Methods Used to Assess the Occurrence and Availability of Ground Water in Fractured-Crystalline Bedrock: An Excursion into Areas of Lithonia Gneiss in Eastern Metropolitan Atlanta, Georgia

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Methods Used to Assess the Occurrence and Availability of Ground Water in Fractured-Crystalline Bedrock: An Excursion into Areas of Lithonia Gneiss in Eastern Metropolitan Atlanta, Georgia

Compiled by
Lester J. Williams, U.S. Geological Survey

INTRODUCTION

This guidebook is for a half-day field trip into DeKalb and Rockdale Counties to examine methods being used to assess the occurrence and availability of ground water in fractured-crystalline bedrock in the Piedmont of northern Georgia. The U.S. Geological Survey (USGS) prepared this guidebook for the American Institute of Hydrology 2003 Annual Fall Conference, entitled "Achieving Sustainable Water Resources in Areas Experiencing Rapid Population Growth," held October 19–22, 2003. Ground water—being one of the Nation's most important natural resources—provides drinking water to communities, supports industry and agriculture, and sustains streams and wetlands. Many areas in the Piedmont and Blue Ridge Provinces of northern Georgia, particularly those experiencing rapid population growth, are likely to rely increasingly on water supplies from fractured-crystalline-bedrock aquifers.

Considerable potential exists for future development of ground water in the crystalline bedrock areas of northern Georgia. Ground water in these areas could be used to supply water to small communities that now solely depend on surface-water, or to furnish water to the larger surface-water systems in times of drought, for emergency supplies, or as a long-term[1] continuous source to increase the capacity of these systems to meet supply demands. There is much work to be done in this area to comprehend fully and understand the limits on development of this resource.

Understanding how ground water flows through fractured-crystalline-bedrock aquifers is crucial to the management and development of sustainable water resources. Because ground water in crystalline bedrock occurs in irregularly distributed, highly localized, and discontinuous water-bearing zones, there is no single method that can be used to map productive water-bearing zones. One focus of this field trip is on geologic mapping techniques used to locate high-yielding zones in crystalline-bedrock aquifers. By using careful site selection techniques, adequate well yields for such uses as industrial and municipal supply can be obtained in many parts of northern Georgia.

Another focus is on borehole geophysical logging techniques used to characterize the depth and nature of subsurface water-bearing fracture zones. Data collected using borehole geophysical logging techniques provide essential information needed to derive better conceptual models of subsurface fracture distribution and to identify fracture zones contributing to pumping wells. Finally, for those who operate an existing well system, a variety of monitoring techniques can be used to determine the sustainability of ground-water resources and optimize these systems for long-term production. Monitoring will likely become increasingly important as crystalline-bedrock aquifers are further developed.

1. In this paper, the term "long-term" refers to supplies that are in use for several years or tens of years.

ITINERARY

The general field-trip route and locations of stops are shown in figure 1. From Atlanta, we will traverse across part of the southern Piedmont into eastern DeKalb County—an area underlain by the Lithonia Gneiss.

Stop 1 – The first stop will be at the Vulcan Materials Quarry located in an area just southeast of Pine Mountain, DeKalb County, Georgia. From Interstate 20 East take the Turner Hill exit, cross over the interstate north on Georgia Highway 124, and take the first right (east) onto Covington Highway. The quarry entrance is 0.7 mile on the left. Pine Mountain is a granite gneiss monadnock that rises about 150 feet above land surface. The quarry is on the southeast flank of Pine Mountain on a broad gentle slope underlain by barren, exposed granite gneiss. The stop at the quarry will provide an opportunity for observing the types of bedrock fractures typical in the area including stress-relief joints, zones of steeply-dipping joints, and brittle faulting. Many of these features are water bearing. From the quarry floor, or from one of several elevated benches, these fracture types are easily visible and will be the main topic of our discussions at the quarry. Dave Prowell (USGS, Atlanta) will provide a brief overview of the tectonic framework that has directly influenced or developed many of these fractures. From stop 1 to stop 2 we will have a short trip, only about 3.5 miles, into an area of Rockdale County (Conyers) underlain by the Lithonia Gneiss.

Stop 2 – Take a left (east) out of the Vulcan Materials Quarry onto Covington Highway. past Sigman Road, to the large elevated water tank on right (2.7 miles). Go past the water tank and take a right onto Blacklawn Drive, go 0.4 mile and take a left onto Veterans Road and go to end of road. The Lithonia Gneiss at stop 2 is similar to the rocks at stop 1 but with a distinct characteristic of having thin layers, lenses, and pods of feldspathic biotite gneiss, amphibolite, and muscovite schist. The significance of the Conyers area is that many wells that penetrate the Lithonia Gneiss are high yielding even though this rock type is low-yielding elsewhere. At stop 2, the main topic will be on saprolite mapping, rock-type identification, and other mapping techniques used by Tom Crawford and

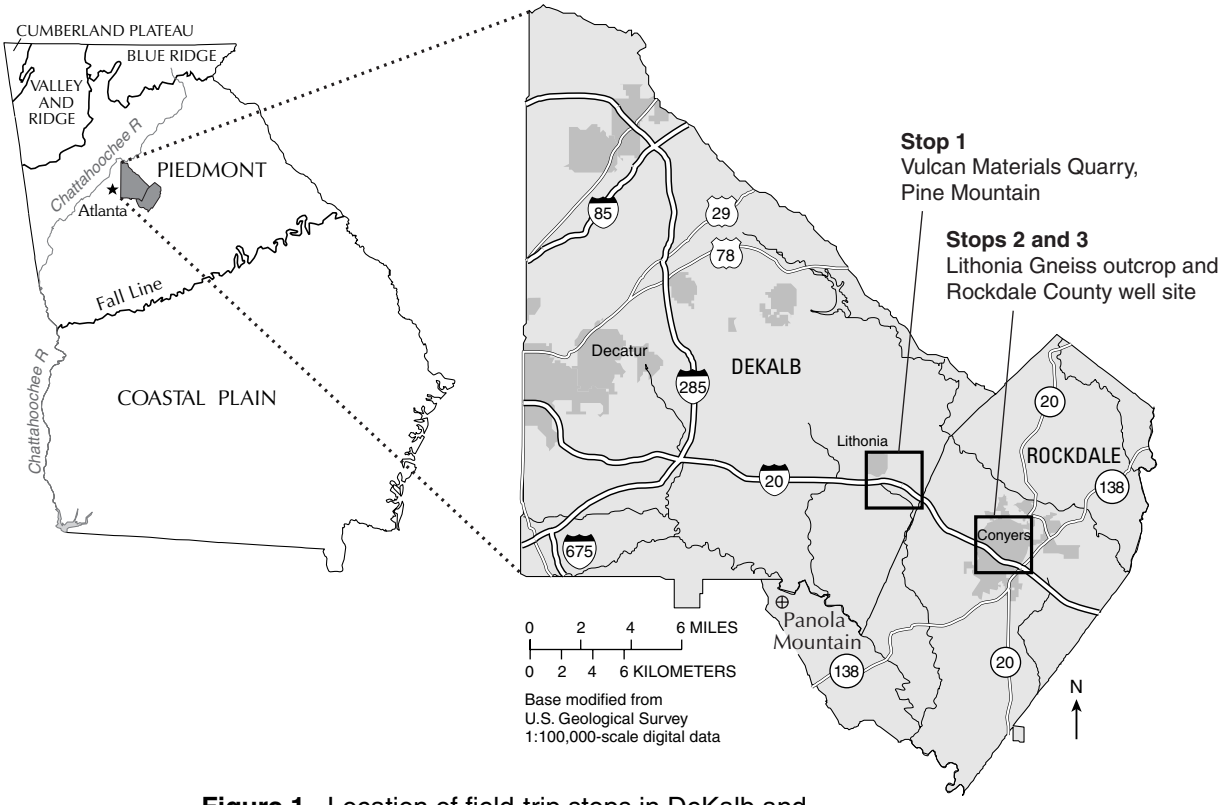


Figure 1. Location of field-trip stops in DeKalb and Rockdale Counties, eastern Metropolitan Atlanta, Georgia.

Randy Kath (State University of West Georgia, Carrollton) to site high-yielding wells in Piedmont and Blue Ridge Provinces. Tom and Randy will discuss the major factors considered and provide insight into the practical application of these mapping techniques. The short hike from stop 2 to stop 3 traverses the Lithonia Gneiss to an old, currently unused water-supply well. The hike from stop 2 to stop 3 will be used to observe the rocks in their typical weathered state (see if you can identify any contacts).

Stop 3 – Follow Veterans Road to Blacklawn. Take a right on Blacklawn Drive, go 0.4 mile to Covington Highway, take a left and go west to the elevated water tank on left. At the final stop we will discuss and demonstrate the use of electric logs, borehole imaging techniques, and other borehole geophysical logging techniques used to characterize subsurface bedrock fractures. The main tools that will be shown will be the 3-arm caliper, combination tool[1], acoustic televiewer, and downhole camera. Weather permitting, one or more geophysical logs will be collected at a well and the results reviewed with the field-trip participants. Discussion will focus on several applications for characterizing subsurface water-bearing fracture zones. Ample time is scheduled during stop 3 for participants to ask questions and for additional discussion of other topics—such as ground-water-level monitoring, and streamflow-monitoring techniques.

PAPERS INCLUDED IN THIS GUIDEBOOK

Several papers are included in this guidebook that provide information on the regional setting and methods that will be discussed during the field trip. The first paper, by Lester Williams (USGS, Atlanta), provides some background on the geology, ground-water availability, and ground-water exploration and development in the region. Donna Khallouf and Dave Prowell (USGS, Atlanta) provide descriptions of typical water-bearing fractures in the Vulcan Materials Quarry that will be observed at the first stop; a map of the quarry and photographs are provided in this paper. The third paper, by Lester Williams, contains more detail about the ground-water resources in Rockdale County, which is the main focus area of the field trip. Tom Crawford and Randy Kath (State University of West Georgia) describe ground-water exploration techniques they have used for many years in fractured-crystalline bedrock. Ground-water exploration techniques are not well documented in the literature; thus, the inclusion of this paper in the field guide is a great contribution to our further under-standing of these techniques. Carole Johnston and John Williams (USGS Office of Ground Water, Branch of Geophysics), provide a description of borehole geophysical techniques that are most applicable to crystalline-bedrock areas. Phil Albertson (USGS, Atlanta) provides a description of an investigation that is assessing and monitoring the sustainability of two large municipal well fields in Lawrenceville, Georgia. This is one of the first studies that attempts monitoring of large-scale withdrawals in the crystalline bedrock areas of the State. Finally, Norman (Jake) Peters (USGS, Atlanta), James Freer (Institute of Environmental and Natural Sciences, Lancaster University, United Kingdom), and Brent Aulenbach (USGS, Atlanta) describe findings from the Panola Mountain Research Watershed in the southwest part of Rockdale County, just south of the field-trip area.

Acknowledgments

This trip would not of been possible without the assistance of Dave Prowell who arranged entrance into the Vulcan Materials Quarry through Chuck Michael, the quarry superintendent. Sincere thanks goes to Chuck Michael for taking the time and effort required for our visit to the quarry. This part of the trip provides us with a rare opportunity to observe subsurface structures that could otherwise only be seen in isolated boreholes. Tom Crawford and Randy Kath are gratefully acknowledged for their help in the geologic mapping part of the field trip. Many of their ideas and methods have great application to ground-water resource investigations. Thanks go to the Rockdale County Board of Commissioners and the Rockdale County Water Resources Department for allowing the use of the well for the geophysical logging part of the field trip. Finally, Dr. William H. McLemore, State Geologist, Georgia Geologic Survey, is gratefully acknowledged for supporting the preparation and publication of this field guide.

1. The combination tool contains spontaneous potential, natural gamma, 16-inch normal resistivity, 32-inch resistivity, lateral resistivity, fluid temperature and fluid resistivity

Overview of Geology, Ground-Water Availability, and Ground-Water Exploration and Development in the Greater Atlanta Region

by Lester J. Williams
U.S. Geological Survey

INTRODUCTION

Despite the common misconception that little ground water is available from crystalline rocks underlying the Piedmont physiographic province, the greater Atlanta region (fig. 1) has a large potential for the development of ground-water supplies for municipal, irrigation, or for small industrial use. Previous studies (Cressler and others, 1983; Clarke and Peck, 1991) indicate that large ground-water supplies have been developed in a variety of geologic and topographic settings in the region. However, because ground water is distributed in highly variable and discontinuous water-bearing zones, the exploration for and development of these supplies has been limited, especially the development of large municipal and industrial supplies. This paper provides information to supplement the American Institute of Hydrology (AIH) field trip entitled "Methods used to assess the occurrence and availability of ground water in fractured-crystalline bedrock: an excursion into areas of Lithonia Gneiss in eastern Metropolitan Atlanta, Georgia," held in October 2003. The paper includes an overview of (1) geology in the region, (2) ground-water availability, and (3) ground-water exploration and development in the greater Atlanta region. The greater Atlanta region, as used in this paper, includes 25 Piedmont counties used by Cressler and others (1983) and 5 additional Piedmont counties in the south metropolitan area used by Clarke and Peck (1991).

GEOLOGY

The 8,800-square-mile (mi^2) greater Atlanta region is underlain by dense igneous and metamorphic "crystalline" rocks that in their unweathered state afford little capacity for storage of ground water. From the northwest to southeast, the area is almost entirely in the Piedmont physiographic province, which is subdivided by the Brevard Fault Zone into the northern and southern Piedmont (McConnell and Abrams, 1984) (fig. 1).

The crystalline-igneous and metamorphic rocks underlying the greater Atlanta region are interpreted as stacks of folded thrust sheets that were transported almost continuously from middle Ordovician through Carboniferous time (Higgins and others, 1988). A generalized geologic map of the Atlanta region is shown in figure 2. The folding and deformation in the rocks were caused by the moving thrust sheets and thrust stacks. Plutonic intrusions—caused by insulating effects, overpressures, and depths of burial—were emplaced during different stages of thrusting and metamorphism. One set of highly deformed and metamorphosed plutons cuts across the lowermost thrust sheets but not the upper sheets. Another group of metamorphosed and deformed plutons were emplaced during the Silurian-Devonian Periods (Higgins and others, 1988) but do not penetrate the upper parts of the thrust stack. The youngest group of plutons, interpreted to be Carboniferous in age, cuts across all the thrust sheets; the best known of these younger plutons is the Stone Mountain Granite (Herrmann, 1954) located east of Atlanta (unit Cg in fig. 2).

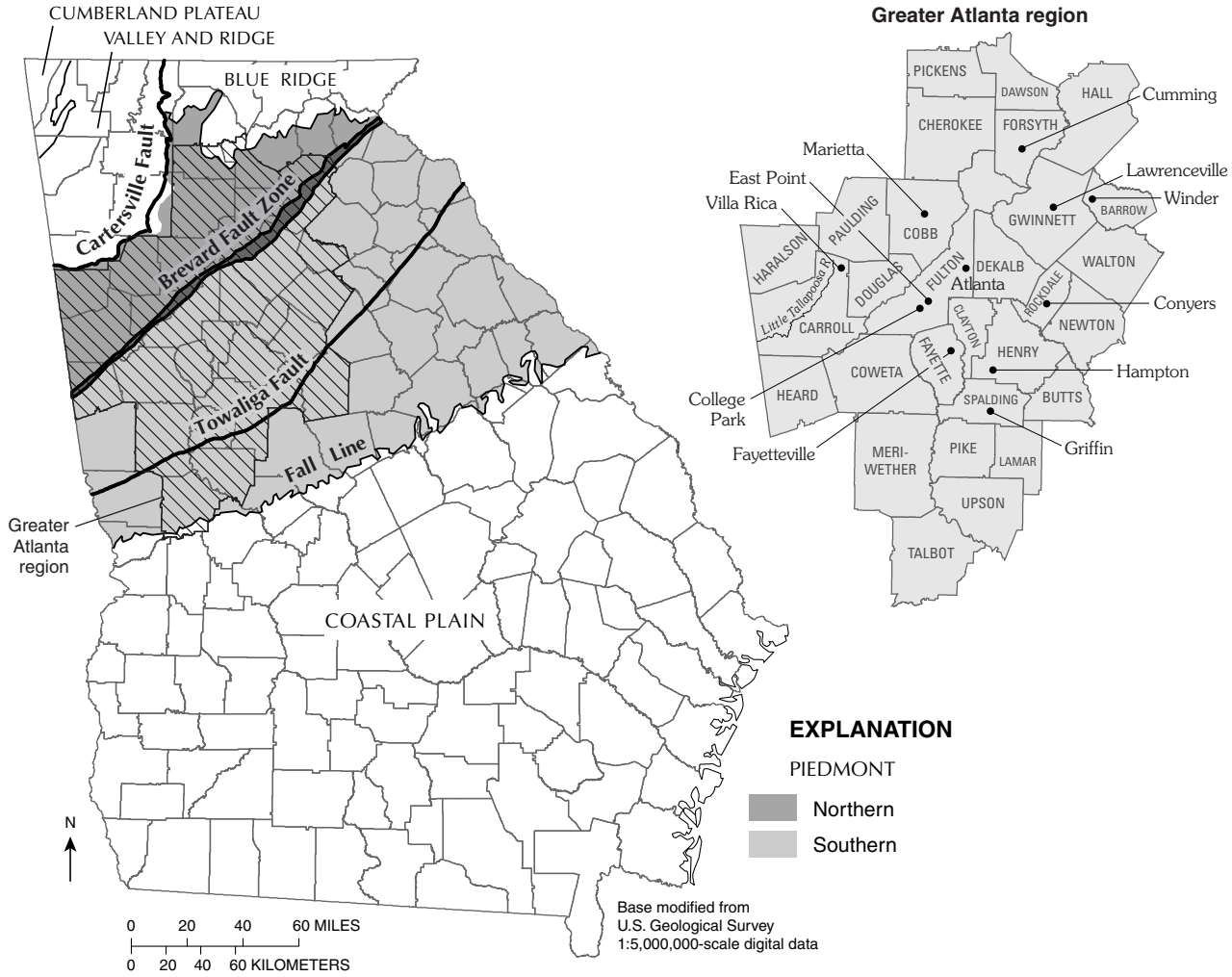


Figure 1. Physiographic provinces of Georgia and major faults in the Piedmont.

The AIH field trip focuses on the eastern part of Atlanta in an area underlain by the Lithonia Gneiss (Crawford and others, 1999) (unit Slg in fig. 2). The Lithonia Gneiss in the area of the field trip is migmititic, contains xenoliths of country rock, and has a swirly texture at many localities.

GROUND-WATER AVAILABILITY

Ground water in the greater Atlanta region occupies pore spaces in the overlying mantle of regolith (soil, saprolite, and alluvium) and in joints and fractures, voids, and other weathered openings in the bedrock. The main source of water to the crystalline-bedrock aquifer is from precipitation infiltrating into the regolith. The regolith acts as a "sponge" that feeds water down into the bedrock and also stores most of the ground water in the aquifer. Ground water is available in virtually all areas of the Piedmont; however, there are a few isolated areas that are mostly "barren" of water.

Types of Wells

Three types of wells are used in the area: bored, dug, and drilled. Bored and dug wells obtain water from the shallow saturated portions of the regolith and rarely exceed depths of greater than 60 feet, whereas drilled wells that derive water from bedrock fractures may be several hundred feet deep. Drilled wells typically have an open uncased borehole beneath a surface casing. All three types of wells are used for supplying small to moderate quantities of water for residential and domestic use. Deep drilled wells also are used to supply water for municipal and industrial use where larger yields can be obtained. Because of their relatively shallow depth, bored and dug wells show a pronounced response to climatic conditions and may "go dry" during drought.

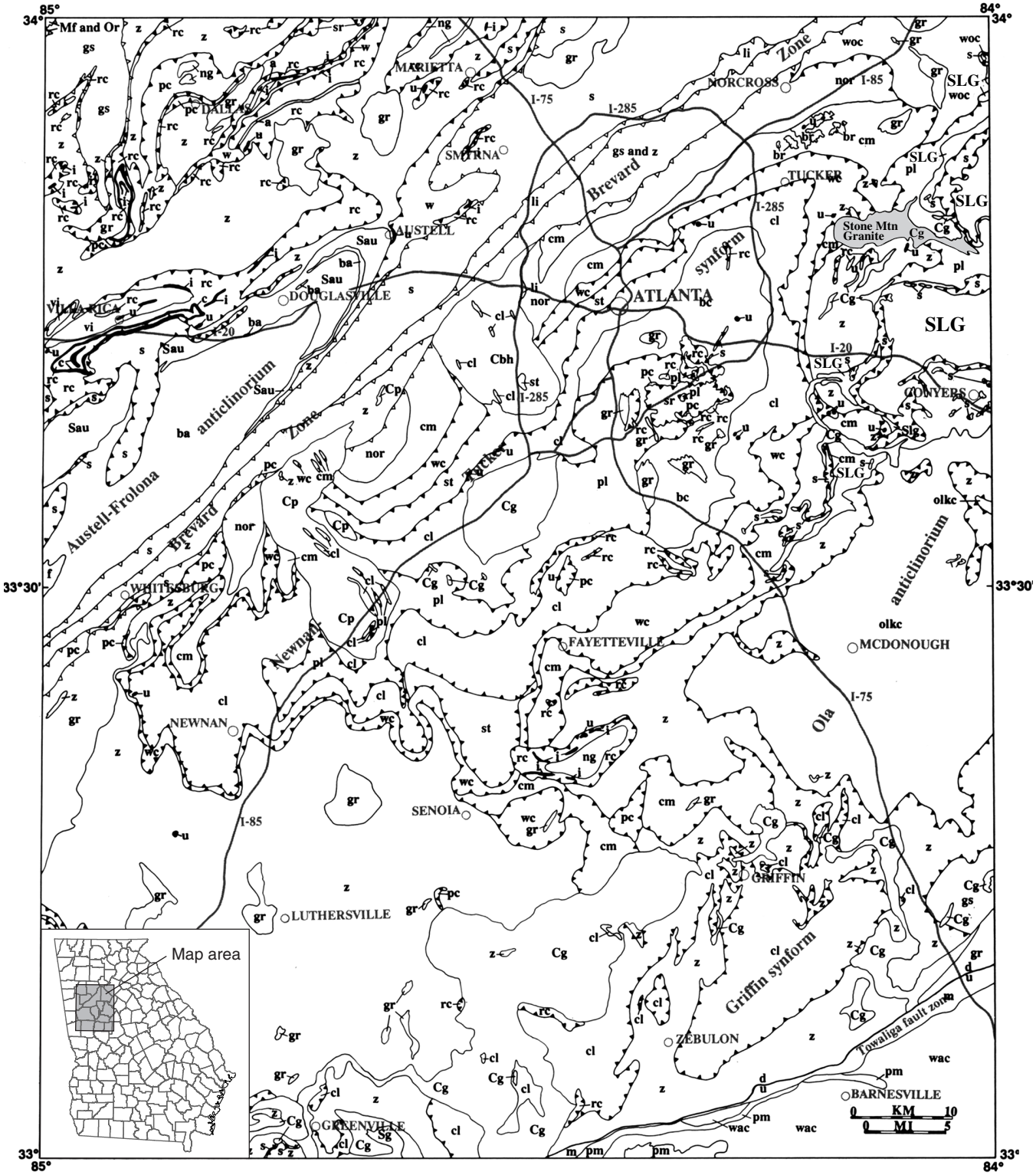
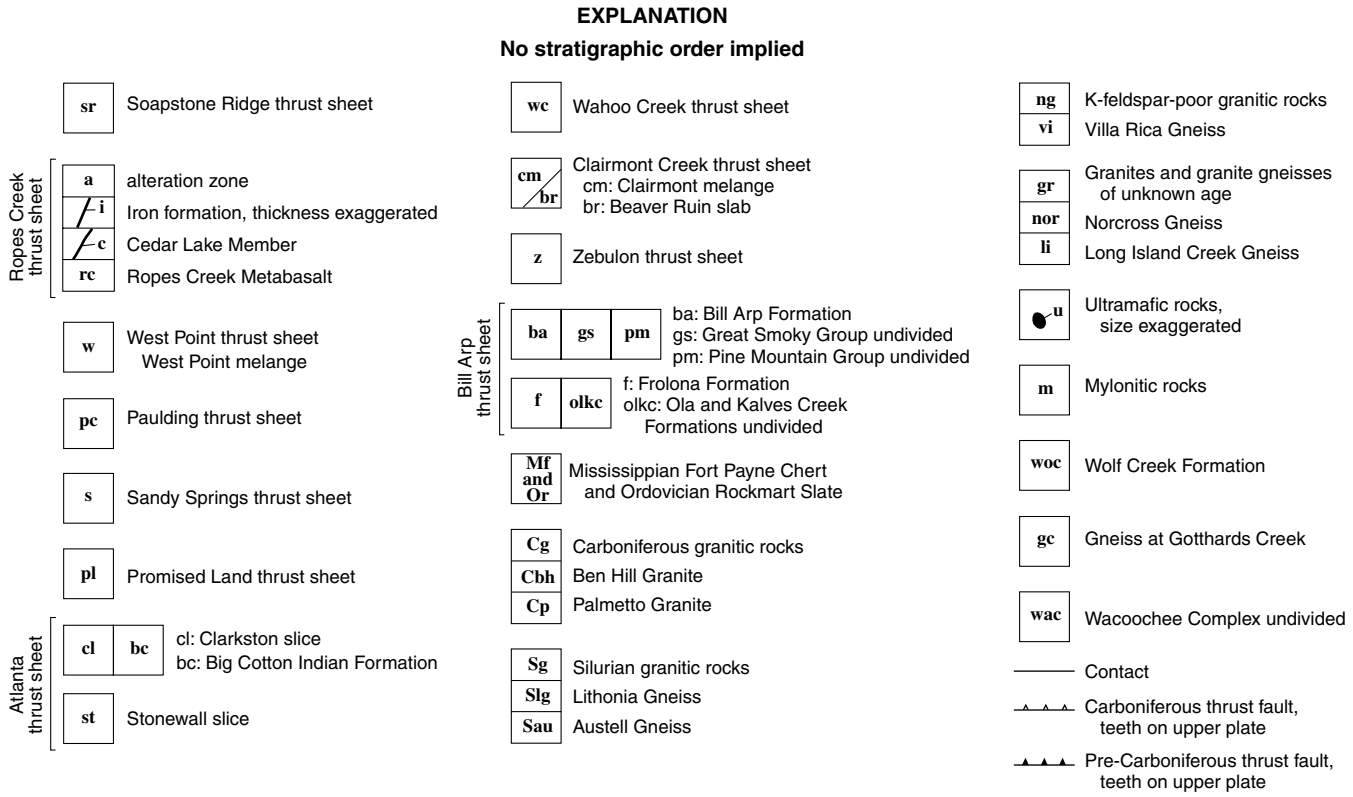


Figure 2. Generalized geologic map of the Atlanta, Georgia, and Griffin, Georgia, 1° x 30' quadrangles (from Higgens and others, 1988).



Well Yields

Well yields in the region vary widely from less than 1 gallon per minute (gal/min) to several hundred gal/min or more. Cressler and others (1983) used 25 gal/min to define "high-yielding wells"; many of the small domestic and rural wells in the region yield much less. Large well yields of greater than 25 gal/min have been reported in almost all parts of the Atlanta region (Cressler and others, 1983; Clarke and Peck, 1991). Most of the 1,165 high-yielding wells inventoried by Cressler and others (1983) had reported yields ranging from 40 gal/min to greater than 200 gal/min, suggesting that high-yielding wells needed for municipal and industrial use can be obtained in many parts of the region. The reported yield for 406 wells inventoried by Clarke and Peck (1991) ranged from less than 1 gal/min to 700 gal/min, and averaged 43 gal/min. For the greater Atlanta region as a whole, average well yields[1] are about 50 gal/min for drilled wells and 4 gal/min for shallow bored or dug wells, with a large variation in yield for both types of wells (fig. 3).

FACTORS INFLUENCING WELL YIELD

A number of factors influence the well yield of drilled wells in the greater Atlanta region. Cressler and others (1983) reported that large well yields occur only where "localized increases in permeability" occur, usually in association with structural and stratigraphic features including (1) contact zones between rocks of contrasting character and within multilayered rocks, (2) fault zones, (3) stress-relief (horizontal) fractures, (4) zones of fracture concentration (5) small-scale geologic structures that localize drainage development, (6) folds that form concentrated jointing, and (7) shear zones. Other factors—such as rock type, depth of weathering, saturated thickness of the regolith, and topographic setting—also were identified as important factors influencing the availability of ground water. Clarke and Peck (1991) indicated that most of the high-yielding wells in the southern metropolitan Atlanta area were near contact zones between rocks of contrasting lithologic and weathering properties.

1. Statistics based on 1,482 bedrock wells and 38 regolith wells inventoried in the 30-county greater Atlanta region; data from the USGS National Water Information System.

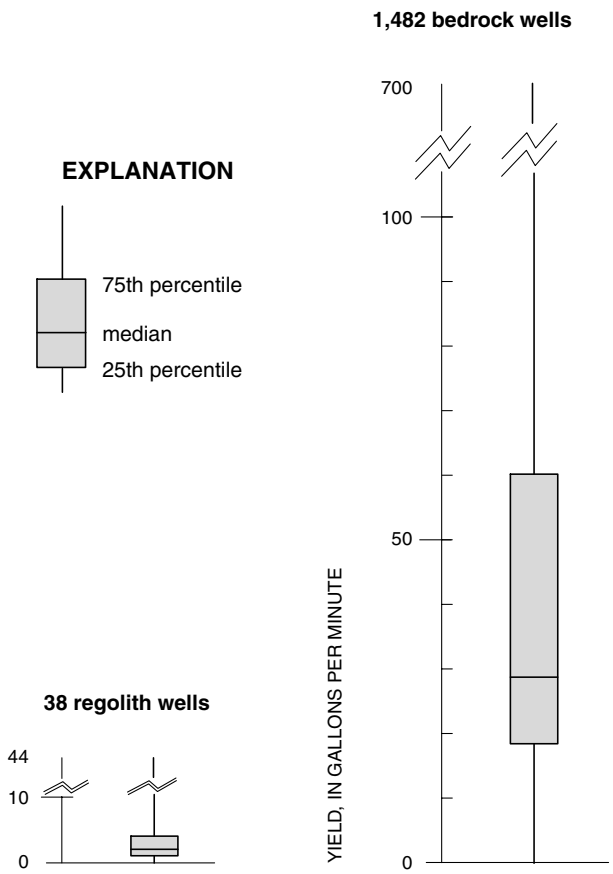


Figure 3. Boxplots showing the range of yields for regolith and bedrock wells in the greater Atlanta region. Data from USGS National Water Information System, July 1, 2003.

Relation of Rock Type and Structure to Well Yield

Finding large amounts of ground water in the Piedmont province can be enhanced by understanding the relation between rock type and geologic structure to well yield. Rock type and geologic structure, to a large extent, control the types of water-bearing zones and the interconnection of these zones to sources of recharge. Early reports, such as one by Herrick and LeGrand (1949) recognized the importance of rock type and structure by stating "wells located in areas of gentle dip intersect more parting planes along which ground water occurs then those where steep dips prevail" (Herrick and LeGrand, 1949). In discussing recharge, they stated that it "would seem advisable to locate wells in such a manner as to intersect water-laden schistose openings that have adequate access to influent seepage"; hence, alluding to the relation of structure to sources of recharge. In recent studies conducted in the Lawrenceville area, many high-yielding wells were found to derive water from fracture openings formed along foliation and compositional layering in layered sequences of rocks—indicating strong lithologic control on well yield in that area (Williams, 2003).

A great deal can be learned about the potential water-bearing properties of crystalline-bedrock aquifers by observing the rock types and structure, usually through geologic mapping of saprolite exposures at the land surface. Geologic mapping is used to define the overall geometry of rock units and general structural style; strike and dip of the major and minor lithologic units and pervasive foliation, if present; and the relative weathering characteristics of the different lithologies, such as at contacts between rocks of contrasting character. Mapping data are collected by walking traverses along roads, creeks, and rivers and noting physical characteristics such as the lithology, strike and dip of foliation and layering, and relative degree of jointing. After discerning the relation between rock type and well yield, water-bearing rock types are "targeted" in such a way as to intercept these rock types at favorable topographic and structural positions for recharge.

The relation of well yield to the various rock types in the Piedmont is often ambiguous and unclear. For example, a biotite gneiss may be productive in one area but not in another; a low-yielding schist may be locally productive. Some of this ambiguity is probably due to the general lack of subsurface information on which to fully understand rock type/well yield relations. Many wells in the Lawrenceville area, for example, penetrate three or four subsurface lithologic units but produce water from only one of these at depth (Chapman and others, 1999). In such instances, making a correlation between the rock type at land surface to well yield has little applicability, and underscores the need to collect subsurface data to confirm productive units. Previous studies indicate that much of the variation in well yield in the Piedmont is controlled by a few key factors including: rock type, presence of structural discontinuities, topographic position, depth of weathering, and recharge potential (Crawford and Kath, 2001; Kath and others, 2001). Still, there is no direct correlation that can easily be applied across the region.

Although there is no single relation between rock type, structure, and well yield, some generalizations

can be made. In general, wells penetrating metamorphosed layered rocks in the region are more productive than wells penetrating massive rocks[1]. Similarly, wells penetrating rocks with abundant structural discontinuities generally are higher yielding than wells penetrating rocks lacking discontinuities (Tom Crawford, State University of West Georgia, oral commun., 2003). In short, with increasing layering and structural discontinuities the potential increases for larger ground-water yield.

Types of Water-Bearing Fracture Zones

Identification of water-bearing fracture zones is needed to formulate an understanding of (1) depth, orientation, and density of fracturing; (2) extent and degree of interconnectedness of water-bearing fracture zones; and (3) the contributing zones or areas of recharge to wells. Water-bearing fracture zone identification typically is accomplished by direct observation in boreholes using a downhole camera or by using borehole-geophysical techniques.

In general, water-bearing zones in the greater Atlanta region are grouped into two broad classes: (1) brittle features that form as a result from the tectonic process of breaking (or shattering) the rock, and (2) features that are lithologically and structurally controlled as a result of weathering or dissolution of rock materials along rock layering, folds, or other structural and stratigraphic features. The combination of these two broad classes creates a variety of different fracture styles. Characteristics of the most common types of water-bearing fractures are illustrated in figure 4.

Brittle features include: stress-relief fractures, faults, zones of fracture concentration, and sets of steeply-dipping joints (fig. 4). Stress-relief fractures, also known as sheet fractures, occur in massive homogeneous rock bodies, are reported to be more numerous and have a higher water-bearing capacity near the surface, and become tighter and more widely spaced with increasing depth. The horizontal orientation of stress-relief fractures makes them ideal conduits for transmitting water laterally in the bedrock. Several productive wells in the Conyers area penetrate horizontal fractures with reported yields ranging from 100 to 350 gal/min (Cressler and others, 1983).

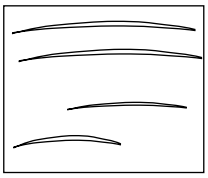
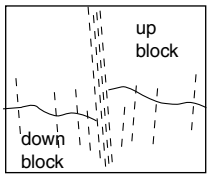
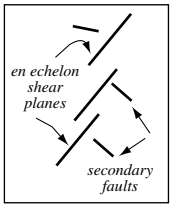
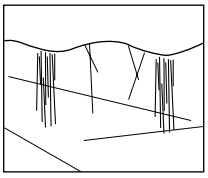
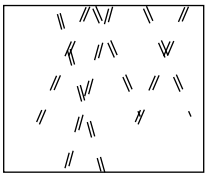
Brittle fault zones, which shatter the bedrock to an indefinite depth, also provide zones of secondary permeability in the bedrock; however, little is known about the present-day distribution of brittle fault zones. These are rarely observed in outcrops because of their narrow width, nearly vertical orientation, and laterally discontinuous extent (fig. 4). Prowell (1988) discussed Mesozoic-Cenozoic brittle faulting in the southeastern United States and indicated that brittle fault zones typically are composed of a series of northeast-southwest trending steeply-dipping en echelon shears. Prowell's observations provide a framework for understanding the distribution of these potentially permeable zones.

Zones of fracture concentration (Cressler and others, 1983), which are similar to brittle fault zones described above, consist of sets of closely spaced fractures in zones from 30- to 200-feet wide along which bedrock is fractured by numerous, nearly vertical fractures (fig. 4). Cressler and others (1983) reported that six wells penetrating zones of fracture concentration in Cherokee County yielded between 50 and 200 gal/min.

In contrast to the intense fracturing associated with brittle faults and zones of fracture concentration described above, steeply-dipping joints (fig. 4) constitute an almost ubiquitous system of crisscrossing joints in many parts of the greater Atlanta region. Steeply-dipping joints generally form low-yielding systems of fractures except where the joints are dilated or enlarged from dissolution and chemical weathering. In the Lawrenceville area, open steeply-dipping joints typically yielded between 1 and 5 gal/min (Williams, 2003).

Lithologic and structurally controlled features that influence water availability include contact zones and combinations of small-scale structures that concentrate and localize drainage development. Contact zones constitute a major class of water-bearing fracture zones in the greater Atlanta region (fig. 4). These types of water-bearing fracture zones are lithologically controlled and probably originate from extensive downdip differential weathering along bedrock layers. Cressler and others (1983) reported that large yields between 50 and 200 gal/min may be obtained from wells penetrating contact zones between rocks of contrasting lithologic character and contacts within multilayered rocks.

1. All rock types in the Atlanta region, including massive nonlayered rocks, have some degree of ground-water potential. Variations in ground-water yield are governed by many factors. Given ideal structural, topographic, and recharge conditions, a low-yielding rock type in one area may have a greater potential in another area.

Brittle Features		Characteristics
Stress-relief fractures		Sheet-like fractures formed from upward expansion of the rock column in response to erosional unloading. May form significant water-bearing openings in large bodies of gneiss. Occur in sets of horizontal joints. Reported to be most numerous and have a higher water-bearing capacity near the surface and become tighter and more widely spaced with increasing depth. May be hundreds of feet in lateral extent and penny-shaped in plan view.
Brittle faults		Zones of parallel, closely spaced, en echelon faults up to 5 miles long (David C. Prowell, U.S. Geological Survey, oral commun., 2002). Primary northeast trending faults are accompanied by secondary faults oriented at acute angles. Individual fault zones can be only tens of feet wide and have a wide range of brittle deformation in and around the fault. Gouge and more intense deformation in center of fault and less intense fracturing out away from center. Fractures may resemble zones of fracture concentration and show small offsets. Rarely observed in outcrops because of their narrow width, nearly vertical orientation, and en echelon geometry (see map view to right). Map pattern of brittle faults 
Zones of fracture concen-tration	 (Modified from Cressler, 1983)	Consist of closely spaced fractures in zones 30 to 200 feet wide along which bedrock is shattered to an indefinite depth by numerous, nearly vertical fractures. Zones follow straight or slightly curved lines that range in length from a few hundred feet to several miles. Zones of fracture concentration tend to localize valley development from increased chemical weathering, coupled with erosion. Can be identified by distinctive straight stream and valley segments, abrupt angular changes in valley alignment, and alignment of gullies, depressions, and vegetation. Chances of obtaining high-yield wells is good in the floors of valleys. (Cressler and others, 1983).
Steeply-dipping joints		Consist of sets of crisscrossing joints and fractures in both massive and layered rocks. May form significant water-bearing zones only where joints are concentrated and opened through chemical dissolution. Extent of individual joint sets highly variable from tens to hundreds of feet laterally and indefinite depth.

Lithologic and Structurally Controlled Features (weathering)

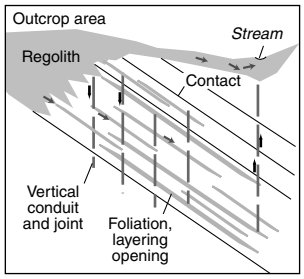
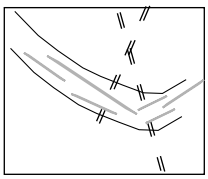
Contact zones	 (Modified from Williams, 2003)	Form discontinuous fracture openings parallel to layering and foliation in layered rocks. Fractures range from a single parting or a group of small partings up to large (1- to 8-inch) openings formed parallel to compositional layering and foliation. Larger openings may form significant water-bearing zones. Variable aperture in these types of fractures cause wide range in well yield even with wells located proximal to each other. Highest yields can be expected where contact zones are penetrated on the floors of valleys and in structural positions that favor recharge. Chances of high-yielding wells is increased in areas where layering is flat lying or gently dipping. Recharge occurs directly from outcrop area or through other vertical conduits. Flowing artesian wells are commonly on the floodplain of streams. Extent of fractures controlled by lithology and zones of increased weathering.
Small-scale structures that localize drainage development	 NONE TO SCALE	Increased weathering along small-scale features such as joints, compositional layers, foliation planes, cleavage; axial planes of small folds allows water to be concentrated along these weaknesses. Bedrock is more permeable parallel to discontinuities than perpendicular to them. High yields can be expected where small-scale structures concentrate the flow of water and form avenues of increased permeability. Joint concentrations along fold axes and shear zones may be productive where projected into low areas favoring deep weathering and increased recharge. Shear zones consisting of "flinty crush rock" and sheared country rock showing little to no replacement mineralization may localize drainage. Shear zones vary in length from 1 to 7 miles and may form distinctive topographic lineaments (Cressler and others, 1983).

Figure 4. Characteristics of common water-bearing fractures in crystalline bedrock.

At Lawrenceville, these types of fracture openings were called "foliation fractures" and were penetrated in many of the high-yielding wells in that area (Williams, 2003). Some of the larger individual foliation fracture openings identified in the Lawrenceville wells had yields as high as 50 to 100 gal/min. A good example of differential weathering along layering was recently observed in layered rock at a quarry in Cumming, Georgia (fig. 5). Extensive zones of weathering are present structurally downdip several thousand feet from the outcrop area along a sequence of biotite gneiss (weathered) and quartzite (unweathered). At another location in this quarry, saprolite could be dug out of the quarry face between a schist layer and a gneiss layer at a depth of more than 400 feet below land surface. The observations of weathering at the Cumming quarry illustrate the great depths that zones of weathering can extend into the subsurface.

The last major category of water-bearing features is related to weathering along joints, fractures, shear zones, and structural and stratigraphic features that together form significant water-bearing zones in the bedrock (fig. 4). Increased weathering along combinations of small-scale structural features—such as joints, compositional layers, foliation planes, and small folds—allow water to concentrate along bedrock weaknesses. Folding, which varies widely in the greater Atlanta region from large open folds several miles across to smaller amplitude folds ranging from less than 75 to more than 600 feet across (Cressler and others, 1983), provide structural discontinuities along which water-bearing zones can develop. Where folds can be mapped, they can be projected into low areas favoring deep weathering and increased recharge. In favorable topographic settings, combinations of small-scale features may localize drainage development and produce zones of increased permeability.

Municipal and Industrial Ground-Water Use in the Greater Atlanta Region

Historically, ground water was a major source of water supply in the greater Atlanta region. Prior to the mid-1940s, many towns and cities around Atlanta relied almost exclusively on ground water and supplemented their water supply with surface water only where the need was great[1]. Several examples of this early municipal ground-water use include:

- **Conyers, Rockdale County.** Prior to the mid-1950s, ground water was the main source of supply to Rockdale County including the city of Conyers, which continued to use ground water to supplement their surface-water supply until 1985 (Scott Emmons, Rockdale County Water Resources, written commun., 2002). During 1943, one well yielded 110 gal/min and another 45 gal/min when pumped continuously. The more productive well reportedly yielded 100,000 gallons per day (gal/day) for 11 years of continuous pumping (Herrick and LeGrand, 1949).

- **College Park, Fulton County.** During the 1940s, College Park, with a population of 8,213, used five wells for its water supply; each of the wells yielded 100 gal/min (Herrick and LeGrand, 1949). College Park had grown so large by 1945 that it needed to supplement its water supply with surface water from the East Point water system.

- **East Point, Fulton County.** During 1939, East Point—with a population of 12,403—obtained water from about 15 wells dispersed around the city. The combined yield from the East Point wells was 1.2 million gal/day, which dropped to about 800,000 gal/day during the prolonged drought of 1939 (Herrick and LeGrand, 1949). By 1945, the ground-water supply was no longer sufficient to meet existing needs of the growing city, and East Point abandoned its wells in favor of using treated surface water from the city of Atlanta.

- **Marietta, Cobb County.** During June 1947, the city of Marietta used 13 wells yielding 390,000 gal/day with individual wells yielding an average of 25 gal/min (Herrick and LeGrand, 1949). The average depth of these wells was 400 feet and the average pumping level was 200 feet below land surface. Nearly all the producing wells were located in a northeast-trending belt of hornblendic rocks that had jointing across the foliation and parallel with it (Herrick and LeGrand, 1949).

1. Today the opposite trend is true. Municipalities rely heavily upon surface-water sources and supplement with ground water only where it is readily available.

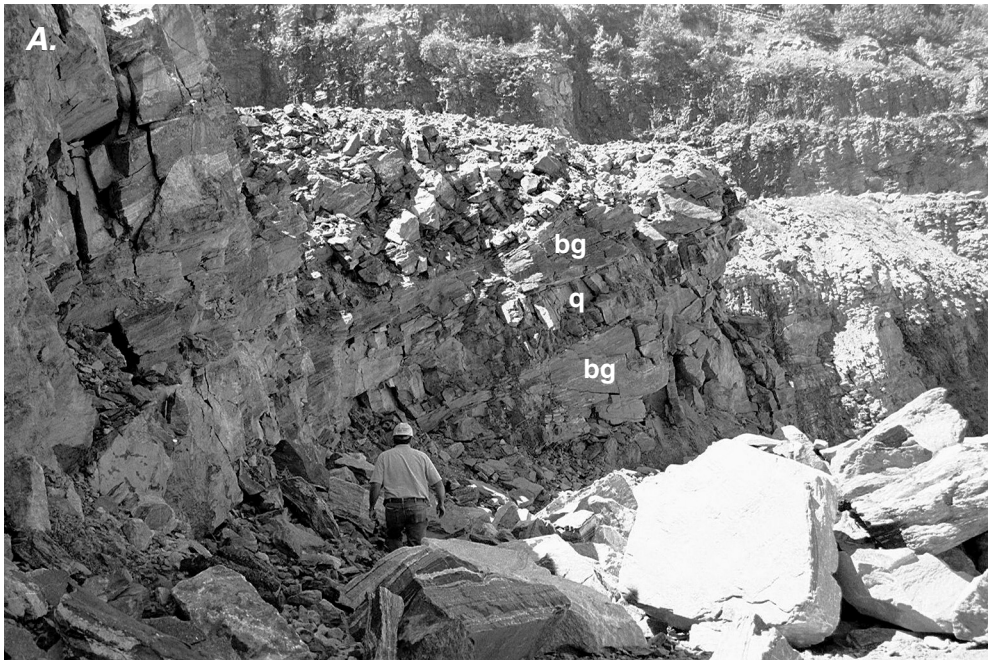


Figure 5. Weathering along rock layering in a quarry, Cumming, Forsyth County, Georgia (see figure 1 for location). *(A)* Inclined sequence of biotite gneiss (bg) and quartzite (q); quarry face shown is about 400 feet below the original land surface and is structurally several thousand feet downdip from the outcrop area. Person for scale. *(B)* Close-up of extensive differential weathering and saprolite in the biotite gneiss layers in the same outcrop shown in *(A)*. Rock hammer for scale. Photographs by Lester J. Williams, U.S. Geological Survey.

- **Industrial Supply, Atlanta.** Ground water was an important source of water for industrial use in the greater Atlanta region. According to Carter and Herrick (1951), estimated total pumpage from industrial wells was 3.5 million gal/day. Yields from the more productive industrial wells averaged about 40 gal/min (Carter and Herrick, 1951). Since the 1950s, commercial and industrial ground-water use in the Atlanta area has declined slightly—Fanning (2003) reported that in 2000, only about 2 million gal/day was used in a nine-county area around Atlanta that includes: Clayton, Cobb, DeKalb, Douglas, Fayette, Fulton, Gwinnett, Henry, and Rockdale, which is nearly the same area used by Carter and Herrick (1951).

Currently, only a small amount of ground water is used for water supply in the greater Atlanta region. Combined surface-water and ground-water withdrawal totaled[1] about 1,632 million gal/day during 2000 of which ground water accounted for about 3 percent; the remainder was withdrawn from surface-water sources. Of the estimated 46.28 million gal/day withdrawn from ground-water sources during 2000, 68 percent was used for domestic supply, 20 percent for public supply, 8 percent for industrial/commercial purposes, 4 percent for irrigation, and less than 1 percent for other uses (Fanning, 2003). Within the 30 counties in the greater Atlanta region, about 220 water systems use ground water as the primary source (Georgia Environmental Protection Division data accessed March 22, 2003, on the World Wide Web at URL http://www.state.ga.us/dnr/environ/ regulated community water; withdrawal permits). The majority of these water systems supply water to small communities such as neighborhoods and trailer parks, outside of the existing surface-water systems.

GROUND-WATER EXPLORATION AND DEVELOPMENT

Many city and county governments in the greater Atlanta region are conducting, or have conducted, ground-water exploration studies in an effort to supplement their water supply. Advances in exploration techniques have improved considerably the likelihood of obtaining high well yields, as demonstrated by case studies in Spalding, Cobb, Carroll, and Gwinnett Counties.

In a study conducted for the city of Griffin, Spalding County (fig. 1), during a period of severe drought in the summer of 2000, exploratory test drilling in that area targeted the Ison Branch Formation, a calcareous metamorphosed tuff. Before drilling, Tom Crawford and Randy Kath (see Crawford and Kath, this guidebook) reasoned that the calcareous tuff likely had the greatest water-bearing potential because of its mineralogy and vuggy weathering characteristic. Of the 10 wells drilled, 6 penetrated productive water-bearing zones resulting in yields ranging from 110 to 280 gal/min, thus providing the city of Griffin a much-needed emergency water supply (Randy Kath, State University of West Georgia, oral commun., 2003).

The Carroll County Water Authority began a countywide ground-water exploration effort in the summer of 1998. After an attempt at using a dowser[2] failed to produce satisfactory results, the Water Authority began using geologic criteria for site selection. Areas favorable for drilling high-yielding wells were identified using the relation among several factors including (1) distribution of rock types, (2) geologic structure (presence, orientation, and concentration of discontinuities), (3) topographic position, (4) depth of weathering, and (5) recharge potential (Crawford and Kath, 2001; Kath and others, 2001). Based on a relative ranking of many potential well sites, the Carroll County Water Authority drilled five wells. The first and the most productive of the five wells was drilled on the floodplain of the Little Tallapoosa River in north-central Carroll County. This 605-foot-deep well, known as the "Abilene well," penetrates a muscovite-biotite-quartz-feldspar gneiss containing layers of amphibolite and schist (Tom Crawford, State University of West Georgia, oral commun., 2003). Under continuous pumping, the Abilene well currently produces 345 gal/min with a pumping water level at about 104 feet (Jim Baxely, Carroll County Water Authority, oral commun., 2003). The Abilene well currently (2003) produces 500,000

1. Figures are based on 30 Georgia counties in the greater Atlanta region. See figure 1 for counties included.
2. A person who uses a rod, stick or other device—called a dowsing rod, dowsing stick, or divining rod—to search for subsurface water or other mineral resources.

gal/day, making it one of the higher yielding wells in the greater Atlanta region. Another well drilled north of Villa Rica in the northwestern part of the county yields 82 gal/min when pumped continuously, and a third well in the southern part of the county is being operated at a rate of 80 gal/min on a cycle of 8-hours on and 4-hours off. The county is planning additional drilling later this year (Jim Baxely, Carroll County Water Authority, oral commun., 2003).

Another exploratory program was conducted in Cobb County by the Cobb County-Marietta Water Authority in the early 1990s. During the initial studies, no substantial fieldwork was conducted other than drilling and monitoring a single well. The initial studies included compiling data into a geographic information system and computer-aided design to help analyze geologic, hydrologic, water-use, land-use, potential threats to ground water, and water-distribution network data (Chapman and Peck, 1997). Subsequent work involved detailed geologic mapping throughout the county; photo-lineament analysis; collection of background well information, topography, soil data; assessing watershed geomorphology; assessing contamination potential; and drilling from10 to 15 wells (Emery and Garrett Groundwater, Inc., written commun., 1994). The results of this work eventually produced four permitted supply wells, two of which currently are being operated on peak demand (Glenn Page, Cobb County–Marietta Water Authority, oral commun., 2003). The two peak-demand wells yield about 555,000 gal/day operated on a schedule of 4 to 5 days on and 2 to 3 days off and have been in operation for about 4 years.

The city of Lawrenceville, Gwinnett County, recently developed a substantial amount of ground water that will be used to supplement their existing water supply. During 2001, the city drilled 12 test wells, 8 of which had yields ranging from 100 gal/min to 350 gal/min. The test wells, which were part of a USGS–city of Lawrenceville cooperative water-resource investigation, were used to investigate the yield potential of different geologic settings in the study area. Aquifer tests and water sampling conducted by the city indicate that six of the wells can be used for municipal water supply. Lawrenceville currently (2003) plans to pump approximately 2 million gal/day from three separate well fields (Jim Steadman, city of Lawrenceville, oral commun., 2003).

Other ground-water exploration and development studies recently undertaken in the greater Atlanta region include studies in Clayton County (Guy Pierria, Clayton County Water Authority, oral commun., 2003), Coweta County (Bill McKinley, Coweta County Water and Sewer, oral commun., 2003), Douglas County (Johnny Barron, Douglasville-Douglas County Water and Sewer Authority, oral commun., 2003), city of Fayetteville (Claude Cormier, Hydrosource, oral commun., 2003), city of Hampton (Randy Kath, Petrologic Solutions Inc., oral commun., 2003), and city of Winder (Claude Cormier, Hydrosource, oral commun., 2003).

CONCLUSION

Considerable potential exists for ground-water development in the greater Atlanta region. This potential exists mainly for developing small- to medium-sized ground-water systems that could be used for municipal, irrigation, or small industrial supplies. Such use has been used historically in the Atlanta region and will likely become an increasingly important source of water in the future. Exploration for water, however, has always been and will probably continue to be difficult because of the complexity of the water-bearing zones in crystalline bedrock. Use of geologic and geophysical techniques can greatly enhance exploration and development of ground water in the greater Atlanta region.

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Description of Water-Bearing Features in the Vulcan Materials Quarry, Eastern DeKalb County, Georgia

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INTRODUCTION

Rarely is there an opportunity to directly observe subsurface water-bearing features in the crystalline-rock terranes of north Georgia. This part of the field trip will focus on the Vulcan Materials Quarry (fig. 1), where many typical water-bearing features that are typical can be observed in the Piedmont physiographic province. Understanding the scale of these features and their interconnection is the first step in relating geology to ground-water occurrence. The main features in the quarry are (1) saprolite, which stores water above the bedrock; (2) steeply-dipping joints, which transfer water from the saprolite into the bedrock; (3) subhorizontal joints, which control lateral movement of water; and (4) faults, which are potential pathways for water movement across great distances. These features combine to increase the permeability of the bedrock and are important for understanding the relation between the occurrence and availability of water in crystalline rocks.

Location

The Vulcan Materials Quarry is located southeast of Lithonia, Georgia, in southeastern DeKalb County (fig. 1). Clifford Hill Inc. opened this quarry, in the Lithonia Gneiss, in the mid-1970s. The McDowell Company later acquired it; then Vulcan Materials Corporation purchased it in 1986. Approximately 1 million tons of construction products, such as aggregates and manufactured sand, are produced annually at this site (Chuck Michael, Vulcan Materials Corporation, oral commun., 2003). A sketch map showing the main quarry pit is shown in figure 2.

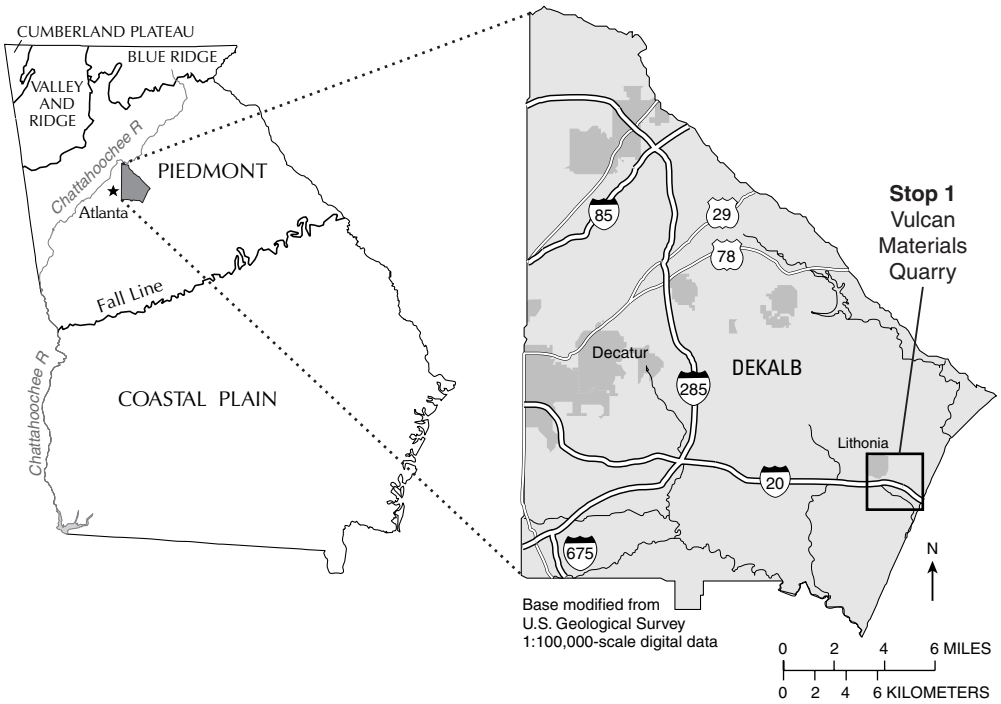

Figure 1. DeKalb County, Georgia, and location of field-trip stop.

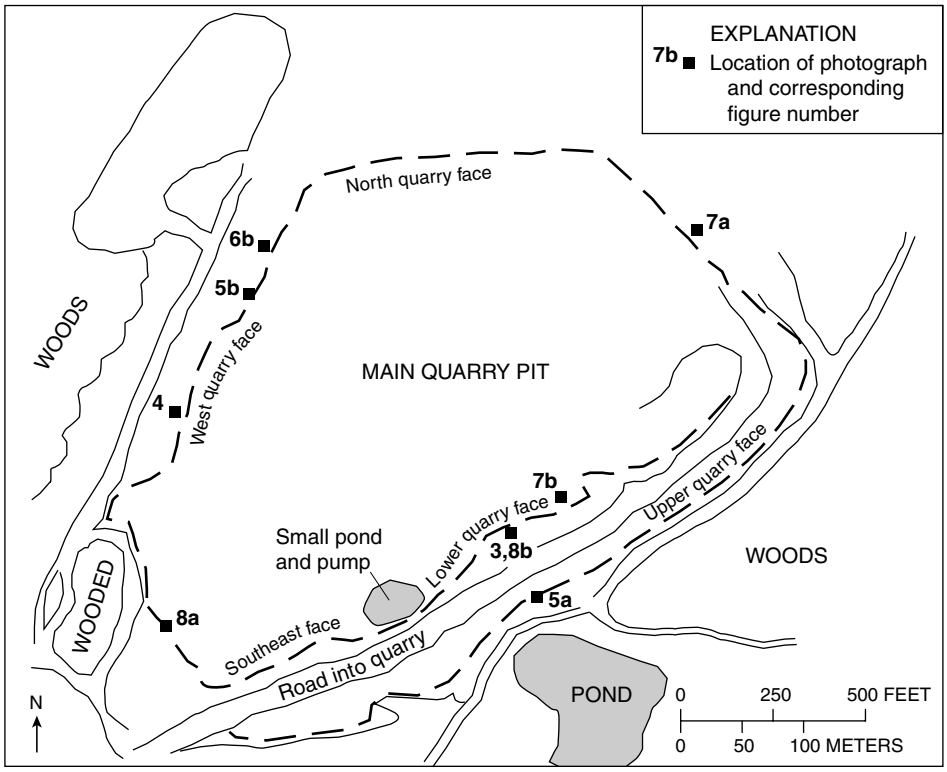

Figure 2. Sketch of the main quarry pit at the Vulcan Materials Quarry, DeKalb County, Georgia. Map by Lester J. Williams, USGS, 2003.

Geologic Setting

The Piedmont is a physiographic province consisting of middle- to high-grade metamorphic rocks that trend northeast-southwest from Alabama into Georgia, North Carolina, South Carolina, and Virginia. In Georgia, the Piedmont lies between the Coastal Plain and the Blue Ridge and Valley and Ridge physiographic provinces (fig. 1). The Vulcan Materials Quarry in DeKalb County is located in the Lithonia Gneiss, a migmatized granite gneiss that intrudes older sequences of metamorphosed rocks of sedimentary and volcanic origin (Crickmay, 1952; Hermann, 1954).

The Lithonia Gneiss is a medium-grained metamorphosed granite gneiss that underlies large parts of eastern Atlanta, as well as other areas of the Georgia Piedmont. It generally is light gray and is a muscovite-biotite-microcline-oligoclase-quartz gneiss with amphibolite xenoliths (Crawford and others, 1999; Hermann, 1954). Thin, dark bands of biotite are interlayered with wider, lighter bands of quartz and feldspar. Foliation in this unit tends to be weak; however, the Arabia Mountain migmatite facies of the Lithonia Gneiss (Hermann, 1954) has a well-defined, swirled gneissic structure. Some areas of the migmatite contain very small garnet crystals, which form thin bands that typically are composed of biotite. The Lithonia Gneiss commonly forms pavement outcrop and weathers to a yellowish white sandy soil (Higgins and others, 1998).

The southern half of the Vulcan Materials Quarry primarily is granite gneiss, containing small zones (as much as 3 feet [ft] wide) of large black tourmaline crystals. The granite gneiss grades into migmatite in the northern half of the quarry, where fine-grained garnets occur as thin, horizontal bands or as thin swirls.

Several northeast-striking, northwest-dipping, en echelon faults cut across subhorizontal and steeply-dipping joints in the quarry (fig. 3). These features channel water from the surface to the subsurface. The dark stains shown in figure 3 are from intermittently flowing water that seeps from the joints. In the quarry, the permeability of the Lithonia Gneiss is partly dependent on the density of these joints and how well they are interconnected.

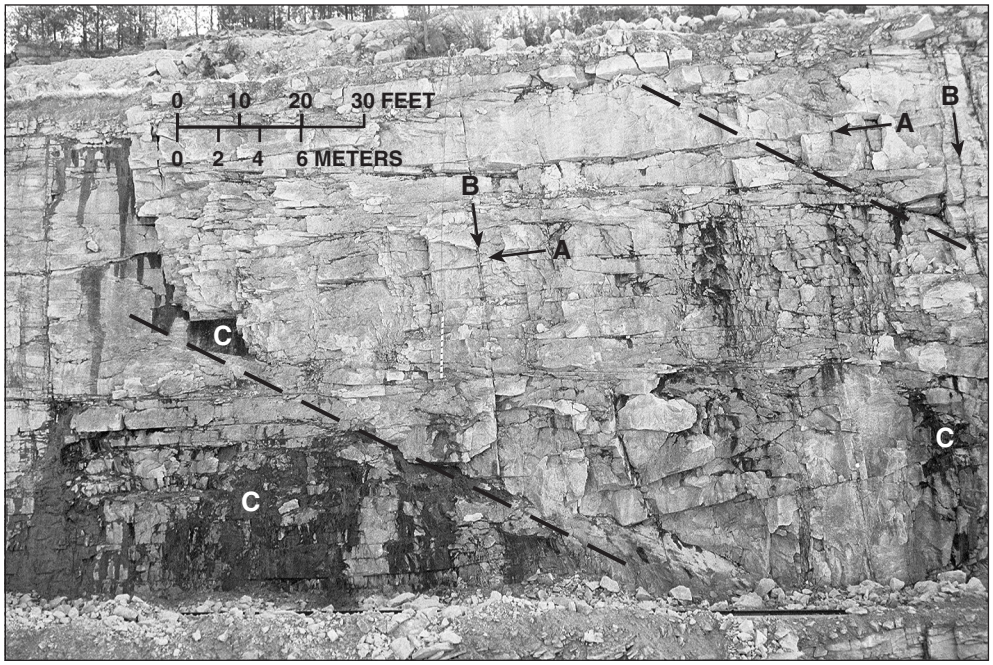

Figure 3. Quarry wall showing several water-bearing features, including numerous subhorizontal joints (**A**), prominent vertical joints (**B**), and two en echelon faults (dashed lines show the fault traces). The dark stains (**C**) on the wall are actively flowing water or old water stains. View is to the southeast. Photograph by Donna D. Khallouf, USGS.

WATER-BEARING FEATURES IN THE VULCAN MATERIALS QUARRY

This section describes typical water-bearing features of Piedmont rocks that can be seen in the Vulcan Materials Quarry. These features are shown in the accompanying photographs, which are located by number in figure 2.

Saprolite

Saprolite ("rotten rock") is chemically weathered rock that retains the structures of the parent rock, such as foliation, bedding, and veining. It is produced during the latter stages of chemical weathering, where more than 20 percent of weatherable minerals are altered (Govett and others, 1992). By contrast, less than 20 percent of weatherable minerals are altered in "saprock" (Govett and others, 1992). Saprock is produced during the early stages of chemical weathering, primarily along microfractures or mineral contacts. Together, the saprolite and saprock constitute the lower part of the regolith.

The regolith as a whole is an integral part of ground-water recharge. The highly weathered parts of the saprolite store water from the surface; this water eventually flows downward through steeply-dipping joints and is stored in subhorizontal joints. Dissolution along joint faces often results in widening of the joints and increases the capacity for ground-water transmission. Larger joints result in larger volumes of water being stored and transmitted into the subsurface.

Weathering effects often accentuate the joints in a rock. Joints in the saprolite outcrop shown in figure 4 can be distinguished because they are preferentially weathered compared to the surrounding materials. The area near the scale in figure 4 shows where preferential weathering along subhorizontal and steeply-dipping joints has altered the rock to clay- and sand-sized particles, and left areas in between relatively intact (saprock). This outcrop exhibits how weathering progresses more rapidly along structural weaknesses in the rock.

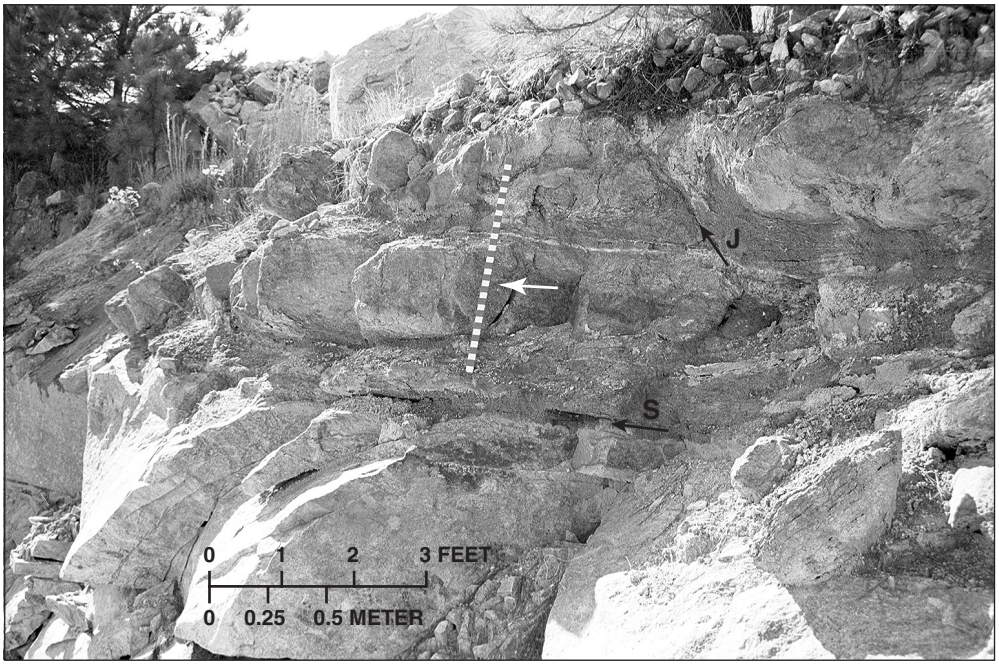

Figure 4. Saprolite outcrop of Lithonia Gneiss, showing preferential weathering along subhorizontal (**S**) and steeply-dipping joints (**J**). The bar (white arrow) in the middle of the photograph is 3 feet long. View is to the west. Photograph by Lester J. Williams, USGS.

Steeply-Dipping Joints

Steeply-dipping joints at the Vulcan Materials Quarry are near vertical and may occur in sets as close as 1 ft apart or as far as 100 ft apart. Typically, these joints are about 10 ft apart. A steeply-dipping joint can occur as a zone of fracturing or as a single fracture (figs. 5a and 5b, respectively). Some joints extend from land surface to the quarry floor, whereas others terminate at intersections with subhorizontal joints.

A steeply-dipping joint, extending to the quarry floor (approximately 150 ft below land surface), is shown in figure 5b. The depth of weathering, as seen from the staining on the rock, makes it easy to distinguish this joint from other features in the west quarry face. Note that the saprolite is thicker directly above this joint than elsewhere on this wall. More water is likely stored in this thicker zone of saprolite, which probably allows for preferential weathering along this joint.

Weathering along zones of joint concentration can cause localized valley development, as illustrated in figure 6a. In the center of the photograph in figure 6b, a set of joints is positioned near a topographic low. These joints are so concentrated that the increased weathering along the zone of joints facilitates surface erosion.

Tensile (dilation) fractures, such as the steeply-dipping joints in the quarry, are dependent on the strength of the rock and the local stress field acting on the rock. From crosscutting relations observed in the quarry, the longer steeply-dipping joints probably formed first when the weight of the overlying rock exceeded the tensile strength of the rock. Once the overburden began to erode away, subhorizontal joints most likely began to form as a result of stress relief. Steeply-dipping joints continued to form in response to changes in the vertical stress; however, these latter joints appear to be shorter, probably because they stopped propagating once they intersected a subhorizontal joint.

Subhorizontal Joints

Subhorizontal joints in the quarry are spaced anywhere from less than 1 ft to more than 30 ft apart (see figs. 7a and 7b). In general, the distance between these joints diminishes with proximity to the land surface. Throughout the quarry, numerous steeply-dipping joints and a few faults intersect these subhorizontal joints.

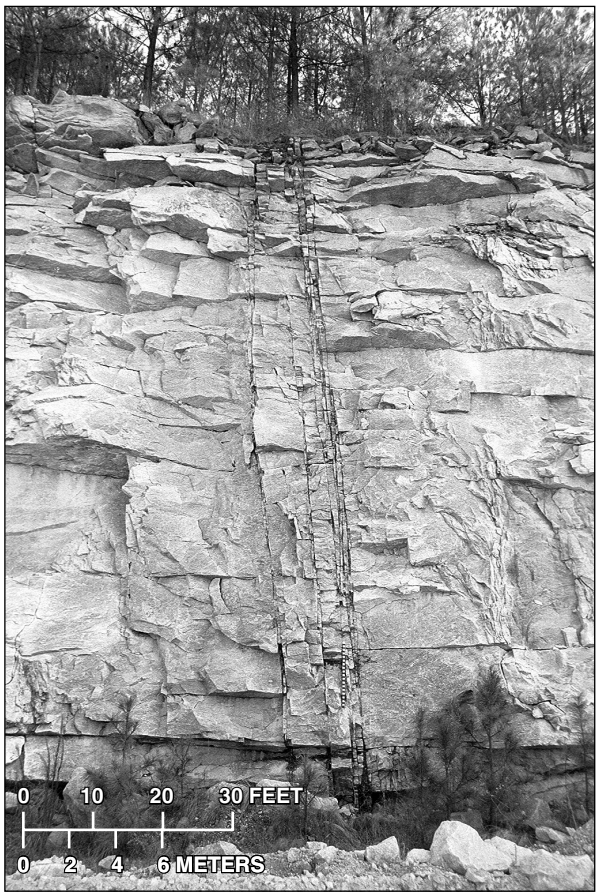

Figure 5a. Zone of concentrated, steeply-dipping joints. View is to the southeast. Photograph by Lester J. Williams, USGS.

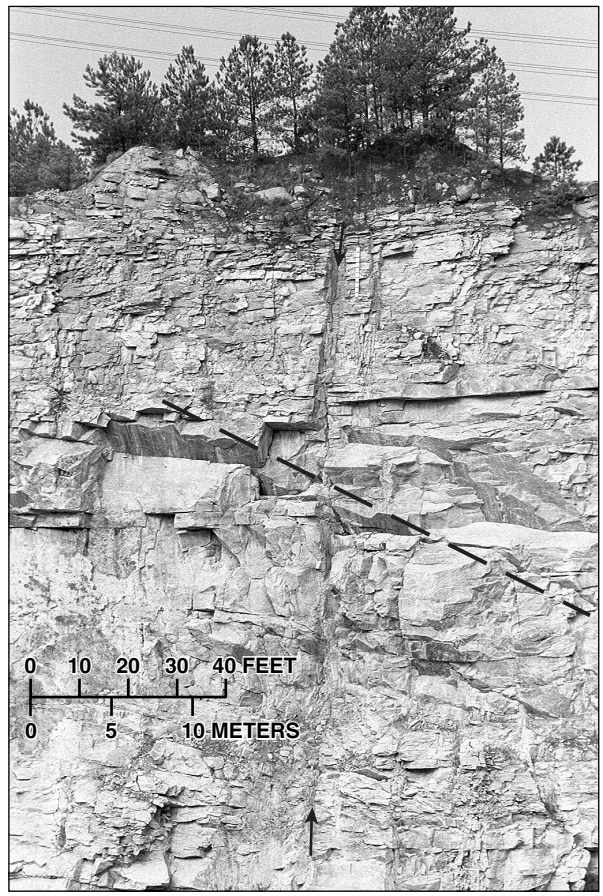

Figure 5b. Weathering along a single steeply-dipping joint (arrows), extending 150 feet below land surface. Notice the thickness of the saprolite directly above this joint. Slickensides are visible on a fault plane (dashed line). This fault is parallel to the one shown in figure 3. View is to the northwest. Photograph by David C. Prowell, USGS.

Iron stains and flowing water are visible in some parts of the quarry; these stains appear as dark areas in figure 7a. The water appears to have seeped out from the subhorizontal joints rather than from the steeply-dipping joints because the stains do not extend all the way to the surface along any steeply-dipping joints. Water most likely flowed downward from the surface into unexposed steeply-dipping joints and into these subhorizontal joints. Water appears to have seeped out from subhorizontal joints with the relatively wider openings. Figure 7b shows that a greater area of seepage (see wet areas and iron oxide staining) is coming from the subhorizontal joints.

These subhorizontal joints also are tensile fractures; but, whereas steeply-dipping joints are created by vertical compression, the subhorizontal joints are created by vertical tension. Vertical compressive stresses on the rock mass are lowered as erosion removes the overburden, causing the rock to expand upward until subhorizontal joints eventually form. Subhorizontal joints in the quarry and in drill holes show that spacing increases with depth (Cressler and others, 1983).

Faults

Three northeast-striking, northwest-dipping, en echelon fault planes (shown in fig. 8a) are approximately 60–160 ft apart and cut across numerous subhorizontal and steeply-dipping joints. The slip surfaces have chlorite-coated slickensides (fig 8b), which indicate the dip-slip movement of the faulting.

The origin of these faults is not known, but may be related to regional compressive stresses that produce young faulting elsewhere in the eastern United States (Prowell, 1988). These faults could potentially transmit water across great distances if they are indeed regional features. The faults observed in the quarry do not appear to be related to Paleozoic ductile shearing, which characterizes typical Piedmont faults. Rather, they are much younger, brittle structures that fracture the rock mass in the Piedmont.

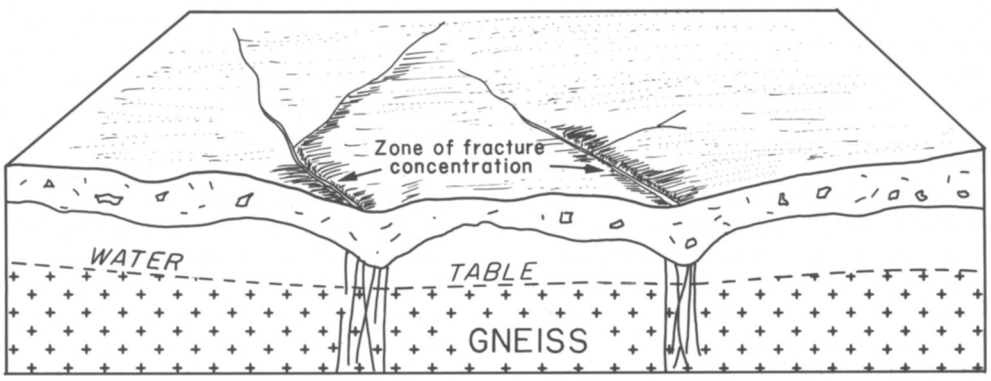

Figure 6a. Diagram showing how valleys form along a zone of concentrated joints (from Cressler and others, 1983).

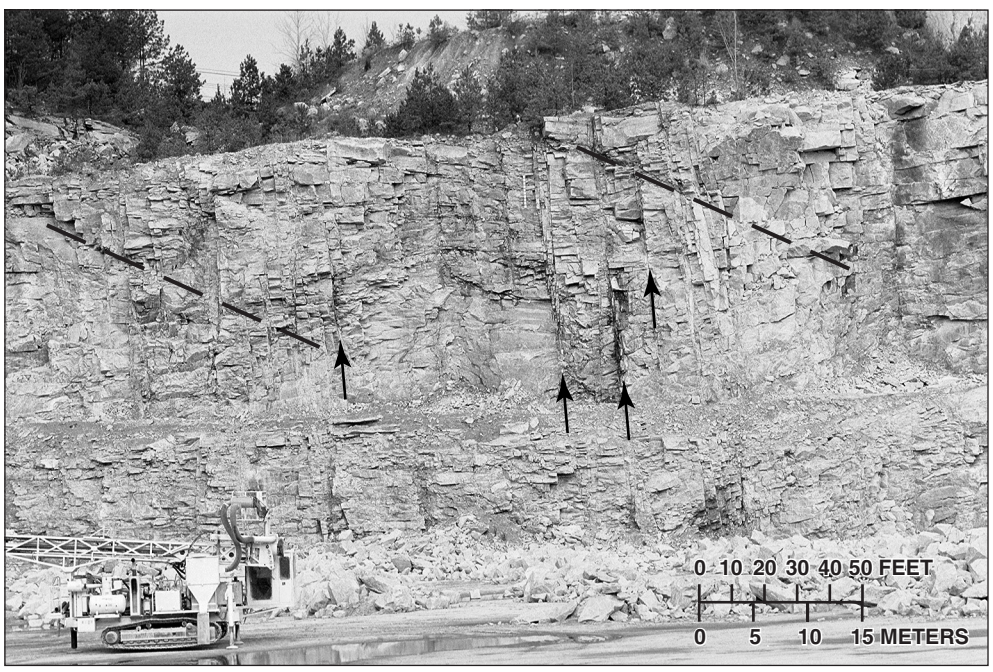

Figure 6b. A concentration of steeply-dipping joints (arrows) results in a topographic low. Traces of two en echelon faults, approximately 160 feet apart, are shown by dashed lines. View is to the northwest. Photograph by David C. Prowell, USGS.

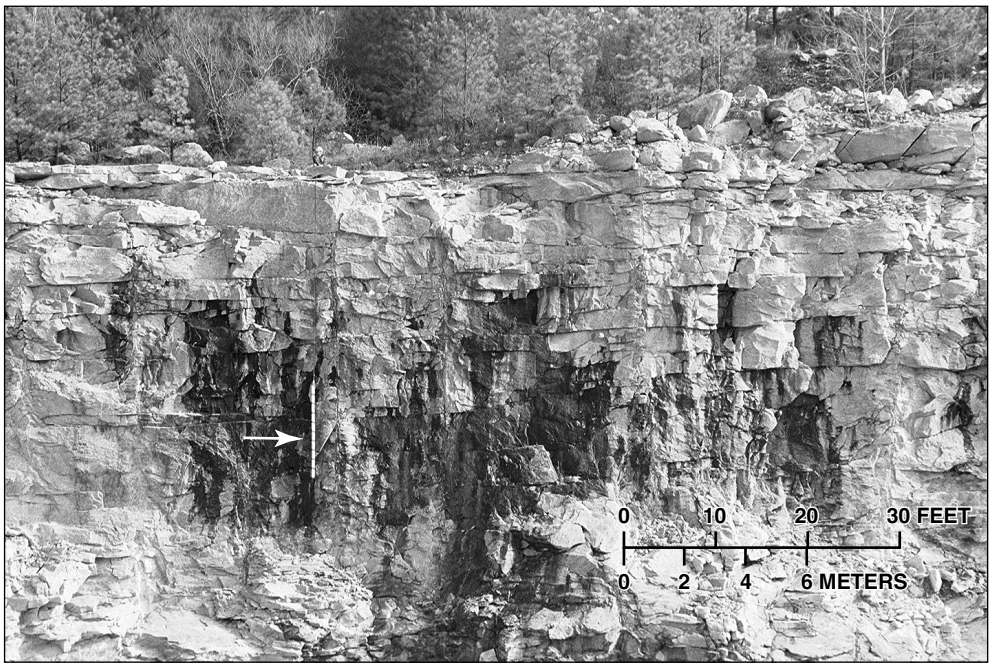

Figure 7a. Subhorizontal joints with varying distances between each joint. The dark water stains are created by water seeping out from subhorizontal joints. The bar (arrow) in the middle left of the photograph is 10 feet long. View is to the north. Photograph by David C. Prowell, USGS.

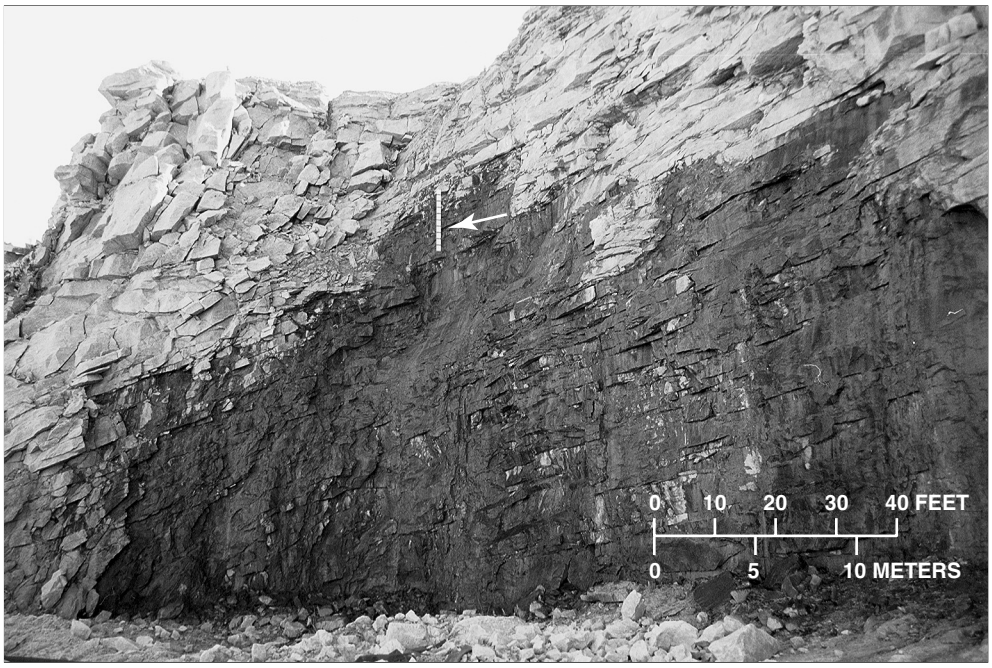

Figure 7b. Intense iron oxide staining in an area with ground-water seeps. The water appears to be seeping from the subhorizontal joints. The bar (arrow) in the upper middle of the photograph is 10 feet long. View is to the east. Photograph by Donna D. Khallouf, USGS.

Figure 8a. Three northeast-striking, northwest-dipping en echelon faults (dashed lines). These faults are approximately 60–160 feet apart. Quarry wall is approximately 150 feet high. View is to the southwest. Photograph by David C. Prowell, USGS.

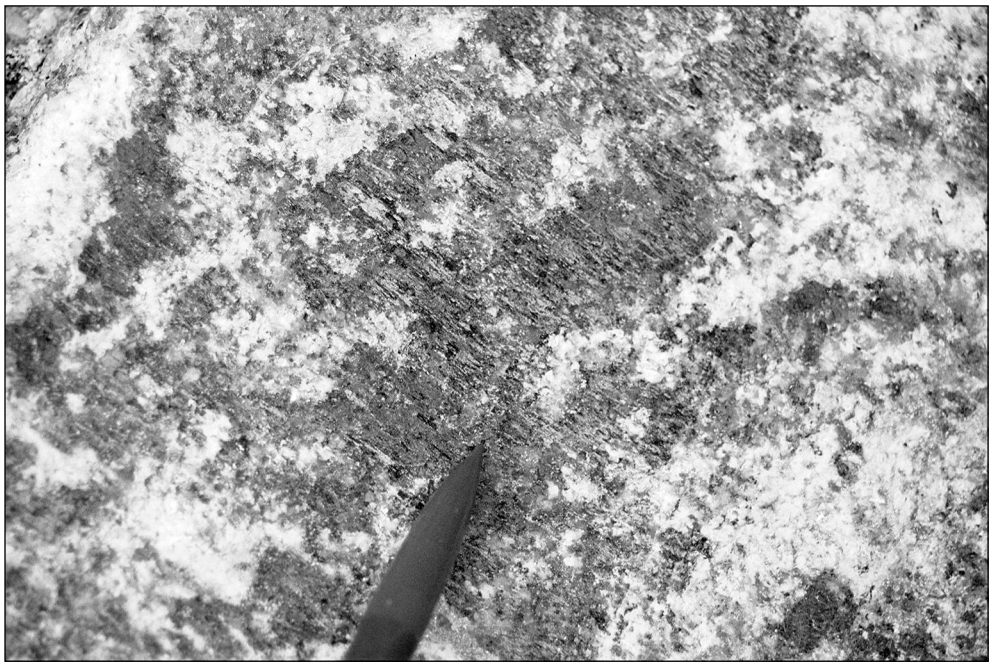

Figure 8b. Chlorite-coated slickensides on the fault surface shown in figure 3. Tip of pencil for scale. Photograph by Lester J. Williams, USGS.

SUMMARY

The Vulcan Materials Quarry is an excellent location to observe some of the water-bearing features of Piedmont crystalline-rock aquifers. Saprolite, steeply-dipping joints, subhorizontal joints, and faults each play a role in the storage and transmission of ground water. On a local scale, water stored in the saprolite moves downward into the bedrock through steeply-dipping joints. Subhorizontal joints control lateral movement of water in the bedrock. On a regional scale, faults may play a role in transmitting water across long distances. All of these features interact to increase the permeability of the bedrock, influencing the availability of ground water in the Piedmont.

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General Geology and Ground-Water Resources of Rockdale County, Georgia

by Lester J. Williams
U.S. Geological Survey

INTRODUCTION

The second part of the field trip is in Rockdale County, about 20 miles east of Atlanta (fig. 1—where the U.S. Geological Survey (USGS) in cooperation with Rockdale County—is conducting a ground-water resource investigation. Two distinct hydrogeologic terranes underlie Rockdale County. Massive granite gneiss underlies the northern part of the county; wells completed in this unit are extremely low yielding. Layered rocks—including gneiss, schist, quartzite, and amphibolite—underlie the southern part of the county. Between these two contrasting hydrogeologic terranes is an intercalated sequence of granite gneiss and layered rocks. Stops 2 and 3 focus on this central area, near Conyers, where many high-yield[1] wells have been drilled (fig. 1).

This paper describes (1) the geology and the major rock units underlying Rockdale County, (2) the ground-water resources of the county, and (3) ongoing USGS water-resource investigations in the county. The area of study includes the entire county; several wells ranging in depth from about 100 to 780 feet have been drilled in the study area. Because the geology and ground-water resources in Rockdale County are similar to other areas in the Piedmont physiographic province, the methods and techniques discussed on the field trip have direct application to other areas of the Georgia Piedmont.

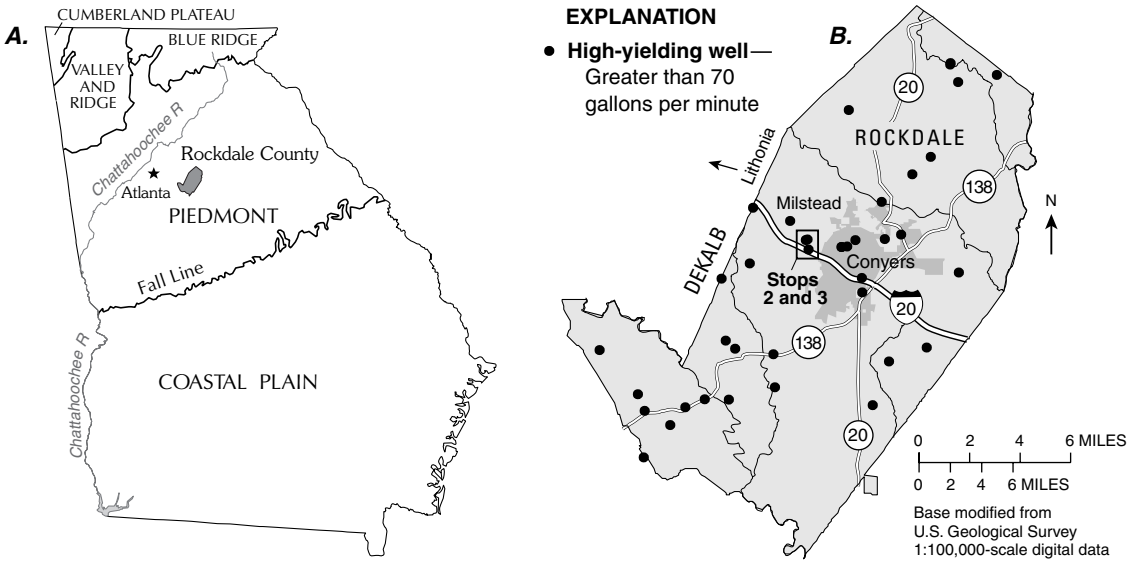


Figure 1. *(A)* location of Rockdale County and *(B)* high-yielding wells.

1. In this paper, "high-yield" refers to wells having a reported yield of 70 gallons per minute (gal/min) or greater. Cressler and others (1983) defined "high-yield" as 25 gal/min or greater.

I am greatly indebted to the Board of Commissioners, Mr. Scott Emmons, Mrs. Lauri Ashmore, and the staff of the Rockdale County Water Resources for providing valuable assistance during the course of the cooperative water-resource study in Rockdale County. I thank the hundreds of residents in Rockdale County who have graciously offered information about their wells. Much of this information contributes to a better understanding of ground-water resources in the area.

GEOLOGY

Igneous and metamorphic crystalline rocks that have undergone intense metamorphism and deformation underlie Rockdale County. Mineralogy, textural variations, structural features, and rock types can vary within a few feet. Most of these rocks also have been subjected to intense weathering, resulting in the formation of voids and widening of fractures in the bedrock and saprolite near land surface. Saprolite is the in-place, chemically weathered product of the underlying bedrock and commonly retains relic structures of the bedrock.

Regional Geology

Rockdale County lies in the Piedmont physiographic province—an area underlain by highly deformed crystalline rocks. In Georgia, the Piedmont is located between the Valley and Ridge and Blue Ridge provinces to the north and the Coastal Plain to the south (fig. 1). Atkins and Higgins (1980), McConnell and Abrams (1984), and Higgins and others (1984, 1988, 1998) have described the geology of the Piedmont. Higgins and others (1988) proposed one of the more widely accepted structural geologic interpretations for the area. They suggested that the movement of massive stacks of thrust sheets during the Middle Ordovician through Carboniferous time essentially formed much of the deformation and metamorphism in the Atlanta region. The thrust sheets were injected by igneous intrusions at various times during thrusting. Thrust stacks and igneous intrusions were further metamorphosed, folded, and faulted, resulting in a complex distribution of lithologies.

Geologic units in the southern part of Rockdale County comprise several major thrust sheets, including portions of the Bill Arp, Clairmont, Sandy Springs, and Zebulon thrust sheets (Higgins and others, 1988). Massive granite gneiss underlying the northern part of the county is assigned to the Lithonia Gneiss, the type locality being at Lithonia, Georgia, just west of Rockdale County in eastern DeKalb County. The Lithonia Gneiss is grouped with the Silurian-Devonian igneous intrusions (Higgins and others, 1988), which were subsequently deformed and metamorphosed by regional thrusting.

Local Geology

The most detailed account of the geology in Rockdale County is by McCollum (1966), who grouped the rocks into six major and several minor rock units (fig. 2; table 1). The major rock units include the Lithonia Gneiss (Watson, 1902; Herrmann, 1954) in the northern part of the county, a porphyroblastic biotite gneiss (Stonewall Gneiss of Crawford and others, 1999) in the southern part of the county, and the Panola Granite (Herrmann, 1954), in the southwestern tip of the county. Other major, but less extensive, units are garnet-mica schist (Sandy Springs Group of Crawford and others, 1999), muscovite quartzite (Chattahoochee Palisades Quartzite of the Sandy Springs Group of Crawford and others, 1999), and an unnamed amphibolite gneiss. All of the rock units are injected by aplite and pegmatite dikes. A series of northwest-trending diabase dikes cuts the Lithonia Gneiss in the northern part of the county.

At land surface, most of the exposed bedrock has been weathered, forming a layer of saprolite. Saprolite thickness ranges from a few feet to greater than 150 feet. Beneath the saprolite, voids, fractures, and other openings occur along structural weaknesses in the underlying bedrock. Structural weaknesses include features such as foliation planes, compositional layers, and joints. Ground water occupies fracture openings in the bedrock and fills pore spaces in the overlying saprolite, soil, and alluvium[1].

1. In this paper soil, saprolite, and alluvium overlying the bedrock surface is collectively referred to as “regolith.”

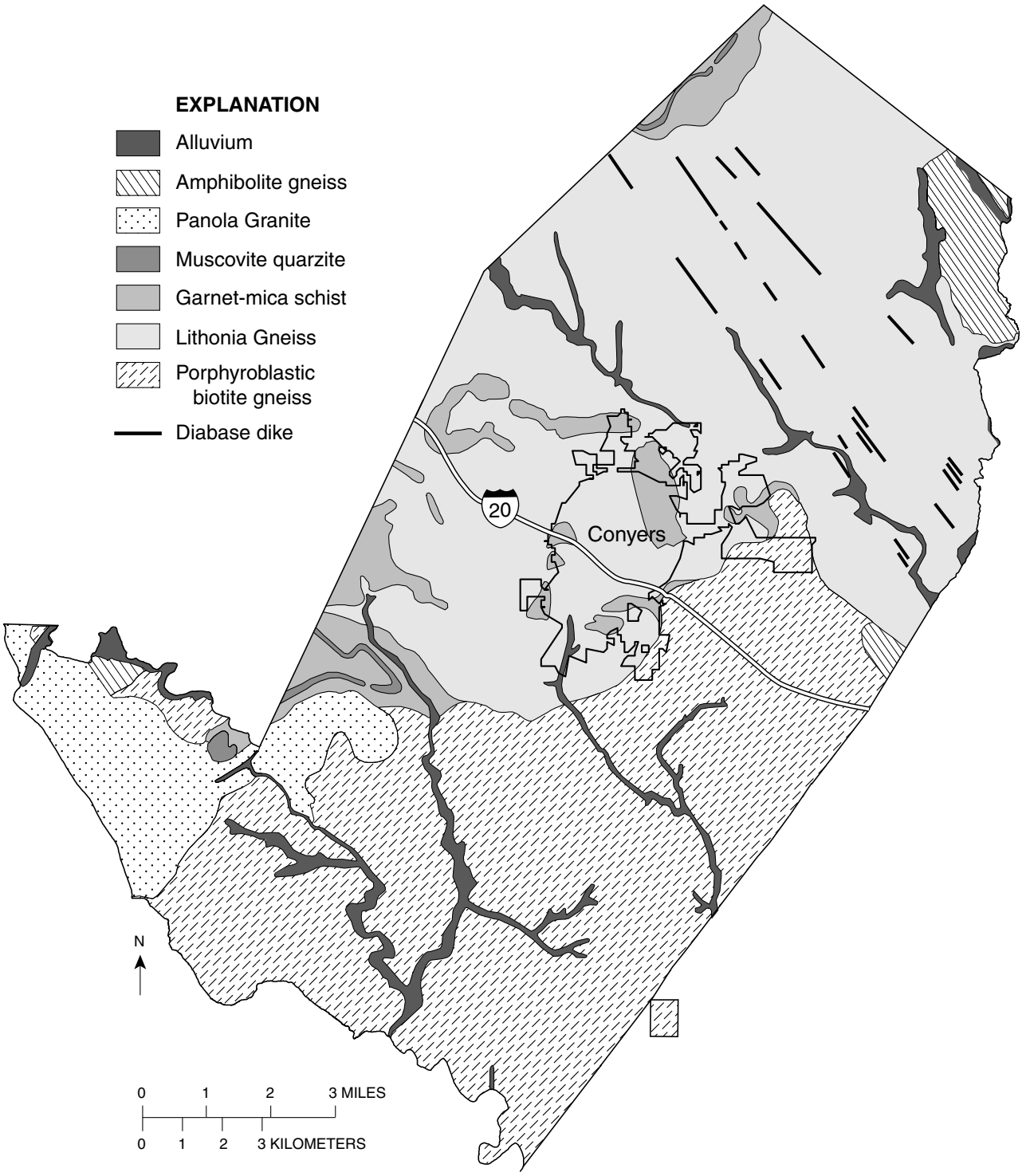


Figure 2. Geologic map of Rockdale County, Georgia (modified from McCollum, 1966).

Table 1. Lithologic and structural characteristics of rock units in Rockdale County, Georgia

[Modified from McCollum, 1966]

Rock Unit and Rock Types	Description	Structural Features	Weathering Characteristics
Lithonia Gneiss (granite gneiss)	Light-gray to whitish-gray medium-grained muscovite-biotite-microcline-oligoclase-quartz gneiss (Herrmann, 1954); contains xenoliths of amphibolite, locally contains garnet segregations, and commonly forms pavement outcrops. Herrmann (1954) classified it as a migmitite, based on its contorted foliations. Forms distinctive areas of pavement outcrop in the northern part of Rockdale County.	Massive to finely laminated; characteristically swirled and sheared. Numerous aplite and pegmatite dikes intrude this unit. Fracture types include zones of steeply-dipping joints (rare to common) and sheet fractures (common).	Weathering produces a thin saprolite that typically is a light whitish-yellow sandy soil. The saprolite is reddish brown in areas of higher biotite concentrations. Rock exposures form pavement outcrops in small isolated patches or large exposed surfaces up to several acres in extent.
porphyroblastic biotite gneiss (biotite gneiss, sillimanite-quartz schist, muscovite-biotite schist, quartzite, and amphibolite gneiss)	Light gray to whitish gray, medium- to coarse-grained, porphyroblastic muscovite-biotite-quartz-feldspar gneiss with layers, lenses, and pods of fine-grained biotite gneiss, sillimanite-quartz schist, muscovite-biotite schist, quartzite, and amphibolite gneiss.	Massive to thinly layered. Hard to determine folding and structural dip of rock layers because of deep weathering. Structures include composi-tional layering, foliation, small- to large-scale folds, and steeply-dipping joints.	Weathering produces a brownish-red clayey saprolite. Muscovite and weathered biotite (vermiculite) abundant. Differential weathering occurs between biotite gneiss and more resistant layers of amphibolite and sillimanite-quartz schist.
Panola Granite (granite)	Light-gray to whitish-gray medium-grained muscovite-biotite-feldspar-quartz granite. Forms a large dome-shaped granite monadnock in the southwestern part of Rockdale County.	Massive. Numerous aplite and pegmatite dikes intrude this unit. Fracture types include steeply-dipping joints (rare), and sheet fractures (common).	Weathering produces a thin light whitish-yellow sandy saprolite. Shallow weathering and pavement outcrops over much of the outcrop area.
garnet-mica schist (garnet mica schist, fine-grained biotite gneiss, and amphibolite gneiss)	Gray to grayish brown to dark gray, fine to medium grained, biotite-rich gneiss, and garnet mica schist with fairly common layers, lenses, and pods of hornblende-plagioclase amphibolite.	Schist, biotite gneiss, and amphibolite gneiss are in distinct small bands and layers. Structures include composi-tional layering, foliation, small- to large-scale folds and steeply-dipping joints.	Weathering produces a fairly uniform, slightly micaceous, dark-red saprolite and clayey dark-red soil, except where thin resistant layers of amphibolite occur; weathered biotite (vermiculite) abundant.
muscovite quartzite (muscovite schist, quartzite)	Light-gray to brownish-gray muscovite quartzite and muscovite schist. Persistent ridge-forming character makes this unit a good marker horizon for mapping. A persistent ridge of quartzite outcrops in the southwest portion of Rockdale County.	Discontinuous due to tectonic thinning or faulting along thrust contacts. Structures include compositional layers, foliation, steeply-dipping joints, and small- to large-scale folding.	Weathering produces a micaceous saprolite that has varying colors from light whitish yellow to purplish red to dark red. Depth of weathering appears to be shallow.
amphibolite gneiss (amphibolite and hornblende gneisses with layers of biotite gneiss and biotite schist)	Dark green to greenish black, ocher-weathering, generally pyrite-bearing, generally epidotic, hornblende-plagioclase, and plagioclase-hornblende amphibolites. Forms a distinctive large mass in the northeastern part of Rockdale County.	Massive to finely layered, locally laminated. Structures include compositional layers, foliation, small- to large-scale folds, and steeply-dipping joints.	Weathering produces a distinctive, ocherous yellowish-brown to reddish-brown to dark-red clayey saprolite. Differential weathering occurs between resistant amphibolite and less resistant biotite gneiss layers.
pegmatite dikes (pegmatite)	Coarse-grained muscovite-quartz-feldspar pegmatite, mostly forming discordant veins and dikes. Typically range in width from a few inches to several feet across. With exception of one large mass, about 500 feet across, none are large enough to map.	Intrudes all rock units. Dikes generally are discordant to the regional structure, but a few are injected parallel to layering.	Weathering produces a distinctive weathering product consisting of large weathered feldspar crystals, quartz float and large muscovite flakes. Irregular masses most common.
aplite dikes (aplite)	White to tan, very fine-grained igneous rock consisting of muscovite, quartz, and feldspar.	Intrudes all rock units. Exten-sively intrudes the Lithonia Gneiss creating migmititic and contorted banding.	No distinctive weathering product where it intrudes light-colored granite and granite gneisses. Forms irregular, white clayey saprolite in bands and layers elsewhere.
diabase dikes (diabase)	Fine- to medium-grained, dark gray to black plagioclase-augite diabase. Diabase forms dikes generally 10- to 30-feet wide. Most dikes are mapped on the basis of residual boulders.	Northwest-trending dikes cross-cutting all other lithologies. Orientation is similar to diabase dikes mapped by Herrmann (1954) in the Stone Mountain-Lithonia District and Lester and Allen (1950) elsewhere.	Weathering of the dikes forms a dark reddish- to yellowish-brown ocherous clay. Distinctive nodular masses of diabase “float” is used for identifi-cation. When broken, weathered nodular masses have fresh rock inside a yellowish-brown ocherous rind.

GROUND-WATER RESOURCES

Ground water occupying voids and fractures in the underlying bedrock and filling the pore spaces in the regolith forms an aquifer suitable for drinking-water use in most parts of Rockdale County. Ground water is used as a source of water for individual households, trailer parks, and some small subdivisions—mostly in areas outside of the large countywide municipal water system. Ground water also is used as a supply of water for irrigation at some of the golf courses and athletic fields in the area, and for light industry. In the past, ground water was used heavily to supplement the municipal water systems in the cities of Conyers and Milstead.

Currently (2003), few ground-water resources have been developed outside of Conyers and Milstead. The main use of ground water is for domestic supply; however, these wells are widely dispersed in most parts of the county and do not constitute large withdrawals from the aquifer. If developed, ground water from the crystalline-bedrock aquifer potentially could be used to supplement municipal systems, as was done in the past, or could be used to supply water for light industry. A fairly large source of water is thought to be available based on the presence of many high-yielding wells in the county—at least 27 of which have a reported yield of 70 gallons per minute (gal/min) or greater. Other parts of Rockdale County are distinctly low yielding—and wells would not likely sustain large yields. Development of large water supplies in the county is dependent on rock type, structure, and other geologic controls affecting the occurrence and availability of water.

Ground-Water Occurrence

Ground water occupies pore spaces in the regolith and irregularly distributed, highly localized, and discontinuous water-bearing fractures in the underlying bedrock. Recharge to the aquifer occurs when rainfall that is not lost to evaporation, transpiration, and runoff, infiltrates downward into the zone of saturation. Infiltration, or recharge, is the amount of water that seeps down into the regolith or directly into joints, fractures, and other weathered openings in the bedrock. A rise in the water table reflects increased water storage, whereas a lowering of the water table reflects decreased water storage. During long periods of time, the amount of water recharging the aquifer is generally equal to the amount of water discharging to streams, lakes, springs, and wells.

In nonlayered massive rocks, ground water occurs in the overlying mantle of regolith and in voids and fractures of the underlying bedrock (fig. 3). Shallow regolith wells are best located in low-lying areas where water tends to accumulate on top of the bedrock surface. Drilled wells penetrating nonlayered massive bedrock intercept water-bearing fractures—the most common type being sheeting fractures (stress-relief fractures)—formed roughly parallel to the land surface. Stress-relief fractures are caused by the upward expansion of the bedrock in response to erosional unloading (Cressler and others, 1983). Numerous high angle joints that connect upward with the saturated zone commonly intersect these subhorizontal stress-relief fractures; consequently, stress-relief fractures may supply moderate to large amounts of water when tapped by wells.

Approximately perpendicular to the stress-relief fractures are sets of subparallel steeply-dipping joints, which are locally well-developed in outcrops and quarries in the area. Streams flowing across these zones commonly are aligned with the joint trend, resulting in a rectilinear drainage pattern that can be easily identified on topographic maps and aerial photographs of the area. Steeply-dipping joints provide an avenue to transmit water from the overlying regolith into deeper bedrock fractures.

In layered rocks, ground-water movement is largely controlled by voids and fractures parallel to contacts between layers and between lithologic units of contrasting lithologic character (fig. 4). Fractures and voids parallel to contacts of layers result from stress-relief and extensive differential weathering along layering and other structural weaknesses in the bedrock (Williams, 2003). Higher well yields can be expected where wells penetrate layers that intersect sources of recharge, such as high-angle fractures, surface-water bodies, and the regolith. Drilled well B shown on the left side of figure 4 would likely have less ground-water potential and lower yield than drilled well A shown on the right side of figure 4, which is positioned favorably to intercept recharge. Also, the regional orientation trends of layering may influence yield; if the rocks are gently dipping then fractures formed along layering will be more laterally extensive, receive recharge from larger areas, and likely be higher yielding than those in steeply-dipping rocks.

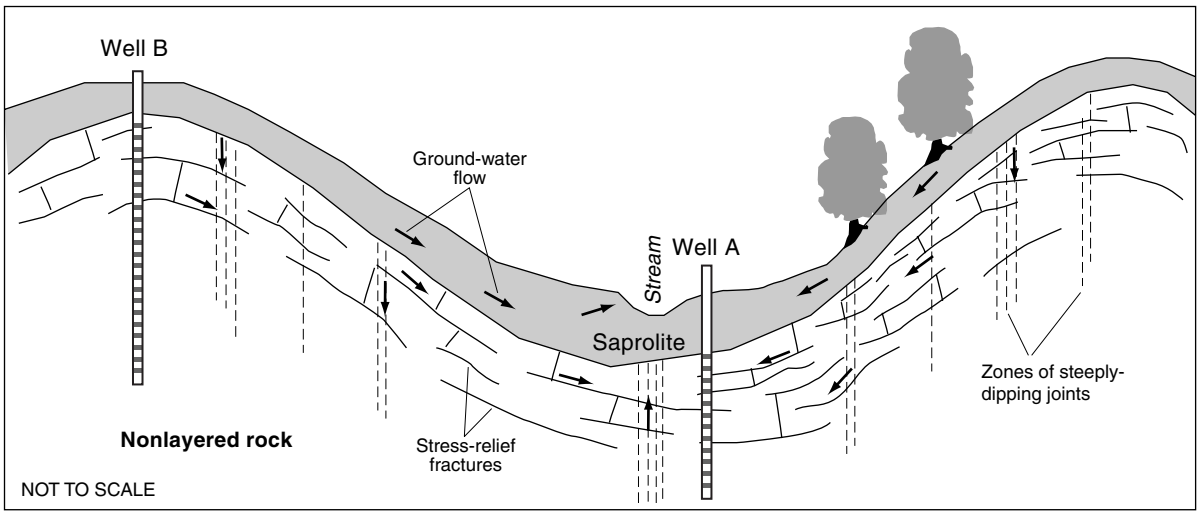


Figure 3. Relative positions of wells tapping nonlayered rock. **Well A** in a topographically favorable position for intercepting recharge; **well B** in a topographically less favorable position (modified from McCollum, 1966).

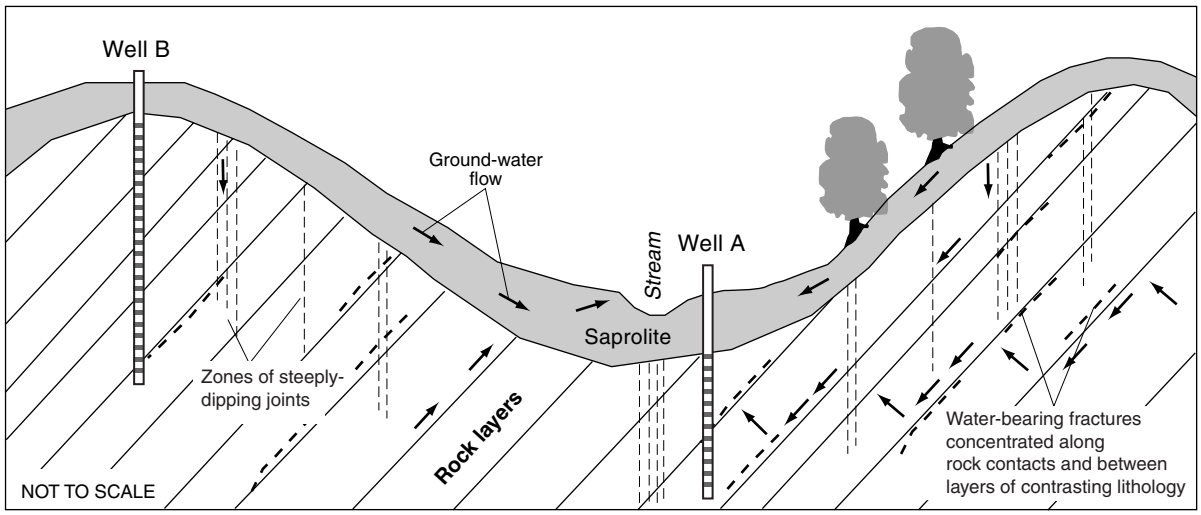


Figure 4. Relative positions of wells tapping moderately-dipping layered rock. **Well A** in a topographically favorable position for intercepting recharge; **well B** in a topographically less favorable position (modified from McCollum, 1966).

Ground-Water Availability

Ground water is available from dug and bored wells, or from deeper drilled wells in virtually all but a few isolated areas[1] of the county. Dug and bored wells, which are shallow wells open to the regolith, typically range in yield from about 1 to 28 gal/min. Dug and bored wells provide a dependable source of water in places where the well is deep enough to accommodate normal seasonal fluctuations in the water table. During severe drought, dug and bored wells may go dry when the water table falls below the bottom of the well.

Drilled wells in Rockdale County range in yield from less than about 1 to 350 gal/min. Drilled wells provide a more dependable source of water than dug and bored wells because drilled wells typically have greater well-bore storage and derive water from deep bedrock fractures, which are less susceptible to water-table fluctuations. Also, springs in Rockdale County, which are most abundant in the northern part of the county, provide an additional source of water to residents. Yields of springs vary from several gallons per minute up to 30 gal/min (McCollum, 1966).

Large yields needed for municipal and industrial supply are available only in zones of increased bedrock permeability, which occur in association with (1) contact zones between rocks of contrasting lithologic character and within multilayered rocks, (2) fault zones, (3) stress-relief (subhorizontal sheeting) fractures, (4) zones of fracture concentration, (5) small-scale geologic structures that localize drainage development, (6) folds that form concentrated jointing, and (7) shear zones (Cressler, and others, 1983). One area of high yield is in central Rockdale County along Interstate 20 in the Conyers area (fig. 1), where high-yielding wells penetrate the Lithonia Gneiss and garnet-mica schist rock units (fig. 2). Productive fractures in two Conyers area wells appear to occur along bedrock layering and at contact zones between the garnet-mica schist and the granite gneiss units (Khallouf and Williams, 2003[1]). Other high-yielding wells are in areas of southern Rockdale County, presumably tapping into water-bearing zones in layered rocks (based on the geologic map of McCollum, 1966).

Municipal Supply Wells

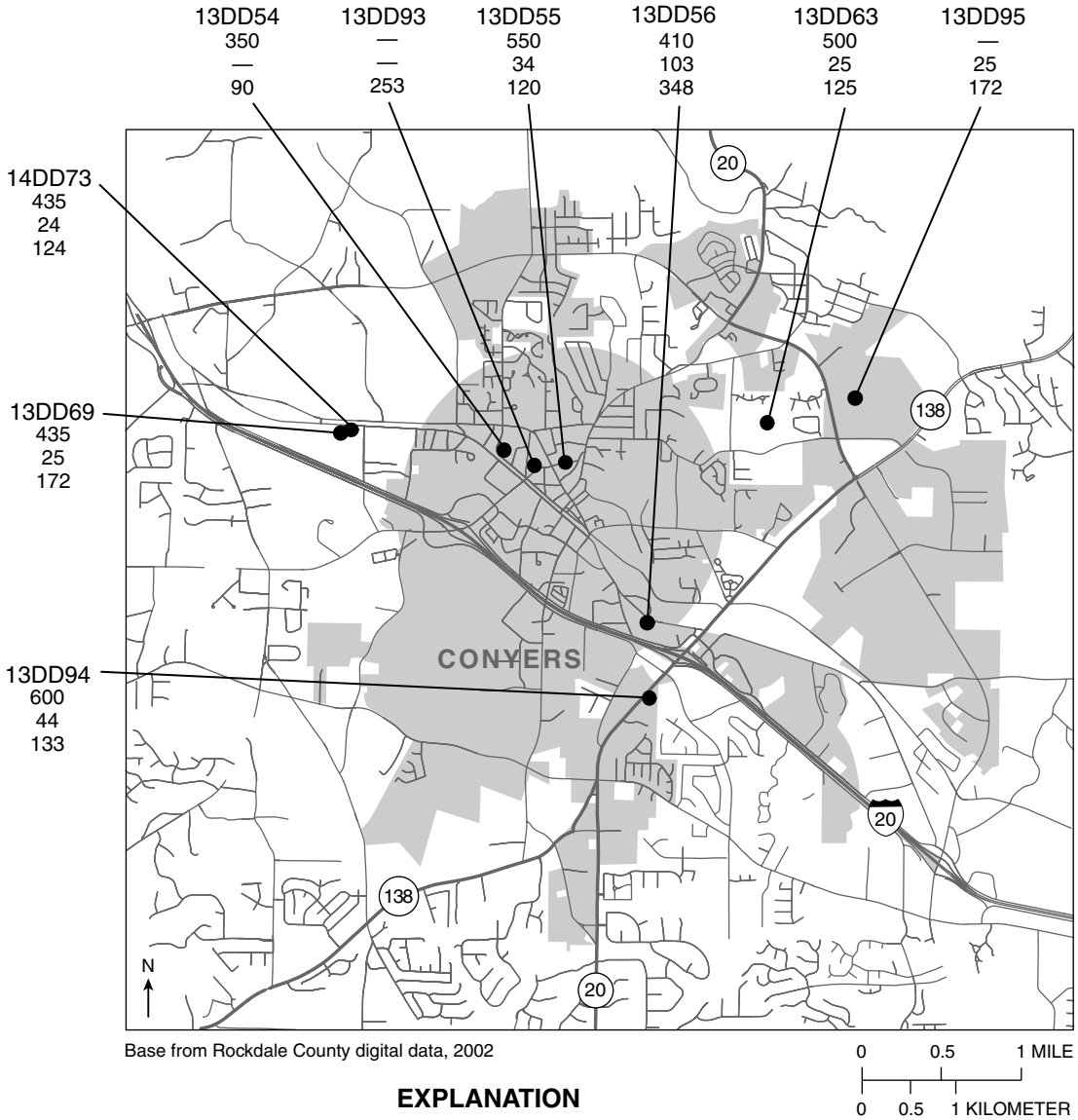
In the 1940s, Herrick and LeGrand (1949) reported that the Conyers water system was supplied by two wells, each in excess of 300-feet deep. When continuously pumped, one well (13DD55) yielded 110 gal/min and the other 45 gal/min (13DD54). The more productive of the two wells, near the center of town (13DD55 on fig. 5), reportedly yielded more than 100,000 gallons per day (gal/day) for 11 years, making it one of the most productive wells in the Atlanta area at that time (Cressler and others, 1983).

The Milstead system was supplied by two deep wells and one spring, producing a combined yield of 100 gal/min (Herrick and LeGrand, 1949). One Milstead well, which was on a hilltop of exposed Lithonia Gneiss, had a yield of 20 gal/min. The other well, with a yield of 60 gal/min, was near a spring on a lowland slope.

Municipal wells continued to be used to supplement the city/county water system until 1985. When the wells were taken offline in 1985, the Conyers well system was producing 290,000 gal/day with a peak use of 469,000 gal/day, according to ground-water use reports on file at the Georgia Environmental Protection Division office in Atlanta.

The long-term sustained pumping from the cities of Conyers and Milstead municipal wells indicates that a large supply of water is available in those parts of Rockdale County. Cressler and others (1983) reported that some of the wells had been in continuous use from 12 to more than 30 years. Wells 13DD56 and 13DD63 had been in continuous use for 12 to 20 years, and wells 13DD54 and 13DD55 had been pumped for more than 30 years (fig. 5).

1. Khallouf and Williams, 2003, redefine the “garnet mica schist” to “biotite gneiss” based on the dominance of biotite gneiss in this unit identified while mapping during 2002.



EXPLANATION

13DD94 ●	WELL AND IDENTIFICATION NUMBER
600	Well depth, in feet (—, not reported)
44	Casing depth, in feet (—, not reported)
133	Yield, in gallons per minute

Figure 5. Municipal wells in the Conyers area, Rockdale County, Georgia.

ONGOING STUDIES

The USGS, in cooperation with Rockdale County, is conducting a ground-water resource investigation to better define the ground-water resources and water quality in crystalline rocks. The investigation is being conducted in two phases. Phase 1, which was conducted between April 2001 and September 2002, focused on conducting (1) well surveys to determine the locations of high-yielding wells in the area, (2) detailed geologic mapping in smaller subareas around well sites of interest, (3) geophysical logging, and (4) water-quality sampling. Phase 2, which currently is under way, focuses on more detailed evaluations of the hydrogeology in Rockdale County. This phase includes expanded geologic mapping throughout the county, borehole geophysical logging, ground-water-level monitoring, test-well construction, and flow-meter surveys. To date (2003), the investigation has produced several findings that are helping to better define geologic controls influencing high well yields in the Conyers area. Additional work currently is being done in the low-yielding areas in the northern part of the county and in high-yielding areas in the southern part of the county to identify specific geologic controls affecting the occurrence and availability of ground water.

As part of a separate study in Rockdale County, the USGS is operating a streamflow-gage network. Data from the streamflow-gage network are being incorporated into the ground-water resource investigation to develop better estimates of baseflow contributions to streams, and to better understand how baseflow relates to recharge to the crystalline-bedrock aquifer.

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Ground-Water Exploration and Development in Igneous and Metamorphic Rocks of the Southern Piedmont/Blue Ridge

by Thomas J. Crawford[1] and Randy L. Kath[2]

INTRODUCTION

Concepts of ground-water movement in igneous and metamorphic rocks in areas with a subtropical climate, such as that of the southeastern United States, have evolved over many decades. However, because of the dearth of research directed toward an understanding of the variables involved, much of the data set concerning the hydrogeology of igneous and metamorphic rocks is empirical data generated by ground-water exploration and development. Some of the concepts derived from these empirical observations and from limited applied research, have been presented and discussed in various papers dealing with the hydrogeology of igneous and metamorphic rocks in the southern Piedmont/Blue Ridge.

Igneous and metamorphic rocks have, in many places, very diverse properties that change over short distances both vertically and horizontally. Our experience during the last 35 years indicates that, because of this, ground-water movement is often most influenced by the *relative properties* of various rock units or discontinuities rather than by *absolute properties* of a particular rock unit or discontinuity. This relationship greatly complicates attempts to understand the hydrogeology of igneous and metamorphic rocks and emphasizes the need for a strong and broad data base where it is desirable to make predictions concerning ground water. This paper discusses some of the major controls of ground-water occurrences in igneous and metamorphic rocks. Determining and evaluating these controls on a site-specific basis greatly enhances the probability of successful ground-water exploration, development, and management.

MAJOR CONTROLS OF GROUND-WATER MOVEMENT IN IGNEOUS AND METAMORPHIC ROCKS

Rock Type

As in any study of shallow subsurface earth processes, the study of ground water in igneous and metamorphic rocks demands knowledge of the rock types involved. Metamorphic rocks and intrusive igneous rocks have very little primary porosity or permeability. Secondary porosity and permeability develop as these rocks are subjected to tectonic stresses and weathering stresses.

Because different rock types will react differently to the same stresses, it is important in any study area to determine: the areal distribution of each rock type; projections of these into the shallow subsurface; the major minerals, and general compositional percentages; grain size distribution; and the texture. Each of these has a direct bearing on the rock's reaction to tectonic stress, physical weathering stress, and chemical weathering stress.

The areal distribution of rock types and the variations within a single rock type are critical. Often the difference between adjacent rock units has more influence on ground water than the characteristics of either individual rock unit. There is perhaps no rock type that is totally devoid of large-yield wells, with good water quality. There are, however, rock types which are "more likely" or "less likely" to have positive values in the variables. This allows some predictability concerning well yield and water quality, and is of utmost importance in exploration and development.

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Discontinuities

A "discontinuity," as the term is used here, refers to any feature that interrupts the homogeneity of the rock. In igneous and metamorphic rocks, the most common discontinuities are: compositional layering, foliation, joints, faults, and irregular random fractures (fig. 1). Of these, only compositional layering and foliation can be primary features; they may also be secondary, as are all the others. Regardless of their origin, once formed, all of these discontinuities have the potential to enhance the porosity and permeability of the rock, providing storage and pathways for movement of ground water.

Each discontinuity is a plane of "different" strength/weakness in relation to the boundaries of the interface. As such, it will react differently to stress, whether tectonic or nontectonic. Weathering, either chemical or physical, will proceed along the discontinuities at a rate different than that outside the discontinuities. A determination of the presence of discontinuities, and an understanding of their nature, size, abundance, structural attitude, degree to which they are interconnected, and areal distribution are critical to a study of ground water in any area of igneous or metamorphic rocks.

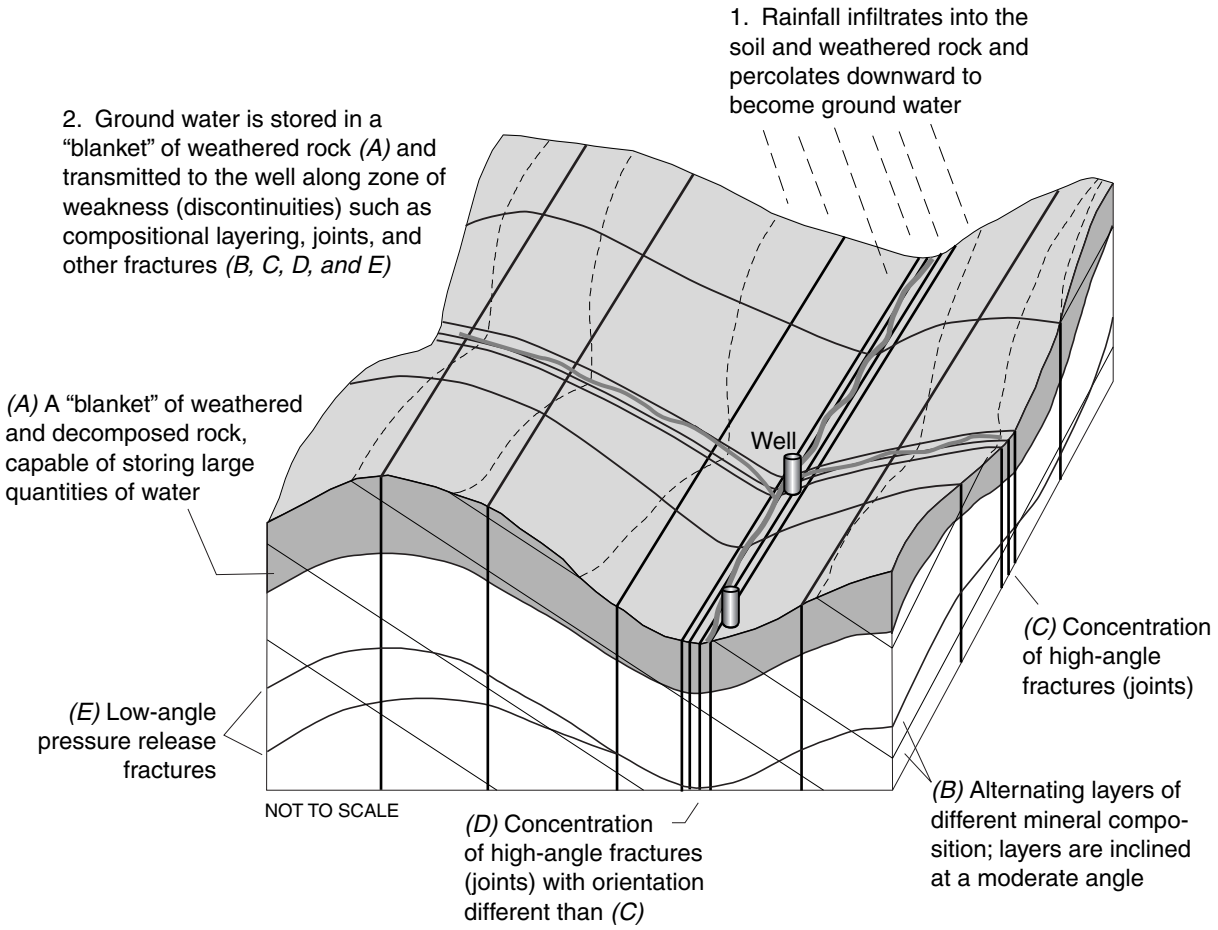

Figure 1. Hydrogeologic features in igneous and metamorphic rocks of the southeastern Piedmont/BlueRidge.

Much of the work related to hydrogeology of igneous and metamorphic rocks is categorized as "hydrogeology of fractured rock." Certainly fractures are important, but not all-important; and we are not implying that research and application referred to as "fracture hydrogeology" ignores all other discontinuities. However, from reading the literature and seeing the practice, we do believe that the emphasis on "fractures" to the virtual exclusion of consideration of other discontinuities and other variables has hampered development of a fuller understanding of the "hydrogeology of igneous and metamorphic rocks." Equal emphasis should be placed on all discontinuities and all variables, and the relationship of each to the others (fig. 1).

Topography

Topography is a major factor in determining the percentage of precipitation runoff, and its direction and velocity. As such, it exerts a major influence on infiltration and consequent chemical and physical weathering. Just as basically and by the same token, topography exerts control on ground-water recharge.

Topography is greatly influenced by rock type and discontinuities. The *relative* resistance to physical and chemical weathering is a major control. Consequently, the juxtaposition of rock units of greatly contrasting physical and chemical properties can offer good ground-water exploration targets. Linear discontinuities along such contacts are often enhanced by joint sets and faults which may have a pronounced influence on development of topographic features.

For large-yield wells, sustainability of production is always a concern. Topography is a major factor in predicting recharge potential; 3rd order, or greater stream valleys are desirable for large sustainable yields. There are many notable exceptions to this, but where the exceptions will occur is not predictable.

Depth of Weathering

Weathering generally increases the porosity and permeability of igneous and metamorphic rocks. However, some processes taking place in this zone, such as the growth of clay minerals, mineral deposition in fractures, and development of iron oxide "hardpan," can significantly decrease the permeability of the weathered zone.

At the interface between unweathered rock and weathered rock, there is commonly a "transition zone" where chemical weathering has changed the chemistry and created open spaces but not yet destroyed the rock's texture. This weathered rock, referred to as "saprolite," is generally more permeable than the overlying residuum, and in some places is more permeable than the underlying fresh rock and serves to concentrate ground water along a tabular zone of enhanced permeability. A thick (several 10's of feet) soil weathered zone above the saprolite will store ground water and allow it to move into the saprolite and fresh rock on a continuous basis; provided it can be recharged, and permeability has not been too severely limited by the growth and concentration of clay minerals.

A soil/weathered rock/saprolite thickness of approximately 30 to 60 feet seems optimum for successful ground-water development. Less thickness seems to inhibit infiltration and storage of water; greater thickness (greater than 150 to 200 feet in many instances) seems to inhibit movement of water into the more permeable fresh rock, where it can be recovered.

Here, too, there are notable exceptions: large-yield wells where fresh rock is at or very near the surface; and large-yield wells where soil/weathered rock/saprolite has a thickness in excess of 200 feet. Regardless of the choices, and other variables being equal, moderate thicknesses are preferred.

Because the rate of weathering is so strongly influenced by mineralogy and texture, topographic position may be misleading. In many instances, rocks in the lower part of a drainage basin may form "pavement" exposures unsuitable for drilling; while different rock types topographically higher in the same basin may show great potential.

Nature and Extent of the Recharge Area

The amount and rate of recharge at any given point (well) is, of course, a function of the nature and extent of the recharge area. The nature of the recharge area is evaluated in the manner already discussed by determining the rock types and discontinuities, and relating these to topography and depth of weathering.

Alluvial and colluvial material in the recharge area will have characteristics different from residual material and saprolite, and need to be evaluated differently. Grain size and sorting of the alluvium will have major influence on ground-water movement; as will the nature of the underlying material and the topography of the interface between the alluvium and the underlying material. Clay layers and iron-oxide hardpan in particular will be major impediments to water movement through the alluvium.

ENHANCING PERMEABILITY OF METAMORPHIC AND INTRUSIVE IGNEOUS ROCKS

The tectonic stresses which create fractures in metamorphic and intrusive igneous rocks are a major factor in developing secondary porosity/permeability, which enhances ground-water movement. A second factor in permeability enhancement is compositional layering. Where it is well developed, compositional layering forms zones of weakness which react to both physical and chemical stress, enhancing ground-water movement.

A third factor in porosity/permeability enhancement, which may be critical in creating the setting for many high-yield wells, is the nontectonic process of unloading. With compositional layering and fracture networks already in place, unloading through erosional development of broad valleys could be the "stress release" which causes opening of the fracture system, further weakens the compositional layering planes, and allows ground water to move more freely and to greater depths. As these processes continue they feed on their own success.

The "stress release" envisioned here is not a release of "built-in" stress such as might be associated with deep-seated igneous plutons. Rather, it is more comparable to a "bulge," where rock expands upward and outward due to removal of overlying rocks in restricted geographic areas such as broad valleys, causing opening of previously developed discontinuities such as compositional layering and tectonically induced joints and random fractures.

Joints and Random Fractures

Rocks may react to stress by breaking. Where these breaks are planar or curvi-planar and no movement has occurred parallel to the fracture surface, they are called joints. Numerous parallel breaks in any given area are referred to as a joint set. In much of the southern Piedmont/Blue Ridge, rocks contain two dominant joint sets, and in many areas there are several subsidiary joint sets.

Joints enhance the permeability of rocks a little or a lot, depending on: the roughness of the joint surface; the spacing; the width of the openings (dilation); the nature of any infilling; the degree to which they are through-going; and the degree to which they are interconnected.

Joints should be described and measured throughout a study area, and used in helping evaluate potential for ground-water movement in each lithologic unit. Different rock types react differently even when subjected to the same stresses. This has a direct influence on the ground-water storage and transfer capabilities of the various lithologic units.

Random fractures, those with no discernible pattern, can be abundant. These can exert considerable influence on ground water but, because of their randomness, are not as useful in evaluating ground-water resources.

Faults

Igneous and metamorphic rocks in the Piedmont/Blue Ridge have been extensively faulted. There are faults coincident with lithologic contacts, faults which cut across lithologic units, and faults within single mappable units.

The major criteria for faulting in the southern Piedmont/Blue Ridge are: discontinuity of lithologic units; omission or repetition of lithologic units in a sequence; and the presence of shear textures, mylonite, or breccia. In many cases the size of the area mapped for a particular study does not allow a valid application of this approach to determine whether any given lithologic contact is also a fault contact.

However, such a determination is of little, if any, value to the purpose of most hydrogeologic studies. If there is no evidence of brittle fault deformation along lithologic contacts in a given study area, the most important determination hydrogeologically is differences in the mineralogy and texture of adjacent rock units.

Most of the faults in the southern Piedmont/Blue Ridge occurred at great depths, under high confining pressures and elevated temperatures. Consequently, brittle deformation was minimal and/or was healed during the tectonic processes, and produced little, if any, increase in porosity or permeability.

Many geologic maps show some lithologic contacts as faults. This does not mean that deformation associated with faulting has enhanced permeability along that contact. The faulting may have, in fact, decreased permeability of the rock. For example, shearing and mylonitization reduce particle size, and are often accompanied by silicification; both tend to decrease permeability. The value of such a fault from a ground-water perspective would be in whether or not it juxtaposed lithologic units with great differences in lithology and/or texture.

Lithologic Contacts

Lithologic contacts can exert considerable influence on ground-water movement. The magnitude of the influence is directly related to the differences in the units which are juxtaposed, and the structural attitude of these units. Where similar lithologic units are in contact, the contact zone has little influence. Many mappable units have greater internal differences in lithology and texture than the differences across contacts. In such cases, the contact zone would not enhance ground-water movement.

Compositional Layering and Foliation

Most rocks of the southern Piedmont/Blue Ridge are compositionally layered and foliated, although the degree of development of these features varies greatly. More often than not, compositional layering and foliation are parallel, but this must be determined on a site-specific basis. Structural attitude of these planar features varies from vertical to horizontal, with moderate angles of inclination being most common.

Areas underlain by rocks with horizontal or low-angle lithologic units, compositional layering, and foliation generally show considerable potential for ground water. Areas where the same features are steeply dipping or vertical show less promise.
The discontinuities defined as compositional layering and foliation can be extremely important in ground-water studies. They define planes and zones of weakness which serve as preferred pathways in a primary sense; and they are further weakened by weathering processes associated with ground-water movement. Additionally, they guide partings resulting from "unloading" stress release.

Where there are great differences in the mineralogy and texture of compositionally layered rocks, differential weathering along this discontinuity may give compositional layering a stronger influence on ground water than that of joints. A well-developed foliation parallel to compositional layering enhances the influence of layering. Too often, these discontinuities have been ignored in studies of the hydrogeology of "fractured" rock.

GROUND-WATER RESOURCES OF THE PIEDMONT/BLUE RIDGE—REVIEW AND CONSIDERATIONS

The ground-water potential of the igneous and metamorphic rocks of the Piedmont/Blue Ridge is tremendous. However, in the southeast this source of water has historically been either ignored or grossly underrated. There are exceptions, but for the most part hydrogeological consideration of these rocks was, until recently, cursory, local, and half-hearted. There is some justification for this; for hydrogeology cannot be adequately assessed until the geology is understood—and in the Piedmont/Blue Ridge it is only recently that we have had results from long-term geologic studies and detailed analyses of regional areas sufficient for a general understanding of ground-water conditions.

Even now, very little of the Piedmont/Blue Ridge has published geologic maps of sufficient accuracy and detail that they can be used for water-well siting without on-site geologic mapping. All geologic mapping is extremely slow and site studies are very time-consuming, particularly if the geologist is not acquainted with the local stratigraphy. Further, after the geologic mapping is accomplished, there are still many other on-site observations to be made which are essential for proper evaluation of ground-water potential and/or selection of drilling sites.

Most of the water wells drilled in the southern Piedmont/Blue Ridge have been drilled at sites selected on the basis of four criteria:

1. It's convenient to get the rig in,
2. It won't cost anything (much) to prepare the site,
3. It's close to where the water is needed, and
4. It's close to a source of power.

Even with these bases, which have no bearing on the amount of water likely to be encountered in a drilled hole, there have been many adequate wells completed. This fact should be reason enough to pursue an understanding of ground water in metamorphic and igneous rocks with a goal of obtaining a higher water yield per dollar spent in exploration and development.

Whereas surface water is "seeable" and "measurable," drilling a hole in the ground is considered "risky." It took several drought years in succession, and then a gradual realization that even in "normal" times surface water supplies will not be able to meet the growing water demands of an expanding and more demanding population—and now, suddenly we are trying to catch up on the concepts and understanding of metamorphic and igneous rock geology, hydrogeology and hydrology; which we must have in order to successfully explore for, produce, and properly manage this considerable, extensive, and extremely valuable natural resource.

We have enough information now to understand that ground-water movement and ground-water production in igneous and metamorphic rocks are controlled largely by six factors: (1) rock type(s), which includes all inherent characteristics of the rock, but primarily mineral composition and texture; (2) discontinuities resulting from compositional differences, joints, random fractures, and/or faults; (3) topography; (4) depth of weathering (5) area of recharge; and (6) spatial relationships of rock types and discontinuities to each other, and to topography, depth of weathering, and area of recharge.

Precise siting of wells in relation to these six factors is critical if water needs are to be satisfied and, particularly, satisfied at the least possible cost. The need may be a home owner who requires 3,000 gallons of water a day; a small town, industry, office complex, or housing development needing 300,000 gallons of water a day; or a larger town, county, or industry requiring 3,000,000 gallons a day. For the individuals involved, each quantity is important. Because it is possible to have extreme differences in the amount of property available for exploration, the small water demand often requires just as much precision and effort in well siting as does the large.

Ground-water potential of the Piedmont/Blue Ridge is tremendous and very much under-utilized. Employing careful and precise exploration and development methods described in this paper has proven to be a cost-effective means for developing ground-water supplies in the southeastern Piedmont/Blue Ridge. These methods have substantially improved the ability to develop large supplies needed for business, industrial, and municipal supply, far beyond what is generally thought possible.

SUMMARY AND RECOMMENDATION

Exploration for, and development of, ground water in deformed igneous and metamorphic rocks in a region with a subtropical environment has been little studied; and it is little understood. Much of the funded research and many of the recent and current studies in this regard seem to focus on the physics of ground-water movement in fractured rock. During the last several decades these studies have been driven by environmental containment and remediation problems and concerns. For this, the objectives and goals are quite different from that required for exploration and development of water as a resource, where the quantity, quality, and sustainability of the resource are all of utmost importance.

Thirty-five years of exploration and development of ground-water resources in igneous and metamorphic rocks of the Southern Piedmont/Blue Ridge has convinced us that, among the many factors that influence water in these rocks, the single most important factor is ***rock type***. Rock type directly influences all other factors. Without knowing the detailed geology of an area/site, all other factors influencing ground water lack a full and meaningful context.

For success in ground-water exploration and development in igneous and metamorphic rocks, more than an understanding of the physical parameters controlling ground-water movement is necessary. The interrelationships, both inherent and spatial, of rock type, structure, type and depth of weathering, and topography must be known and understood.

Many Hydrologists/Geologists/Hydrogeologists making decisions on ground-water exploration and development—and writing laws/rules/guidelines regulating such—lack either the ability or time, or both, to geologically map the areas of concern. It is critical that influential organizations such as the American Institute of Hydrology lobby for and support 1:24,000-scale geologic mapping by organizations such as the U.S. Geological Survey and State Geological Surveys. Though rarely of sufficient detail for determination of water well drilling locations, such maps serve as an excellent beginning for more detailed study and analysis.

Hydraulic Logging Methods – A Summary and Field Demonstration in Conyers, Rockdale County, Georgia

by Carole D. Johnson and John H. Williams
USGS, Office of Ground Water, Branch of Geophysics

INTRODUCTION

Geophysical surveying techniques provide important information for ground-water investigations (Zohdy and others, 1974; Keys, 1997; Haeni and others, 2001). Subsurface-geophysical methods are used to delineate and characterize hydraulically active zones; the extent of contamination, and contaminant sources; identify geologic features; optimize monitoring well placement; and guide remediation efforts. Borehole-geophysical methods provide information about the physical, chemical, and hydraulic properties of rock, sediments, and fluids in the subsurface and provide important information on subsurface bedrock structures including lithology, rock fabric, location, orientation, and hydraulic properties of fractures (Keys, 1990).

Effective use of geophysical data requires that the data be interpreted in the context of known local and regional geology and hydrogeology. In addition, because of the complexity and heterogeneity of crystalline-rock aquifers, a suite of borehole-geophysical methods is used to determine the location, extent, and nature of fractures and other structural features in the bedrock aquifer. The geophysical data from each borehole and method are analyzed together to provide an integrated interpretation, thereby reducing the ambiguity that can occur by interpreting each geophysical log individually (Shapiro and others, 1999).

Previous work using borehole geophysics to characterize ground-water availability in crystalline-rock aquifers includes Chapman and Lane (1996), Mack and others (1998), and Johnson and others (1999). Other investigations that focused on contamination in fractured-rock aquifers used geophysical methods to relate highly transmissive features to structural features in the bedrock (Hansen and Lane, 1995; and Lane and others, 2002).

REVIEW OF LOGGING METHODS

Improvements in technology, portable computers, and data collection software have increased the potential for rapid, noninvasive, and cost-effective subsurface characterization through the application of geophysical methods. The logging methods demonstrated on this field trip are used to collect data on subsurface characteristics and properties, which are acquired with a personal computer, computer-driven software, a portable winch, and selected geophysical tools (fig. 1). The logging methods reviewed in this field trip include caliper, single-point resistance, normal and lateral resistivity, electromagnetic induction, fluid resistivity, fluid temperature, flowmeter under ambient and stressed conditions, camera and acoustic televiewer, and deviation. Information about these methods is summarized in table 1.

Caliper logging is used to generate a continuous profile of the borehole diameter measured in units of length with depth. The caliper tool is pulled up the borehole, allowing three spring-loaded arms to open or close as they pass borehole enlargements, or restrictions (Keys, 1990). Changes in the borehole diameter generally are related to fractures but also can be caused by changes in lithology or borehole construction or integrity. Fracture openings in the bedrock are easily distinguished from the changes that correspond to borehole enlargements as shown in the caliper log obtained from a crystalline-bedrock well in Lawrenceville, Gwinnett County, Georgia (fig. 2). The log can be collected relatively quickly and is one of the least expensive tools to run, process, and interpret data.

Single-point resistance logging measures the electrical resistance between a surface electrode (or mudfish) and an electrode in the down-hole probe. The measurement, which is highly influenced by

Table 1. Summary of selected geophysical logging methods

[Relative cost: 1–3 inexpensive to expensive; time: 1–3 fast to slow; relative difficulty: 1–3 easy to difficult]

Method	Purpose	Property measured	Cost	Time	Difficulty
Caliper	Generate continuous profile of borehole diameter	Borehole diameter	1	1	1
Single-point resistance	Delineate changes in lithology, porosity, and (or) clay content of surrounding formation or changes in porosity and total dissolved solids in the formation water	Resistance of formation, fluids in formation, and borehole fluids	1	1	1
Normal resistivity	Determine changes in resistivity of the fluids in the formation and (or) lithology	Resistivity of the formation; with additional data, true resistivity can be calculated	1	1	1
Electromagnetic induction	Delineate changes in rock type or in electrical properties of fluids in the rock formation; corroborate surface resistivity surveys	Bulk apparent conductivity of the formation and pore fluids surrounding the borehole	1	2	2
Fluid resistivity	Identify differences in concentration of total dissolved solids in borehole fluid; these differences typically indicate sources of water that have come from different transmissive zones	Electrical resistivity of borehole fluid, from which specific conductance is calculated	1	1	1
Fluid temperature	Identify where water enters or exits the borehole	Temperature of borehole fluid; differential temperature (rate of change of the temperature) is calculated	1	1	1
Heat-pulse, electromagnetic, and spinner flowmeter	Map fluid flow regime and transmissive fractures in the borehole	Direction and magnitude of vertical flow within the borehole	3	3	3
Camera	Characterize rock type, identify changes in rock type and small-scale geologic structures, locate and describe fractures, describe borehole construction, and identify problems with borehole integrity and (or) possible signs of contamination	Visual fish-eye view and side-looking view of borehole	2	2	2
Acoustic televiewer	Map location and orientation of fractures intersecting borehole and generate a high-resolution acoustic-caliper log	Amplitude and travel time of the reflected acoustic signal	3	3	3
Deviation	Three-dimensional geometry of the borehole	Azimuthal direction and the inclination of the borehole	2	2	2

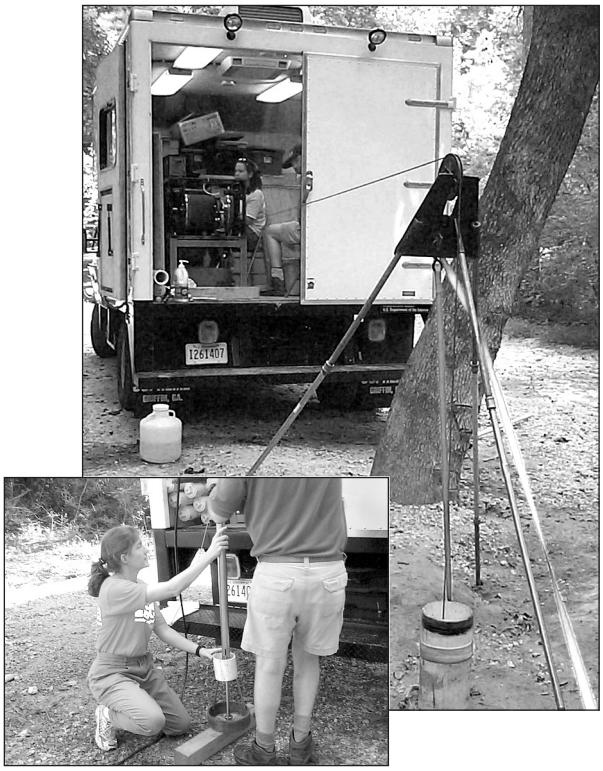

Figure 1. Logging a 6-inch-diameter crystalline-bedrock well in Lawrenceville, Georgia. Inset shows a 3-arm caliper tool being calibrated with a steel ring. Photographs by Lester J. Williams, USGS.

borehole diameter, includes the resistance of the formation, fluids saturating the formation, and fluids in the borehole. The resistance, which is recorded in ohms, is highly influenced by borehole diameter. Increases in borehole diameter typically are associated with a decrease in resistance. Single-point resistance can be used to delineate changes in lithology, clay content, porosity, and total dissolved solids in the formation water. The single-point resistance log can be collected relatively quickly and is one of the least expensive tools to run, process, and interpret data.

Long- and short-normal **resistivity logging** measures the apparent resistivity of the formation in ohmmeters. The tool applies a constant current across two electrodes while measuring the potential between two other electrodes. The volume of investigation is a sphere whose diameter is equal to twice the potential-electrode spacings, which are typically 16 or 64 inches. However, the shape and volume of investigation change depending on the resistivity of the formation. The apparent resistivity has to be corrected for borehole diameter, drilling mud invasion, and formation bed thickness to obtain true resistivity.

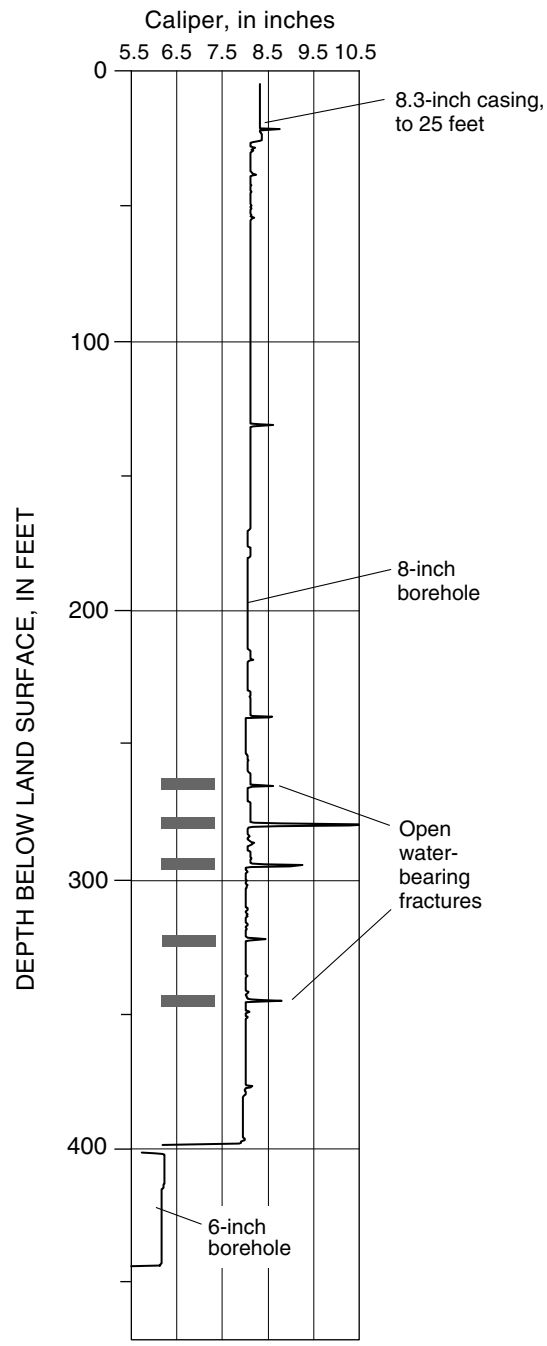

Figure 2. Caliper log from a crystalline-bedrock well in Lawrenceville, Georgia. Thick bars denote fracture openings. Hole is about 8 inches in diameter to 400 feet and 6 inches below that depth.

The apparent resistivity is helpful for corroborating results of two-dimensional surface-resistivity surveys and for determining changes in lithology and resistivity of the fluids in the formation. The normal resistivity can be calibrated by placing known resistors between the electrodes (Keys, 1990).

The lateral resistivity tool is similar to the normal resistivity tool in that it applies a current across two electrodes, while measuring potential across the other two electrodes. The potential electrodes are separated by 2.6 feet (ft). The current electrodes asymmetrically straddle the potential electrode pair with the upper electrode set 4.85 ft above the center point of the potential electrodes, which is considered to be the measurement point. Because the electrode spacing in the lateral resistivity tool is larger than the electrode spacing of the long- and short-normal resistivity tool, lateral resistivity measurements sample a larger volume of the formation. Because of the electrode geometry, lateral resistivity anomalies are nonsymmetrical. Best results are obtained when the bed thickness is twice the offset spacing (2 x 4.85 ft). Results are expected to be marginal in saline water and resistive rocks (Keys, 1990). Although lateral resistivity logs have not been used extensively for environmental applications, the tool has been used to identify fracture zones in crystalline rocks in the Lawrenceville area.

Resistivity logs are relatively cost-effective and easy to collect and interpret. Their most useful application in crystalline rocks is in regimes where the resistivity of the formation is too high for the induction conductivity meter to resolve. In hard, resistive crystalline bedrock, water-bearing zones typically are indicated by low resistivity. An annotated lateral resistivity log, shown in figure 3, easily distinguishes the water-bearing zones in a crystalline-bedrock well in Lawrenceville.

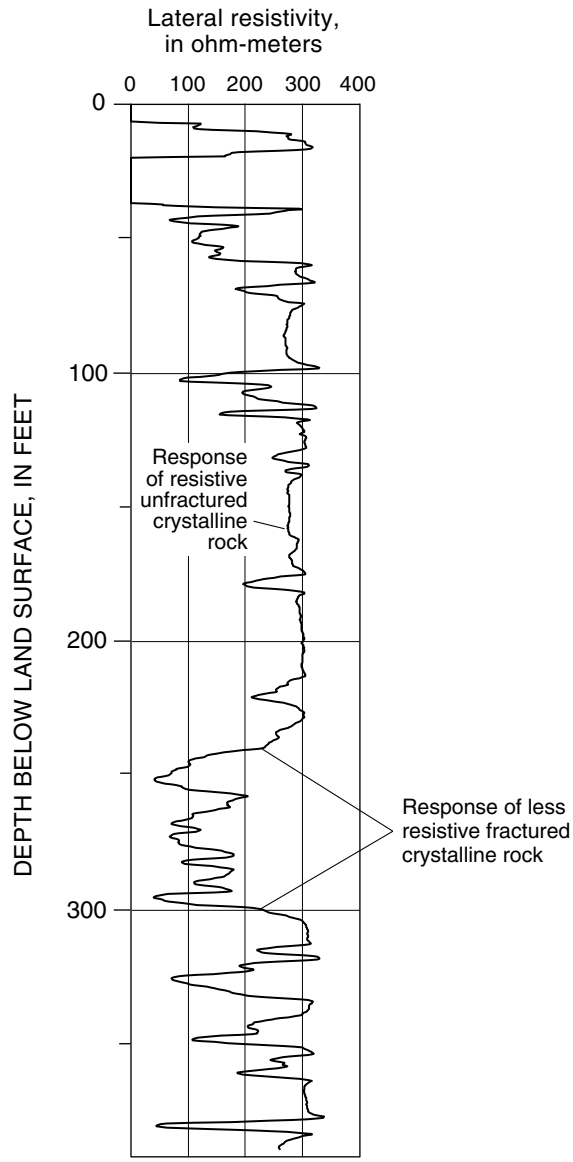

Figure 3. Lateral resistivity log from a crystalline-bedrock well in Lawrenceville, Georgia. Same well as shown in figure 2.

Electromagnetic (EM)-induction logging records the bulk electrical conductivity of the rocks and the fluids in the rocks surrounding the borehole (Williams and others, 1993). The tool uses an electromagnetic induction field to induce an electrical current in the surrounding formation. The induced current in the formation generates a secondary electromagnetic field. At low induction numbers (less than 100 millimhos/meter), the strength of the electromagnetic field is proportional to the formation conductivity. Changes in electrical conductivity are caused by variations in porosity, borehole diameter, dissolved concentration of the water in the rocks, and metallic minerals. The EM-induction probe is designed to maximize vertical resolution and radial penetration and to minimize the effects of the borehole fluid. The tool response is most sensitive to the bedrock and pore water approximately 1 ft away from the probe, and the tool has a vertical resolution of approximately 2 ft. In boreholes with diameters of 6 inches or less, the specific conductance of the borehole fluids has a negligible effect on the induction log response (Keys, 1990). The log is used to delineate changes in rock type or in electrical properties of water in the rock formation.

These logs are relatively inexpensive to collect. Field calibration is done with a calibration ring of known conductivity and with the tool held in low-humidity air for zero conductivity. In humid climates, high- and low-conductivity rings can be used for the

calibration. Field calibration done with calibration rings may be time consuming but is important for collection of accurate data. Because the induction tool is temperature sensitive, it should be allowed to equilibrate to borehole conditions with tool power on for at least 20 minutes prior to logging.

Fluid logging methods measure properties of the water column in the borehole and commonly include the simultaneous measurement of fluid resistivity and temperature. Fluid logs are typically run first to measure an undisturbed water column that represents the ambient conditions in the borehole. The fluid logs can be collected again under stressed conditions (pumping or injection), and a comparison between ambient and stressed conditions can be used to identify the location of the contributing inflow zones. These logs are relatively easy and inexpensive to collect and interpret.

Fluid-resistivity logging measures the electrical resistivity of the borehole fluid from which its inverse, the specific conductance, is calculated. Changes in the specific conductance indicate differences in the concentration of the total dissolved solids in the borehole fluid (Williams and Conger, 1990). These differences typically indicate water that comes from different sources with contrasting chemistry, originating from different transmissive zones. The specific conductance is calibrated with standards or with two fluids of known specific conductance.

Fluid-temperature logging is used to identify where water enters or exits the borehole (Williams and Conger, 1990). In the absence of fluid flow in the borehole, the temperature gradually increases with the geothermal gradient, about 1° Fahrenheit per 100 ft of depth (Keys, 1990). Deviations from the expected geothermal gradient indicate possible transmissive zones in the borehole. Changes in the fluid temperature indicate water-producing and water-receiving zones. Intervals of vertical flow are characterized by little or no temperature gradient (Johnson and others, 1999).

The differential temperature log, which is calculated as the first derivative of the temperature log, can help identify changes in the slope of the temperature and deviations in the geothermal gradient. This log provides valuable information on the fluid in the borehole and may indicate flow dynamics of the borehole.

Flowmeter logging measures the direction and magnitude of vertical fluid flow within the borehole. Flowmeter measurements are collected at discrete locations, usually above and below fractures identified in the other geophysical logs, or as a continuous log in a trolling mode. Heat-pulse, electromagnetic, and spinner flowmeter methods are used to map the fluid flow regime and identify the transmissive fractures penetrated by the borehole.

The heat-pulse flowmeter uses a thermal trace to measure the direction and rate of vertical flow in a borehole (Hess and Paillet, 1990). It is used at stationary points along the borehole above and below fractures. Used in conjunction with other geophysical logs, individual fractures or fracture zones where water enters or exits the borehole can be identified.

The electromagnetic flowmeter can be used in a combination of stationary-mode and trolling-mode measurements to determine vertical flow in the borehole and identify inflow and outflow locations (Moltz and others, 1994). Electromagnetic flowmeter measurements that are collected at stationary locations can provide higher resolution measurements than under trolling conditions. The flow profiles collected under the trolling mode can be proportioned to the higher-resolution measurements made at points. The electromagnetic flowmeter concurrently measures temperature and fluid resistivity.

The spinner flowmeter measures vertical flow by recording the rotation rate of a 3- or 4-bladed impeller mounted with adjustable needle bearings on a freely rotating shaft. Frictional forces associated with shaft rotation must be overcome, and below this threshold velocity the tool does not respond. The threshold velocity of a typical spinner flowmeter is about 5 feet per minute (ft/min), which limits its use to higher flow conditions. Spinner flowmeters can be used in stationary and trolling modes.

Flowmeters can identify the most transmissive fracture in the borehole and other fractures with transmissivities within one or two orders of magnitude. Flowmeters typically are used with a flow diverter fitted to the nominal borehole diameter to channel flow through the measurement channel in the tool. The heat-pulse flowmeter with a flow diverter can measure flows as low as 0.01 +/- 0.005 gallons per minute (gal/min) and as great as 1.5 gal/min. The electromagnetic flowmeter with a flow diverter can measure flows between 0.1 and 15 gal/min. Greater flows (100 gal/min or more) can be measured with proper calibration of the flowmeters while using an underfit flow diverter that allows some of the vertical flow to bypass the tool (Paillet, 2000).

Under ambient conditions, differences in hydraulic head between two sufficiently transmissive fractures produce vertical flow in the borehole. Water enters the

borehole at the fracture zone with the higher head and flows toward and out of the fracture with the lower head. Because vertical flow does not occur between transmissive zones with the same head, flowmeter logging also must be conducted under stressed conditions to identify transmissive fractures with the same head. The electromagnetic flowmeter log in figure 4 indicates the presence of multiple transmissive fractures with differing heads. Under ambient conditions water flowed from fractures with high hydraulic head into the borehole, upward through the borehole, and exited the borehole through fractures with lower head, just below the bottom of casing (fig. 4). In addition, water exited the borehole at the base of casing. Under pumping conditions of 50 gal/min, water entered the borehole at the transmissive fractures with high head and flowed upward in the borehole; however, the pumping did not reverse the ambient flow regime, and water continued to exit the borehole near the base of the casing (fig. 4, top arrows).

Flowmeter logging is expensive relative to the other methods presented in this field trip. The effort in data collection varies, depending on the number of fractures that are hydraulically active, and the flow regimes in the borehole. The time and difficulty of the interpretation also depends on the complexity of the flow regime. The interpretation of flowmeter data can be semi-quantitative or quantitative. The quantitative results can be verified with an iterative modeling approach described by Paillet (1998). Although the interpretation and modeling process is more time consuming, the quantitative results yield a unique solution providing information on the transmissivity and head of individual transmissive zones in the borehole.

Camera logging records both fish-eye and side-looking views of the borehole above and below the water and can provide a direct inspection of the borehole wall and details of the borehole construction.

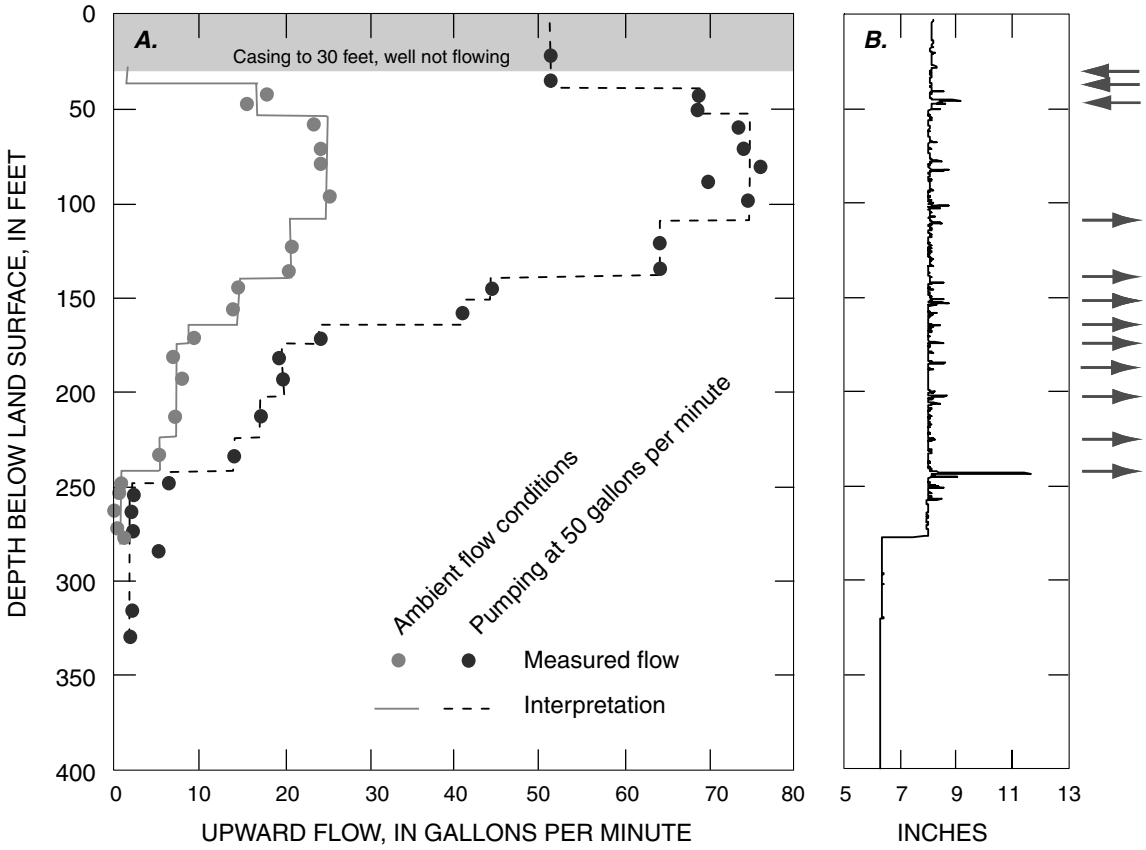

Figure 4. *(A)* Flowmeter logs from a crystalline-bedrock well in Lawrenceville, Georgia, showing ambient and pumping conditions. Top left facing arrows indicate fractures where water is flowing out of the borehole. Right facing arrows show water entering the borehole along artesian fractures between 100 and 250 feet. *(B)* Caliper log shown for reference. Survey conducted on December 4, 2001.

The color images, which are continuously labeled with depth, are collected and recorded on videotape. The images can be used to characterize rock type, identify changes in rock type and small-scale geologic structures, locate and describe fractures, describe the borehole construction, and identify problems with borehole integrity and (or) possible signs of contamination (Johnson and Dunstan, 1998). The images can be used in conjunction with other logs to help interpret anomalies observed in the other logs. This method of borehole imaging is relatively cost-effective, and logs can be collected quickly. However, detailed interpretation of the video logs can be time-consuming.

Acoustic televiewer (ATV) logging produces a high-resolution, magnetically oriented, digital image that is used to map the location and orientation of fractures that intersect the borehole (Williams and Johnson, 2000). The ATV tool emits a narrow acoustic beam that rotates 360° and is focused at the borehole wall. The acoustic wave moves through the fluid in the borehole and is reflected off the borehole wall and recorded by the tool. The log records the amplitude and travel time of the reflected wave, which can be displayed as a flattened 360° image of the borehole wall.

A fracture that intersects the borehole causes scattering of the acoustic wave and appears as a high contrast, low amplitude line (dark feature) on the acoustic amplitude log. On the acoustic travel-time log, a fracture is indicated by an increase in the one-way travel time of the wave, due to an increase in borehole diameter. The "acoustic caliper," which is derived from the travel-time log, provides a much greater resolution measurement of borehole diameter than that collected with a 3-arm caliper. Interpretation of the magnetically oriented images in conjunction with other logs allows for the determination of transmissive fractures structures that may relate to the hydraulics of the aquifer.

The acoustic televiewer is a relatively expensive tool and data collection and interpretation can be time-consuming. Because of the high resolution of data collection, the recommended logging speed of about 5 ft/min is much slower than the logging speed of most other logs, which is 10–20 ft/min.

Deviation logging measures the borehole deviation by providing a record of the three-dimensional geometry of the borehole (Keys, 1990). The deviation log records the azimuthal direction (0–360°) and the inclination (0–90°) over the depth of the borehole. Borehole deviation tools generally indicate direction to within ±2° and inclination to within ±0.5°. Deviation logs are collected simultaneously with acoustic and optical images with the televiewer tools. The results of this log are used to correct the orientation of fractures determined from the acoustic and optical imaging tools.

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Methods Being Used to Assess the Sustainability of Ground-Water Resources in a Fractured-Crystalline-Rock Aquifer, Lawrenceville, Georgia

by Phillip N. Albertson
U.S. Geological Survey

INTRODUCTION

Historically, community ground-water systems developed in fractured crystalline rock in the Piedmont physiographic province of Georgia were widely dispersed and the sustainability of these systems and the effect of pumping on streamflow was not a major concern to regional water managers. As the demand for drinking water increases, however, and the number of community ground-water systems continues to grow, there is a need to assess ground-water sustainability to better manage the resource.

Ground-water sustainability is defined as "development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences" (Alley and others, 1999). Although the phrase "unacceptable consequences" is vague, it can be loosely defined as reductions in ground-water storage and stream baseflow that cause undesirable effects.

The main objective of this study is to monitor hydrologic conditions to better assess the quantity of ground water that can be withdrawn from a fractured-crystalline-rock aquifer in areas of increasing ground-water development. This paper describes methods that are being used to determine the sustainability of ground-water resources in the Lawrenceville area. Streamflow and ground-water levels are being recorded in two watersheds where ground-water resources are being developed, and in the Apalachee River Basin, which serves as a control.

The city of Lawrenceville is located in the Piedmont physiographic province of Georgia (fig. 1). The aquifer that underlies this area consists of structurally complex fractured igneous and metamorphic rock with relatively low ground-water storage capabilities (Chapman and others, 1999). Currently, Lawrenceville obtains about 6 percent of its drinking water from ground water and intends to continue development of ground-water resources in the near future (M. Bowie, City of Lawrenceville Water Department, written commun., 2001). Previous work in the area has documented rapid declines and recoveries in ground-water levels even at great distances from pumping wells, and drawdown across basin topographic divides in response to municipal well pumping about a mile away (Chapman and others, 1999). Furthermore, during dry periods, streamflow is primarily sustained by discharge of ground water. Fractures and joints form a network of conduits in the igneous and metamorphic rock (fig. 2). Pumping water from these fractures may intercept and redirect some of the water that usually discharges to streams.

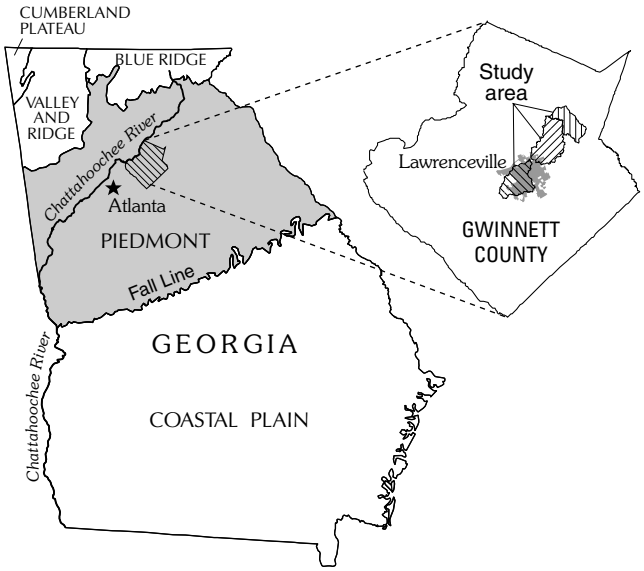


Figure 1. Location of the study area in the Piedmont physiographic province of Georgia.

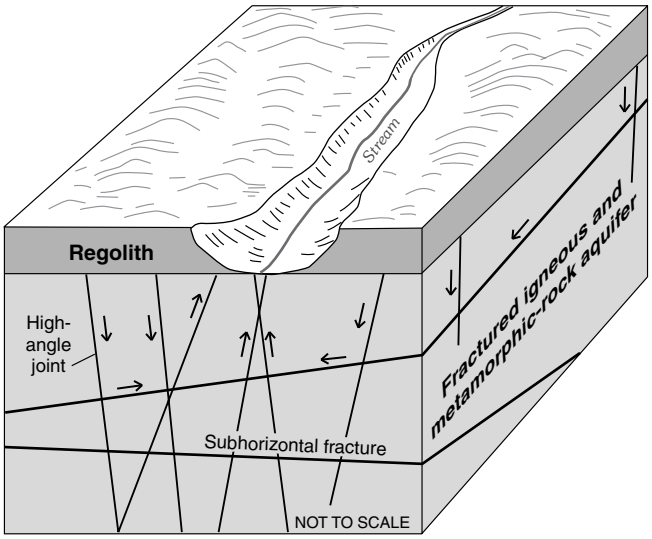


Figure 2. Schematic drawing showing ground-water movement (arrows) through horizontal fractures and vertical joints from upland areas to streams in a fractured igneous and metamorphic-rock aquifer.

DESCRIPTION OF THE STUDY AREA

The study area is located approximately 25 miles northeast of Atlanta (fig. 1) in the Piedmont physiographic province of Georgia, an area underlain by crystalline-igneous and metamorphic rock. Currently, ground-water withdrawal is planned for two areas: the Pew Creek–Redland Creek Basin (7.5 square miles [mi^2]) and in the Upper Alcovy River Basin (9.9 mi^2), between Georgia Highway 316 and U.S. Highway 29 (fig. 3). Headwaters of Redland Creek and Pew Creek lie in the city of Lawrenceville (fig. 3). Waters of Redland Creek and Pew Creek flow southwest where they merge and flow into the Yellow River.

Ground-water and surface-water data collected from the Pew and Redland Creek Basins and the Upper Alcovy River Basin are being compared to data collected in the Upper Apalachee River Basin (fig. 3), which covers approximately 5.7 mi^2 and currently has very little ground-water development. Data from the Upper Apalachee River Basin serve as a control to data collected in the Pew Creek–Redland Creek Basin and in the Upper Alcovy River Basin.

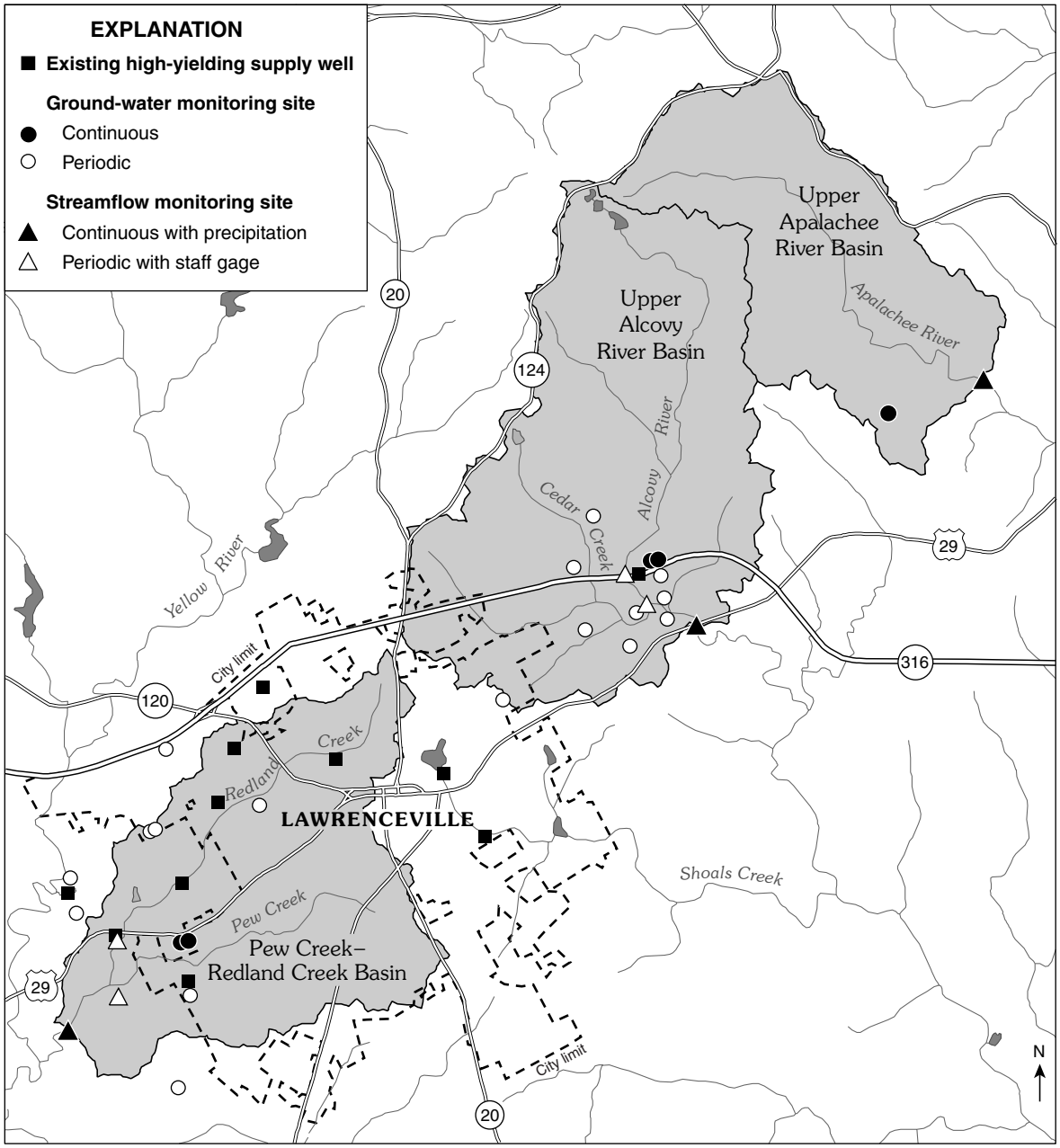
HYDROLOGIC CONTROLS ON GROUND-WATER SUSTAINABILITY

Ground water occurs in joints, fractures, and other secondary openings in bedrock and in the overlying mantle of soil, saprolite, alluvium, and weathered rock, collectively referred to as the regolith. In Lawrenceville, “fractures” refer to openings along foliation planes, joints, and brittle fractures related to faulting. Wells in the area yield from 1 gallon per minute (gal/min) to 471 gal/min (Chapman and others, 1999).

In a bedrock aquifer, most water is stored in the overlying regolith, which is under water-table conditions. Changes in storage in a water-table aquifer are indicated by water-level fluctuations observed over time—increased storage is indicated by water-level rises, whereas decreased storage is indicated by water-level declines.

The amount of water that recharges the aquifer is determined by the amount of precipitation that is not lost to runoff, evaporation, transpiration, or to replenish soil-moisture deficits in the regolith. The amount of recharge available to bedrock aquifer is controlled by (1) the interconnection between the regolith and the underlying bedrock system, (2) the connectivity of water-bearing fractures with the well, (3) the transmissivity of the regolith and fracture network, which enables movement of water from the recharge area into the bedrock, and (4) storage properties of the fractured bedrock and overlying regolith. Under steady-state conditions, ground-water recharge is equal to ground-water discharge; therefore, the amount of water discharging to streams and withdrawn by wells is an approximation of the amount of water recharging the aquifer.

Inflow to the aquifer is primarily recharge from precipitation but also could include interbasin transfer of ground water through transmissive and extensive fracture networks. Inflow also could include future human-made improvements to increase recharge to the aquifer through infiltration fields and catchments. Outflows are from natural ground-water discharge to streams (baseflow) and ground-water pumping.



Base modified from U.S. Geological Survey
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Figure 3. Study watersheds, existing high-yield supply wells, ground-water monitoring sites, and streamflow monitoring sites.

METHODS TO ASSESS GROUND-WATER SUSTAINABILITY

The main objective of this study is to monitor hydrologic conditions to better assess the quantity of ground water that can be withdrawn from a fractured-crystalline-rock aquifer in areas of increasing ground-water development. Meeting this objective requires collecting ground-water-level and streamflow data, inside and outside areas influenced by pumping, and using these data to develop a hydrologic budget for two basins in the Lawrenceville area. In addition to the surface- and ground-water data, climatic data also are necessary to develop a hydrologic budget. Climatic data, including precipitation and temperature data, are being collected at several locations in each of the study basins.

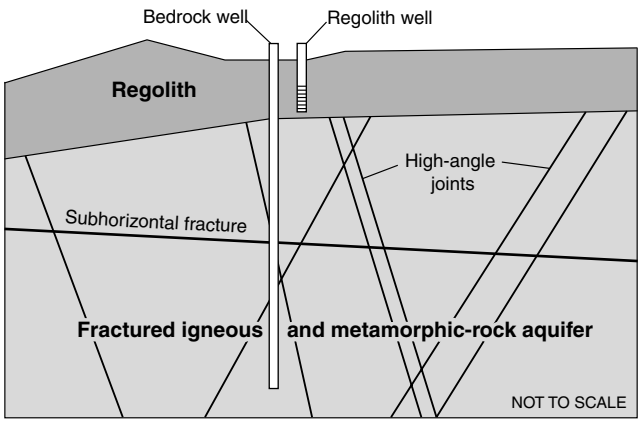

Figure 4. Schematic drawing showing a well pair; one completed in the bedrock and one completed in the overlying regolith.

Ground-Water-Level Monitoring

Ground-water levels in the overlying regolith (10 wells) and in the crystalline-rock aquifer (15 wells) are being collected to document changes in the configuration of the water table and potentiometric surface in order to document changes to aquifer storage.

New observation wells in crystalline bedrock were recently placed in proximity to major pumping centers with horizontal distances based on previous aquifer tests. The wells were placed along the strike of the foliation (generally east to west), which is the preferential drawdown direction observed in the area. New shallow observation wells also were completed to monitor water levels in the overlying regolith, which is the primary source of ground-water storage. These new wells were combined to the existing network of nine bedrock and three regolith wells in the area. At least one site in each of the two basins consists of a pair of observation wells; one in the regolith and one in the bedrock. These are being used to determine the vertical hydraulic gradient between the regolith and crystalline rock, and to assess the effects of large-scale ground-water withdrawal on this gradient (fig. 4).

Continuous ground-water-level data are being collected from at least two wells in each basin as ground-water development proceeds. Continuous data are needed to document small-scale changes in water level caused by both pumping and rainfall variation. In addition to the continuously recorded sites, synoptic water-level data are being collected weekly at 25 wells. More frequent synoptic measurements will be taken when new city wells are brought online to document the effect of pumping.

Surface-Water Monitoring

Streamflow is being monitored in the two basins to document changes that may occur as ground-water withdrawal increases. Continuous streamflow recorders are recording streamflow at the outflow of each study basin (fig. 3) and the Upper Apalachee River Basin. Continuous streamflow data will be used to evaluate baseflow using hydrograph-separation techniques (Sloto and Crouse, 1996; Rutledge, 1998). In addition to the continuous-recording sites, streamflow is being measured weekly at two sites in each basin using a current meter and staff gage to develop a stage-discharge relation. V-notch weirs are used to measure discharge at these sites at times when streamflow is too low to measure discharge accurately with a meter.

Synoptic streamflow measurements will be collected periodically to provide a more detailed picture on the possible effects of pumping on specific stream segments. These “seepage” measurements are used to measure aquifer-stream interactions by quantifying the gain or loss of water to a specific reach of a stream by subtracting discharge at an upstream site from discharge at a downstream site. Seepage measurements are being collected before and after pumping begins at a time when streamflow is primarily baseflow (ground-water contribution to streamflow). These data will be used to assess changes to baseflow in stream segments and may help to identify pumping wells that affect streamflow.

Climatic Monitoring

A nearby weather station of the Georgia Environmental Monitoring Network at Duluth, Georgia (URL http://www.griffin.peachnet.edu/cgi-bin/GAEMN.pl?site=GADU, accessed August, 25, 2003), and the Gwinnett County Airport are supplying some climate data. The data include: precipitation, surface air temperature, humidity, evapotranspiration, and soil moisture. In addition, hourly precipitation is being recorded at continuous streamflow sites in each basin. These data, along with other climatic information, are being used to calculate a water budget for the study basins in the Lawrenceville area.

Development of a Hydrologic Budget

Data from the hydrologic-monitoring program will be synthesized into a hydrologic budget for the Pew Creek–Redland Creek and Upper Alcovy River Basins. The hydrologic budget will be used to estimate available recharge, track the amount of water removed from storage by pumping, and evaluate the effects of pumping on streamflow and on interbasin transfer of ground water. Water managers can use this information to assess the sustainability of ground-water supplies in the two basins.

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Streamflow Generation and Ground-Water Recharge of the Surficial Aquifer at the Panola Mountain Research Watershed

by Norman E. Peters[1], James Freer[2], Brent T. Aulenbach[1], and L. Elliott Jones[1]

INTRODUCTION

Hydrological processes controlling streamflow generation and water yield during hydrologic events have been the foci of countless investigations since the 1950s. The relations between rainfall and runoff have been augmented by the development of catchment hydrologic models, with a primary emphasis on predicting streamflow at various temporal and spatial scales. The development of *smart sensors* and the extensive distribution of these sensors in a few intensively monitored plots/hillslopes/catchments have produced voluminous hydrometric point datasets; and with the more recent addition of isotopic and hydrochemical tracer information, have refined the understanding of small catchment and sub-catchment hydrologic processes. Relations between stormflow characteristics and soil-moisture content, water-table elevation in wells along several transects perpendicular to the stream, and precipitation were evaluated for the Panola Mountain Research Watershed (PMRW), Georgia from water year 1986 through 2001 to refine the conceptualization of hydrologic dynamics, streamflow generation and ground-water recharge.

Study Site

PMRW is a 41-ha forested watershed, 25-km southeast of Atlanta, in Rockdale County, Georgia, (Peters and others, 2000). It is one of five watersheds of the U.S. Geological Survey's (USGS) Water, Energy, and Biogeochemical Budgets (WEBB) Program, which is investigating basic hydrologic and biogeochemical processes to determine the effects of atmospheric deposition, climatic variables, and human influences on watershed processes (Baedecker and Friedman, 2000). The watershed has a naturally regenerated second-growth forest, which developed on abandoned agricultural land, typical of the Piedmont physiographic province. The catchment is 90% forested, dominated by hickory, oak, tulip poplar, and loblolly pine, and 10% partially vegetated (lichens and mosses) bedrock outcrops (fig. 1). The basin relief is 56 m and slopes average 18%. The forested area varies from 100% deciduous to 100% coniferous (Cappellato and Peters, 1995). The bedrock is predominantly the Panola Granite (granodiorite composition), which contains pods of amphibolitic gneiss, particularly at lower elevation. Soils are predominantly ultisols developed in colluvium and residuum, which intergrades to inceptisols developed in colluvium, recent alluvium, or in highly eroded landscape positions. Typical soil profiles are 0.6 to 1.6 m thick grading into saprolite of variable thickness.

Zumbuhl (1998) conducted a detailed (10-m grid) survey of soil plus regolith depths in the 10-ha headwater catchment (drainage of gauge B in fig. 1), and the survey results suggest that the catchment can be represented by three landscape units (Peters and others, 2003), two of which represent distinct unconfined aquifers. Bedrock outcrops comprise a small landscape unit (~10%) that has little or no soil cover (area 1 in figure 1). Hillslopes are another landscape unit comprising most of the catchment (>75%) and has soil-plus-regolith thicknesses of less

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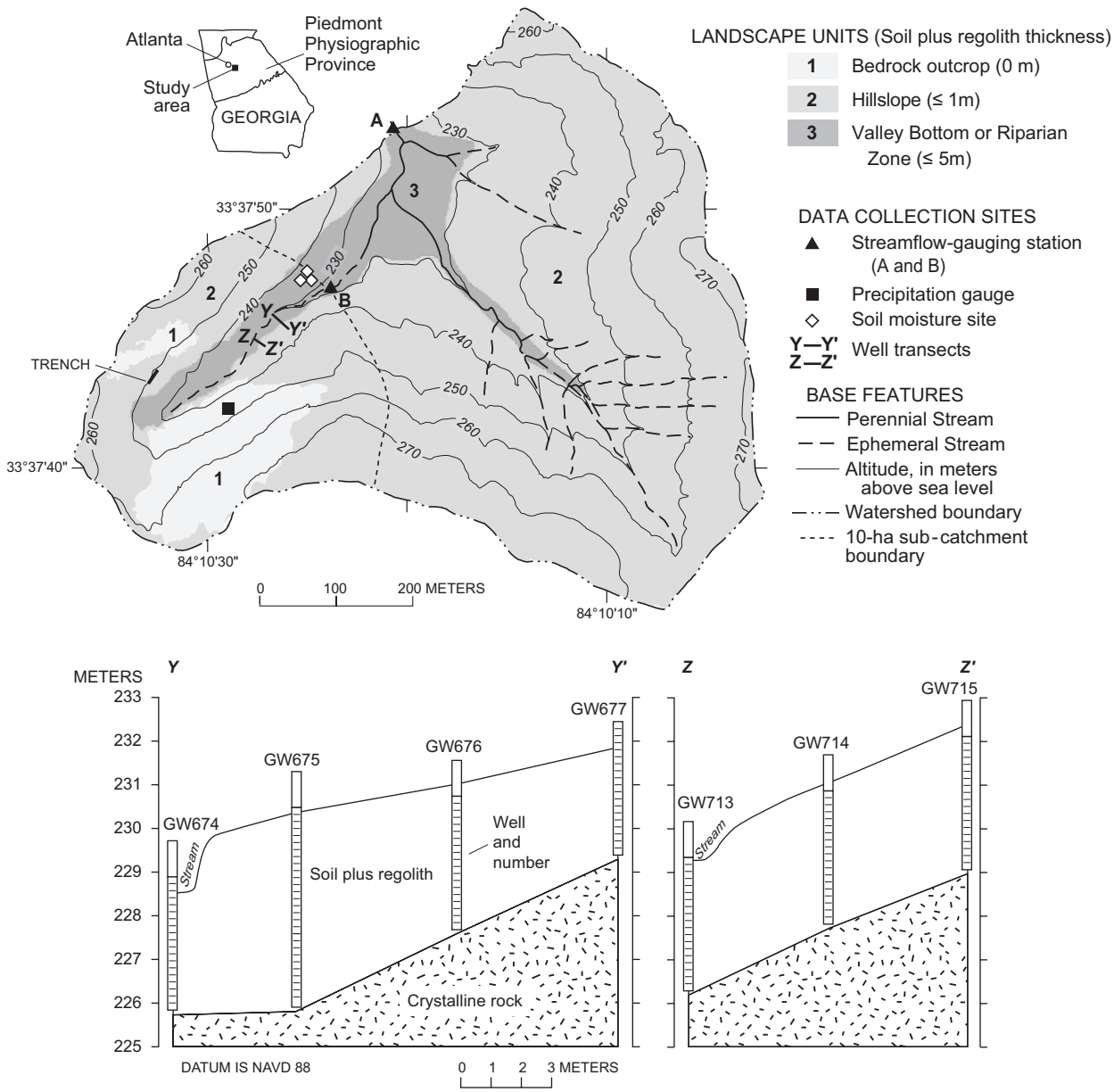

Figure 1. Location of the Panola Mountain Research Watershed and selected hydrometric measurement locations and cross-sections for well transects *Y-Y'* and *Z-Z'*.

than 1 m (area 2 in fig. 1). The third and most important landscape unit for ground-water storage is the riparian zone, which is the thickest unconfined surficial aquifer (5 m), but is relatively narrow (<50 m) and generally is in the valley bottom (area 3 in fig. 1). The aquifers consist of a shallow one on the hillslope and a deeper one in the riparian zone, and can be conceptualized as buckets containing soil and regolith of variable thickness, determined from the knocking pole measurements of Zumbuhl (1998) and ground-water wells augered to refusal, which generally is assumed to be the bedrock surface.

Climate is humid continental to subtropical. A long growing season, warm temperatures, and many sunny days result in a high evapotranspiration (ET) demand, particularly during the summer. Air temperature averages 15.2°C and the average monthly temperatures range from 5.5°C during January to 25.2°C during July. During the spring and summer from April through September, rainstorms

are convective (high intensity and short duration). During the remainder of the year, precipitation is dominated by synoptic weather systems (low intensity and long duration). Less than 1% of the precipitation falls as snow or sleet.

Streamflow is flashy and has been attributed to runoff generated from the 3.6-ha bedrock outcrop in the headwater (Shanley and Peters, 1988). Although streamflow decreases rapidly during recession, baseflow is sustained throughout the year, but the tributaries are perennial for only a short distance above the their confluence (fig. 1). When sufficient runoff is generated by rainfall on the bedrock outcrop, which typically occurs during convective rainstorms with greater than 15 mm of rainfall, a flood wave develops, which propagates rapidly downstream from the base of the outcrop. Discharge from the flood wave typically peaks at gauge B 15 to 20 min after initiation of flow in the channel at the base of the outcrop, and at gauge A about 20 min later (fig. 1). The time to maximum flow is less when the watershed is wet.

METHODS

Data Collection

Rainfall is recorded at 1-min intervals from several tipping bucket gauges in and adjacent to the catchment; these data series were combined to yield one rainfall time series for the catchment. Streamflow is monitored at two gauges, stream gauge A is at the basin outlet (41 ha drainage area) and stream gauge B is on an ephemeral tributary (10 ha drainage area), draining from the southwest, midway between the basin outlet and the large (3.6 ha) bedrock outcrop (fig. 1). Discharge was determined from a stage-discharge rating using stage measurements recorded by a datalogger. The datalogger is wired to a potentiometer and a float-counterweight system, which monitors water level in a stilling well connected to a compound 90° V-notch weir. The stage data are output routinely at 5-min intervals and 1-min during stormflow. Ground-water elevation was determined by measuring the depth to the water table was measured using the same type of measuring device in a 5.1-cm diameter PVC well (fig. 2). The wells were hand augured to refusal and are primarily in the riparian zone upstream of gauge B (fig. 1). Rainfall and runoff have been recorded continuously since October 1985. Although the depth to the water table has been recorded continuously in a few wells since 1986, the network was expanded and the data have been more rigorously verified from manual water-level measurements since the mid-1990s. Data for 15-water years (WY: October through September) from 1986 to 2000, where available, were used in the analysis herein.

Soil-moisture content was determined from pairs of 50-cm parallel-spaced, time-domain reflectometry (TDR) probes at three locations adjacent to gauge B on the south facing hillslope (fig. 1). One soil-moisture site is at base of the hillslope in the riparian zone and the other two sites are on the hillslope 15 and 25 m upslope of the riparian zone. The TDR probes were inserted parallel to the slope at 15, 40, and 70 cm below the soil surface. The soil-moisture measurements commenced during April 1994 and were discontinued during February 1999. Equipment failures, however, resulted in many periods with no data.

Flow from a hillslope was determined from ten 2-m wide sections and several macropores in a 20-m trench, which was excavated to bedrock across a hillslope in the headwaters (McDonnell and others, 1996; fig. 1 herein). Trench flow was measured using tipping bucket gauges, for which the tips were recorded every minute. The data-collection system has been in operation since 1995, but the delivery system has not been regularly maintained and between clogs and leaks may not accurately reflect the flow for the individual sections. Consequently, the trench-flow data are used qualitatively for evaluating the hydrologic conditions during which flow occurs.

Data Analysis

Stormflow generation and relations with soil water and ground-water levels

Runoff was determined by summing the streamflow for the appropriate time period. Daily baseflow was estimated from the minimum daily runoff for prior 14 days and stormflow was computed as the difference between the daily runoff and baseflow runoff. The monthly hydrologic characteristics (and the stormflow discussed below) also were grouped by season (winter was from January through March; spring was from April through June; summer was from July through September; and fall was from October through December). The relations among these components were assessed using linear regression.

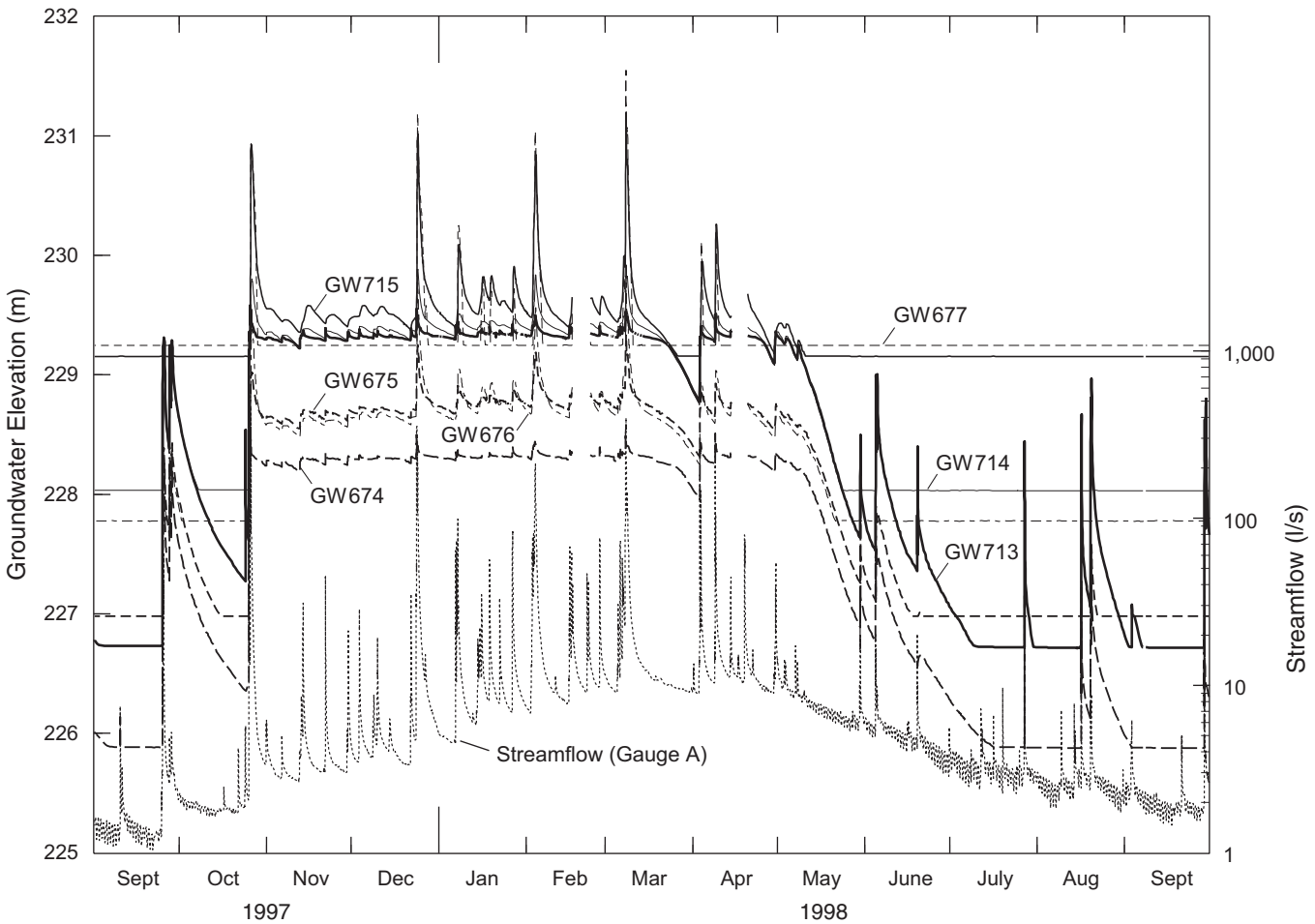

Figure 2. Temporal variations of runoff at gauge A and ground-water elevation (two well transects) from September 1997 through September 1998. Wells 674 through 677 are from transect *Y-Y'* and wells 713 through 715 are from transect *Z-Z'* in figure 1. The absence of a line for a given period indicates missing data, e.g., see the ground-water elevation of wells during February and April. Also, the wells were dry during periods with no response, i.e., flat lines, particularly during summer.

In addition to the assessment of the daily data, stormflow was computed by subtracting the baseflow, as determined from the pre-event streamflow, from the total runoff during the rainstorm. A hydrologic event was identified by the minimum of a 0.4 $l\ s^{-1}$ streamflow increase or a 15% streamflow increase within a 2 h period. The end of the rainstorm was determined when the streamflow decreased below the smaller of 1.5 $l\ s^{-1}$ and a streamflow, computed as 4% of the maximum change in streamflow above the pre-event streamflow plus the pre-event streamflow. Many of the rainstorm start times were adjusted to 10 minutes before the initial rainfall to include rainfall prior to the initial increase in streamflow. For sequential rainstorms, the rainstorm end times of subsequent rainstorms were adjusted to the beginning of the next rainstorm, i.e., to correspond to end immediately before the next pulse of rainfall. The average values and the minimum and maximum values for soil-moisture content, water-table elevation and streamflow were used to evaluate spatial and temporal patterns in the hydrologic response of the catchment during rainstorms (Note: during the 15 years of record, snowmelt occurred during six periods that produced 15 relatively minor hydrologic events, which were not used in this analysis).

Ground-water recharge

The continuous daily runoff series were analyzed using the USGS hydrograph separation computer program, RORA (Rutledge, 1993). The recharge was evaluated with respect to the basic water-balance components annually and seasonally, i.e., the growing season is from April through September and dormant season is from October through March.

RESULTS AND DISCUSSION

Precipitation, which, in the long term, is distributed uniformly throughout a year, averages 1,220 mm annually and ranges from 760 to 1580 mm; water yield averages 30% and ranges from 16% to 50%. Stormflow is highly correlated with rainfall. Ground water in the riparian zone of the headwater catchment (above Gauge B in fig. 1) responds rapidly to rainstorms, particularly those above 15 mm and when the watershed is wet (fig. 2). For 759 rainstorms identified during 16 water years, stormflow water yield correlates with maximum soil-moisture content and with maximum water-table elevation; the relations are linear above thresholds for the entire period and by season. Relations among wetness parameters and stormflow water yield are better (less scatter) and more consistent during seasons when the catchment is wet and the rainstorm is moderate to large than when the catchment is dry. Soil-moisture content (minimum or maximum) during rainstorms is highly correlated among soil depths and water-table elevations, particularly during the dormant seasons when the watershed is wetter as reflected by higher baseflow. Stormflow water yield is linearly related to soil-moisture content at the deepest location (70 cm) above 37% volumetric moisture content (fig. 3). Maximum water-table elevation is linearly related to maximum soil-moisture content above a threshold, and the soil-moisture threshold increases with position of the well away from the stream channel or upstream location. Further upslope, a soil-moisture threshold increased to 41% before flow occurred at a trenched hillslope site. The relation generally is linear for wells in the stream channel without any apparent threshold for rainstorms that generate from a 10-ha sub-catchment.

The variations in water-table elevation and soil moisture content are useful in limiting the contributing areas to stormflow and characterizing the spatial extent of the hydrologic response for most rainstorms. The combination of thresholds of maximum soil-moisture content and maximum water-table elevation, coupled with landscape position and streamflow are consistent with the variable-source-area concept of streamflow generation (Hewlett and Hibbert, 1967), which suggests that saturated-area contributions to streamflow expand as the watershed or catchment becomes wetter as is typical with increasing storm rainfall.

Following a typically long dry summer, the surficial aquifer at PMRW recharges during the fall (e.g., WY1998 in figure 2), beginning as early as October in some years. The annual RORA recharge estimates are highly correlated with precipitation (fig. 4). The difference in the recession recharge and total recharge is the recharge that was lost to ET during the growing season. The difference between the annual measured runoff and the total recharge is the stormflow runoff; the annual stormflow contribution to runoff increases with increasing precipitation ranging from 8.8% to 22.7% and averaged 15.2%. In absolute terms, the recession recharge, the water that was not lost to the atmosphere through ET, varied by more than a factor of 4 from 88 mm to 410 mm and averaged 204 mm for the 15-year period of record.

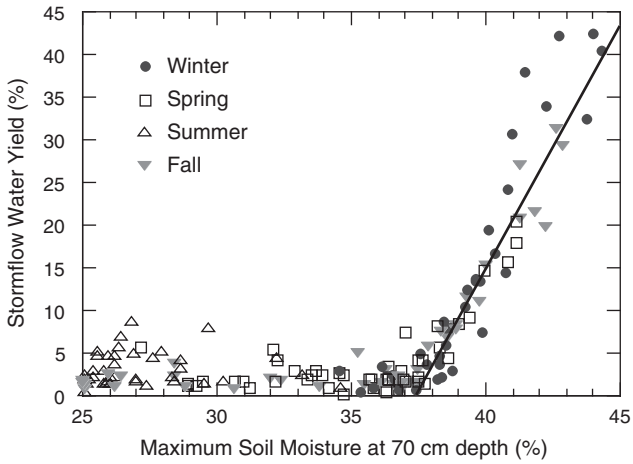

Figure 3. Relation between stormflow water yield and maximum soil-moisture content at 70 cm depth at PMRW.

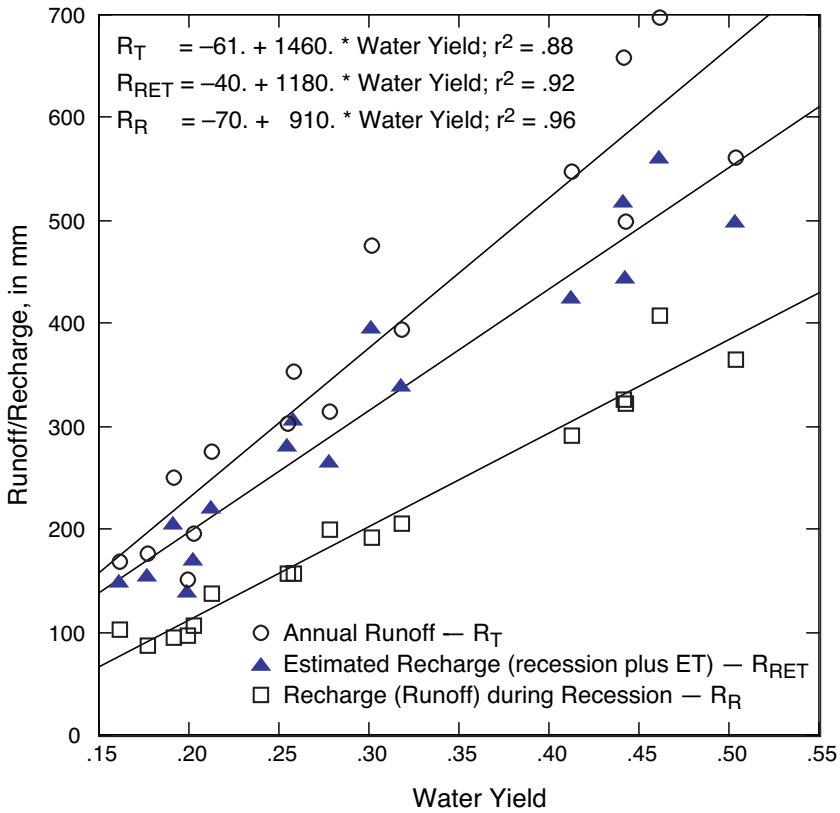

Figure 4. Relation between RORA estimates of recession recharge and total recharge, which includes recession recharge and ET, and the measured annual runoff for WY1986 through WY2001.

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