	x	x	x	x	—	x	x	x
14FF46	x	x	x	—	—	x	x	x	—	—	—	—	—	—	—
14FF47	x	x	x	—	—	x	x	x	—	—	—	—	—	—	—
14FF49	x	x	x	—	—	x	x	x	—	—	—	—	—	—	—
14FF50	x	x	x	—	—	x	x	x	—	—	—	—	—	—	—
14FF52	x	x	x	—	—	[3]x	—	x	—	—	—	—	—	—	—
14FF53	x	x	x	—	—	x	—	x	—	—	—	—	—	—	—
14FF55	x	x	x	x	—	—	x	x	—	—	—	—	—	—	—
14FF56	x	x	x	x	x	—	x	x	—	—	—	—	—	—	—
14FF57	x	x	x	—	x	—	x	x	—	—	—	—	—	—	—
14FF58	x	x	x	—	x	—	x	x	—	—	—	—	—	—	—
14FF59	x	x	x	x	—	—	x	x	—	—	—	—	—	—	—

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

[2]Logs, include borehole deviation

[3]Partial, incomplete, or poor visibility log

Characterization of Fractures in Open Boreholes

Imaging techniques used in this study permitted direct observation of lithology, compositional layering, foliation, and other structures in relation to the depth and nature of the intersecting fracture plane. When viewing fractures, some interpretation was required to separate them into several main types.

Determination of Type, Depth, and Orientation of Fractures

ATV and BIPS logs, in combination with borehole-camera surveys, were used to determine the type of fractures in open boreholes. The strike and dip of intersecting fractures were compared to surrounding foliation and compositional layering and classified as "joints" where fractures crosscut rock foliation and compositional layering, "open joints" for fractures with visible openings that could be seen intersecting the borehole wall, "foliation partings" for small openings formed parallel to foliation or compositional layering, and "major foliation openings" for large openings formed parallel to foliation or compositional layering. Irregular openings, for which a category was not readily apparent, were classified into the primary feature being weathered. For example, weathered and dissolutioned joints were included in the open joint category and irregular openings along foliation planes were included as a foliation parting or a major foliation opening depending on the size of the fracture.

Depths of fractures identified from the ATV and/or BIPS logs were depth corrected to align vertically with the caliper and other geophysical log data. In order to make the correction, the caliper log and the image logs first were plotted on the same scale, and then prominent fractures on the image logs were matched to peaks on the caliper log. An average depth offset was then computed to make the depth correction. For example, if the caliper log indicated fracture openings at 10 ft, 100 ft, and 245 ft that corresponded to fractures observed on the image log at 11 ft, 101 ft, and 246 ft, then a depth correction of 1 ft was used for the ATV or BIPS log. In this manner, the fractures and other structural features identified with geophysical tools were shifted to a common reference point—that being the caliper log, which is referenced to land surface. Small offsets in vertical alignment commonly occur because of different tool sizes and shifts in the reference point used for logging.

Overall, the caliper log, in combination with the borehole ATV and/or BIPS logs, provided ample information to locate most of the fractures in the open boreholes of wells. In many wells, however, the borehole-camera log was used to aid in identifying less obvious joints and fractures that were difficult to see in the ATV or BIPS log. Correlating between the high-resolution camera log and the image logs was an effective means for identifying less obvious intersecting joints and fractures. Small openings, such as foliation partings, rarely were accompanied by an observable caliper peak; therefore, camera logs were necessary for identifying these small features.

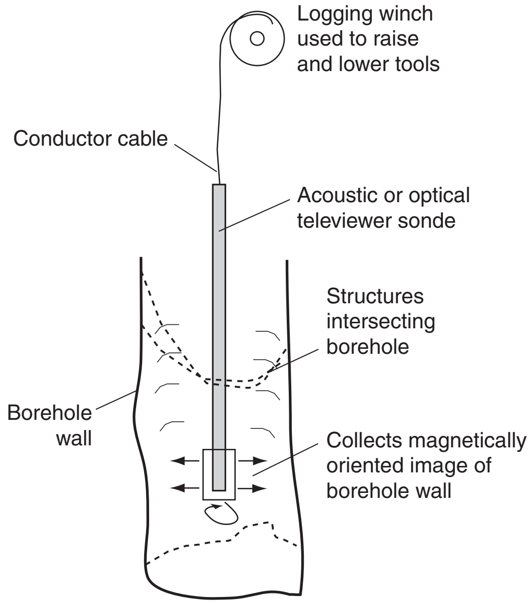
The orientation (strike and dip) of fractures was determined from the ATV and BIPS logs. The strike and dip indicate the orientation of the layer or planar feature relative to a horizontal plane. Strike is the compass direction of a line formed by the intersection of the surface of an inclined feature with an imaginary horizontal plane (fig. 3). Dip is the tilt or angle, perpendicular to strike, of an inclined feature measured downward from a horizontal plane. In figures included in this report, the structural orientation of features is shown in terms of the dip angle (measured from horizontal) and the dip azimuth (using 360-degree compass direction) using a tadpole plot (fig. 3).

WellCad©, a commercial log processing program from Advanced Logic Technology (ALT), was used to calculate the strike and dip of structural features identified in televiewer logs. When viewed in a two-dimensional projection of the borehole wall, planar-dipping features form an ellipse across the borehole, which appears as a sinusoidal wave on a two-dimensional depiction of the borehole wall (fig. 3). The lowest point on the sinusoidal wave gives the direction of the dipping plane. The true strike and dip were calculated using the WellCad© image-processing module, which corrects for borehole deviation (fig. 3). A rotation of 3.5 degrees west of "true" north also was applied to the data to correct for magnetic declination in the study area.

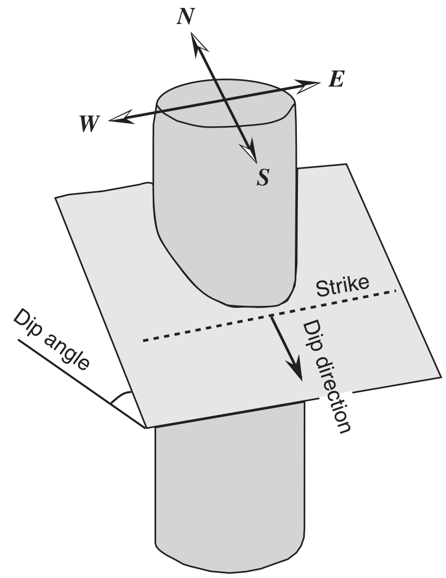
Identification of Water-Bearing Fractures

Water-bearing fractures in open boreholes of wells were identified by comparing the depth and yield of individual water-bearing zones identified during drilling to fracture data compiled from geophysical logs, ATV and BIPS televiewer image logs, borehole-camera images, and flowmeter logs. Water-bearing fractures were confirmed using multiple lines of evidence, such as a caliper peak (indicating a physical opening), low-resistivity response on resistivity logs, and inflections on fluid temperature and fluid resistivity logs. The geophysical log data were used in combination with "visual" observations of the fracture trace in the ATV or BIPS log, and borehole-camera log. Using these sources of data, the main water-bearing fractures were interpolated and denoted on geologic logs for each well. It should be noted that the water-bearing zones identified in this study represent primary water-bearing fractures in each well. Joints and fractures not contributing substantially to the yield of a well (much less than 1 gal/min) were not of concern unless the well was low yielding.

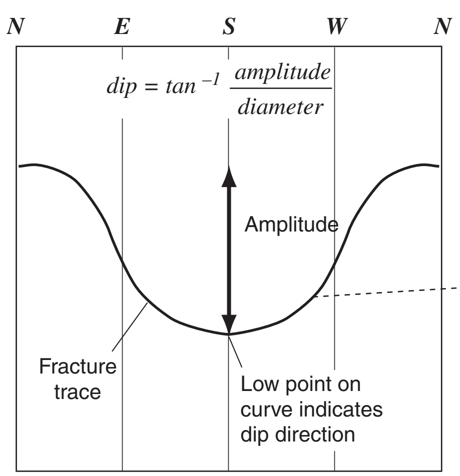
In some cases, water-bearing fractures were identified, but the yield from individual fractures could not be quantified with the available data. For example, in some wells the yield gained along a vertical section of borehole could not be attributed to a specific zone. In these vertical sections, the water-bearing zones were called *potential production zones* to indicate the relative uncertainty of the exact depth of the production zone. The term *potential production zone* also was applied to the most likely production zones in some of the older existing wells for which drilling observations were not available.



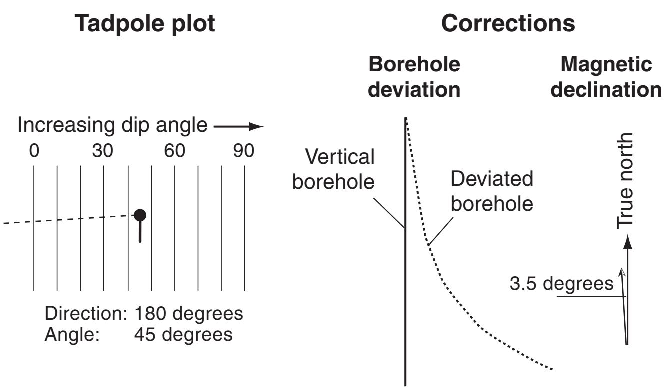
A. Diagram showing logging winch and geophysical sonde used to collect image of borehole wall.



B. The orientation of a planar feature intersecting a borehole is described by the strike (azimuth direction a straight line would make from the intersection of an inclined plane with the horizontal) and dip angle (tilt from horizontal). In this diagram dip direction is south.



C. The trace of an intersecting plane makes a sinusoidal wave on a two-dimensional projection of the borehole wall. The amplitude of the wave and diameter of the borehole are used to calculate dip angle and dip direction.



D. Tadpole plots are used to show the dip direction and dip angle. The "tail" of the tadpole points in the dip direction (similar to a plan view on a map). From left to right, the symbols are plotted with increasing dip angle. Horizontal = 0, vertical = 90.

Figure 3. Schematic diagrams illustrating how the strike and dip of a planar feature intersecting a borehole are determined. The calculation assumes the feature is planar (not curved). Corrections are made for borehole deviation and magnetic declination.

Estimating Yield Contribution from Individual Water-Bearing Fractures

The yield contribution from individual water-bearing fractures was estimated from air-lift yield tests at the time of drilling and then confirmed later with flowmeter surveys. The combination of these two methods provided the most effective means of characterizing the yield contribution from individual water-bearing fractures intersecting the open boreholes of wells.

Estimating Yield during Drilling

The depth and yield of fractures were initially estimated during drilling by carefully observing the drilling rate, identifying "drilling breaks," and measuring the amount of water being evacuated from the test well during air-percussion rotary drilling. A drilling break occurs when the down-hole air hammer penetrates an open void, a zone of increased fracturing, or weakness in the rock. An increase in "chattering" of the drill rod, followed by a distinct drop, and an almost immediate increase in the return volume were indicative of large, open, water-bearing fractures. Small openings and/or low-yielding fractures typically corresponded with small drilling breaks, chattering, and small rod drops, but without an increase in return volume.

The color and size of the rock cuttings also were used as an indicator of potential water-bearing fracture zones. Water-bearing fracture zones commonly are accompanied by an increase in the size of the drill cuttings, iron-oxide staining on the cuttings, and large angular rock fragments broken out of fracture zones.

The air-lift yield was checked after each potential water-bearing zone was penetrated to determine any increase in yield from the zone. The yield measurement generally was made by conveying the return water into a bucket or 55-gallon drum and using a stopwatch to compute the discharge rate. At well sites where there was no practical means to convey the water into a bucket, the air-lift yield was estimated by the driller. After making the measurement, the increase in air-lift yield was attributed to the zone penetrated. For example, if the well was blowing "dry" down to 150 ft and "chattering" and a rod drop was observed at 151 ft, followed by an increase in yield of 5 gal/min, then a 5-gal/min water-bearing fracture was noted at a depth of 151 ft. If another zone was penetrated at 200 ft, with a total discharge of 20 gal/min (increase of 15 gal/min), then a 15-gal/min fracture zone was noted at 200 ft. This process was repeated for all potential water-bearing fracture zones in the well.

The yield contribution of individual fractures and fracture zones was later estimated by carefully correlating air-lift yield increases observed during drilling (described above) with the depth of fracture zones identified using geophysical logging. In some zones, the correlation was clear and unambiguous—an increase in air-lift yield, for example, may have been observed within 5 ft of a large fracture opening or fracture zone observed in an ATV log. In other zones, increases in yield could not be correlated with a specific fracture observed in the borehole geophysical logs. In these cases, the increase in air-lift yield was attributed to one or more previously penetrated (shallow) fracture zones near the depth of yield increase. A shallow fracture zone, within 15–25 ft of the increase, often was identified as the most likely water-bearing fracture zone. The yield estimated in this manner should be regarded only as a rough estimate of the yield from the fracture or fracture zone. Limitations of this method are: (1) accurately measuring the amount of water being lifted out of the well during drilling—some were measured and others estimated; (2) identifying the precise location of slight increases—increases of 1 to 10 gal/min may not be recognized until starting a new segment of drilling rod; and (3) detecting small increases in yield below one or two major producing zones—for example, an increase from 1 to 5 gal/min may be indistinguishable from a shallow (previously penetrated) fracture zone producing 100 gal/min.

Flowmeter Surveys

Flowmeter surveys, conducted under ambient and pumping conditions, were used to identify water-producing and water-losing fracture zones in open-bedrock wells. Water-producing zones are defined in this report as discrete zones that yield measurable amounts of water to the borehole when pumped or where water is flowing into the borehole during ambient conditions. Water-losing zones are defined as zones where water exits the well through fractures or zones of lower hydraulic head.

The technique of locating water-producing and water-losing zones involves using a flowmeter to measure the flow velocity (up or down) along segments of open borehole or at discrete depths, such as above or below previously identified fractures. Data are obtained by either measuring flow at a stationary point or by trolling along sections of a borehole to produce a flow profile (Johnson and Williams, 2003). Differences in flow rate detected with the flowmeter along the borehole are attributed to water-producing or water-losing zones. For this study, the stationary-point method was found to be the most reliable method for measurement of borehole flow, and those are the data reported.

Two types of flowmeters were used for flow measurement: a heat-pulse flowmeter (HPFM) and an electromagnetic (EM) flowmeter. The HPFM can measure flow rates as small as 0.01 gal/min and was used for wells having a borehole flow of less than 2 gal/min. The EM flowmeter has a larger operating range and was used for wells having a borehole flow of greater than 2 gal/min.

With the exception of well 14FF59, two separate flowmeter surveys were conducted in each well: (1) a nonpumping "ambient" survey and (2) a pumping survey. In each well, an ambient survey was first conducted to document the ambient flow into or out of the borehole prior to pumping. These surveys provided information on whether there was any ambient flow resulting from differences in head and hydraulic conductivity of the water-bearing fractures intersecting the well. The rate of flow from higher head fractures to lower head fractures is largely controlled by the hydraulic conductivity of the fracture and by differences in hydraulic head between fractures. Following the ambient survey, a submersible pump was installed near the top of the well and the well was pumped at rates ranging from several gallons per minute to as much as 60 gal/min. After the drawdown in the well had stabilized, a second flowmeter survey was completed, measuring the flow at similar depths recorded during the ambient survey. The results of the ambient and pumping surveys then were plotted to show the relative contribution of water-bearing fractures with depth. An interpretive line was drawn through the data points to produce a best fit for the data, stepping the graph at interpreted inflow or outflow points. The depths of water-bearing zones determined from geophysical logs were taken into consideration in determining where to designate the inflow or outflow for each log.

Aquifer Testing

The City of Lawrenceville, or its contractor, conducted aquifer tests to determine pumping drawdown and yield for water-production engineering. Because the goal of these tests was for engineering purposes without determination of hydraulic properties, typical aquifer-test procedures and protocols were not used. Close attention was paid, however, to the drawdown in the pumped well, pumping rate, and drawdown in observation wells.

For the aquifer tests, pressure transducers and water-level data recorders were installed in both the pumped well and nearby observation wells. These water-level recording devices were left in place for a period of time ranging from a few days to several weeks, depending on the amount of time required for recovery of the water level after pumping. Barometric pressure and rainfall gages were used during some of the tests so that barometric changes and rainfall recharge effects could be accounted for, where necessary. Discharge was regulated using gate valves and measured with a flowmeter or an orifice weir. The discharge from the aquifer tests was conveyed away from the pumped well by routing the flow along a ditch or piped to the nearest stream or water body. The discharge rate was checked by taking a volumetric measurement using a stopwatch and a bucket. These “bucket checks” routinely were taken several times during the test for quality-assurance purposes.

To avoid dewatering fractures, most of the aquifer tests were conducted by pumping at a rate large enough to draw the water level in the pumped well down to a few feet above the uppermost water-bearing zone and holding the level above that zone for the remainder of the test. As each test proceeded, the pumping rate was decreased, if necessary, to maintain the pumping water level above the uppermost water-producing fracture zone. A small-diameter stilling well (typically 1 inch) was used to make manual water-level measurements in the pumped well. The stilling well prevented cascading water in the pumped well from interfering with water-level measurements.

Analysis of the data consisted of plotting the drawdown in the pumped well with respect to time and evaluating if the pumping water level stabilized. From these observations, the pumping rate and pumping water level were determined. Drawdown in observation wells also was evaluated to see if any anisotropic response could be identified. Quantitative analysis for determination of aquifer coefficients using the drawdown and recovery data is beyond the scope of this report.

Packer Testing

Inflatable straddle packers were used to isolate and hydraulically test individual discrete fractures in well 14FF59 (figs. 1, 4). To conduct each test, the packers were inflated to isolate a section of borehole, water was pumped from the isolated section, and pressure transducers were used to monitor the hydraulic response within, above, and below the pumped zone.

A special packer system (fig. 4) was designed to conduct packer tests in the Lawrenceville area. The packer system consisted of two inflatable rubber packers, a submersible pump, and pressure transducers for monitoring above and below the packers (top and bottom transducers) and the isolated interval (middle transducer). Pass-through tubes connect pressure transducers to monitoring intervals. Because the pass-through tubes are open ended and trap air when lowered into the borehole, an air-actuated valve was used to evacuate trapped air in the pass-through tubes. The rubber packers were inflated using nitrogen delivered through a ¼-inch polyethylene air line. The pressure in the packers was monitored using a pressure gage. The pumping rate was monitored at the land surface with a flowmeter and checked with a calibrated bucket and stopwatch.

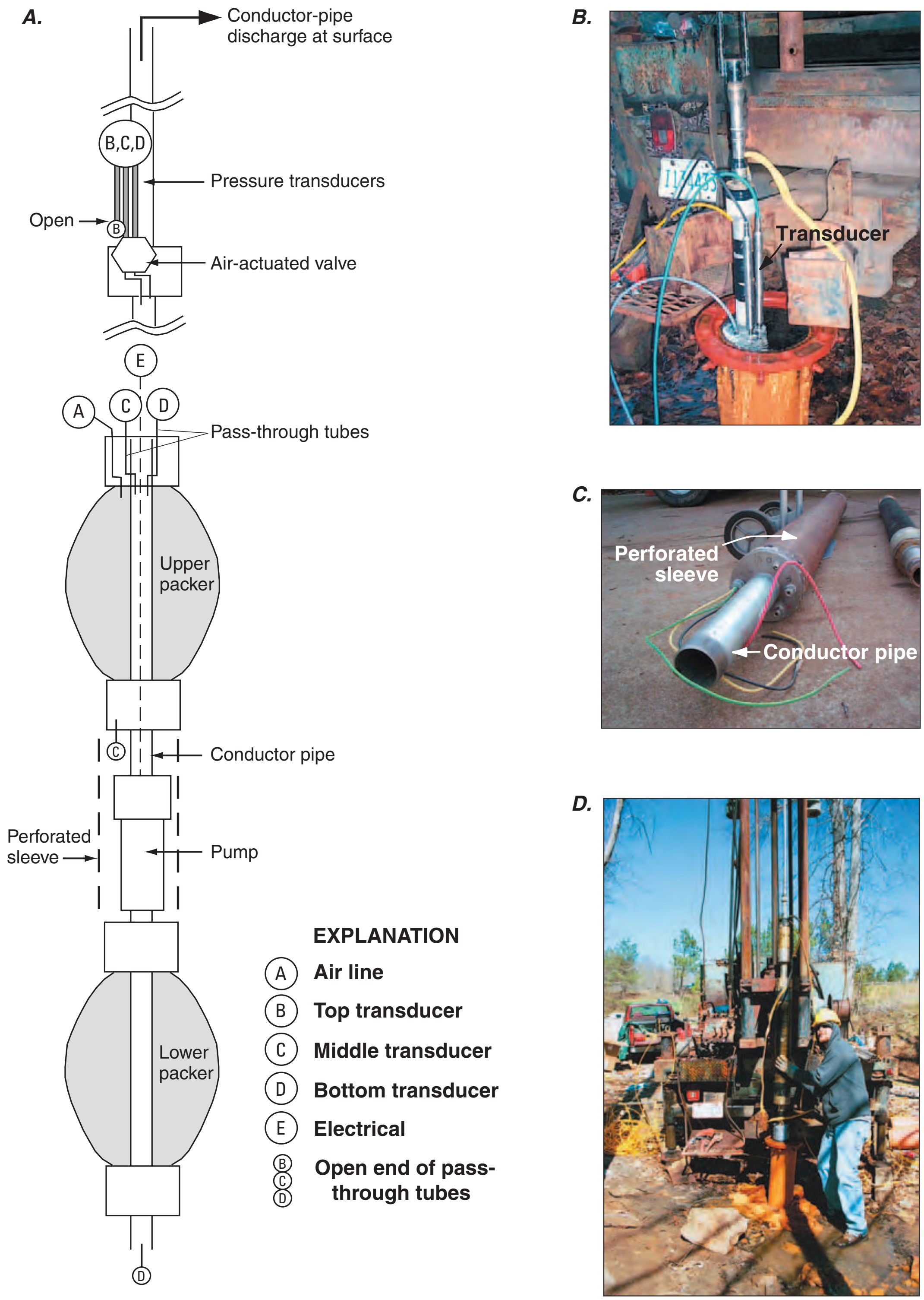
Following inflation of packers and stabilization of the water levels in the three zones, the submersible pump was used to pump water from the isolated interval. Each test continued until the water level in the pumped interval was static or nearly static. Following the pumping phase of the test, the pump was stopped and water-level recovery was monitored.

The data were analyzed by plotting the water-level response in the three zones with respect to time. This allowed a qualitative analysis of the data to determine the hydraulic response within and between discrete water-bearing fractures.

Water-Level Monitoring

Water levels were measured synoptically, where many wells were measured during a short period of time, and continuously to monitor the water-level fluctuation in response to seasonal variations in rainfall and pumping.

Synoptic water levels were measured in 30 wells throughout the study area on October 31, 2001. An electronic water-level tape was used to measure the depth of water below land surface and a pressure transducer was used to measure water levels in flowing wells. Water levels above land surface are expressed as negative numbers. Continuous water levels were measured using data recorders installed in 26 wells for periods of time ranging from more than 1 month to several years. Water-level recorders were installed and operated using standard procedures of the USGS. All data were entered into the USGS National Water Information System database.



Note: Air-actuated valve is triggered using a separate air line; trapped air in the pass-through tubes is released after assembly is below water level

Figure 4. Down-hole packer assembly used during the study showing (*A*) schematic of packer assembly, and photos of (*B*) pressure transducers secured to top of packer assembly, (*C*) conductor pipe and perforated pump sleeve, and (*D*) lowering packer assembly into well 14FF59, Lawrenceville, Georgia.

Hydrogeologic Data

Thirty-two bedrock wells, ranging in depth from 180 to 630 ft, were used to characterize the lithology, yield, and fracture characteristics in the Lawrenceville area. In addition, several shallow regolith wells were used as observation wells during aquifer tests and for long-term monitoring. For each well, the latitude, longitude, land-surface altitude, top of casing altitude, well depth, casing depth, casing diameter and type, ream depth, well yield, and geologic units are listed in table 2. Well locations are shown in figures 1 and 2.

Fracture Data

Fracture data, compiled from geophysical and borehole-camera logs in 32 bedrock wells, were used to determine the depth, nature, and yield of bedrock fractures in the Lawrenceville area. These data were plotted on standard figures for each well as illustrated in figures 5 and 6. Typically, two or three main water-bearing fractures were detected in each well during drilling. Although geophysical surveys indicated numerous fractures in each well, flowmeter surveys and packer tests identified only a few of these as water bearing—typically the larger "open" fractures intersecting boreholes.

Using borehole imaging data and correlating these data to individual fracture yield, two main systems of water-bearing fractures were identified: (1) joints, open joints, and zones of joint concentration consisting mostly of steeply-dipping low-yielding fractures; and (2) small and large openings along foliation planes and layering consisting of discontinuous but high-yield fractures, which are defined in this report as "foliation parallel-parting systems" and originally described by Williams (2003) as "foliation fracture systems." Water-bearing zones also are formed from the dissolution of preexisting crosscutting mineralized joints, which form irregular openings that cross foliation and layering. Chemical dissolution along joints, foliation planes, and contacts between compositional layers also form a variety of irregular-shaped voids and irregular fractures.

Individual Fracture Yield

Yield of individual water-bearing fractures and fracture zones was estimated by carefully correlating air-lift yield increases observed during drilling with identified subsurface fractures. Yields determined for individual fractures and fracture zones in 32 wells, ranged from less than 1 gal/min to 240 gal/min (table 5).

In general, increases in yield during drilling were found to be associated with one or more of the following features:

- joints, open joints, and zones of joint concentration;
- foliation partings and major foliation openings along foliation and layering of the rock;
- dissolution openings of mineral infilling of a joint or vein; and
- irregular-shaped voids and fractures.

Joints, Open Joints, and Zones of Joint Concentration

Joints generally are complex "crisscrossing" fractures that break up the rock into blocks and slabs of differing dimensions. In boreholes, joints are differentiated from other fractures by their occurrence in sets, common planar geometry, and orientation cutting across rock foliation and layering. Most joints observed in boreholes appeared as hairline fractures and typically were not significant water-bearing zones.

Open joints and zones of joint concentration typically were associated with increases in air-lift yield from 1 to 5 gal/min, although slightly higher or lower yields are common for these types of fractures. Several wells intercept zones of intensely jointed rock. One such well, 14FF58, penetrates multiple zones of joint concentration. Despite these many zones of joint concentration, however, only three open joints were identified for a combined yield of about 1 gal/min. In other wells, high yields were obtained from zones of joint concentration and open joints: the highest yielding zone was found in well 13FF22, where a yield of about 30 gal/min was reported for a zone of concentrated jointing and multiple open joints (table 5). This zone of concentrated jointing showed extensive dissolution around the joint faces, which apparently has enhanced the yield from this specific zone. Other wells producing water from joints, open joints, or zones of joint concentrations include wells 13FF15, 13FF23, and 14FF17.

Foliation Partings and Major Foliation Openings

Foliation partings and major foliation openings are fractures formed nearly parallel to foliation and compositional layering; thus, they occur only in layered metamorphic rock sequences such as the amphibolite, biotite gneiss, button schist and quartzite/schist units. A foliation parting is defined in this report as a small fracture with an aperture typically less than 0.5 inch. A major foliation opening is a much larger fracture with an aperture typically ranging from 1 to 8 inches, with some larger.

Individual foliation partings were associated with increases in air-lift yield from 1 to 15 gal/min (table 5). In some wells, groups of foliation partings or single partings yielded substantial amounts of water. A zone of water-bearing foliation partings in well 14FF52, from a depth of 158 to 159 ft, yielded 30 gal/min; and a single foliation parting in well 13FF23, from a depth of 82.5 to 83.5 ft, yielded 33 gal/min. In another well, 14FF27, a yield of 50 gal/min was estimated for a group of foliation partings and one open joint in a zone between 410 and 435 ft (table 5).

Major foliation openings yielded substantially more water than the smaller foliation partings described above. A range in yield from 50 to 100 gal/min is typical for these larger fracture openings (table 5), making these the primary water-bearing features responsible for high-yield wells in the Lawrenceville area. All the high-yield wells studied in the Lawrenceville area penetrate at least one major foliation opening. In some wells, such as wells 13FF16 and 13FF21, only one major foliation opening was penetrated; whereas, in other wells such as well 13FF23, multiple foliation openings were penetrated.

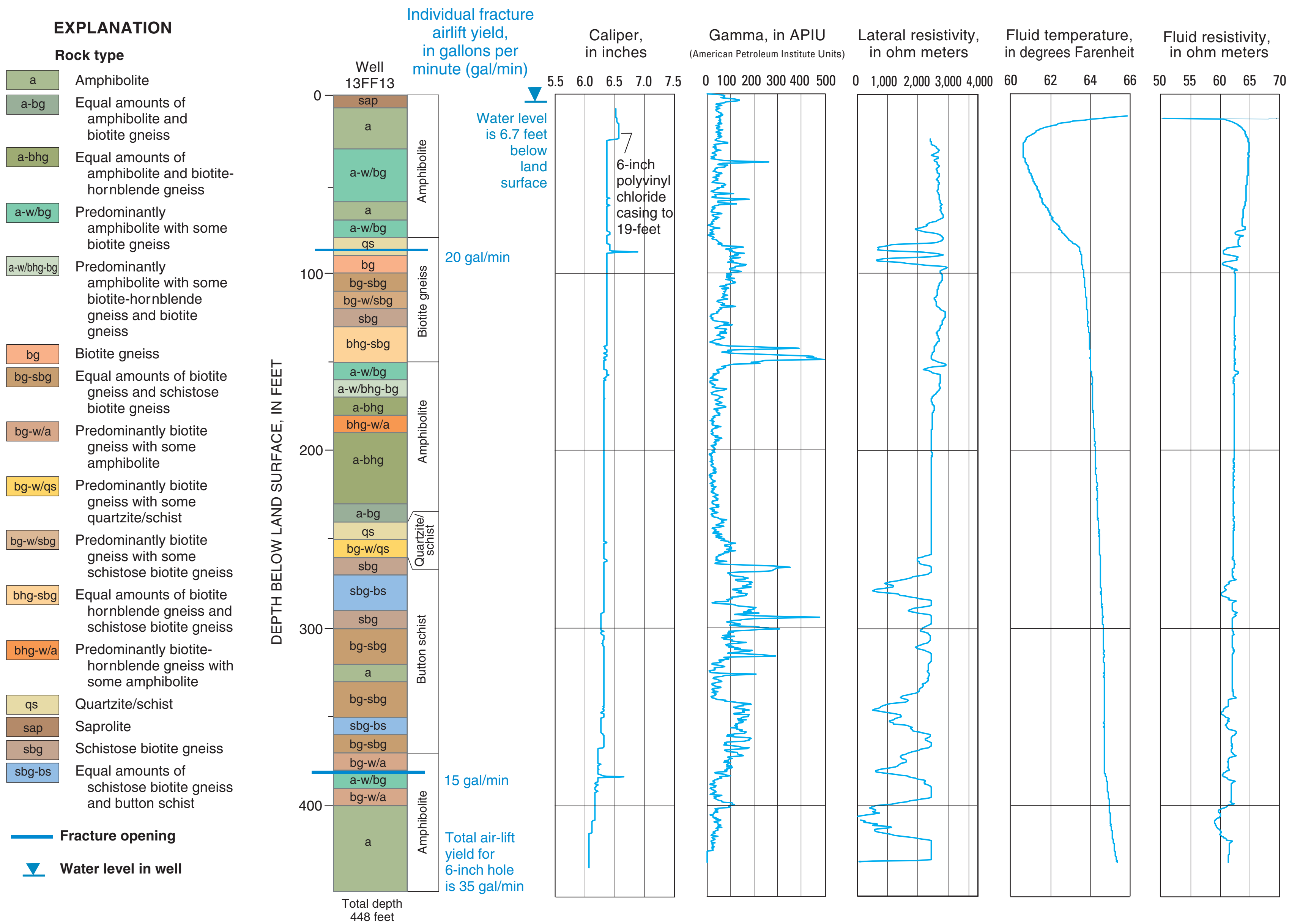


Figure 5. Example lithologic units and geophysical log figure showing caliper, gamma, lateral resistivity, fluid temperature, and fluid resistivity, Lawrenceville, Georgia.

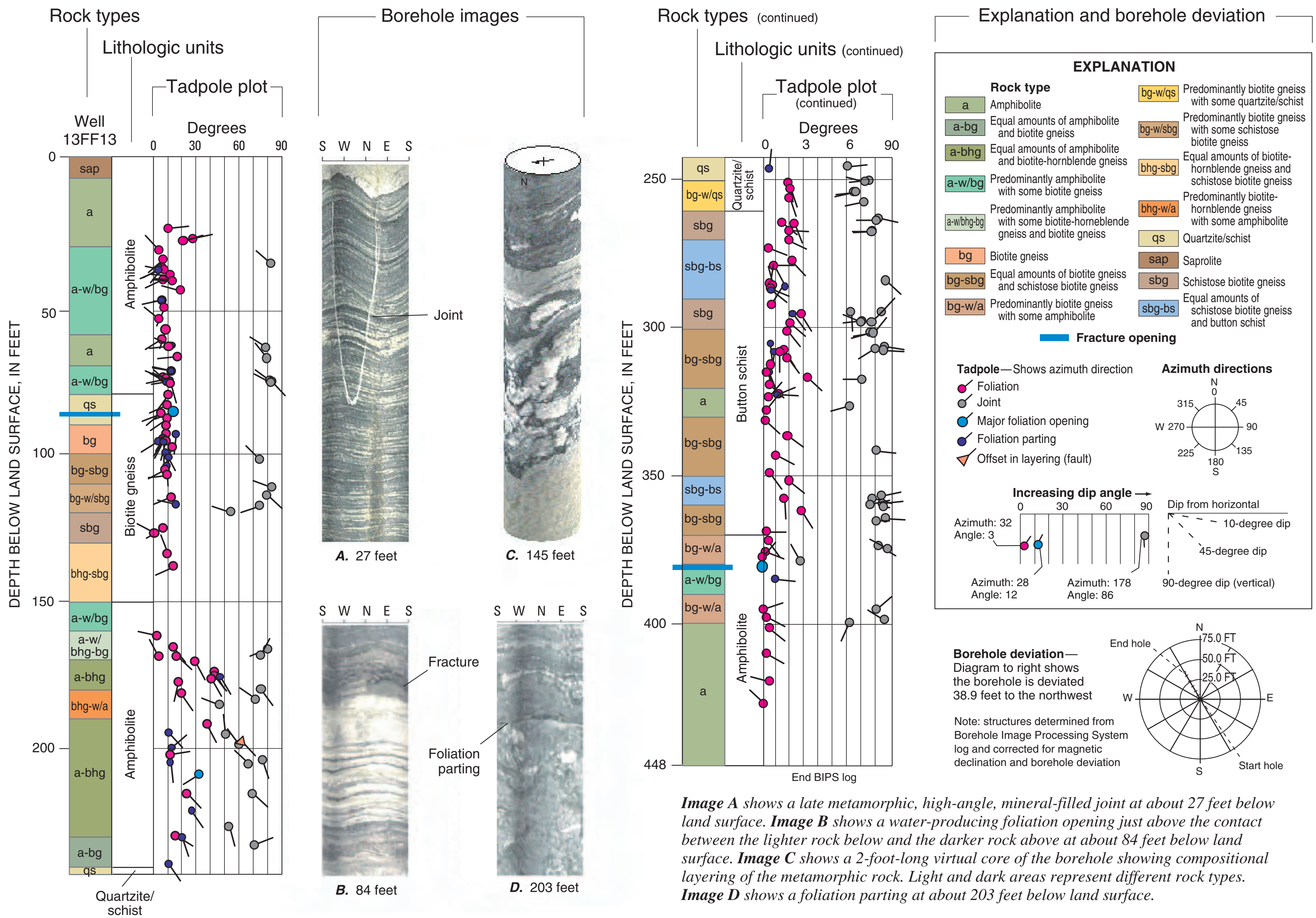


Image A shows a late metamorphic, high-angle, mineral-filled joint at about 27 feet below land surface. Image B shows a water-producing foliation opening just above the contact between the lighter rock below and the darker rock above at about 84 feet below land surface. Image C shows a 2-foot-long virtual core of the borehole showing compositional layering of the metamorphic rock. Light and dark areas represent different rock types. Image D shows a foliation parting at about 203 feet below land surface.

Figure 6. Example structure log figure showing rock types, lithologic units, tadpole plots, borehole images, and borehole deviation, Lawrenceville, Georgia.

Table 5. Depth, yield, and structural features of water-bearing fracture zones in the Lawrenceville, Georgia, area.

[ft, foot; BLS, below land surface; PPZ, potential production zone; PZ, production zone; do, ditto; gal/min, gallons per minute; —, data not collected. Geologic units: a, amphibolite; bg, biotite gneiss; bs, button schist; gg, granite gneiss; qs, quartzite/schist; +, plus]

Well name	Depth (ft BLS)	Yield	Structural features
13FF12			
Total yield:	111.0–111.5	PPZ	Foliation parting + joint
254 gal/min	116.5–117.5	PPZ	Joints
(bg, bs, bg, a)	123–123.5	PPZ	Foliation parting
	128.5–132.3	PPZ	Multiple joints
	208.8–209.8	PZ	Major opening along foliation/layering
	212.2–213.8	PZ	Do.
13FF13			
Total yield:	87.2–88.2	20 gal/min	Major opening along foliation/layering + foliation parting opening
35 gal/min	380–381.5	15 gal/min	Major opening along foliation/layering
(a, bg, a, qs, bs, a)			
13FF14			
Total yield:	231–232	PPZ	Dissolution along mineral-filled joint
140 gal/min	269–270	PZ	Foliation parting
(a, bg)	271–273	140 gal/min	Major opening along foliation/layering
13FF15			
Total yield:	115–116	5 gal/min	Joints and open joint
250 gal/min	129–130	PPZ	Open joint
(bg)	139–140	5 gal/min	Do.
	199.5–201	240 gal/min	Major opening along foliation/layering
13FF16			
Total yield:	169.5–170	10 gal/min	Foliation parting
75 gal/min	179.5–180.5	PZ	Do.
(a, bs, a, bg)	182.5–184	65 gal/min	Major opening along foliation/layering + foliation parting
13FF17			
Total yield:	48–49	6 gal/min	Major opening along foliation/layering
90 gal/min	64.5–65	60 gal/min	Major opening along foliation/layering + joints
(a)	197–198	24 gal/min	Foliation parting
13FF18[1]			
Total yield:	38–39	—	10 gal/min, sealed off
100[2]/150[3] gal/min	54.5–55	—	18 gal/min, sealed off
(a)	82.25–83.25	63 gal/min	Foliation parting
	100.8–101.8	83 gal/min	Major opening along foliation/layering
	159.1–160.1	4 gal/min	Foliation parting
13FF19[4]			
Total yield:	35–37.5	5 gal/min	—
[2]250/[3]350–400 gal/min	58–61	20 gal/min	Do.
(a)	198–199	15 gal/min	Foliation parting
	245.5–246.5	100 gal/min	Major opening along foliation/layering
	356–357	10 gal/min	Foliation parting
13FF20			
Total yield:	373.5–374.5	1 gal/min	Major opening along foliation/layering
35 gal/min	392.25–393	34 gal/min	Do.
(a, bs)			
13FF21[1]			
Total yield:	240.5–241.5	125 gal/min	Major opening along foliation/layering
[2]130/[3]125 gal/min			
(bg, a)			
13FF22			
Total yield:	23–25	5 gal/min	Multiple joints
100 gal/min	47.5–48.5	10 gal/min	Foliation parting
(a, bg)	154–155	50 gal/min	Major opening along foliation/layering
	368–369	5 gal/min	Foliation parting
	468–475	30 gal/min	Multiple open joints + foliation parting, dissolution along joints
13FF23[4]			
Total yield:	40–41	0.5 gal/min	Foliation parting
[2]250/[3]350–400 gal/min	50–51	1.5 gal/min	Open joint
(a, bg, bs)	77.5–78.5	PPZ	Foliation parting
	82.5–83.5	33 gal/min	Do.
	101–102	PZ	Do.
	142–143	65 gal/min	Major opening along foliation/layering
	164–165	PZ	Do.
	179–180	PZ	Do.
	242.75–243.75	150 gal/min	Do.
	256.5–257.5	PZ	Do.

Table 5. Depth, yield, and structural features of water-bearing fracture zones in the Lawrenceville, Georgia, area.—Continued

[ft, foot; BLS, below land surface; PPZ, potential production zone; PZ, production zone; do, ditto; gal/min, gallons per minute; —, data not collected. Geologic units: a, amphibolite; bg, biotite gneiss; bs, button schist; gg, granite gneiss; qs, quartzite/schist; +, plus]

Well name	Depth (ft BLS)	Yield	Structural features
14FF08			
Total yield:	49–50	PPZ	Foliation parting
400 gal/min	51–52	PPZ	Multiple openings along foliation/layering
(a, bs, bg, gg)	101–113	PPZ	Major opening along foliation/layering
	185–187	PZ	Do.
	206–207.5	PZ	Multiple small openings along foliation/layering
	222–226	PZ	Major opening along foliation/layering
	231–233	PZ	Do.
14FF10	24–30	PPZ	Cavernous, dewatered during pumping
Total yield:	37–39	PPZ	Cavernous fracture along foliation, dewatered during pumping
270 gal/min	88–89.5	PPZ	Do.
(a)	107–108	PPZ	Open vertical fracture
	129–131	PZ	Major opening along foliation/layering
	175.5–178	PZ	Do.
14FF16	41.5–43.5	Dry	Cavernous, dewatered during pumping
Total yield:	72–76.5	Dry	Do.
471 gal/min	91.5–93	PPZ	Foliation parting
(a, bs)	133.5–135.5	PZ	Major opening along foliation/layering
	169–170	PZ	Do.
	178–180	PZ	Do.
	208.5–209.5	PZ	Do.
14FF17			
Total yield:	34–35	2 gal/min	Major opening along foliation/layering
150 gal/min	67–69	PPZ	Open joint
(a)	70–71	3 gal/min	Do.
	142–143	4 gal/min	Major opening along foliation/layering
	182–183	8 gal/min	Do.
	210–212	133 gal/min	Not determined, bottom hole fracture covered with silt
14FF18			
Total yield:	30.5–32.5	1 gal/min	Foliation parting, dewatered during pumping
100 gal/min	51–52	2 gal/min	Several minor openings along foliation/layering, cascading water during pumping
(a)	105.5–106	27 gal/min	Major opening along foliation/layering, no cascading water when pumped below
	149.5–151	70 gal/min	Major opening along foliation/layering
14FF26			
Total yield:	67–68	PPZ	Foliation parting
—	85.5–86.5	PPZ	Multiple minor openings along foliation/layering
(a, bg, bs, a, bg)	93–94	PPZ	Open joint and multiple joints
	114–115	PZ	Major opening along foliation/layering + foliation parting
	161–162	PZ	Two separate major openings along foliation/layering
14FF27			
Total yield:	62–86	42 gal/min	Not determined, water-bearing zone detected while drilling
150 gal/min	103–104	4 gal/min	Do.
(gg, bg, qs, a, bs)	112–113	4 gal/min	Foliation parting
	163–164	PPZ	Foliation parting + open joint
zone at 62 ft yielded 42	166–168	PPZ	Multiple foliation partings
gal/min, but sealed	174.5–175.5	10 gal/min	Foliation parting
behind casing	296–299	PPZ	Multiple open joints + foliation parting below
	335–345	50 gal/min	Do.
	410–435	50 gal/min	Open joint at 433 ft BLS + multiple foliation parting
	571–572	25 gal/min	Major opening along foliation/layering
14FF39			
Total yield:	36.8–38.8	—	Joint + foliation parting, dewatered during pumping
150 gal/min	119–120	75 gal/min	Major opening along foliation/layering
(a)	170–171	75 gal/min	Do.
14FF42			
Total yield:	76–77	not determined	Joint, cascading water observed
10 gal/min			
(a, bs, bg)			
14FF46			
Total yield:	10–11	10 gal/min	Not determined, detected during drilling
70 gal/min	62–63	35 gal/min	Major opening along foliation/layering
(a, bs, bg)	145.5–146.5	20 gal/min	Do.
	227–228	5 gal/min	Joint

Table 5. Depth, yield, and structural features of water-bearing fracture zones in the Lawrenceville, Georgia, area.—Continued

[ft, foot; BLS, below land surface; PPZ, potential production zone; PZ, production zone; do, ditto; gal/min, gallons per minute; —, data not collected. Geologic units: a, amphibolite; bg, biotite gneiss; bs, button schist; gg, granite gneiss; qs, quartzite/schist; +, plus]

Well name	Depth (ft BLS)	Yield	Structural features
14FF47			
Total yield:	26–35	10 gal/min	Leakage from partially weathered rock, later cased of
25 gal/min	51–52	1 gal/min	Foliation parting
(bg)	172.5–176	PPZ	Multiple joints
	204–205	PPZ	Foliation parting
	235.5–236.5	14 gal/min	Do.
	274–275	PPZ	Foliation parting + joints
14FF49			
Total yield:	86–88	PPZ	Foliation parting
10 gal/min	111–112	PPZ	Do.
(bg, gg)	128–129	PPZ	Multiple minor openings along foliation/layering
	135–136	PPZ	Do.
14FF50			
Total yield:	185.5–187.5	PZ	Major opening along foliation/layering + foliation parting
300 gal/min gal/min	210.5–212.5	PZ	Two separate major openings along foliation/layering
(a, bs, bg, gg)	213.5–214.5	PZ	Irregular opening along foliation
14FF52			
Total yield:	158–159	30 gal/min	Multiple foliation partings
40 gal/min	186–187	10 gal/min	Do.
(a, bs, bg)			
14FF53			
Total yield:	95–96	3 gal/min	Joint
50 gal/min	186–187	12 gal/min	Partial foliation parting on one side of borehole
(bs, a, gg)	298–301	35 gal/min	Dissolution along mineral-filled joint
14FF55[4]			
Total yield:	14–17	15 gal/min	Cavernous, mostly along foliation
[2]250[b]/[3]325 gal/min	31–32	PPZ	Weak friable rock and openings along layering
(bg, a)	50.5–51.5	PPZ	Multiple openings along foliation/layering
	64–65	PPZ	Opening along foliation
individual fracture yield	100.5–101.5	5 gal/min	Foliation parting
based on 6-inch	172.5–173.5	PZ	Major opening along foliation/layering
air-lift yield	181–182	20 gal/min	Do.
	251–252	110 gal/min	Do.
	305.5–306.5	PPZ	Foliation parting
	416–417	100 gal/min	Major opening along foliation/layering
14FF56			
Total yield:	43.5–44.5	30 gal/min	Major opening along foliation/layering
60 gal/min	57.5–58.5	10 gal/min	Do.
(a, bs, bg)	138–139	20 gal/min	Do.
14FF57			
Total yield:	45.5–46.5	2.9 gal/min	Major opening along foliation/layering
3 gal/min	196.5–197.5	0.1 gal/min	Foliation parting
(bg)	340–341	PPZ	Major opening along foliation/layering
14FF58			
Total yield:	42–43	PZ	Open joint
1 gal/min	287.5–288.5	PZ	Do.
(gg)	498–499	PZ	Do.
14FF59[d]			
Total yield:	17.5–18.5	30 gal/min	Opening along layering
[2]180/[3]350-400 gal/min	266.5–267	20 gal/min	Major opening along foliation/layering
(a, bs, bg)	281–282	45 gal/min	Do.
	296–297	30 gal/min	Do.
	324.5–325	5 gal/min	Do.
	347–348	50 gal/min	Do.

[1]Individual fracture yield based on air-lift yield from 8-inch borehole

[2]Air-lift yield from 6-inch borehole

[3]Air-lift yield from 8-inch borehole

[4]Individual fracture yield based on air-lift yield from 6-inch borehole

NOTE: Unless otherwise noted, total yield is from completed well as reported by driller.

Dissolution Openings

Mineral-filled joints, veins, and possibly other features, such as dikes and sills of pegmatite or aplite, appear be susceptible to chemical dissolution, depending on the mineralogy. In several wells, dissolution features along mineral-filled joints or veins were associated with increases in air-lift yield up to 35 gal/min (table 5). This amount exceeds the typical range in yield for open joints and zones of joint concentration described above, indicating the potential importance of dissolution features in the bedrock. One such feature, at well 14FF53 at a depth from 298 to 301 ft, yielded 35 gal/min from a single opening (table 5). These features also were observed in well 14FF26 at a depth of 93-94 ft and in well 13FF14 at a depth of 231–232 ft (table 5). It should be noted that dissolution features may be more common than indicated by the data because their identification requires a clear, high-quality image that shows remnants of the mineral infilling around the edges of the joint or vein. These types of high-quality images were not available in most of the wells studied.

Irregular-Shaped Voids and Fractures

Under close examination, irregular-shaped voids and fractures appear to originate as joints, foliation partings/openings, or a combination of different types of fracture openings that are widened through chemical weathering and dissolution. These features indicate that chemical weathering and dissolution probably are important processes in widening and enhancement of water-bearing fractures in the Lawrenceville area. One example is from a zone of steeply-dipping joints in well 13FF22 at a depth from 468 to 475 ft. In this zone, extensive dissolution around steeply-dipping joints is evident, creating irregular voids around the joints (see well-data summary for well 13FF22 on CD–ROM). Drusy crystalline cement also was observed in this zone, indicating physical openings in the bedrock. Many of the foliation fractures measured in boreholes also showed rounded and irregular forms indicating substantial dissolution of rock materials around the fracture face.

Flowmeter Surveys

Flowmeter surveys were used to confirm the yield from various types of fractures intersecting open boreholes (table 6). In several of the wells—including 13FF23, 14FF55, and 14FF59—these surveys were used to identify confined/semiconfined water-bearing zones. Water from the confined/semiconfined zones flowed from the fracture, flowed up the borehole, and typically exited from the borehole through shallow fractures.

Table 6. Observations from ambient and pumping flowmeter surveys, Lawrenceville, Georgia, area.

[Discharge rate is for pumping survey only; gal/min, gallons per minute; ft, foot]

Well name	Survey date	Discharge (gal/min)	Flow observations	
			Ambient survey	Pumping survey
13FF17	2/4/2001	30	Flow near static entire borehole	Producing from single fracture at 64.5– 65.5 ft
13FF18	12/3/2001	46	Upward flow above 100 ft, static flow below 100 ft	Producing from multiple fractures between 82 and 102 ft
13FF19	11/30/2001	48	Flow nearly static between 0 and 250 ft, upward flow between 250–350 ft, nearly static flow below 350 ft	Producing from single fracture at 245.5– 246.5 ft
13FF20	12/5/2001	10	Flow nearly static entire borehole	Producing from two fractures between 373 and 392 ft
13FF21	12/5/2001	25	Upward flow above 175 ft, downward flow below 175 ft	Producing from single fracture at 240–241.5 ft
13FF22	12/5/2001	48	Upward flow above 450 ft, static below 450 ft	Producing from fracture at 154–155 ft and zone of fractures from 468 to 475 ft
13FF23	12/4/2001	50	Upward flow above 100 ft; approximately 15–20 gal/min exiting borehole at base of casing	Producing from multiple fractures between 100 and 250 ft; water exiting borehole into fractures between 35 and 50 ft
14FF55	11/30/2001	48	Upward flow (8–10 gal/min) from 415 ft; water exits from borehole along small fracture at 64–65 ft	Producing from fracture at 172.5– 173.5 and at 416– 417 ft; water exiting from borehole along fracture at 64– 65 ft
14FF56	12/5/2001	46	Upward flow above 150 ft; near static flow below 150 ft	Producing from fractures at 43.5– 44.5, 57.5–58.5, and 138– 139 ft
14FF57	8/17/2001	1.2	Downward flow above 200 ft; upward flow below 200 ft	Producing from fractures at 45.5–46.5 and 196.5– 197.5 ft
14FF58	8/6/2001	2	Upward flow above 300 ft; near static flow below 300 ft	Producing from multiple fractures including 42–43, 287.5– 288.5, and 498–499 ft
14FF59	12/3/2001	58	Upward flow above 350 ft, increasing in flow up to 58 gal/min above 250 ft	Producing from multiple fractures between 250 and 350 ft; well flowing 58 gal/min

Well 13FF23 is one example where water from confined/semiconfined water-bearing zones flows up the borehole and exits out into shallow fractures. In this well, multiple water-bearing zones were detected between 100 and 250 ft using a flowmeter (fig. 7). Under ambient conditions, water flowed from fractures with high hydraulic head into the borehole, up the borehole, and exited through fractures with lower head below the bottom of the casing (fig. 7a). During pumping conditions, using a pumping rate of 50 gal/min, water entered the borehole at water-bearing fractures with high head and flowed up the borehole; however, the pumping did not reverse the ambient flow regime, and water continued to exit the borehole into fractures near the base of casing (fig. 7b, top arrows). Although beyond the scope of this report, quantitative techniques could be used to infer the interval transmissivity and interval hydraulic head (Paillet, 2000) from these data.

Overall, flowmeter data indicate that ground water, under ambient and pumping conditions, appears to be derived from discrete fractures intersecting the boreholes, rather than evenly distributed along open sections of the boreholes (table 6). Most of the inflow typically was concentrated within two or three intervals, corresponding to the depth of water-bearing fractures identified through other geophysical methods.

Aquifer-Test Data

Aquifer tests were used to determine the long-term yield from the wells, which is the yield of all water-bearing fractures contributing water to the borehole during the period of the test. Data from the aquifer tests also provided information on the direction and magnitude of drawdown resulting from pumping, which is an indicator of the contributing areas to the pumped wells, and potential interference among wells.

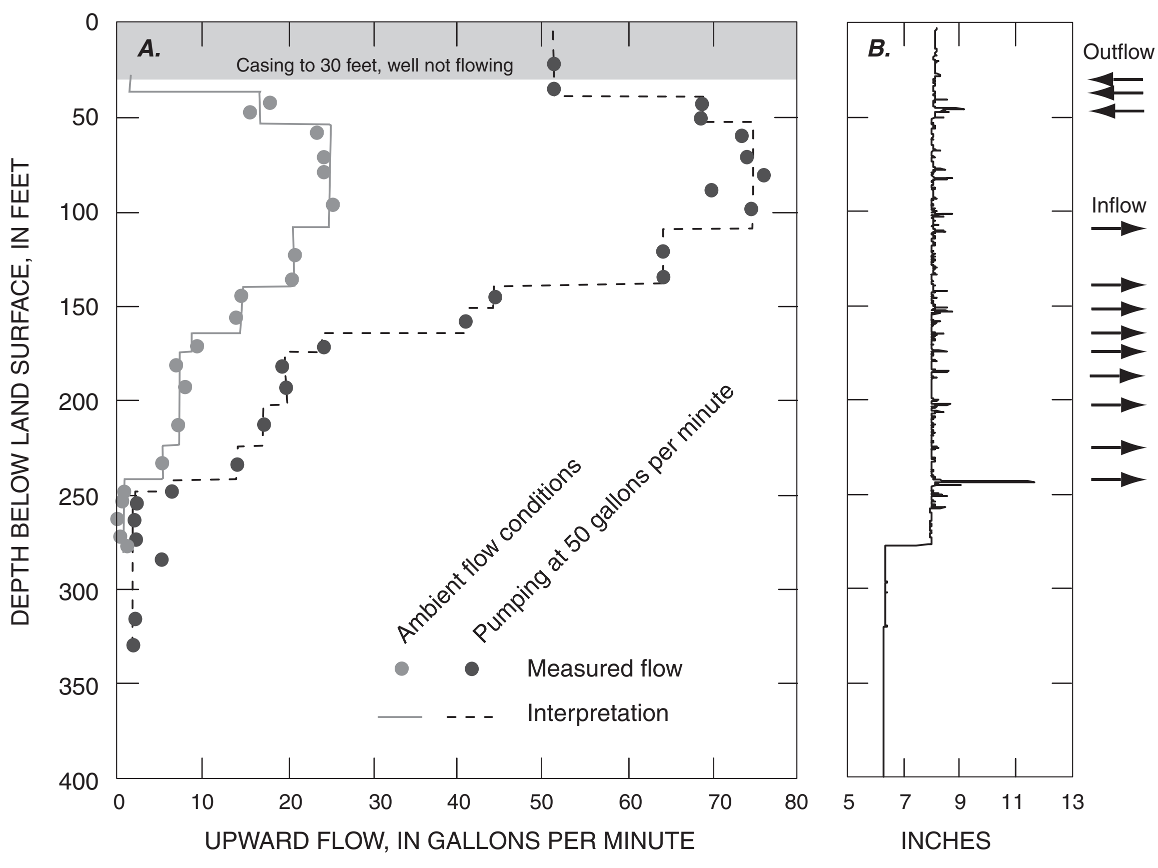


Figure 7. (*A*) Flowmeter logs for well 13FF23, showing inflow and outflow from borehole, Lawrenceville, Georgia. Top left-facing arrows indicate fractures where water is flowing out of the borehole. Right-facing arrows show water entering borehole along factures between 100 and 250 feet. (*B*) Caliper log shown for reference. Flowmeter survey conducted on December 4, 2001.

Aquifer-Test Yield, Drawdown, and Recovery

Yields from aquifer tests ranged from 75 gal/min for well 13FF16 to 600 gal/min for well 14FF50 for the period of the test (table 7). In several wells, such as 13FF19 and 14FF55, the aquifer-test yield was substantially less than the reported air-lift yield (table 2). Well 13FF19 had an air-lift yield of 350-400gal/min compared to an aquifer-test yield of 177 gal/min with about 141 ft of drawdown. Well 14FF55 had an air-lift yield of 325 gal/min compared to an aquifer-test yield of about 241 gal/min with about 92 ft of drawdown. On the other hand, well 13FF21, with an air-lift yield of 125 gal/min was only 18 gal/min less than the yield of 107 gal/min determined from the aquifer test. In other wells, the aquifer-test yield was greater than the air-lift yield; well 14FF50 had an air-lift yield of 300 gal/min, which is half of the aquifer-test yield of 600 gal/min.

Collectively, data from the aquifer tests indicate that the pumped wells were able to sustain large pumping rates[6] for the period of the tests. The recovery of water levels following pumping varied from slow, indicating a small recharge rate to the fracture(s) supplying the well, to fast, indicating a large recharge rate to the fracture(s) supplying the well. One aquifer test, indicating slow recovery, was conducted in well 13FF23. During that test, a pumping rate of 449 gal/min was used for the first 53 hours of the 72-hour test, causing a drawdown of about 65 ft, approximately 18 ft above the uppermost water-bearing fracture. For the remainder of the test, the pumping rate was reduced to 342 gal/min to maintain the pumping water level at about 65 ft. Although the water level stabilized at 342 gal/min, the slow recovery following the end of the test indicated a small recharge rate supplying the well. Another well showing slow recovery was 13FF15, a 605-ft-deep well that was reamed to 250 ft and had about 144 ft of available drawdown to the shallowest water-bearing fracture. The first aquifer test conducted in this well used pumping rates of 210 gal/min for the first 24 hours, from 240 to 290 gal/min for the next 24 hours, and from 175 to 184 gal/min for the remainder of the 96-hour test. Although the water level was nearly stable at the end of the test, it took more than 10 days for the water level to recover 143 ft, which was still about 8.5 ft lower than the initial static water level. Water levels during a second aquifer test conducted in well 13FF15, with a pumping rate of 200 gal/min for 48 hours, never stabilized and required a similar amount of time to recover as that observed in the first test.

In contrast to the wells showing slow recovery, water levels in several other wells recovered rapidly after pumping. Well 13FF21 was pumped at a rate of about 107 gal/min for 72 hours and recovered to 99 percent of the prepumping level in about 35 hours. In another aquifer test, well 14FF59 was pumped for 72 hours using a pumping rate ranging between 301 and 444 gal/min, and the water level recovered in about 6 hours. The rapid recovery in these two wells indicates a large recharge rate into the bedrock fracture system supplying these wells in comparison to other wells in the area.

Table 7. Drawdown, pumping rate, and specific capacity of wells during aquifer tests in the Lawrenceville, Georgia, area.

[hrs, hours; ft, foot; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; do, ditto]

Well name	Date start	Date end	Duration (hrs)	Drawdown (ft)	Ending pumping rate (gal/min)	Specific capacity[1] (gal/min/ft)
13FF15	11/15/1999	11/19/1999	96	153.9	177.0	1.1
13FF15	12/20/1999	12/22/1999	48	99.7	200	2.0
13FF16	2/1/2000	2/2/2000	24	123.5	75	0.6
13FF18	9/4/2001	9/7/2001	70	87.3	135.4	1.6
13FF19	10/2/2001	10/5/2001	72	140.8	177	1.3
13FF21	8/21/2001	8/24/2001	do.	186.7	107	0.6
13FF23	9/18/2001	9/21/2001	do.	66.4	341.8	5.2
14FF50	2/22/1999	2/27/1999	116	82.3	600	7.3
14FF55	8/14/2001	8/17/2001	72	91.8	240.9	2.6
14FF59	10/10/2001	10/13/2001	do.	84.3	301.5	3.6

[1]Calculated by dividing ending pumping rate by drawdown.

[6]In this report, “large pumping rates” refer to discharge rates generally greater than 70 gal/min.

Direction and Magnitude of Drawdown

Ground-water level data collected from observation wells during the aquifer tests were used to determine the direction and magnitude of drawdown and to provide a general indication of potential interference among production wells. The drawdown in the observation wells varied depending on the distance and direction from the pumped well.

One aquifer test was conducted in well 13FF21 located on the floodplain of the Yellow River (fig. 1). During that test, the greatest drawdown occurred in a northwest-southeast direction from the pumped well. A drawdown of 0.75 ft was observed in well 13FF19, located about 6,800 ft from the pumped well and parallel to the strike of lithologic units. No drawdown was observed in well 13FF22 located about 5,400 ft away and perpendicular to the strike of lithologic units. No drawdown was observed in a shallow regolith well located 8 ft from the pumped well, indicating no apparent hydrologic connection between the bedrock fracture system and the regolith at this location.

In an aquifer test conducted in well 13FF18, located on the floodplain of Redland Creek (fig. 1), the greatest drawdown occurred in an east-west direction from the pumped well. A drawdown of 1.4 ft was observed in well 13FF17, located about 2,800 ft west of the pumped well, and a drawdown greater than 22.5 ft was observed in well 13FF13, located about 1,900 ft east of the pumped well. The pumped well and these two observation wells are aligned parallel to the strike of lithologic units and penetrate the same lithologic units. No drawdown was observed in well 13FF16, located about 2,500 ft north of the pumped well and positioned across the strike of lithologic units.

Data collected during aquifer tests in several other high-yield production wells—including 13FF23, 13FF19, and 14FF50—indicate similar drawdown to that described above. In most of these tests, drawdown was greater in the direction of bedrock foliation and layering than perpendicular to it (see table 7 for data from aquifer tests). As a result of this apparent preferential drawdown, pumping interferences probably will occur between certain wells. The largest potential interferences are among wells 13FF21, 13FF23, and 13FF19 (fig. 1). The interferences observed during the aquifer tests indicate that these particular wells, if pumped simultaneously, likely would result in corresponding declines in the pumping rates during long periods of time. Smaller interferences also are evident between production wells at Rhodes Jordan Wellfield (14FF10 and 14FF16) and wells 14FF08, 14FF50, 13FF15, 13FF16, and 14FF55.

Packer-Test Data

Packer-test data were used to determine the hydraulic response among individual high-yield fractures at well 14FF59. Using flowmeter data, six intervals (numbered 1 through 6), each straddling the main water-bearing fractures in the well, were selected for packer testing. Fracture depths, isolated borehole intervals, and the responses observed during the tests are listed in table 8 and illustrated on sets of hydrographs included on this CD–ROM. Each set of hydrographs, representing a single packer test, shows the pressure response recorded in the interval above the packer (top transducer), below the packer (bottom transducer) and in the test interval (middle transducer).

The results of packer tests at well 14FF59 indicate the following:

- Shut-in pressure readings (head) taken before pumping each of the packer intervals were above land surface and substantially higher than the head in shallow fractures, indicating that the water-bearing fractures in this well are confined or semiconfined.
- Pumping from test intervals 2 and 3 indicates that fractures at 267 and 282 ft are hydraulically connected as indicated by the drawdown response in the bottom transducer of the interval 2 test and the smaller drawdown response in the top transducer of the interval 3 test. Conversely, packer tests on intervals 4, 5, and 6 did not show a substantial response in the top and bottom transducers, indicating that hydraulic separation exists among these fractures and the shallower fractures in the well.
- Packer-test intervals 1 and 5 indicate low-permeability fractures are present in these intervals. Low permeability is indicated by the pressure increase on the middle transducer during packer inflation.

The hydrologic responses observed at well 14FF59 indicate that most of the water enters the borehole through foliation openings and not through joints, and confirms the high-yield nature of major foliation openings in the well. A small amount of water probably enters through joints, but this is much less than that derived from the major foliation openings tested. Drawdown responses from the packer tests also indicate a slight but noticeable vertical connection among individual high-yield foliation openings, which likely is attributed to steeply-dipping joints.

Water-Level Data

Ground-water levels in the study area fluctuate in response to seasonal variations in rainfall, stream stage, and ground-water pumping. Synoptic water-level data (table 9) were used to provide information on the variation of water levels across the study area. Continuous water-level data (table 10) were used to monitor seasonal water-level fluctuations in response to rainfall and to monitor drawdown in response to ground-water pumping. Water-level hydrographs are included on this CD–ROM for each well where continuous data were available (table 10).

Open-hole water levels[7] in bedrock wells varied widely across the area ranging from about 10 ft above land surface at well 14FF59 to 54 ft below land surface at well 13FF15 (table 9). Six boreholes had water levels above land surface and four of these flowed when left uncapped. Most of the open-hole water levels were above the bottom of casing, indicating confined/semiconfined conditions in the bedrock fracture system.

[7] An open-hole water level represents a "composite" potentiometric head formed by differing heads of individual fractures intersecting the open section of borehole.

Table 8. Fracture depth, straddle depths, and hydraulic response observed during packer testing of well 14FF59, Lawrenceville, Georgia, area.

[BLS, below land surface; ft, foot; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot]

Interval	Fracture depth (ft BLS)	Straddle packer depths (ft BLS)	Transducer	Hydraulic response	
				Shut in (pre-pumping)	Pumping
1	241	236–245	Top	Stops flowing, head declines 1.45 ft BLS	No response
			Middle*	Pressure buildup due to packer inflation; indicates low-permeability interval between packers	Dewatered
			Bottom	Pressure buildup to 12.70 ft above land surface	No response
2	267	264–273	Top	Stops flowing, head declines level to land surface	No response
			Middle*	Pressure buildup to 8.80 ft above land surface	11.20 ft drawdown at 31gal/min (2.76 gal/min/ft)
			Bottom	Pressure buildup to 9.20 ft above land surface	1.75 ft drawdown response due to pumping of middle interval
3	282	276–285	Top	Stops flowing, head is.70 ft above land surface	Slight but definite response indicating hydraulic connection to zone 2
			Middle*	Pressure buildup to 6.20 ft above land surface	4.37 ft drawdown at 30 gal/min (6.87 gal/min/ft)
			Bottom	Pressure buildup to 9.00 ft above land surface	Slight inflection seen on pressure curve indicates small or indirect connection with pumped interval
4	297	294–303	Top	Stops flowing, head is 1.40 ft above land surface	No response
			Middle*	Pressure buildup to 14.00 ft above land surface	95.30 ft drawdown at 26 gal/min (0.27 gal/min/ft)
			Bottom	Pressure buildup to 9.70 ft above land surface	No response
5	325	319–328	Top	Stops flowing, head is 1.60 ft above land surface	No response
			Middle*	Pressure buildup due to packer inflation; indicates low-permeability interval between packers	Dewatered
			Bottom	Pressure buildup to 9.89 ft above land surface	No response
6	348	341–350	Top	Stops flowing, head is 1.60 ft above land surface	No response
			Middle*	Pressure buildup to 8.80 ft above land surface	4.00 ft drawdown at 31gal/min (7.75 gal/min/ft)
			Bottom	Pressure buildup; indicates low-permeability section of borehole below packer interval	Slight inflection seen on pressure curve indicates small or indirect connection with pumped interval

*Middle transducer in pumped interval

Table 9. Water levels in wells, October 31, 2001, Lawrenceville, Georgia, area.

[BLS, below land surface; ft, foot; Do., ditto]

Well name	Land-surface altitude* (ft)	Water-level BLS[1] (ft)	Water-level altitude* (ft)	Aquifer unit
13FF13	972.3	6.98	965.3	Bedrock
13FF14	987.9	-9	996.9	Do.
13FF15	1,053.2	54.05	999.2	Do.
13FF16	1,004.7	8.2	996.5	Do.
13FF17	990.9	13.34	977.6	Do.
13FF18	953.8	-6.63	960.4	Do.
13FF19	921.8	9.25	912.6	Do.
13FF20	990.1	17.05	973.1	Do.
13FF21	889.4	4.7	884.7	Do.
13FF22	929.7	-0.47	930.2	Do.
13FF23	906.2	-1.3	907.5	Do.
13FF24	889.4	3.45	886.0	Regolith
13FF25	921.6	6.08	915.5	Do.
14FF08	1,019.8	31.85	988.0	Bedrock
14FF16	994.2	[2]43	[2]951.2	Do.
14FF27	1,048.3	15.1	1,033.2	Do.
14FF42	1,082.2	29.46	998.7	Do.
14FF46	1,022.9	0.65	1,022.3	Do.
14FF47	1,004.2	5.86	998.3	Do.
14FF49	1,041.7	36.3	1,005.4	Do.
14FF50	1,019.3	22.21	997.1	Do.
14FF52	1,082.3	18.4	1,063.9	Do.
14FF53	967.7	49.61	918.1	Do.
14FF55	969.6	0.47	969.1	Do.
14FF56	936.3	7.29	929.0	Do.
14FF57	954.1	6.03	948.1	Do.
14FF58	1,030.2	-1.96	1,032.2	Do.
14FF59	952.1	-9.7	961.8	Do.
14FF60	952.8	3.43	949.4	Regolith
14FF61	970.6	5.62	965.0	Do.

*NGVD 29

[1]A negative number indicates water level above land surface.

[2]Water level during pumping.

Seasonal ground-water level fluctuations varied from about 1 to 3 ft for the longer periods of record and varied from 0.25 to 0.5 foot during shorter periods (see hydrographs for wells 13FF13 and 14FF47, CD–ROM) in response to variations in rainfall. In these wells, ground-water levels generally increased during wet periods in response to recharge from infiltrating precipitation and decreased during dry periods in response to ground-water discharge to streams and evapotranspiration. The magnitude of seasonal water-level fluctuations observed in these wells is similar to longer trends observed in other parts of the Piedmont region (Coffin and others, 2003). Note that a large fluctuation of about 9 ft was observed in well 14FF42 from June–November 1996; however, this magnitude of fluctuation seems to be atypical for the Lawrenceville area.

Variations in stream stage also may influence the water level in at least one well. The water level in well 13FF22 increased approximately 1 ft in response to a rise in stream stage (see hydrograph, CD–ROM).

Water levels in about one-half of the wells used in this study fluctuate in response to pumping at the Rhodes Jordan Well Field (table 10). Some of the responses observed are summarized as follows:

- In the immediate vicinity around the wellfield (wells 14FF17, 14FF18, 14FF26, and 14FF39) drawdown in response to pumping ranges between 75 and 135 feet, depending on the rate and duration of pumping. Lowering the water level in the vicinity of Rhodes Jordan Wellfield dewaters the shallow water-bearing fractures. Pumping does not, however, lower the water level in a nearby regolith observation wells (well 14FF36), indicating poor hydraulic connection between the bedrock and regolith at this location.
- Away from the wellfield, drawdown in the bedrock is extensive and observed in wells as far away as 7,000 ft from the center of pumping. Some of these wells are located across a major topographic divide (Chapman, 1999, p. 29; Tharpe and others, 1997), indicating that bedrock fracture system supplying the wellfield is not bounded by topographic basin divides. Well 13FF14, the well farthest from Rhodes Jordan Wellfield that is influenced by pumping, shows a drawdown in the range from 0.5 ft to about 6 ft during longer periods of time.
- Drawdown in bedrock wells varies with the duration, rate of pumping, distance, and direction from the Rhodes Jordan Wellfield. In well 14FF08, located about 4,700 ft west of Rhodes Jordan Wellfield (fig. 1), the water-level drawdown in response to cyclic weekly pumping ranges from about 1 to 2 ft (fig. 8), with a long-term estimated drawdown[8] from 4 to 5 ft. Other wells responding to pumping at the Rhodes Jordan Wellfield are listed in table 10.
- The direction and magnitude of drawdown generally is greater in the east-west direction parallel to bedrock foliation and layering than in the north-south direction, which is similar to the responses observed during aquifer tests described above. The preferential east-west drawdown indicates that recharge and ground-water flow probably is greatest along bedrock foliation planes and compositional layering toward the pumped wells.

[8]Long-term drawdown was estimated using a period of increased pumping from July 9–26, 1996, and a period of decreased pumping from February 5–17 1997

Table 10. Range of dates where continuous water-level data are available and influence from pumping, Lawrenceville, Georgia, area.

[RJWF, Rhodes Jordan Well Field; Do., ditto; ft, foot; <, less than; —, no data]

Well name	Well type	Range of dates[1]	Influenced by pumping at RJWF	Drawdown range[2]
13FF12	Bedrock	10/1998 – 12/1999	Yes	0.5 to 2 ft
13FF13	Do.	7/1998 – 4/1999	No	None observed
13FF14	Do.	7/1998 – 1/2000	Yes	0.5 to 6 ft
13FF17	Do.	8/2001 – 11/2001	No	None observed
13FF19	Do.	Do.	No	Do.
13FF20	Do.	Do.	No	Do.
13FF21	Do.	Do.	No	Do.
13FF22	Do.	Do.	No	Do.
14FF08	Do.	2/1996 – 1/2000	Yes	0.8 to 1.3 ft
14FF16	Do.	7/1995 – 2/1996 7/1996 – 8/1997	Yes	< 135
	Do.	2/1995 – 3/1997	Yes	< 135
14FF18	Do.	2/1995 – 7/1996	Yes	< 135
14FF26	Do.	8/1995 – 12/1995 5/1998 – 11/1999	Yes	< 144
14FF27	Do.	11/1995 – 4/1999	No	None observed
14FF36	Regolith	4/1996 – 12/1996	No	Do.
14FF38	Bedrock	12/1995 – 11/1999	Yes	0.5 to 1 ft
14FF39	Do.	3/1996 – 6/1996 9/1997 – 5/1998	Yes	< 112
14FF42	Do.	6/1996 – 4/1999	No	None observed
14FF46	Do.	5/1998 – 12/1999	Yes	0.5 to 1 ft
14FF47	Do.	8/1998 – 4/1999	No	None observed
14FF49	Do.	9/1998 – 4/1999	No	0.25 to 0.50
14FF50	Do.	9/1998 – 10/1998	Yes	—
14FF55	Do.	8/2001 – 11/2001	Yes	1.5 to 3 ft
14FF56	Do.	Do.	No	None observed
14FF57	Do.	Do.	No	Do.
14FF59	Do.	8/2001 – 10/2001	No	Do.

[1]Approximate range of dates where continuous water-level data are available.

[2]Approximate range of drawdown in feet caused by pumping at RJWF.

Summary and Conclusions

Large ground-water supplies needed for municipal and industrial use have been developed from igneous and metamorphic crystalline rocks in many parts of the Piedmont and Blue Ridge physiographic provinces. Little information generally is available, however, to assess the potential of developing additional ground-water supplies from these complex aquifer systems. The U.S. Geological Survey, in cooperation with the City of Lawrenceville, conducted this study to determine what geologic structures, if any, contribute to the development of increased permeability and high ground-water yield in the area.

Thirty-two wells, ranging in depth from 180 to 630 feet (ft), were used to evaluate the bedrock lithology, fracture, and water yielding characteristics in the Lawrenceville area. The depth and nature of the fractures were determined by directly observing them in 32 open boreholes of wells with a borehole camera and by using borehole-imaging and geophysical techniques. Yield from individual water-bearing fractures was estimated by correlating increases in yield recorded during drilling to the measured depths of these zones. Individual yield of water-bearing zones was confirmed in 12 wells using flowmeter surveys. Ten aquifer tests were conducted to determine longer-term yield from the wells, which is the yield of all water-bearing fractures contributing water to the borehole, and to determine the direction and magnitude of drawdown resulting from pumping. Packer tests were conducted in one well to determine the hydraulic response among discrete water-bearing fractures. Continuous water-level data were collected from 26 wells to monitor the effects of rainfall, stream stage, and pumping on water levels in the study area.

Using borehole imaging data and correlating these to individual fracture yield, two main systems of water-bearing zones were identified: (1) joints, open joints, and zones of joint concentration consisting mostly of steeply-dipping low-yielding fractures; and (2) small and large openings along foliation planes and layering consisting of discontinuous but high-yield fractures, which are defined in this report as "foliation parallel-parting systems." Water-bearing zones also are formed from the dissolution of pre-existing crosscutting mineralized joints; these create irregular openings that cut across foliation and layering. Chemical dissolution along joints, foliation planes, and contacts between compositional layers was apparent in several of the boreholes studied.

Joints generally are complex "crisscross" fractures that break up the rock into blocks and slabs of differing dimensions. In boreholes, joints are differentiated from other fractures by their occurrence in sets, common planar geometry, and their orientation cutting across rock foliation and layering. Most joints observed in boreholes appeared as tight "hairline" fractures and typically did not form significant water-bearing zones. Small to moderate amounts of water—generally in the range from 1 to 5 gallons per minute (gal/min)—were produced from open, steeply-dipping joints and zones of joint concentration.

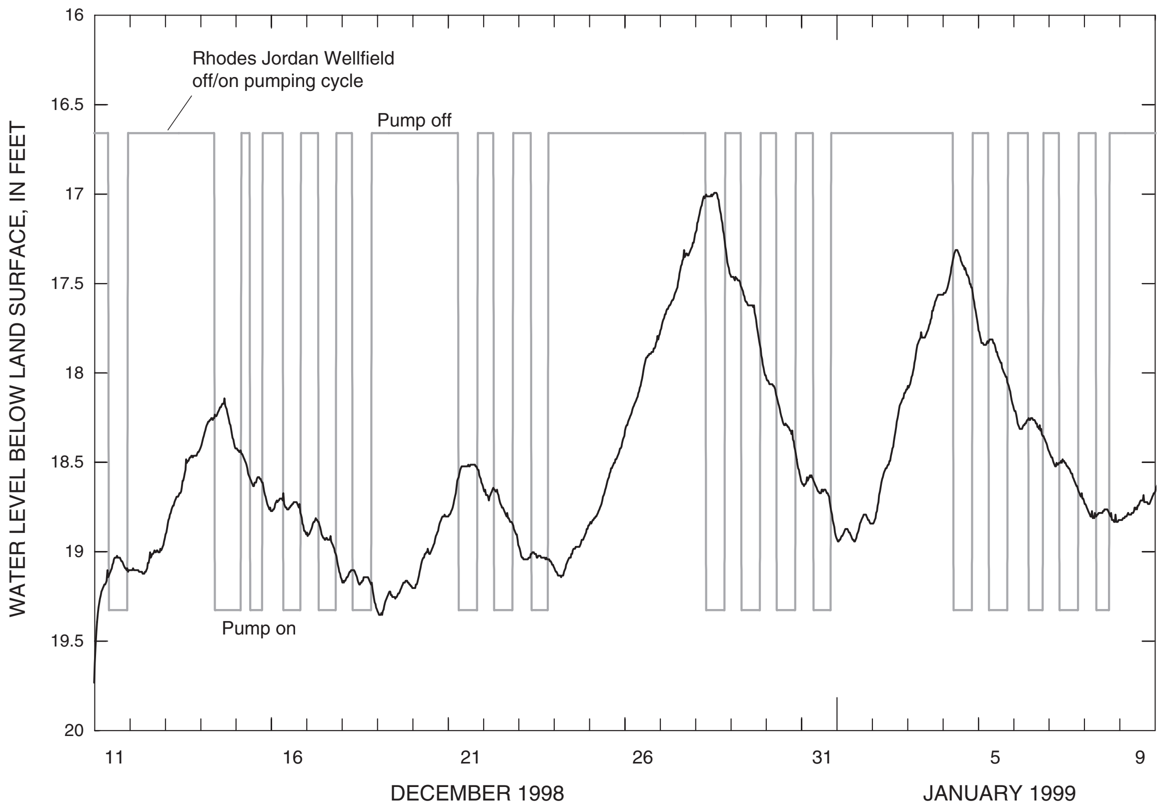


Figure 8. Partial record of water-level hydrograph for well 14FF08 showing effect of pumping at the Rhodes Jordan Wellfield, Lawrenceville, Georgia.

Foliation partings and major foliation openings, which are fractures formed nearly parallel to foliation and layering, yielded large quantities of water to open boreholes in the Lawrenceville area. Foliation partings, which are small openings typically less than 0.5-inch wide, yielded 1 to 15 gal/min, with a maximum value of about 63 gal/min. In some boreholes, groups of foliation partings formed substantial water-bearing zones and yielded as much as 50 gal/min. Major foliation openings, which are large openings typically 1 to 8 inches wide, yielded substantially more water than the smaller foliation partings. A range in yield from 50 to 100 gal/min is typical for these larger fracture openings, making these the primary water-bearing features responsible for high-yield wells in the Lawrenceville area. All the high-yield wells in the area penetrate at least one major foliation opening.

Dissolution openings along mineral infilled joints or veins were observed in a few wells with air-lift yields of up to 35 gal/min. This amount exceeds the typical range in yield for open joints and zones of joint concentration, indicating the importance of dissolution features in the bedrock. Dissolution features may be more common than would be indicated by the data collected because their identification requires a clear, high-quality image that shows remnants of the mineral infilling around the edges of the joint or vein. These types of high-quality images were not available in most of the wells studied.

Flowmeter surveys confirmed the depth and yield contribution from various types of water-bearing fractures in selected wells, specifically the high-yielding nature of foliation partings and major foliation openings. In several wells, flowmeter surveys helped to identify confined/semiconfined water-bearing zones. Water from the confined/semiconfined zones flowed from the fracture, up the borehole, and typically exited from the borehole through shallower fractures. From these data, ground water under ambient and pumping conditions appears to be derived from discrete fractures intersecting the boreholes, rather than being distributed evenly along the open interval. Most of the inflow typically was concentrated within two to three intervals, corresponding to the depth of water-bearing fractures identified through other geophysical methods.

Aquifer tests confirmed that production wells could sustain large pumping rates for the period of the tests. Yields from aquifer tests ranged from 75 to 600 gal/min. In several wells, the aquifer-test yield was substantially less than the reported air-lift yield; whereas in other wells, the aquifer-test yield was greater than the reported air-lift yield. The recovery of water levels following pumping varied from slow, indicating a small recharge rate to the fracture(s) supplying the well, to fast, indicating a large recharge rate to the fracture(s) supplying the well. Drawdown during the tests varied depending on the distance and direction from the pumped well. In most of the aquifer tests, the magnitude of drawdown was greater in the direction parallel to bedrock foliation and layering than perpendicular to it. Aquifer test results also indicated a strong potential for interferences between certain wells. If pumped simultaneously, interferences between wells likely would result in corresponding declines in the pumping rates during long periods of time.

Packer tests conducted in one well indicated that most of the water enters the borehole through foliation openings and not through joints, and confirms the high-yield nature of foliation openings. A small amount of water probably enters through joints, but this is much less than derived from the foliation openings tested. Drawdown responses from the packer tests also indicated a slight but noticeable vertical connection among individual high-yield foliation openings, likely resulting from steeply-dipping joints.

Ground-water levels in the study area fluctuate in response to seasonal variations in rainfall, stream stage, and ground-water pumping. Open-hole water levels rise mostly above the bottom of casing. Water levels measured in open boreholes represent a composite potentiometric head of all the water-bearing fractures. Six boreholes had water levels above land surface and four of these flowed when left uncapped. Seasonal ground-water level fluctuations varied from about 1 to 3 ft in response to variation in rainfall. Ground-water levels generally increased during wet periods in response to recharge from infiltrating precipitation and decreased during dry periods in response to ground-water discharge to streams and evapotranspiration. Variations in stream stage also may influence the water level in at least one well. The water level in this well increased approximately 1 ft in response to the rise in stream stage.

Water levels in about half of the wells used in this study fluctuate in response to pumping at the Rhodes Jordan Wellfield. In the immediate vicinity around the wellfield, drawdown varies between 75 and 135 ft, depending on the rate and duration of pumping. Lowering of the water level in the vicinity of Rhodes Jordan Wellfield dewaters shallow water-bearing fractures but does not lower the water level in a nearby regolith observation well, indicating poor hydraulic connection between the bedrock and regolith at this location. Away from the wellfield, drawdown in the bedrock was observed as far away as 7,000 ft in wells located across a major topographic divide, indicating the bedrock fracture system supplying the wellfield is not bounded by topographic basin divides. Drawdown is from about 4 to 5 ft in one well, located 4,700 ft west of Rhodes Jordan Wellfield. The magnitude and direction of drawdown around the wellfield, is greater in the east-west direction, parallel to bedrock foliation and layering, than in the north-south direction. The east-west drawdown indicates that recharge and ground-water flow probably is concentrated along bedrock foliation planes and layering toward the pumped wells.

Collectively, the data from this study indicate that foliation parallel-parting systems, consisting of discontinuous zones of foliation partings and major foliation openings, strongly influence the yields of wells in the Lawrenceville area. Wells tapping these systems are capable of sustaining large ground-water withdrawals for extended periods of time, as indicated from the continuous operation of the Rhodes Jordan Wellfield since 1995. Open-hole water levels, flowmeter surveys, and preferential drawdown parallel to foliation and compositional layering indicate a general hydraulic confinement of foliation parallel-parting systems and indicate strong lithologic and structural control on the development of these water-bearing fracture systems.

Foliation parallel-parting systems are easily identified in boreholes using geophysical methods described in this report. The yield potential of foliation parallel-parting systems within an individual topographic basin or several topographic basins can be large, depending on the areal extent of the water-bearing zones and the interconnectivity of these zones with sources of recharge.

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