THE IMPORTANCE OF GEOLOGIC SETTING IN DEVELOPING GROUNDWATER FROM FRACTURED, METAMORPHIC ROCK AQUIFERS IN THE VICINITY OF THE GWINNETT COUNTY AIRPORT AND COLLINS HILL ROAD, GWINNETT COUNTY, GEORGIA

by

JOSHUA LEE LAWSON

(Under the direction of Dr. Todd Rasmussen)

ABSTRACT

The purpose of this study is to demonstrate the importance of geologic setting in developing groundwater from fractured, metamorphic rock aquifers. The study included site-specific geologic mapping, followed by the selection and installation of two bedrock wells. A third well, which was previously drilled, was also included in the study. The boreholes were logged for rock type, fracture location and groundwater yield during drilling and further logged after completion with a borehole caliper and two borehole-imaging tools. The success of all three wells is explained using the fundamentals of a groundwater exploration technique not commonly practiced in igneous and metamorphic rock settings. The technique requires an understanding of the components of geologic setting and how they interplay to influence the groundwater potential of a local area. The study concluded that all three wells behaved consistently with the fundamentals of the technique, and that geologic mapping on a site-specific scale is necessary to understand the components of geologic setting.

INDEX WORDS: Geologic setting, Groundwater Exploration, Metamorphic, Site-specific, Geologic mapping, Lawrenceville Georgia, Bedrock wells, Groundwater, Well, Geology, Fractured rock, Bedrock Aquifers

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JOSHUA LEE LAWSON

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JOSHUA LEE LAWSON

Major Professor:	Todd Rasmussen
Committee:	Rob Hawman David Wenner Lester Williams Randy Kath

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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DEDICATION

I would like to dedicate this thesis to my absolutely amazing wife and my wonderful family.

ACKNOWLEDGEMENTS

I would like to first acknowledge my committee who allowed me to do my thing, while at the same providing support whenever I needed it. I extend my thanks to Dr. Todd Rasmussen, Dr. Rob Hawman and Dr. David Wenner.

I would like to thank the United States Geological Survey for all its help and support throughout the development and completion of my thesis. I would also like to thank the City of Lawrenceville who cooperatively funded the USGS project under which the data for this thesis was collected. I extend special thanks to the USGS Hydrologic Studies Section, Georgia District for providing me with the opportunity to work with the USGS. I extend great thanks to Lester J. Williams, Hydrologist, who directed my work and encouraged me to think outside of the box.

I would also like to acknowledge Tom Crawford who conducted initial geologic mapping in Lawrenceville along with Mike Higgins during their tenure with the USGS. Great thanks are extended to Dr. Randy Kath who conducted the site-specific geologic mapping used to site the wells discussed in this study. Dr. Kath's experience and expertise made this thesis possible.

The ideas and exploration methods presented in this thesis are the ideas and methods of Mr. Tom Crawford and Dr. Randy Kath. My greatest thanks are extended to them both.

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CHAPTER 1

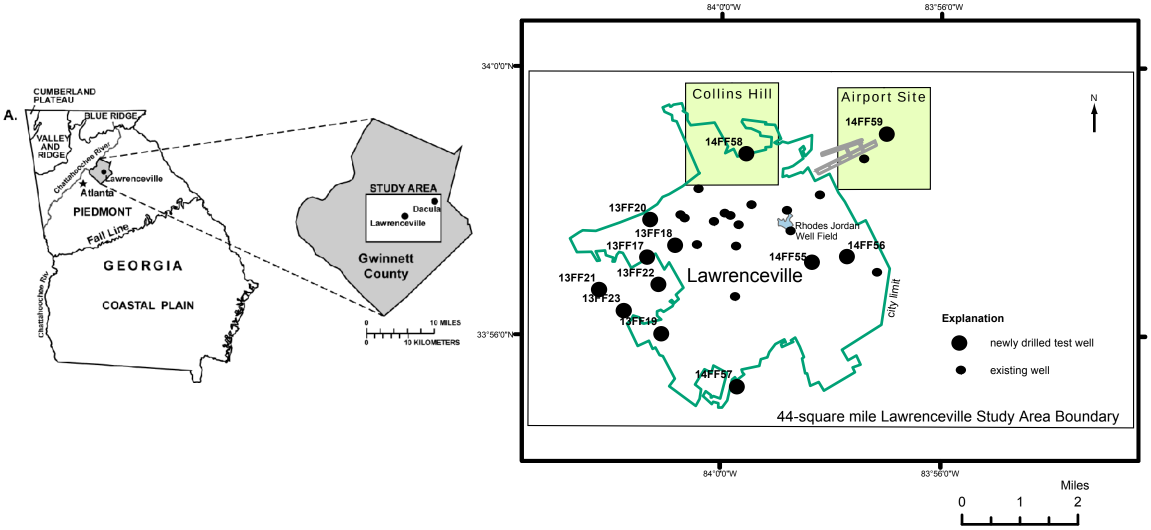
INTRODUCTION

Purpose of Study

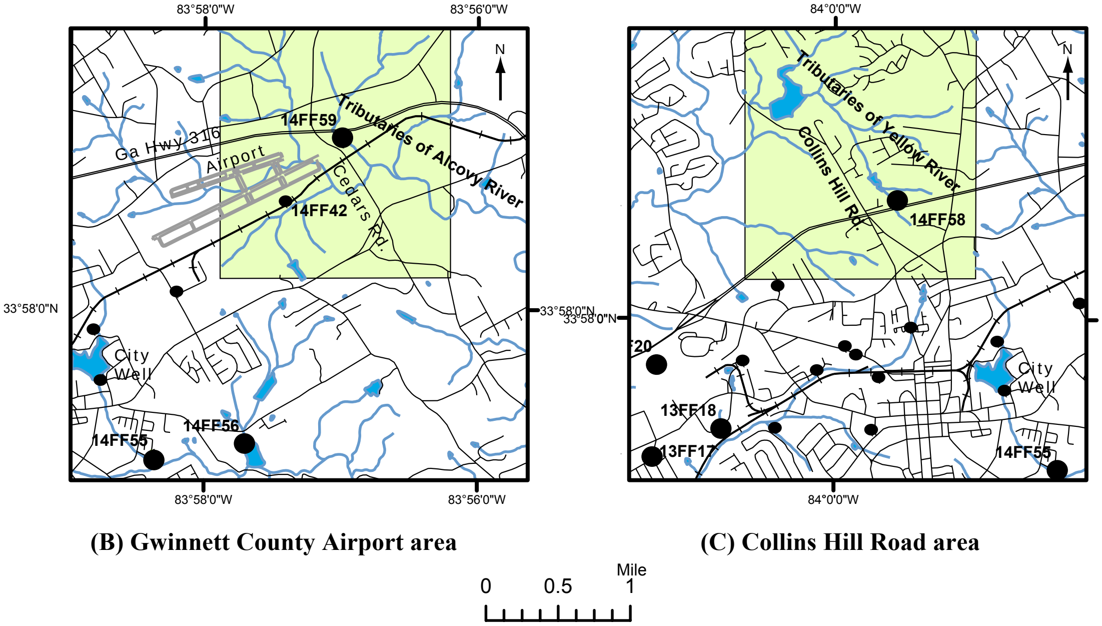
The purpose of this study was to demonstrate the importance of geologic setting in developing groundwater from fractured, metamorphic rocks using site-specific geologic mapping and borehole logging. The study encompasses three bedrock wells in the vicinity of the Gwinnett County Airport and Collins Hill Road, Gwinnett County, Georgia. All three wells are situated in different geologic settings and possess a wide range of yields. Conclusions regarding the level of importance of geologic setting are discussed in terms of rock type, structure, depth of weathering, recharge potential, topographic position, and their interrelationship.

Background

The City of Lawrenceville has a long history of using groundwater as a potable water supply. The first well was drilled in 1912 at the Rhodes Jordan Park (Figure 1). Original records indicate that the well had an estimated yield of as much as 400 gallons per minute (gpm). This well and three additional wells drilled in the 1940's were used as the City's primary water supply prior to 1970. Since the mid 1970's the City has purchased most of its water from Gwinnett County. The average demand for water in the city ranges from about 1.5 million gallons per day (Mgal/d) in the winter to about 2.9 Mgal/d in the summer (E&C Consulting Engineers, Inc., 1995). A small percentage of the City's public water supply (approximately 5 percent) is currently (2001) obtained from groundwater sources.



(A) Physiographic provinces in Georgia and location of study areas



(B) Gwinnett County Airport area

(C) Collins Hill Road area

Figure 1. Location of (A) study areas (shaded) in Gwinnett County and physiographic provinces in Georgia, (B) study area in area of Gwinnett County Airport , (C) study area in area of Collins Hill Road.

The United States Geological Survey (USGS) began a cooperative study in December 1994 with the City of Lawrenceville to determine the hydrogeologic characteristics of the fractured bedrock aquifers in the vicinity of Lawrenceville (Figure 1). The objectives of the USGS study were to (1) evaluate the regional hydrogeologic setting of the Lawrenceville, GA, study area by correlating subsurface and surface lithology; (2) delineate and characterize subsurface fractures that control aquifer permeability; and (3) monitor the response of the bedrock groundwater system to groundwater withdrawals by characterizing aerial influence of groundwater pumping from the fractured bedrock aquifer system.

During the period between 1995 and 2000, the USGS completed both regional scale and local scale studies. The bulk of this work involved detailed fracture characterization in existing or newly drilled wells using borehole geophysical techniques, geologic mapping, surface geophysics, groundwater level monitoring, aquifer testing and collection of groundwater quality data. Concurrently, E&C Integration Services (E&C), a consulting firm for the City, conducted test well drilling, well-head protection and planning, permitting and engineering aspects of the treatment plant construction and distribution. Between 1997 and 2000, E&C completed several groundwater exploration efforts that were only moderately successful.

The USGS expanded its groundwater resources program between 2000 and 2001 in order to gain a better understanding of specific geologic controls affecting groundwater availability in the study area. The USGS completed detailed site-specific evaluations at 12 drilling sites and in other areas where additional hydrogeologic information was needed during this phase. This report describes the results from two of these sites (Figures 2 and 3).

The USGS-City of Lawrenceville water-resources study area is located approximately 20 miles (mi) northeast of Atlanta and encompasses about 44 square miles (mi^2) including the City of Lawrenceville in Gwinnett County, GA (Figure 1). The study area covers the northeastern quarter of the Luxomni and the northern half of the Lawrenceville, USGS 7 ½-minute topographic quadrangles.

The City of Lawrenceville is located in the Piedmont physiographic province, Winder Slope District of the Southern Piedmont Section (Clark and Zisa, 1976). Topography is gently rolling with altitudes ranging from about 780 feet (ft) to 1,170 ft above mean sea level. The Lawrenceville area contains part of the headwaters for the Yellow River and the Alcovy River. The USGS selected this area because the geologic and hydrogeologic settings are representative of the fractured, metamorphic rocks of the Piedmont.

Rivers in the Lawrenceville area exhibit a poorly developed rectangular drainage pattern. This pattern is believed to largely reflect the intricate joint systems that break up the rocks in this area but may also be locally influenced by rock foliation and geologic structures.

The City of Lawrenceville and the smaller study area described in this report are entirely underlain by metamorphic rocks (Figure 1). The rocks that underlie the area have a wide range of lithologies and therefore a wide range of physical and hydrologic properties. The differences in hydrologic properties are mainly the result of differences in chemical weathering of various rock types and the degree and abundance of fracturing

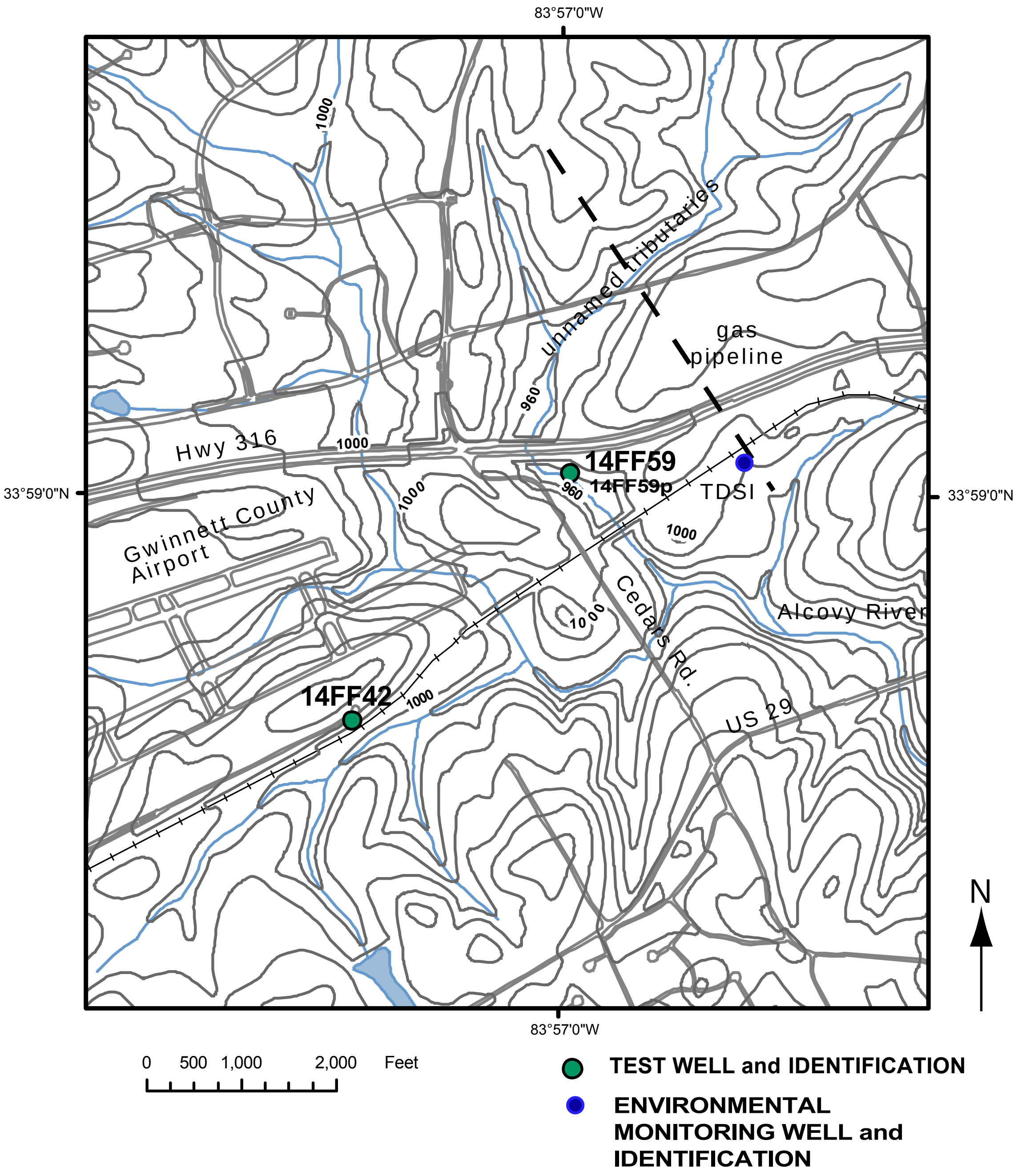


Figure 2. Gwinnett County Airport area showing test-well locations and topography.

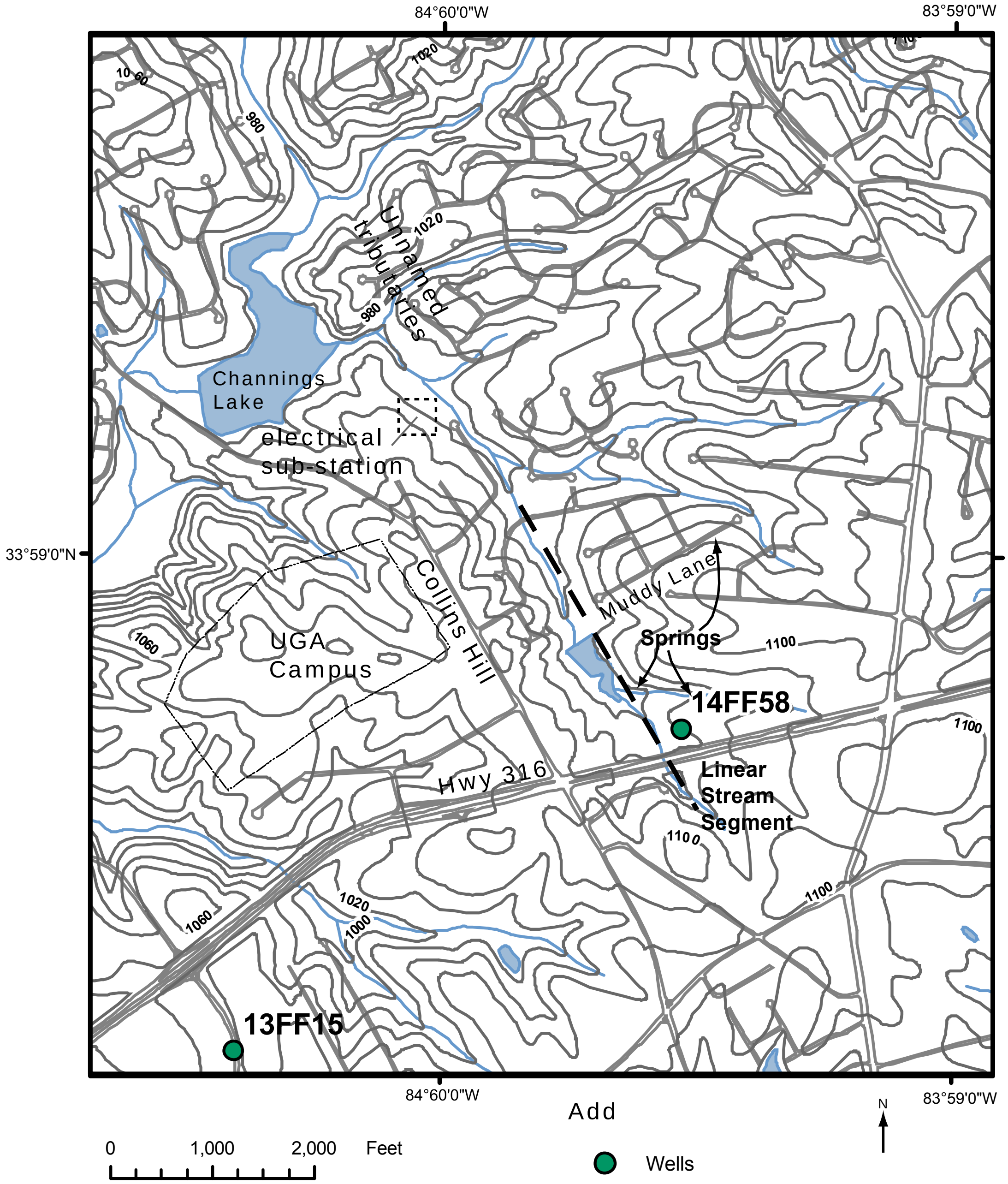


Figure 3. Collins Hill Road area showing test-well locations and topography.

that occurs due to brittle deformation. Brittle deformation is loosely defined in this report to include all of those structures, such as faults and jointing that have broken the rock in a brittle fashion as opposed to the ductile deformation occurring during metamorphism.

The metamorphic rocks in the vicinity of Lawrenceville, and in most areas of the Piedmont, do not have any significant primary porosity or permeability. It is the development of secondary porosity from fractures and the resulting permeability that allows these metamorphic rocks to store and transmit groundwater.

High-yielding, water-bearing fracture zones in the vicinity of Lawrenceville, GA, (Chapman and others, 1999) occur as a result of many factors. The most important factor is believed to be differential weathering that occurs at contact zones between different rock types and along compositional layering in multi-layered rocks (Williams and others, in progress). Differential weathering occurs as a result of rocks of varying composition and texture chemically weathering at different rates. These fractures along with other types of fractures in bedrock can be enlarged by dissolution and if open, can transmit large quantities of groundwater to a single well.

Because the rocks in the Lawrenceville area dip at very low angles, the fractures formed parallel to compositional layering/foliation are sub-horizontal and therefore can receive recharge from a relatively wide area. High-angle joint sets, which are pervasive throughout the rocks in the area, are probable conduits through which groundwater can recharge the sub-horizontal system of foliation fractures. The combination of sub-horizontal water-bearing fractures and high-angle joint sets is thought to be a key reason for the occurrence of the unusually high-yielding wells in the vicinity of Lawrenceville, GA (Williams and others, in progress).

Groundwater storage in metamorphic rocks occurs in fractures and in the overlying soil/saprolite. Conventionally, the soil/saprolite is thought to store the bulk of the groundwater in these systems and is often characterized as a "groundwater sponge" that feeds the underlying fractured rock system. Zones of joint concentration, fractures enhanced by dissolution, and brittle faulting in bedrock could also provide significant groundwater storage on a local scale.

Purpose and Scope

This report addresses results of a local-scale groundwater resource study conducted in the vicinity of the Gwinnett County Airport and Collins Hill Road. This sub-study unit of the larger cooperative groundwater resources project focuses on the importance of understanding geologic setting and its relationship to developing groundwater from fractured, metamorphic bedrock aquifers. Prior to this study, it was generally recognized that well yields in Lawrenceville were often related to lithology and usually associated with a dominant sub-horizontal water-bearing fracture zone. The findings of this study are presented to document the importance of all the aspects of geologic setting that should be considered when locating the most suitable sites for a groundwater supply including: (1) rock types, (2) structure, (3) topographic position, (4) depth of weathering, (5) recharge potential (6) and interrelationship between all the factors. Tom Crawford, retired professor emeritus of Geology at the University of West Georgia, originally proposed these six factors, through many years of experience in studying groundwater resources in the Georgia Piedmont (personal communication).

The results of this report document the geologic setting at three USGS test-drilling sites. Two of the well sites are characterized by poorly developed geologic structure and poor recharge potential. Favorable rock types, structural discontinuities, good topographic position and excellent recharge potential characterize the third well site.

The scope of this study included detailed geologic mapping, test-well drilling and collection of borehole geophysical logs to identify the presence and orientation of subsurface fractures. The surface expression of geologic contacts are presented at the 1:12,000 scale and generally conform to the units mapped at a larger scale during earlier efforts (Chapman, 1999, plate 1).

During my internship with the USGS, my involvement in the overall water resources project was focused on the two sub-areas (Gwinnett County Airport and Collins Hill Road). I logged both new wells during drilling and assisted in the collection of all the geophysical borehole logs discussed in this report. Geologic mapping has been conducted over the duration of the project, and my involvement was isolated to the last phase of mapping.

Location and Description of the Study Area

This report presents data from two study sites in the vicinity of Lawrenceville, GA (Figure 1). The first site encompasses the Gwinnett County Airport and several undeveloped properties located east of the airport near the intersection of Cedars Road and GA Hwy 316 (Figure 2). Well 14FF42, which was previously characterized by Chapman and others (1999), is located south of the airport on a flat ridge top underlain by massive unfractured amphibolite. Well 14FF59, which was drilled during the most recent USGS investigations, is located approximately 3,100 feet east of 14FF42 in the stream valley of the Alcovy River where a jointed amphibolite was noted during field mapping.

This site was selected because it exhibited many of the characteristics often associated with high-yielding well sites in the Lawrenceville area.

The Collins Hill study site is located on the north side of Hwy 316 in a wooded area approximately 1,000 feet east of the intersection with Collins Hill Road (Figure 3). This site was selected because it is near a contact zone between granite gneiss and biotite gneiss. A prominent northwest-southeast trending topographic lineament at this site marks the lithologic boundary between the two rock units (Figure 3). A small spring-fed creek flows from the site into a man-made impoundment several hundred feet north of the well site. The unnamed tributary eventually empties into Channings Lake, one of several large man-made lakes in the headwaters of the Yellow River Basin. The Collins Hill site is characterized by an abundance of springs.

Previous Studies

Herrick and LeGrand (1949), conducted the first major study of groundwater resources in the Atlanta Area. Herrick and Legrand state, “The occurrence of groundwater in the Atlanta area is dependent on many different- though in part closely related- factors. Among these factors are rock type, structure, weathering, and topography” (Herrick and LeGrand, 1949 p. 9).

A report by Cressler and others (1983) on groundwater resources of 27 counties in the Atlanta Metropolitan area was the first comprehensive work to discuss geologic factors affecting groundwater availability in the fractured rocks of the area. Results from that study indicated that large well yields are available only where aquifers have “localized increases in permeability”, usually in association with structural and stratigraphic features including (1) contact zones between rocks of contrasting character and within multi-layered 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. Cressler and others (1983) presented methods for selecting high-yielding well sites using these structural and stratigraphic features.

The most detailed geologic mapping for the Lawrenceville area was presented in Chapman and others (1999). A lithologic map showing the distribution of major rock types and fault contacts at the 1:24,000-scale is provided for the approximately 44-mi2 Lawrenceville area. The authors divide the numerous rock types exposed in the area into seven principal lithologic units. McConnell and Abrams (1984) compiled previous geologic mapping in the Atlanta area. In the Lawrenceville vicinity, they used a map compiled by Atkins and Higgins (1980) in the Luxomni quadrangle and a modification of the 1:24,000-scale reconnaissance map by Atkins and Morris (1982) and Dooley (unpublished). Higgins and others (1988) published a study of the structure, stratigraphy, technostratigraphy, and evolution of the southernmost part of the Appalachian orogen. A geologic map of the Atlanta 30' x 60' quadrangle was also constructed and covers part of the study area and defines the geologic formation names for some of the units west of Lawrenceville (Higgins and others, 1998). Some of the formation names were subsequently revised (Crawford and others, 1999).

The characterization of subsurface fractures at the Rhodes Jordan Wellfield was discussed in Chapman and others (1997) and in Chapman and Lane (1996). Fractures were delineated in four bedrock wells using borehole geophysical logs in correlation with drilling and geologic logs. Chapman has more recently used directional borehole radar surveys to characterize subsurface fractures (personal communication). Orientations (strike and dip) of fractures intersecting the wells have been determined for 21 wells using acoustic televiewer logs, optical televiewer logs, and directional borehole radar surveys.

Chapman and others (1999) present regional-scale results of the ongoing cooperative USGS-City of Lawrenceville water-resources study. In that report, they describe characteristics of major lithologic units, relation of well yield to lithology, and present borehole geophysical logs collected at various well sites. In addition, they present and discuss continuous water-level data collected during the study and the effect of pumping from the Rhodes Jordan well field. Data from wells inventoried during the study are tabulated. Results of groundwater sampling also are presented.

Studies of post-Cretaceous and Cenozoic tectonism are reported by Prowell (1988). Prowell documents the presence of reverse fault systems throughout the Atlantic coastal margin caused by a compressive tectonic stress in eastern continental United States (Zoback and Zoback, 1989). These studies document the presence of Cenozoic age reverse faulting in the southeastern United States. Prowell believes the same compressive tectonism, which is active in other areas of the Atlantic coastal margin, is also actively present in the Piedmont physiographic province of the southeastern U.S. (personal communication, 2001).

Hydrogeologic investigations were performed as part of the refurbishment of the Rhodes Jordan production wells in the early 1990's (Special Environmental Services, 1991; Radzieta, 1993). The investigations consisted of limited geologic mapping, well rehabilitation, test drilling, aquifer testing, watershed analysis and assessment of potential sources of contamination.

CHAPTER 2

METHODOLOGY

General Approach

Many factors must be considered to adequately assess groundwater resources in a fractured, metamorphic bedrock setting. The general approach included first collecting detailed lithologic and structural mapping data and then from this data trying to determine if higher groundwater yields could be predicted prior to test drilling. This project took advantage of the large amount of previous information compiled by the USGS such as the geologic mapping and well inventory characteristics (Chapman and others, 1999). The amount of information available to this study is not typical for the area; most studies would have to collect this basic hydrologic information prior to getting to the level of investigation presented in this study.

In the layered-rock setting at the Gwinnett County Airport area, geologic mapping data were used to project the lithologic units into the subsurface. The position within the basin where the drilled well would ideally intercept specific rock units in the subsurface at depth was determined from this geologic mapping. The USGS had previously determined that sequences of amphibolite, biotite gneiss, and in some cases button schist where exposed to deep chemical and physical weathering in Lawrenceville. These sequences have the propensity for the development of productive sub-horizontal foliation fracture systems in the area, and therefore these rock types were considered favorable for high groundwater yields. Consideration was also given to topographic position, recharge potential and depth of weathering.

A topographic lineament in the Collins Hill Road massive-rock setting was noted during mapping and appeared to be the result of preferential weathering along a zone of intense jointing. It was thought that the zone of jointing may possibly extend into the bedrock and result in a high-yielding well, despite the relatively low yields previously observed from wells penetrating this unit. Considerations were also given to the possibility of intercepting other sequences of rocks in the borehole at this location.

Test borings were drilled in each area to document the subsurface lithology and yield. The USGS conducted geophysical logging at each of the well sites to determine the subsurface characteristics, including documentation of the location and yield characteristics of subsurface bedrock fractures.

Additional detailed geologic mapping was conducted in each area following the subsurface characterizations to confirm geologic contacts. During this period, efforts were taken to try to correlate surface and subsurface relations.

Site Selection

As first noted by Cressler and others (1983), high-yielding well sites needed for municipal supply are only found in areas where the bedrock aquifers exhibit local increases in permeability. Six factors are proposed in controlling well yield in metamorphic and igneous rocks: (1) rock type(s); (2) structure: discontinuities due to compositional differences and fractures; (3) depth of weathering; (4) topography; (5) area of groundwater recharge; and (6) spatial relationship of rock type and discontinuities to topography, depth of weathering, and potential recharge area (Crawford and Kath, 2001; Kath and others, 2001). These authors indicate that rock type is by far the most important factor since rock type controls the type of water-bearing structures that will be developed, and it controls the depth of weathering which affects the thickness of saprolite and hence groundwater storage in the aquifer.

Well sites14FF59 and 14FF58 were selected using some of the above factors and from using local knowledge of the hydrogeology in the area (Table 1).

Table 1. Geologic factors considered during selection of drilling sites

Factors	Well 14FF58 (Collins Hill Road)	Well 14FF59 (Hwy 316)
Rock types	Biotite gneiss (favorable) and granite gneiss (unfavorable)	Amphibolite (favorable), button schist (unfavorable), biotite gneiss (favorable)
Structure	Major contact between rocks of contrasting character, zone of joint concentration expressed by topographic lineament	Concentrated jointing noted in rocks exposed in stream valley; brittle features noted in rocks east of well site; compositional layering/foliation dipping down basin
Depth of weathering	Deep	Shallow
Topography	Slope near headwaters of small creek	Stream valley
Area of groundwater recharge	Small; non-favorable rock types for depths of weathering in upstream portions of basin	Large; favorable deeply weathered rock types exposed in upstream portions of basin
Spatial relation of all factors	Layering in biotite gneiss dips toward (southeast) a major contact with granite gneiss; well developed joint sets	Southward dipping sequence of amphibolite, button schist and biotite gneiss dips gently toward the low part of basin; well developed joint sets
Special Features	Spring activity and jointing noted in field surveys	Button schist (non-favorable) is a concern

Site-Specific Geologic Mapping

Site-specific geologic mapping refers to the detailed mapping conducted near a potential well site in order to identify the major and minor lithologic units and to identify potential structural and textural characteristics that may enhance groundwater availability at the site. The USGS conducted mapping by walking traverses along roads, creeks and rivers throughout the area.

The first step in the geologic mapping effort was to identify the major rock types outcropping in the area and to differentiate them into mappable lithologic units. The lithologic units originally defined by Chapman and others (1999) were used for the mapping with some refinement. Textural and structural characteristics were also taken into account when differentiating the mapping units.

The accuracy to which a specific unit can be mapped is partly a function of the scale at which the map will be drawn. For the purpose of this project, the maps were constructed at a 1:12,000-scale. The following features, if present, were recorded at each mapping station: (1) rock type(s); (2) strike and dip of foliation and/or compositional layering; (3) strike and dip of joints and degree of jointing; (4) trend and plunge of small scale fold axes; (5) observed thickness of overlying soil/saprolite; (6) nature of differential weathering on different rock types and (7) brittle features.

In the absence of exposed hard bedrock, the general character of the saprolite was used to identify the underlying rock type(s). Where exposed, saprolite often retains relic structures such as foliation and joint surfaces that can be measured. The strike and dip of planar features such as joints or foliation planes were measured with a Brunton compass and recorded in a field notebook by station number.

Joints are the most common and easily recognizable structural features in outcropping rocks in the study area. The strike and dip of individual joints and joint sets were noted. The relative degree of jointing was recorded as “abundant” if the joints were repeated numerous times across the outcrop, “common” if the joints had a normal occurrence in relation to the regional area, and “scarce” if only a single joint was observed. The above terminology was used by Chapman and others (1999) during their original mapping in the area.

Structural information was obtained in some areas on small-scale folds that were on the order of several 10’s of feet in amplitude. Trend and plunge of fold axes were measured where these features were identifiable.

It was possible to get a qualitative sense of the depth of weathering by noting the exposed thickness of saprolite along stream banks, road cuts and other man-made excavations throughout the mapping areas. The most significant of these excavations were along an alignment of a gas pipeline that was being installed during the fall of 2000 and spring of 2001 (see dashed line, Figure 2). The presence of rock fragments and exposed bedrock was taken as an indication of thin saprolite development. Thin saprolite development generally occurs on exposed granite gneiss, amphibolite, and button schist in the area. The absence of rock fragments and poor exposure of rock outcrops in stream valleys and on hilltops was taken as an indication of a thicker saprolite development. The feldspar-rich biotite gneiss unit appeared to exhibit the deepest depth of weathering of the rock types mapped in the area.

Brittle fracture zones were observed in outcropping rocks on very rare occasions. These features are characterized by the presence of abundant irregular fractures, brecciated and broken rock and small offsets indicating movement along these zones. A zone of intense fracturing and brecciation of rock was observed at the end of the pipeline excavation just south of Hwy 316 on a property owned by Total Distribution Services Inc. (TDSI) (Figure 4).

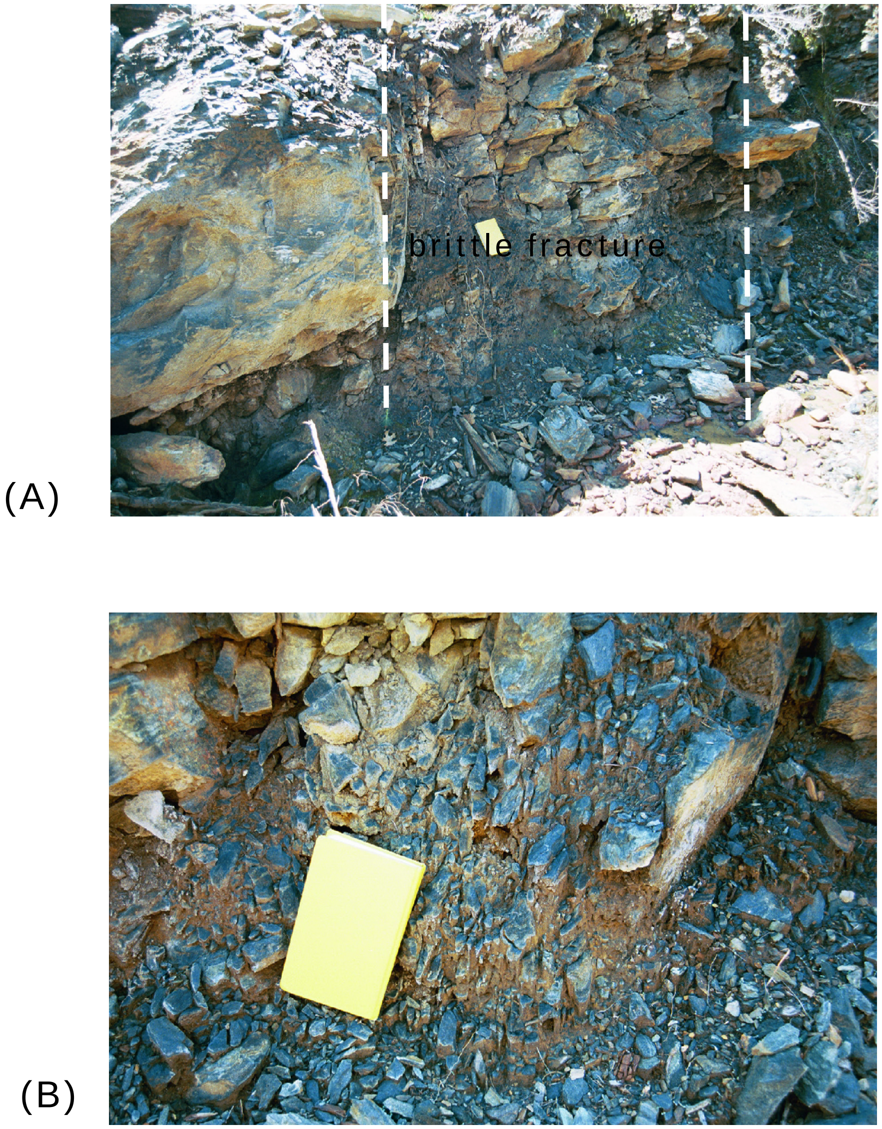


Figure 4. Heavily fractured and jointed amphibolite exposed in pipeline trench near Total Distribution Systems Inc. showing (A) a 10-foot wide fracture zone, between dashed lines; zone is roughly oriented NE-SW and is steeply dipping, and (B) close up of fracture zone showing angular pieces of amphibolite (black). Notebook for scale.

Test Drilling and Well Completion

Drilling was used to obtain detailed information about rock types, fracture zones, rock fabric and aquifer properties (Figure 5). High-yielding water-supply wells in the Piedmont are usually “drilled” as open-rock wells although some shallow bored wells have been known to supply moderate amounts of water. Two of the three test-wells (14FF58 and 14FF59) discussed in this report were completed using air-rotary drilling methods and constructed as open-rock wells. Well 14FF42 was initially drilled with wire-line coring to a four-inch diameter and later reamed out (enlarged) to a 6-inch diameter drilled, open-rock well. Drilled, open-rock wells installed during this study were constructed by first advancing a large-diameter boring through the unconsolidated soil, saprolite and broken rock using air-rotary drilling methods. A foaming agent was added to the air stream in order to stabilize the borehole and prevent collapse. A length of casing made of PVC was lowered into the borehole and bentonite was used to seal off the overburden. Carbon steel casings are required for all public water supply wells, but PVC can be used as temporary casing. All of the test-wells drilled in this study were initially cased with PVC and sealed with bentonite so that the casing could be more easily removed later. Because of the high yield, well 14FF59 was later reamed and completed with steel casing.

An open borehole, the same diameter as the casing, was drilled into the underlying bedrock following casing installation. Rock cuttings, which were returned to the surface via air and water, were collected during drilling at 10-foot intervals. Cuttings for wells 14FF58 and 14FF59 were first logged at the well site and then later examined more carefully with a hand lens and stereomicroscope to determine the mineralogy. The

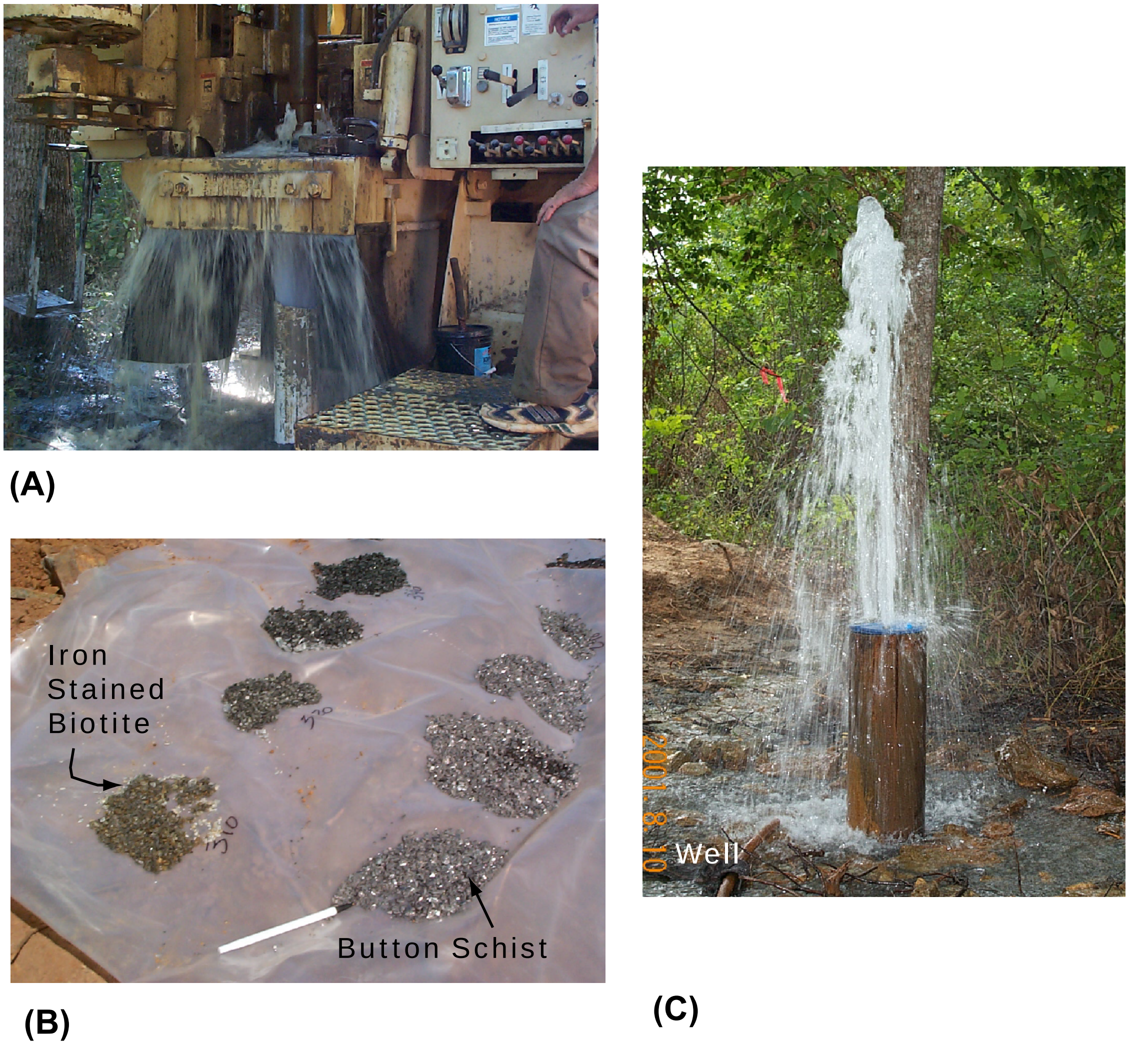


Figure 5. (A) Air-rotary drilling of 6-inch borehole, (B) rock drill cuttings and, (C) completed well 14FF59 flowing approximately 40 gal/min out of two 1-inch openings through the blue pressure cap installed at the top of casing. The top of the stream of water is about 5.5 feet above ground surface. Photo C by Randy L. Kath.

rock-core collected at 14FF42 was previously logged by the USGS (Chapman and others, 1999). Lithologic logs, as they are presented in this report, were then prepared based on this data.

Depth, changes in lithology, drilling rates, size of rock fragments and the color of the drilling fluid were recorded during drilling. If the color of the drilling fluid changes, it can indicate a lithology change. Relative changes in drilling rates could also be the result of a change in rock type or the presence of a fracture.

Water-bearing zones in crystalline rocks were also identified during the drilling process by carefully observing the drilling rate, denoting “drilling breaks”, and frequently measuring the amount of water being evacuated from the borehole. A “drilling break” occurs when the down-hole air hammer (which is exerting considerable pressure) encounters either an open void, a zone of increased fracturing, or a weak area in the rock. Large, open, water-bearing fractures exhibited an increase in “chattering” of the drill rods followed by a distinct vertical drop and an almost immediate increase in the returned volume of water. Non-water-bearing or low-yielding fractures cause drilling breaks having minor chattering and small rod drops, but without an increase in returned volume of water. Water-bearing fracture zones also typically resulted in an increase in the size of the drill cuttings, presence of iron oxide staining on the cuttings, and in some cases large angular rock fragments that appeared to be broken out of fracture zones.

The airlift yield was typically checked after encountering a water-bearing zone by conveying the return water into a bucket where a stopwatch can be used to calculate the flow rate. Reported airlift yields are generally thought to be accurate enough to determine the approximate contribution from various water bearing fracture zones.

Both wells 14FF58 and 14FF59 were originally constructed as 6-inch diameter open-rock wells with 6-inch temporary PVC casing. Well 14FF59 was initially inspected with a downhole camera to identify shallow fractures and was later reamed to an 8-inch diameter and finished with a permanent steel casing. Well 14FF59 required a casing depth of 25 feet in order to seal off shallow fractures and meet the state requirements for casing depths for public water-supply wells.

Installing the 2-inch monitoring well at site 14FF59 involved advancing a 6-inch air-rotary borehole down to the top of competent bedrock, assembling the monitoring well and then lowering it into the open borehole. Filter-sand was poured down the open borehole and tamped around the screened portion of the well to approximately 2 feet above the top of the screen. Bentonite chips were used to fill the remainder of the borehole annulus and allowed to hydrate.

Borehole Development and Driller's Short-Term Yield

Drilled, open-rock wells do not require significant cleaning or "development" to prepare them for permanent use. The driller will continue to air-lift water out of the borehole once the total depth is reached until the return water is relatively clear and does not contain appreciable sand or rock fragments. Higher yielding wells (i.e. 14FF59) usually take longer to develop than lower yielding wells (i.e. 14FF58).

Well 14FF59 had a reported air-lift yield of 180 gpm after completion of the original 6-inch diameter test-hole compared to the 400-500 gpm air-lift yield obtained after reaming. The drill rig reached its capacity while airlifting the 6-inch borehole, and therefore probably under-estimated the airlift.

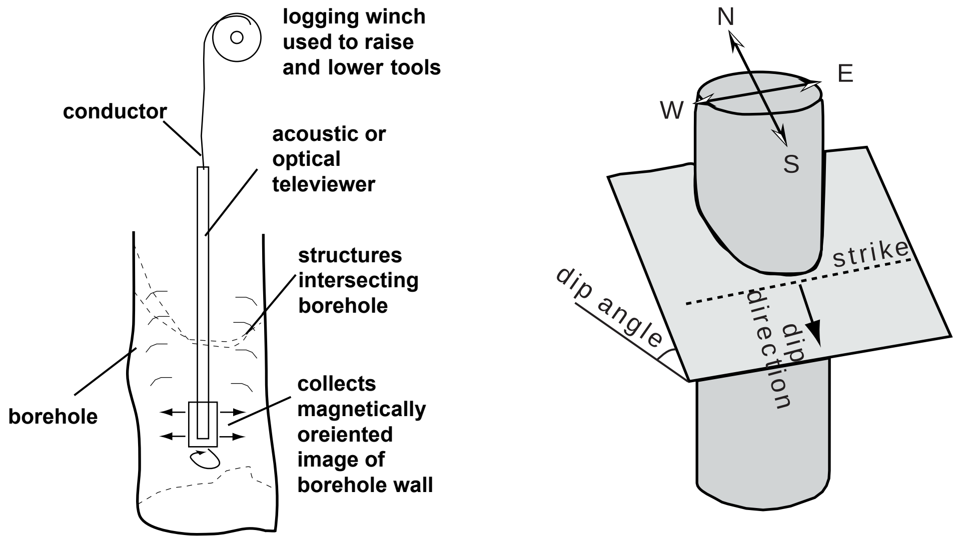
Borehole Camera

The color borehole television camera or "downhole camera" was used to visually inspect open-rock boreholes and to document the presence of intersecting joints, fractures and other structures in the subsurface. Borehole camera surveys were conducted on all three of the wells included in this study. A GeoVISION^{TM} high-resolution camera was used to collect the video images. Because the GeoVISION^{TM} camera has a fixed head, a survey was first conducted with the camera head pointed straight downward and a second survey with the head oriented in a horizontal position. The downward-looking survey provided the best view of high-angle fractures and large, open fractures intersecting the boreholes. The horizontally oriented survey allowed viewing of small-scale structures and allowed viewing back into open, horizontal fractures.

Borehole Geophysical Logging

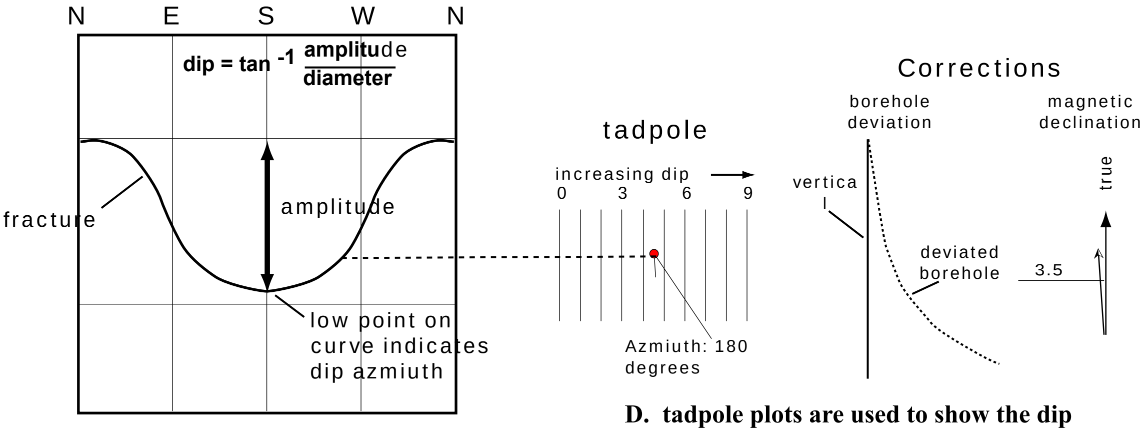
Borehole geophysical logs provide the most effective means available to study the location and nature of water-bearing fracture zones in open-rock wells (Figure 6). A suite of geophysical logs was run in wells 14FF42, 14FF58, and 14FF59. The logging results indicated that borehole imaging techniques using a acoustic televiewer (ATV) or BIPS in combination with the caliper log revealed the best information to locate and characterize subsurface structures in the boreholes. Therefore, this report only addresses the caliper and borehole imaging.

The three-arm caliper tool measures the average diameter of the borehole and is useful in identifying fracture zones in open-rock wells. A "breakout" is defined as an area along a caliper log where the borehole diameter is enlarged. Breakouts are often associated with open fractures (Figures 7, 8 and 9). Zones of weaker or more friable rock



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

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



C. The trace of an intersecting plane makes a sinusoidial wave on a 2-dimensional projection of the borehole wall. The amplitude of the wave and diameter of the borehole are used to calculate dip angle and dip direction.

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

Figure 6. Schematic diagrams illustrating how the strike and dip of a planar feature intersecting a borehole are determined. The calculation assumes the feature is planar (not curved). Corrections for borehole deviation and magnetic declination also is made.

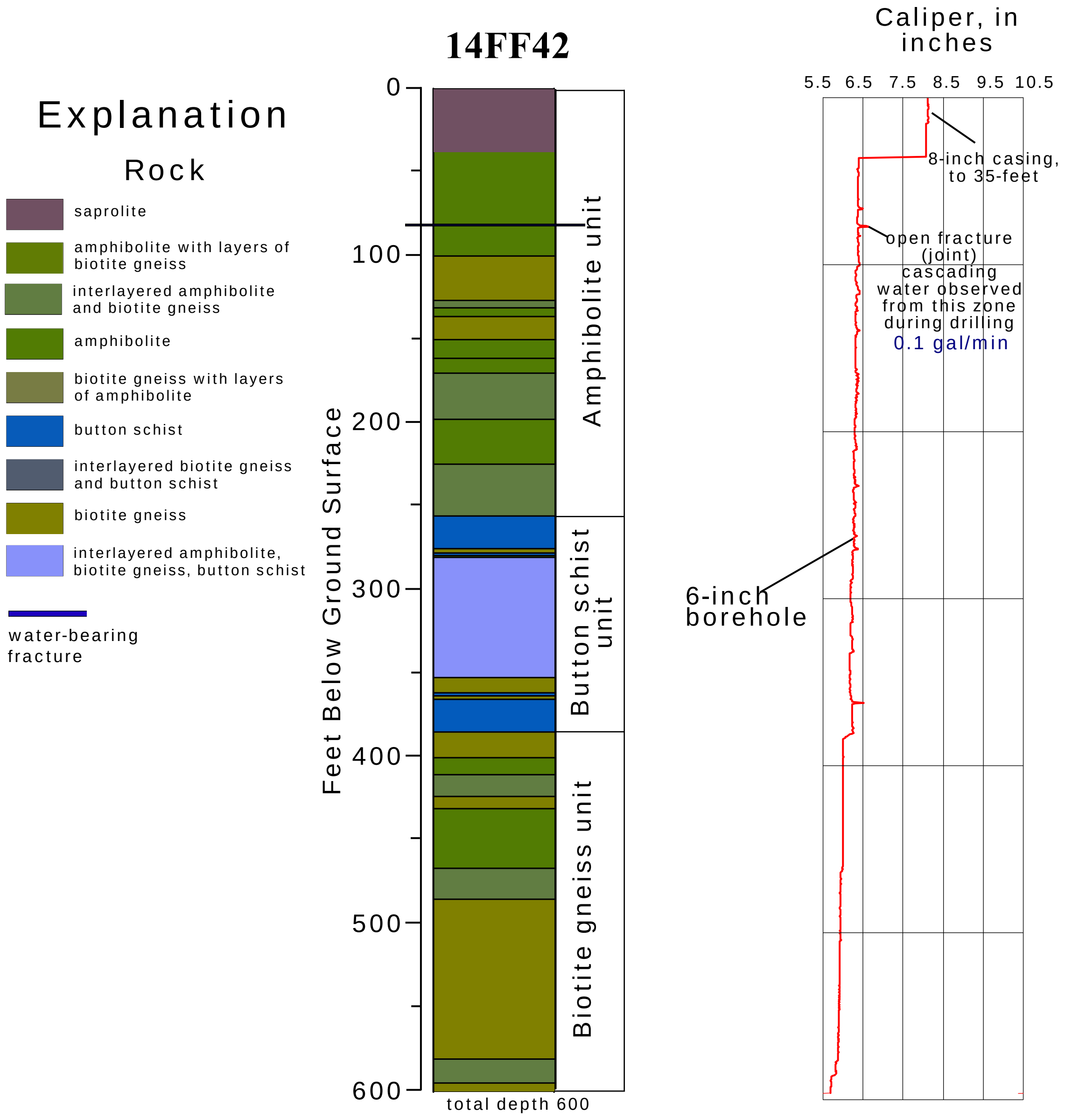


Figure 7. Lithology and borehole caliper log for well 14FF42.

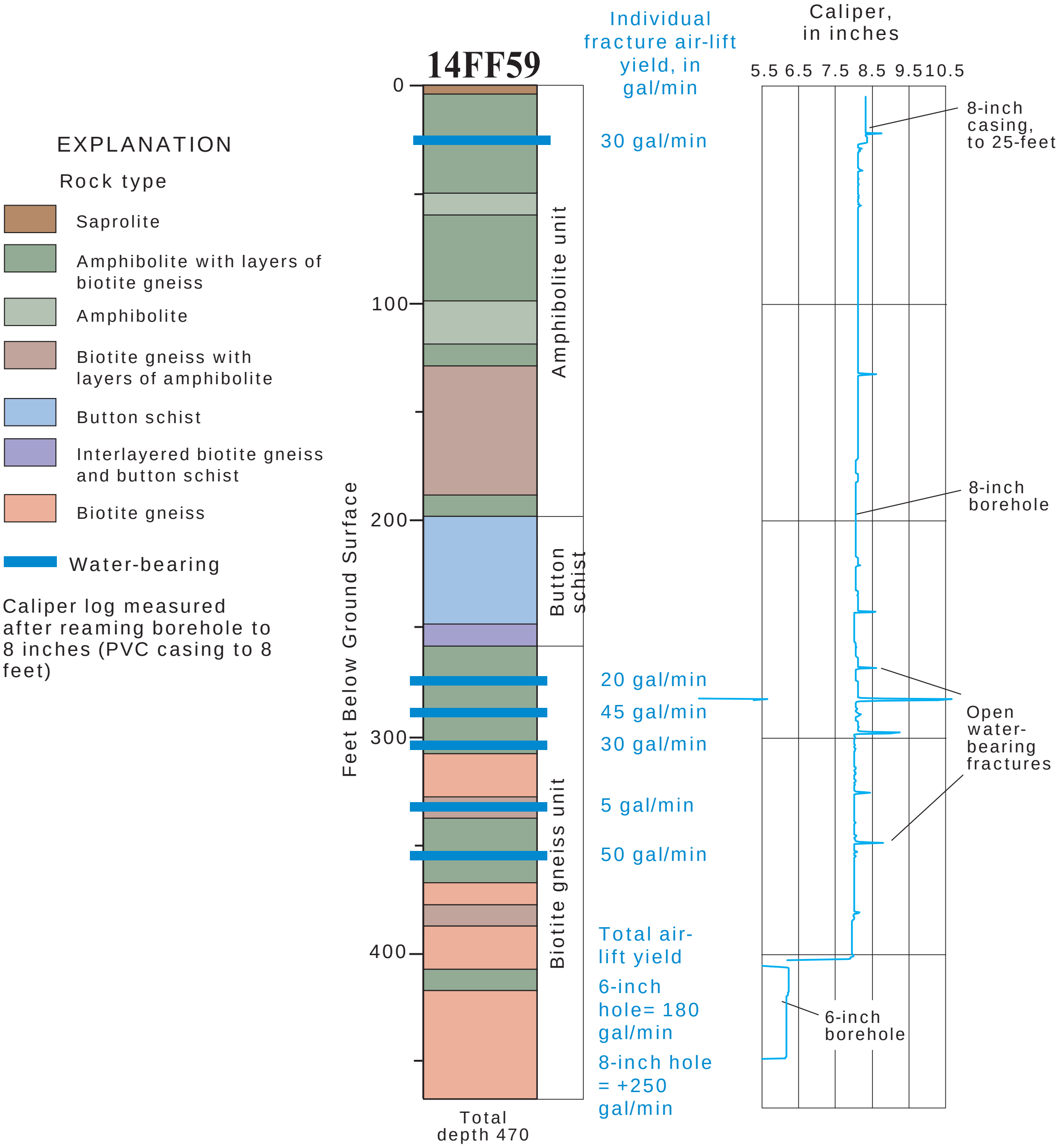


Figure 8. Lithology and borehole caliper log for well 14FF59.

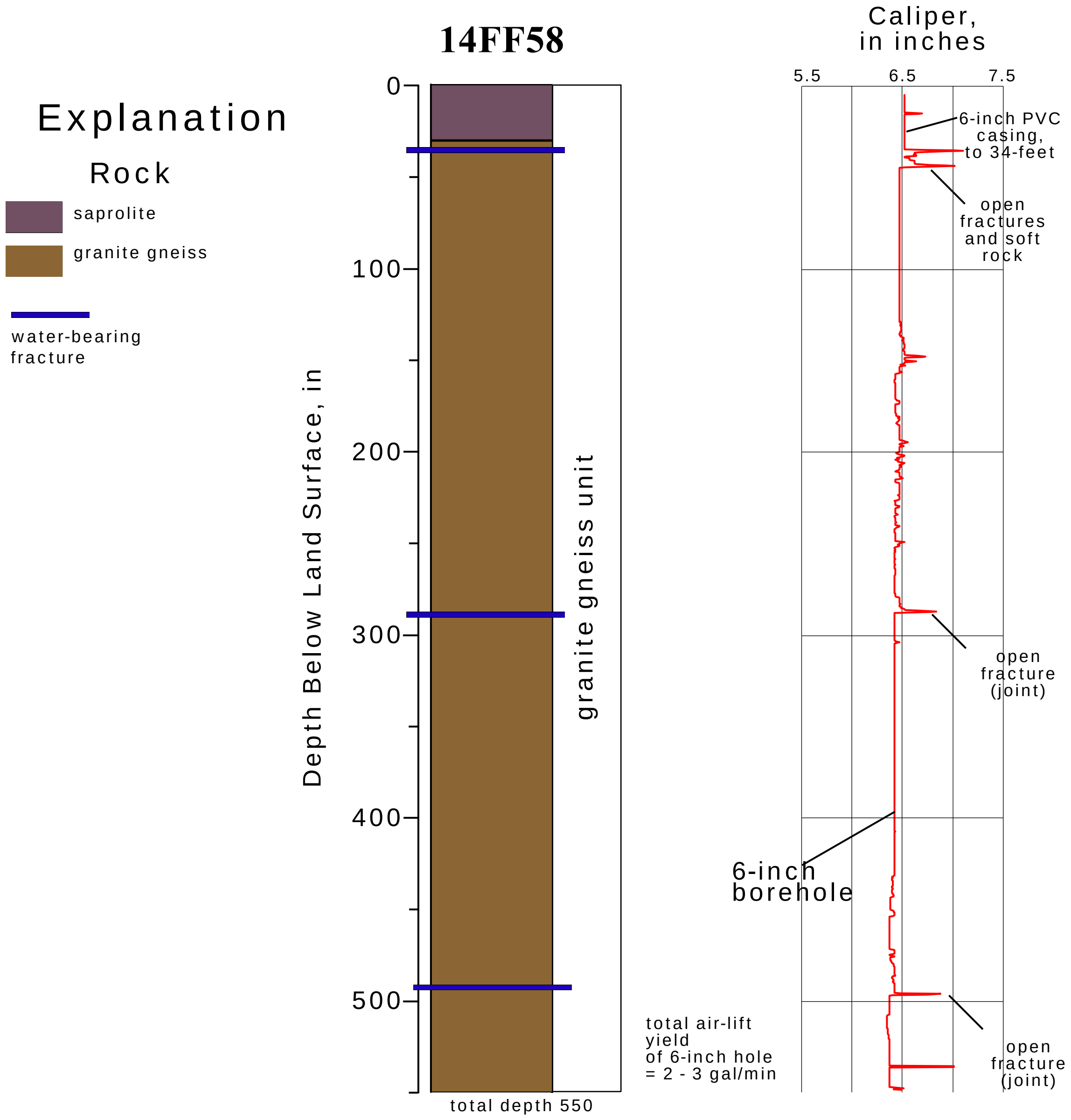


Figure 9. Lithology and borehole caliper log for well 14FF58.

can also create breakouts and therefore should be examined with an ATV and/or a borehole camera. Tight high-angle joints were usually not distinguishable from the caliper logs.

The ATV uses sound waves to collect a magnetically oriented image of the borehole wall. Features such as fractures, voids, and foliation can be identified in the digital acoustic image. The image can be imported into a computer program where the orientation (strike and dip) of planar features can be determined. The ATV requires a fluid-filled hole and therefore can only obtain images below the watertable.

Unlike the ATV, which uses sound waves, the BIPS tool records an optical image of the borehole wall. The BIPS log is significantly higher resolution and allows for more subtle features to be identified. The BIPS image was used in the same manner as the ATV log.

ATV and BIPS logs from many wells in the Lawrenceville area have revealed horizontal or sub-horizontal fractures with apertures of 1-inch to greater than 10-inches in vertical dimension (Williams and others, in progress). Structural interpretations of fracture orientations determined from the ATV and BIPS logs are presented later in this report.

X-ray Diffraction

X-ray diffraction (XRD) was conducted on rock cuttings obtained during drilling of wells 14FF58 and 14FF59 to determine the general mineralogy of the rocks penetrated by each borehole. XRD was conducted at the Department of Geosciences, State University of West Georgia using the reference intensity method (RIM) for determining weight fractions of each component in the rock sample. The reader is referred to Kath and others (1991) for more information about the XRD methodology.

CHAPTER 3

RESULTS

Gwinnett County Airport Vicinity

This section of the report presents data from the Gwinnett County Airport vicinity (GCAV) and wells 14FF42 and 14FF59. Data is presented from 1:12,000-scale geologic mapping and various borehole logs. The major lithologic units are identified and discussed, and observations made from borehole analysis including lithology and fractures are presented.

Geologic Mapping (GCAV)

The map constructed for the area (Figure 10) is a "lithologic map" which separates the major lithologic units underlying the area. A lithologic unit is a specific rock type or a sequence of layered rocks that were grouped into a mappable unit. The amphibolite unit, for example, is actually composed of layers of amphibolite (major rock type) and layers of biotite gneiss. The relative subdivision of rock types into lithologic units, as presented in this report, follow the same nomenclature defined by Chapman and others (1999).

The results of detailed geologic mapping in the GCAV indicate a southward dipping sequence of amphibolite, button schist and biotite gneiss (Figure 10). Each of these units has distinctive lithologic or textural characteristics that allow them to be differentiated. Although this area has a significant amount of exposed bedrock, most of the GCAV was mapped by using saprolite. Saprolite mapping provided a very effective way to determine the underlying bedrock and to estimate the contact

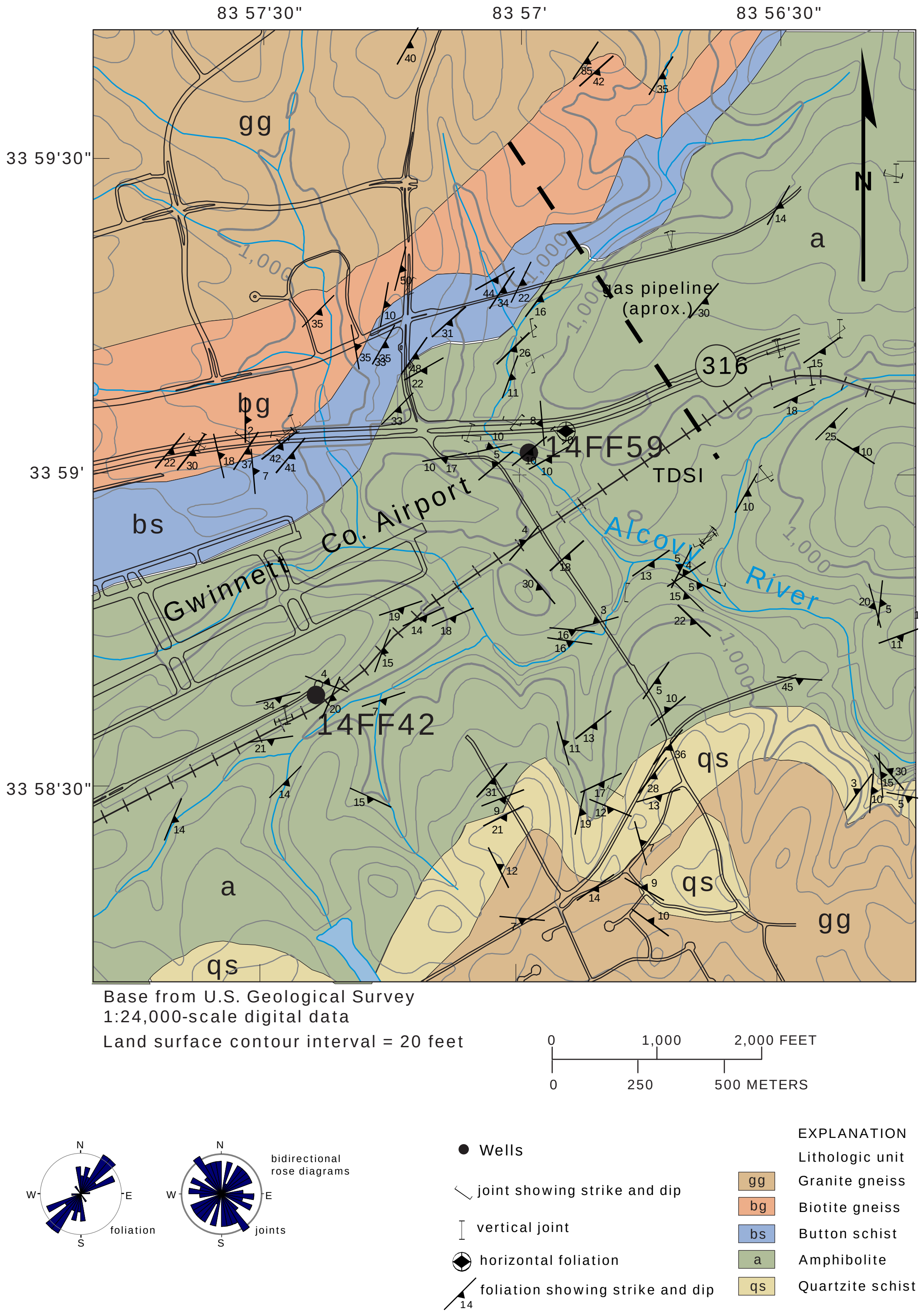


Figure 10. Geologic map for Gwinnett County Airport area. Mapping done by the USGS (R. Kath, T. Crawford, M. Higgins, L. Williams, J. Lawson and others).

location between rock units (Figures 11, 12 and 13). Contacts shown on the lithologic maps are projections and are only accurate where the contacts were noted at specific map stations.

In addition, saprolite/rocks were also exposed along a 3,600-foot pipeline excavation that was made in 2001. The location of the pipeline excavation is shown with a dashed line on Figure 10 based on GPS coordinates collected during field mapping. The pipeline trench exposure allowed a refinement in the contacts between rock units in this area (specifically the button schist contacts) and provided an opportunity to observe the degree of weathering and degree of layering that exists in the rocks of this area. In addition, a smaller section of the pipeline trench located near TDSI and the CSX railroad (Figure 10) revealed a heavily fractured and jointed section of amphibolite. Photographs of the fractured and jointed amphibolite are shown in Figure 4. Because of the intensity of jointing and presence of brecciated rock, this northeast-southwest trending fracture zone was identified as a “brittle fracture zone”. The extent of the brittle fracture zone observed at TDSI is not known. This type of extreme deformation was not seen in any other parts of the study area

Borehole Lithologic Units in the Gwinnett County Airport Vicinity

Wells 14FF42 and 14FF59 were drilled to depths of 600 and 470 ft below ground surface (bgs) respectively. Geologic logs indicate that these wells penetrate three lithologic units: amphibolite, button schist, and biotite gneiss (Figures 14A, 14B, 15A and 15B). The amphibolite unit at 14FF59 extends to a depth of 200 ft bgs and is an interlayered sequence of amphibolite and lesser amounts of biotite gneiss. In this section, the upper 130 ft consist predominantly of unfractured amphibolite and minor layers of

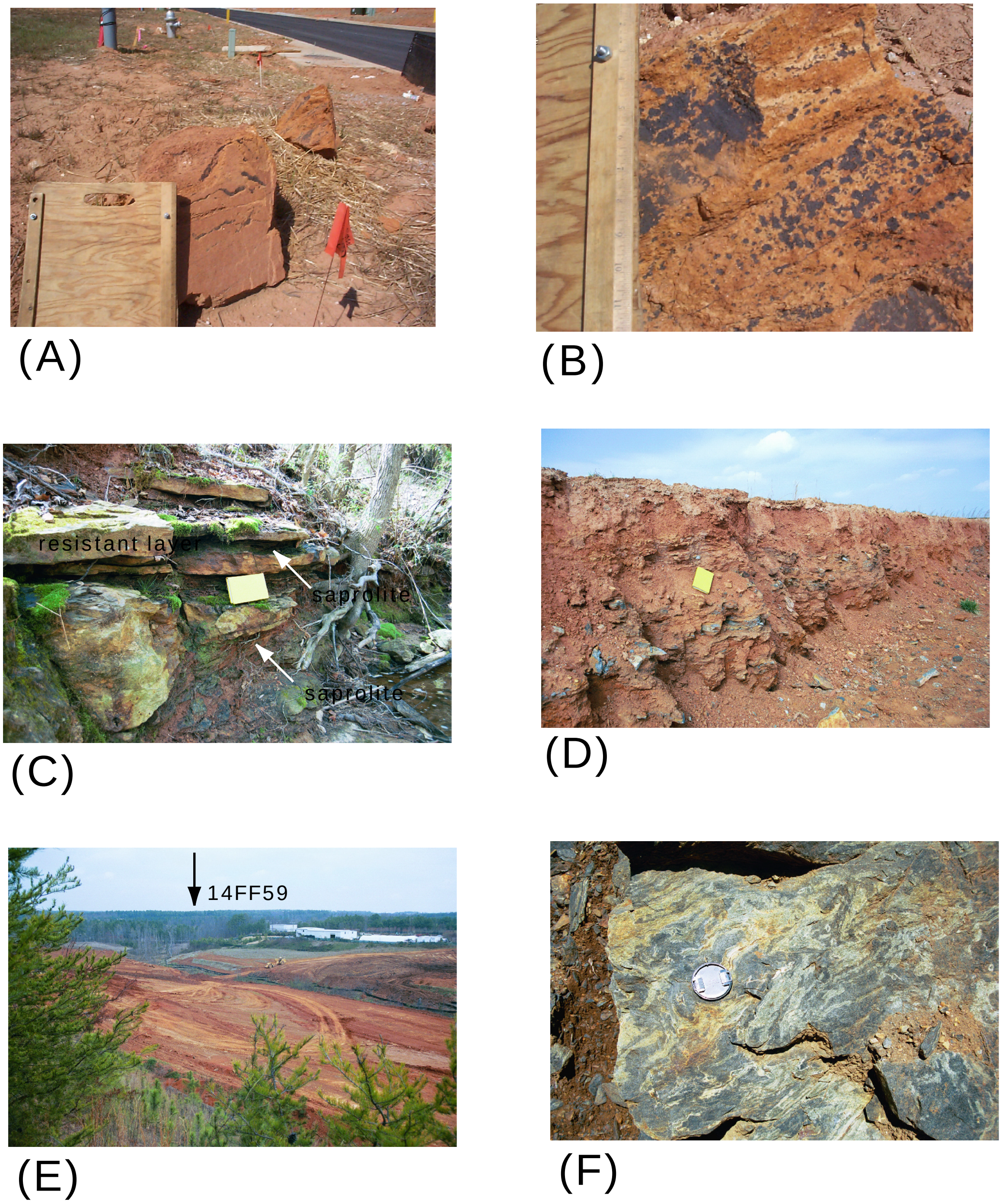


Figure 11. Photographs of amphibolite showing (A) characteristic blocky reddish saprolite formed from amphibolite, (B) close up of saprolite texture, black splotches are probably manganese oxide staining along a relic joint face, (C) outcrop 250 feet north of well 14FF59 showing more resistant layers of amphibolite separated by saprolite, (D) excavation showing deep reddish amphibolite saprolite with thin layers of black amphibolite rock, (E) construction site showing amphibolite saprolite, view is looking north toward well 14FF59 and, (F) unweathered amphibolite showing internal folding in rock. Notebook, lens cap and map board for scale.

(A)

(B)

Figure 12. Photographs of button schist showing (A) button schist saprolite (reddish micaeous soil) with residual mica buttons, (B) button schist outcrop showing well developed button texture. Both photos taken along same road cut. Notebook for scale.

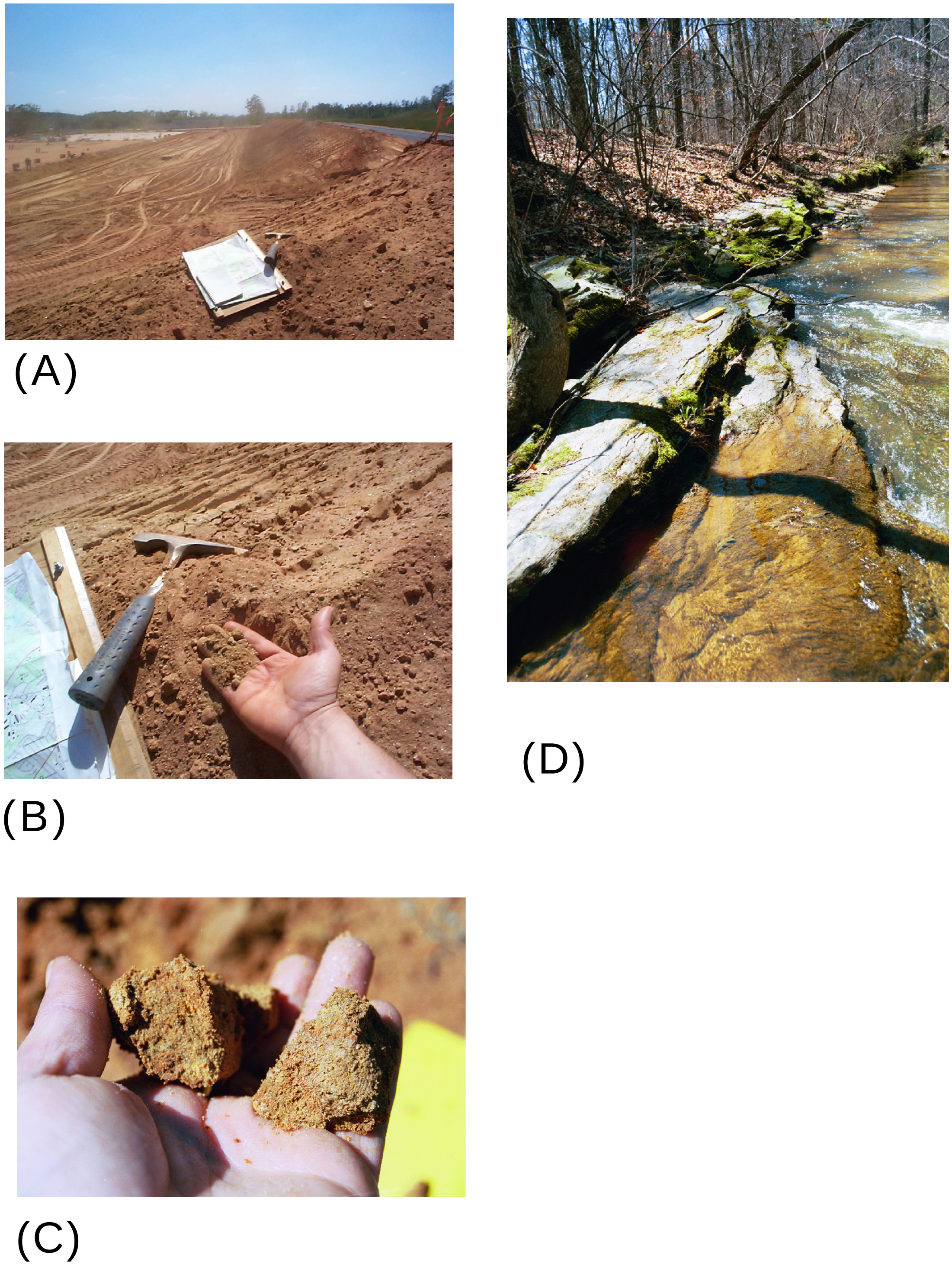


Figure 13. Photographs of biotite gneiss showing (A) biotite gneiss saprolite at a construction site west of Collins Hill Road, (B) closeup of biotite gneiss saprolite texture, note lack of any rock fragments (C) closeup of bitotite gneiss saprolite, note the goldish flakes of vermiculite that are characterisitc of this saprolite, (D) inclined (dipping) layers of biotite gneiss rock exposed along a tributary of the Alcovy River north of Hwy 316. Notebook for scale.

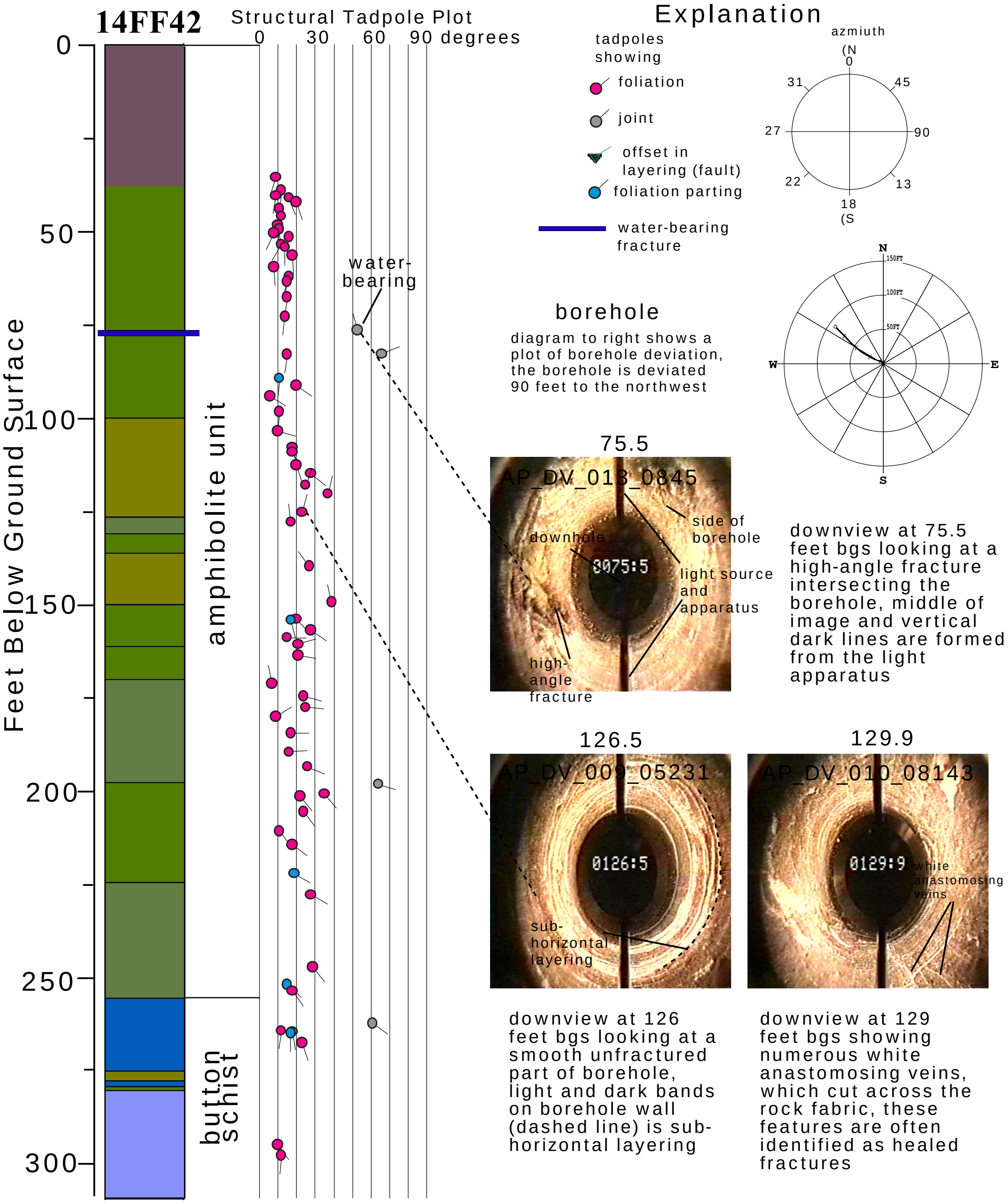


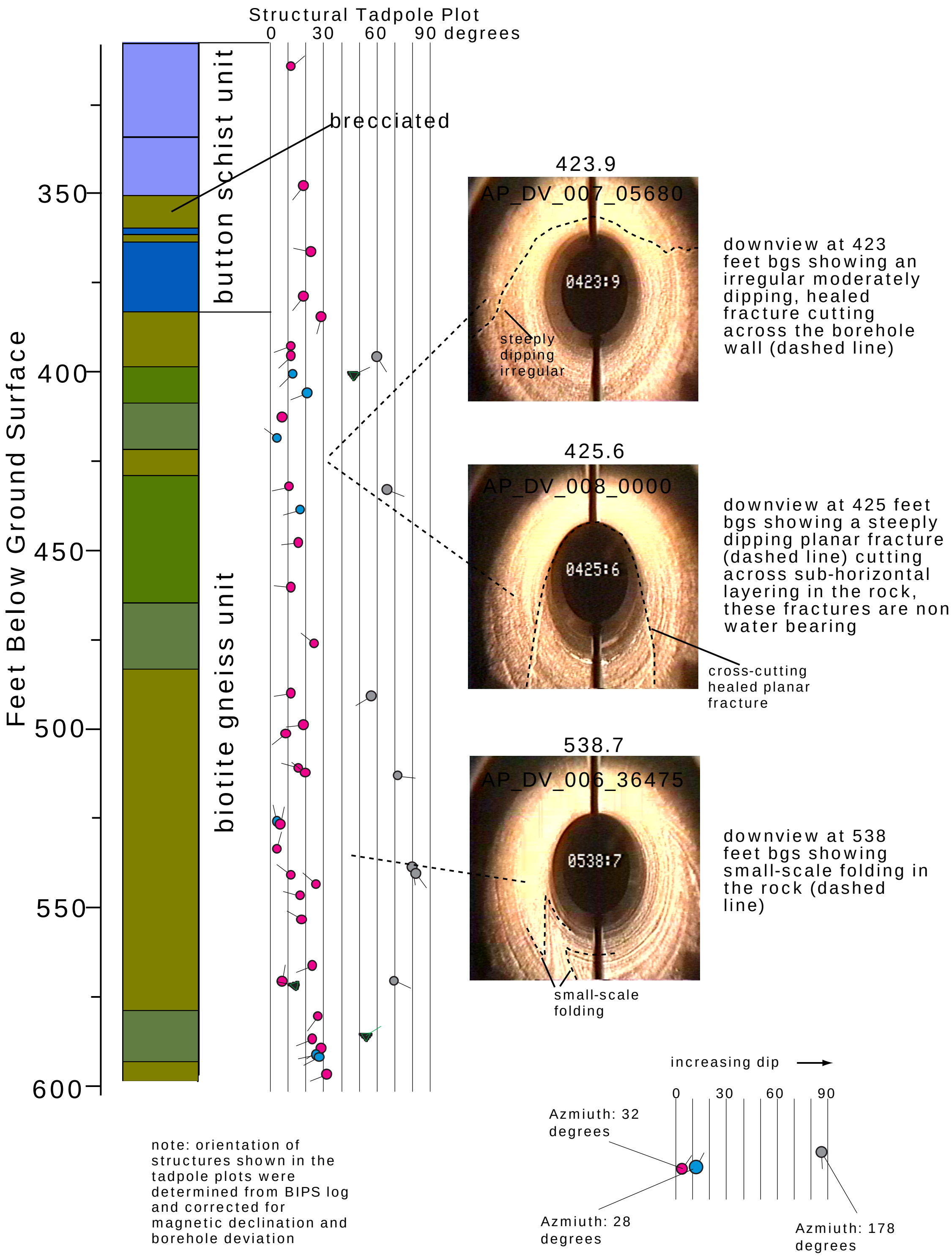
diagram to right shows a plot of borehole deviation, the borehole is deviated 90 feet to the northwest

downview at 75.5 feet bgs looking at a high-angle fracture intersecting the borehole, middle of image and vertical dark lines are formed from the light apparatus

downview at 126 feet bgs looking at a smooth unfractured part of borehole, light and dark bands on borehole wall (dashed line) is sub-horizontal layering

downview at 129 feet bgs showing numerous white anastomosing veins, which cut across the rock fabric, these features are often identified as healed fractures

Figure 14A. Structural tadpole plots and downhole camera images for well 14FF42.



downview at 423 feet bgs showing an irregular moderately dipping, healed fracture cutting across the borehole wall (dashed line)

downview at 425 feet bgs showing a steeply dipping planar fracture (dashed line) cutting across sub-horizontal layering in the rock, these fractures are non water bearing

downview at 538 feet bgs showing small-scale folding in the rock (dashed line)

note: orientation of structures shown in the tadpole plots were determined from BIPS log and corrected for magnetic declination and borehole deviation

Figure 14B. Structural tadpole plots and downhole camera images for well 14FF42.

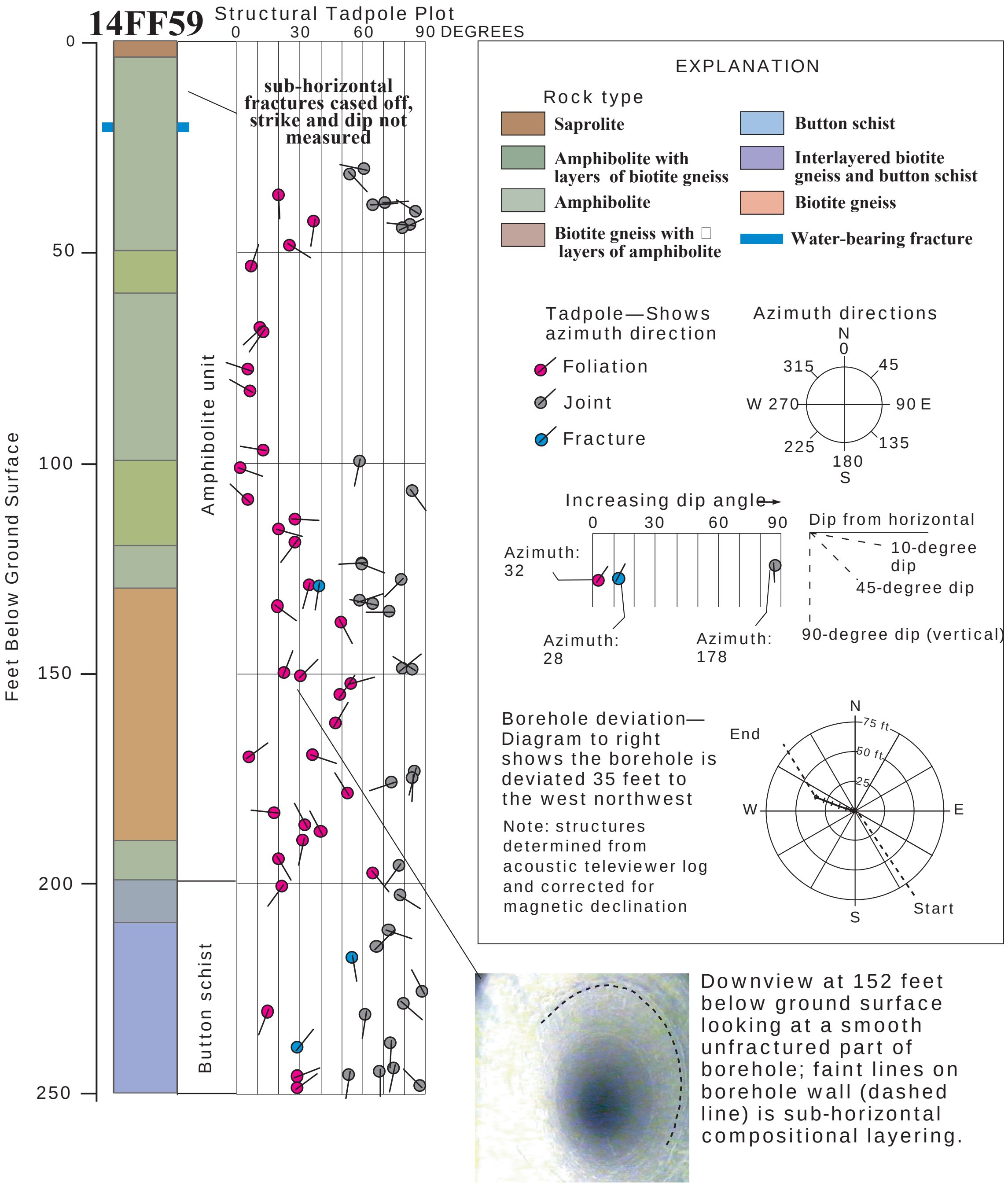


Figure 15A. Structural tadpole plot and downhole camera images for well 14FF59.

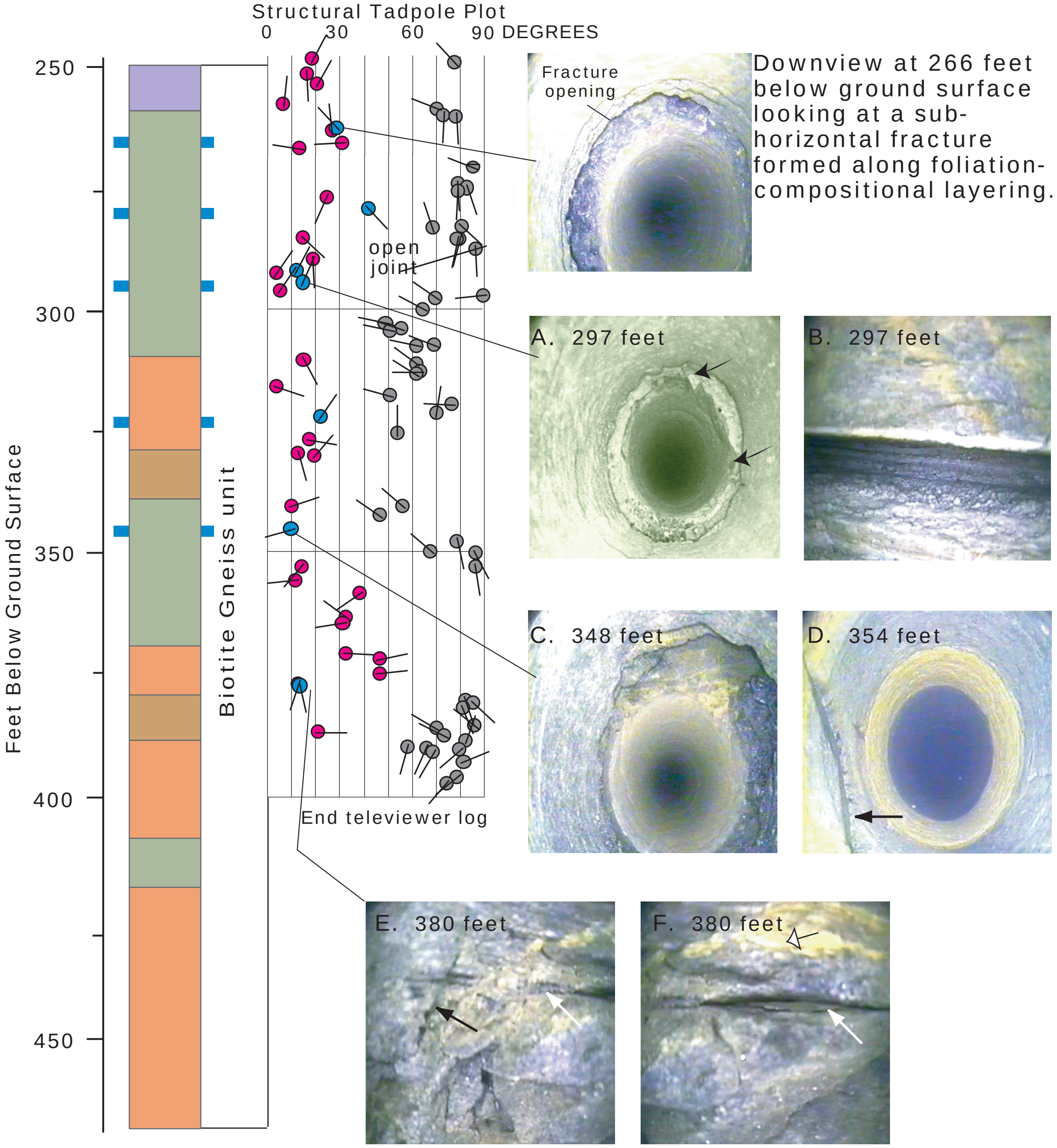


Figure 15B. Images A and B show sub-horizontal fracture at 297 feet below ground surface formed parellel to compositional layering; high-angle joints (black arrows) terminate into the fracture from below; aperature is 3–4 inches. Image C shows the fracture formed at a contact between a darker rock above and a lighter rock below at 348 feet below ground surface, Image D shows layering of light and dark rock and a high-angle joint face (black arrow). Images E and F show the same partially developed fracture (white arrows) along foliation-compositional layering during rotation of the downhole camera, these fractures probably are being enhanced by chemical weathering; yellowish material (open arrow) is a chemical preciptate (calicite or zeolite) formed in small openings of the rock; black arrow shows high-angle joint.

biotite gneiss. Below this, extending to 200 ft, is a unit composed primarily of biotite gneiss and minor layers of amphibolite. This section contains a few intersecting joints but is otherwise relatively unfractured. During drilling, only one large, open fracture was encountered at a depth of 17.5 ft, which airlifted approximately 30 gpm. This fracture was later cased off (Figures 15A and 15B).

Four 10-foot composite samples representing the varying compositions of the interlayered unit were selected for XRD-analysis. The results of XRD-analysis indicate that the amphibolite unit is primarily composed of hornblende and feldspar with varying amounts of biotite (Table 2).

Table 2. Quantitative/qualitative mineralogy of the four samples collected from the amphibolite unit in well 14FF59.

Depth Interval (ft)	**Lithologic Unit**	**Mineral Percent Weight**	**ΔμS**
30 to 40	Amphibolite	57.40% albite, 35.41% hornblende, 7.18% quartz	2.23
100 to 110	Amphibolite	71.81% hornblende, 24.50% albite, 2.07% epidote, 1.62% phlogopite	-8.42
110 to 120	Amphibolite	60.84% albite, 34.46% hornblende, 4.70% biotite	-4.59
170 to 180	Amphibolite	65.82% hornblende, 23.14% bytownite, 11.04% biotite	-2.09

A ΔμS of ±5.00 is needed to establish a good quantitative analysis. Analyses that record a ΔμS over ±5.00 should be considered qualitative and not quantitative.

The amphibolite is composed of hornblende, feldspar, quartz, muscovite, epidote, biotite, garnet, and pyrite in varying amounts. The hornblende tends to be magnesium-rich as opposed to iron-rich. Most of the feldspars were identified as albite during XRD analysis but are more likely oligioclase or andesine. Bytownite was identified in one sample, indicating that the calcium content in the feldspars can vary between the two plagioclase end-members, albite and anorthite. Quartz is not abundant and in some samples is totally absent. Muscovite, biotite, and epidote, when present, were in small amounts (1-11%). Pyrite and garnet were not detected using XRD analysis but were noted as a minor constituent in hand sample.

The button schist unit underlies the amphibolite unit and extends to 260 ft bgs. The cuttings obtained from the upper 10 ft of this section were a mixture of amphibolite and button schist. Below this point, the button schist unit is foliated and exhibits well-developed button texture. Because of its soft character, this unit drilled at a much faster rate than the overlying amphibolite. No significant water-bearing zones were encountered in the button schist. The bottom 10 ft of this section is a gradational zone between button schist and biotite gneiss (Figures 15A and 15B).

Two 10-foot composite samples were selected for XRD-analysis, which represent the varying composition of the button schist unit. The results of XRD-analysis indicate that the button schist unit is primarily composed of biotite, feldspar, and quartz (Table 3).

Table 3. Quantitative/qualitative mineralogy of the two samples collected from the button schist unit in well 14FF59.

Depth Interval (ft)	**Lithologic Unit**	**Mineral Percent Weight**	**ΔμS**
210 to 220	Button Schist	56.61% quartz, 23.00% albite, 20.39% biotite	25.65
240 to 250	Button Schist	57.78% quartz, 15.69% albite, 11.58% biotite, 11.49% pyrope, 3.46% chlorite	1.85

A ΔμS of ±5.00 is needed to establish a good quantitative analysis. Analyses that record a ΔμS over ±5.00 should be considered qualitative and not quantitative.

The button schist is composed of quartz, feldspar, biotite, chlorite, and garnet. Quartz is the most abundant mineral. Albite was identified as the feldspar during XRD analysis, but the feldspars are more likely oligioclase or andesine. Biotite is abundant in this rock type and tends to be iron-rich. Chlorite, when present, is in small amount (<5%). Garnet is found as an accessory metamorphic mineral, and when present, can be in moderate amounts (>10%).

Biotite gneiss was the last lithologic unit encountered during the drilling of well 14FF59. This unit extends from 260 ft bgs to 470 ft bgs and is an interlayered sequence of biotite gneiss and lesser amounts of amphibolite. The upper 50 ft of this section is a highly jointed amphibolite with layers of biotite gneiss. Three major water-bearing fractures were encountered in this upper 50 ft at depths of 267, 282, and 297 ft bgs. All three fractures parallel the surrounding foliation and had airlift yields of 20, 45, and 30 gpm, respectively. An interlayered amphibolite with biotite gneiss and biotite gneiss with amphibolite was encountered between 310 and 370 ft bgs. This section contains one water-bearing fracture at a depth of 348 ft bgs. This fracture occurs within an amphibolite layer and is not associated with any observable lithologic contact zone. The fracture appears to parallel the surrounding foliation and had an airlift yield of 50 gpm. The remainder of the section is an interlayered sequence of biotite gneiss and lesser amounts of amphibolite. This interval is relatively unfractured except for one area of concentrated jointing between 380 and 400 ft bgs (Figures 15A and 15B).

Two 10-foot composite samples were selected for XRD-analysis, which represent the varying composition of the biotite gneiss unit. The results of XRD-analysis indicate that the biotite gneiss unit is primarily composed of biotite, feldspar, and quartz (Table 4).

Table 4. Quantitative/qualitative mineralogy of the two samples collected from the biotite gneiss unit in well 14FF59.

Depth Interval (ft)	Lithologic Unit	Mineral Percent Weight	ΔμS
320 to 330	Biotite Gneiss	59.93% quartz, 30.11% albite, 5.50% muscovite, 4.45% biotite	-15.4
440 to 450	Biotite Gneiss	43.13% quartz, 28.66% microcline, 24.96% albite, 3.25% biotite	11.97

A ΔμS of ±5.00 is needed to establish a good quantitative analysis. Analyses that record a ΔμS over ±5.00 should be considered qualitative and not quantitative.

The biotite gneiss is composed of quartz, feldspar, biotite, and muscovite. Quartz is the most abundant mineral. Albite was identified as one of the feldspars during XRD analysis, but the feldspar is more likely oligioclase or andesine. Microcline was also identified in one sample. Biotite is not abundant in this rock type but tends to be iron-rich. Muscovite, when present, is in small amount (<5%).

Well 14FF42 penetrates the same apparent sequence of rocks as were encountered when drilling 14FF59. The amphibolite unit in this well extends to 255 ft bgs where it forms a relatively sharp contact with the button schist. Below this point, the rocks are described as a sequence of interlayered button schist, biotite gneiss, and amphibolite to a depth of 385 ft bgs. The remainder of the borehole to 600 ft bgs is an interlayered sequence of biotite gneiss and amphibolite. This well has an estimated yield of less than one gpm (Figures 14A and 14B).

Lithology and Fracture Characterization in Boreholes in the GCAV

Wells 14FF42 and 14FF59 penetrate a similar sequence of amphibolite, button schist, and biotite gneiss, although thickness variations are obvious in comparing the logs from these two wells (Figures 14A, 14B, 15A and 15B). The similarity in lithology appears to be the result of intercepting these rocks in the same structural position along geologic strike (Figure 10). At the high-yielding well 14FF59, the fracture system is characterized by a system of sub-horizontal foliation fractures formed along foliation/layering and by steeply dipping sets of joints (Figures 15A and 15B). Lithology and geologic structure for both wells will be discussed in the following section.

The upper 35 ft of well 14FF59 is cased off with 8-inch steel casing. Casing was set at this depth due to regulations and the presence of a shallow water-bearing fracture encountered at approximately 17 ft bgs. Bedrock, amphibolite interlayered with biotite gneiss (a!-bg, where the exclamation point denotes the more abundant rock type), was encountered at approximately 4 ft bgs. The a!-bg unit has a total thickness of 46 ft. An area of concentrated jointing was encountered in the borehole between 25 and 47 ft bgs. The stereonet in Figure 16 shows that all of the joints located between 25 and 47 ft bgs are relatively high angle (> 45 degrees). The rose diagram in Figure 16 shows that these joints trend in a general north-south direction. All of the joints plotted in Figure 16 are located in the a!-bg unit.

The next area of concentrated jointing in well 14FF59 is between 120 and 155 ft bgs. These joints are located across two rock types: a!-bg and biotite gneiss interlayered with amphibolite (a-bg!). These two rock types are considered part of the larger amphibolite lithologic unit. The stereonet in Figure 17 shows that the dip angles of all

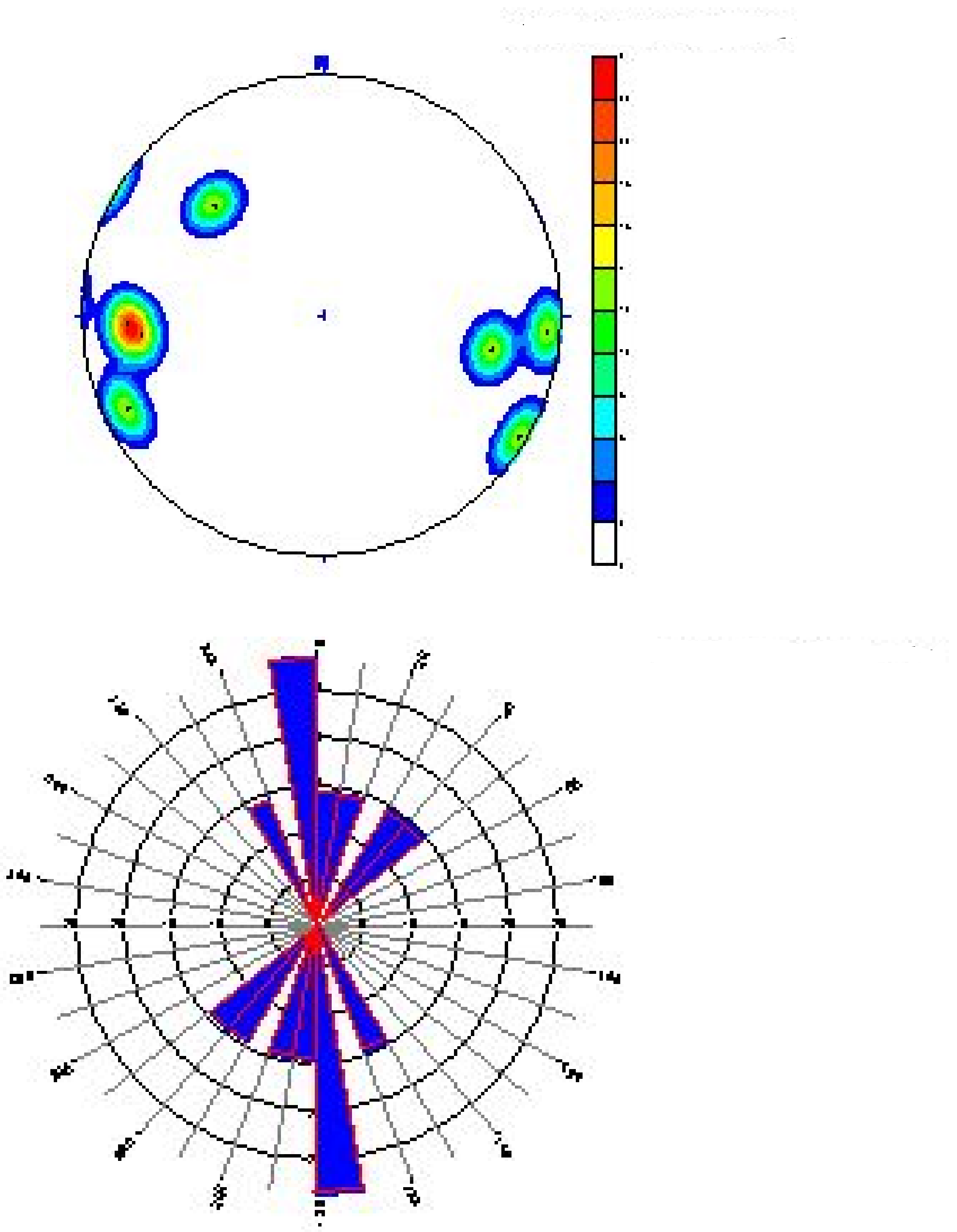


Figure 16. A stereonet and bi-directional rose diagram showing joint orientations in well 14FF59 from 25 to 47 ft bgs. The stereonet diagram on the left is used to show dip angles and joint groupings. The pole to each joint plane is plotted and the relative concentrations are contoured using the color scale to the right of the diagram. Poles that plot on the rim of the circle represent joints with dip angles of 90 degrees. Dip angles decrease moving inward from the rim. Clusters of poles denote joints with similar orientations. The rose diagram on the right is used to show strike directions. The larger petals denote the prominent strike direction.

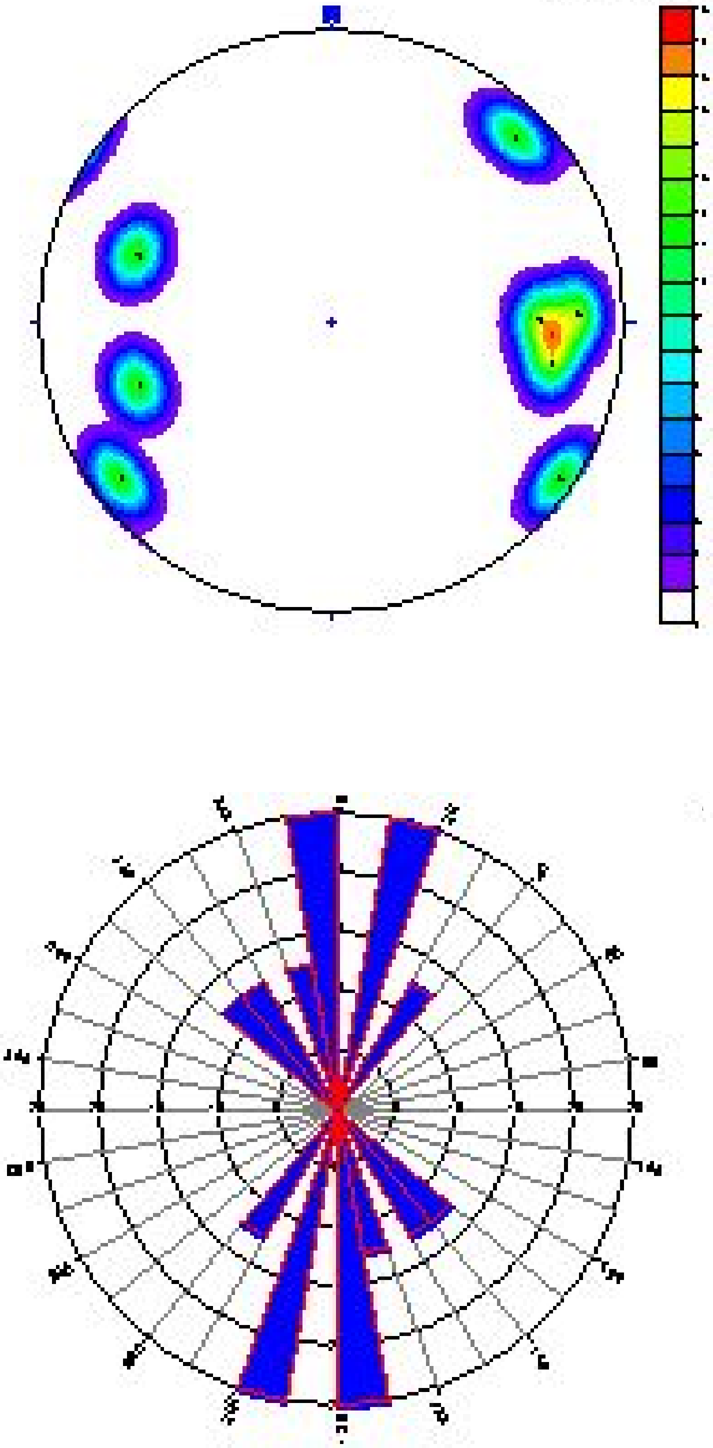


Figure 17. A stereonet and bi-directional rose diagram showing joint orientations in well 14FF59 from 120 to 155 ft bgs.

the joints are relatively high angle, which is very common in the study area. The rose diagram in Figure 17 shows that the prevailing trend is north south, which is the same strike direction recorded between 25 and 47 ft bgs. Another area of concentrated jointing is between 225 and 255 ft bgs. All but one of the joints are located in the button schist (bs). The remaining joint is located in the biotite gneiss interlayered with button schist (bg-bs) rock type. The stereonet in Figure 18 shows that the joints in this interval are high angle and tightly grouped. The rose diagram in Figure 18 shows that the dominant strike direction is east-west. If connected to the joints from shallower concentrations, these joints create the beginnings of an orthogonal joint network, which is beneficial in transmitting groundwater to the borehole.

A concentrated area of jointing was also encountered between 255 and 295 ft bgs. The joints are located in the a!-bg unit. The stereonet in Figure 19 illustrates the same high-angle jointing and well-defined grouping as seen between 225 and 255 ft bgs. The rose diagram in Figure 19 shows the principal strike direction to be east-west. This set of concentrated joints further develops the potential orthogonal joint network.

The next area of concentrated jointing is between 295 and 330 ft bgs. This area of jointing cuts across two rock types: a!-bg and biotite gneiss (bg). The stereonet diagram in Figure 20 shows high angle jointing with a tight grouping. The main strike direction illustrated by the rose diagram in Figure 20 is north-northeast—south-southeast. This orientation further promotes the potential joint network and adds a slightly oblique component.

The last area of concentrated jointing cuts across the a-bg! and the bg units between the depths of 375 and 400 ft bgs. The joint concentration at this depth interval is

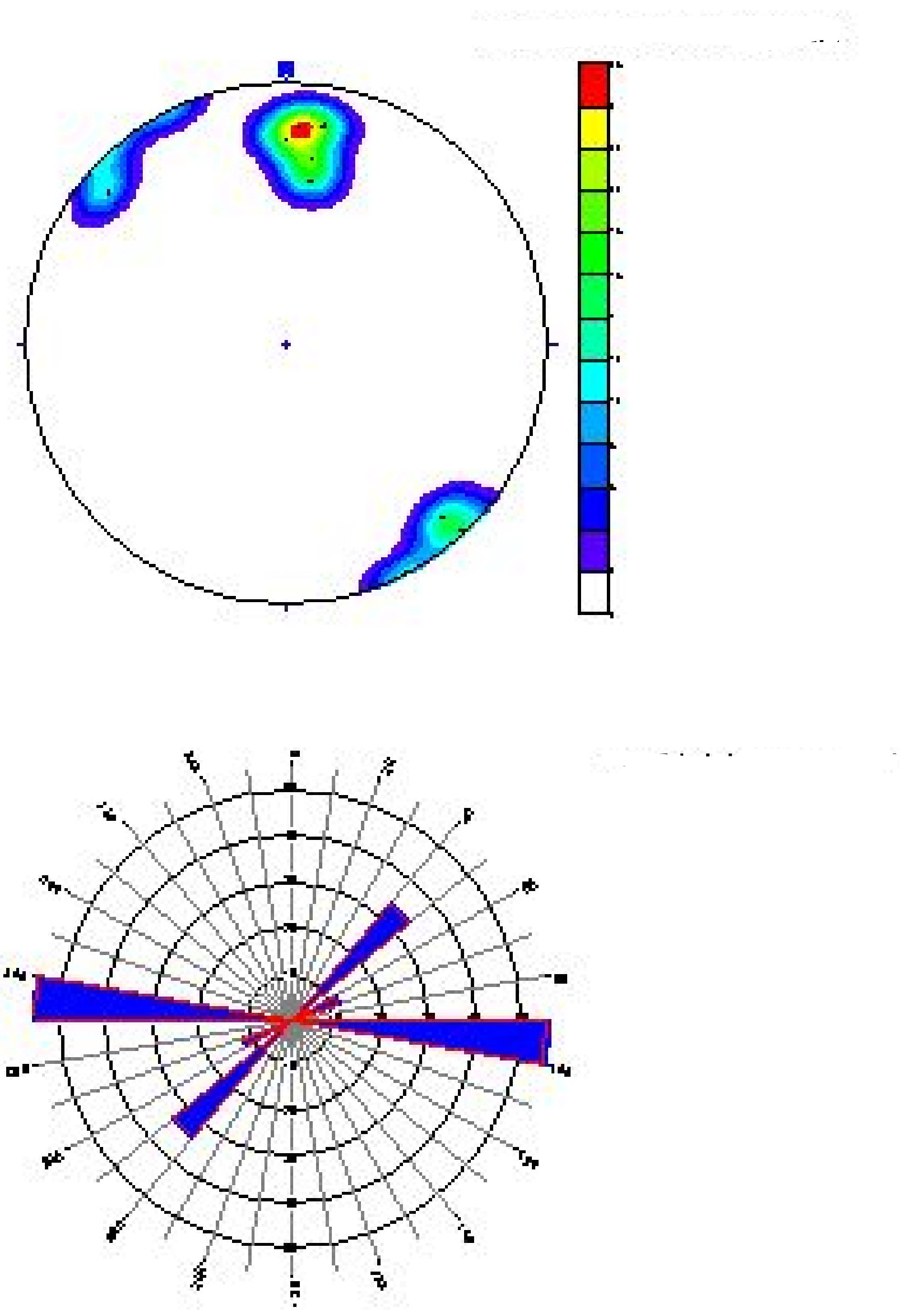


Figure 18. A stereonet and bi-directional rose diagram showing joint orientations in well 14FF59 from 225 to 255 ft bgs.

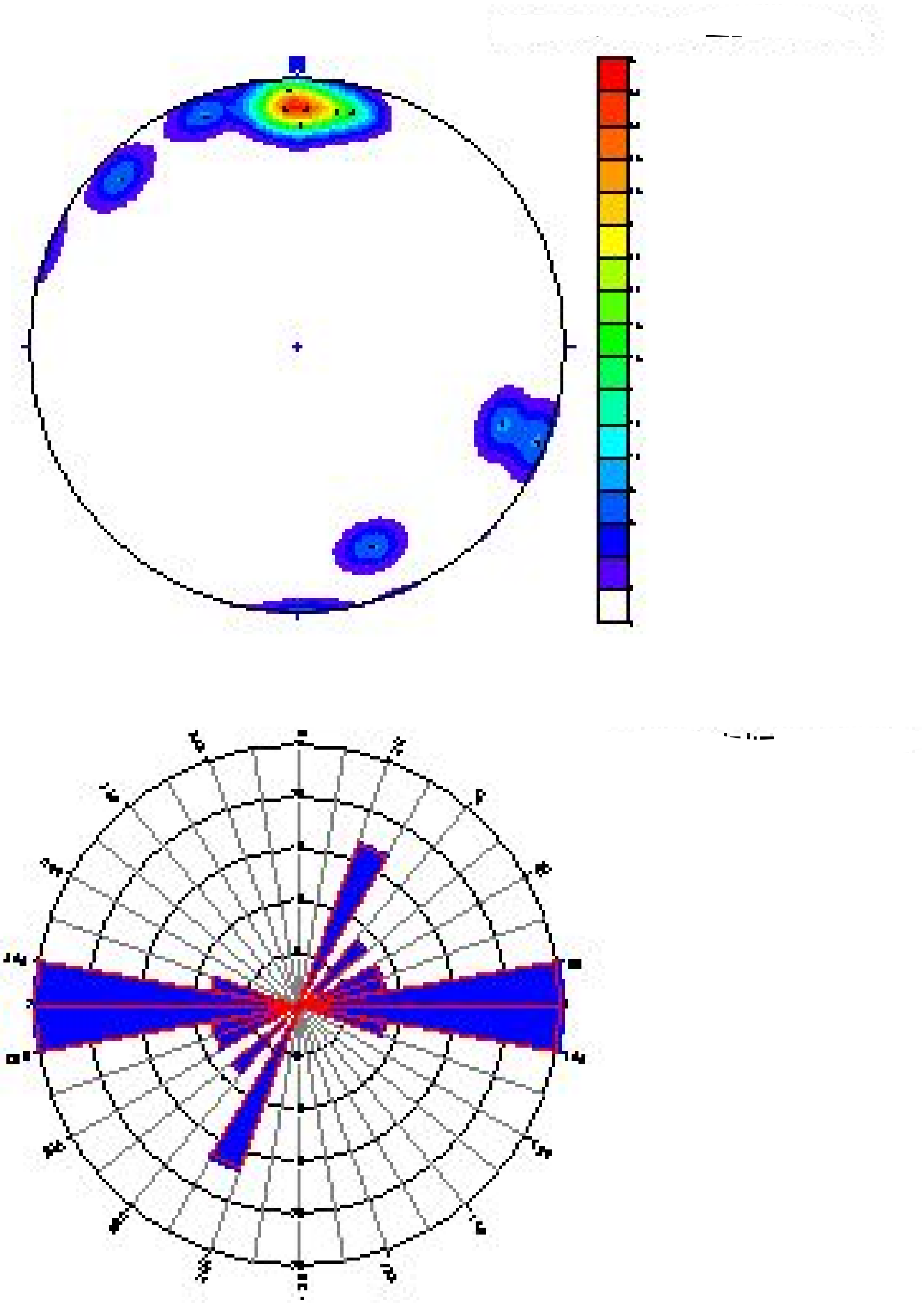


Figure 19. A stereonet and bi-directional rose diagram showing joint orientations in well 14FF59 from 255 to 295 ft bgs.

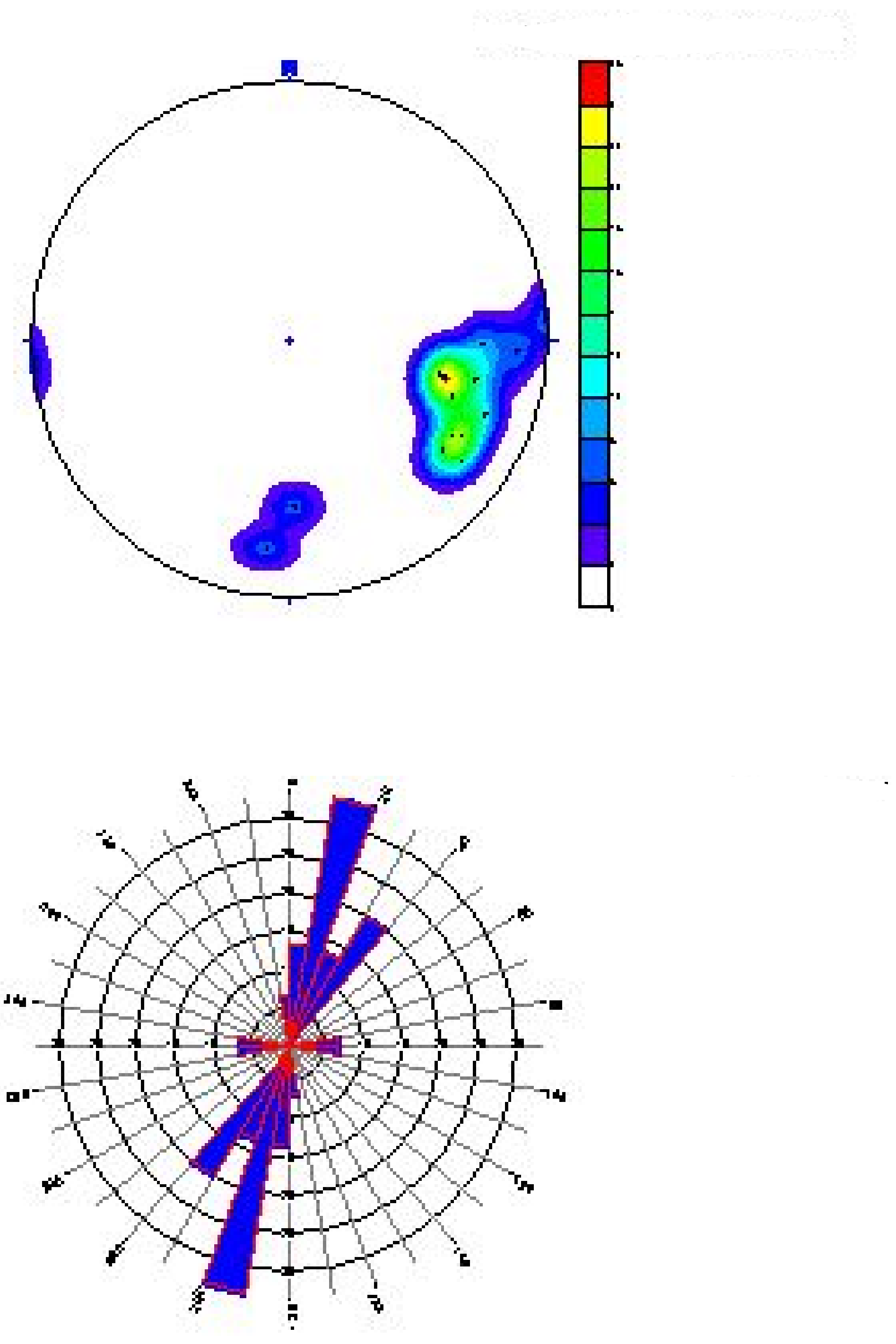


Figure 20. A stereonet and bi-directional rose diagram showing joint orientations in well 14FF59 from 295 to 330 ft bgs.

different from all the previous areas of joint concentrations in well 14FF59. Instead of one prevailing orientation, two dominant strike directions characterize this zone. The stereonet in Figure 21 illustrates that all the joints are high angle and that there are several groupings. The rose diagram in Figure 21 shows that there are two main strike directions, west-northwest—east-southeast and northeast southwest, which are almost orthogonal.

Foliation measurements taken from 14FF59 demonstrate the undulating foliation common in metamorphic terrain. The borehole has been separated into four sections to demonstrate the variations in foliation orientations. The stereonet in Figure 22 illustrates that the foliation tends to be low-angle (< 45 degrees) throughout the first 100 ft of the borehole. The rose diagram in Figure 22 shows that the strike of the foliation ranges almost a complete 180 degrees.

The second section of borehole, 100 to 200 ft, is even more varied. The stereonet in Figure 23 illustrates dips ranging from low to high-angle. The rose diagram in Figure 23 shows a range of 160 degrees in strike. The presence of no discernable pattern on the stereonet plot in Figure 23 emphasizes the variation in foliation orientation.

The third section of borehole, 200 to 300 ft, is slightly more ordered. The stereonet in Figure 24 shows that all the dips are low angle and that some tight groupings are present. The rose diagram in Figure 24 further supports this more consistent foliation orientation by showing a strong east-northeast—west-northwest trend.

The last section of the borehole, 300 to 400 ft, shows the most consistent foliation strike of the entire borehole. The dips illustrated in the stereonet plot in Figure 25 are generally low-angle and moderately grouped. The rose diagram in Figure 25 shows a

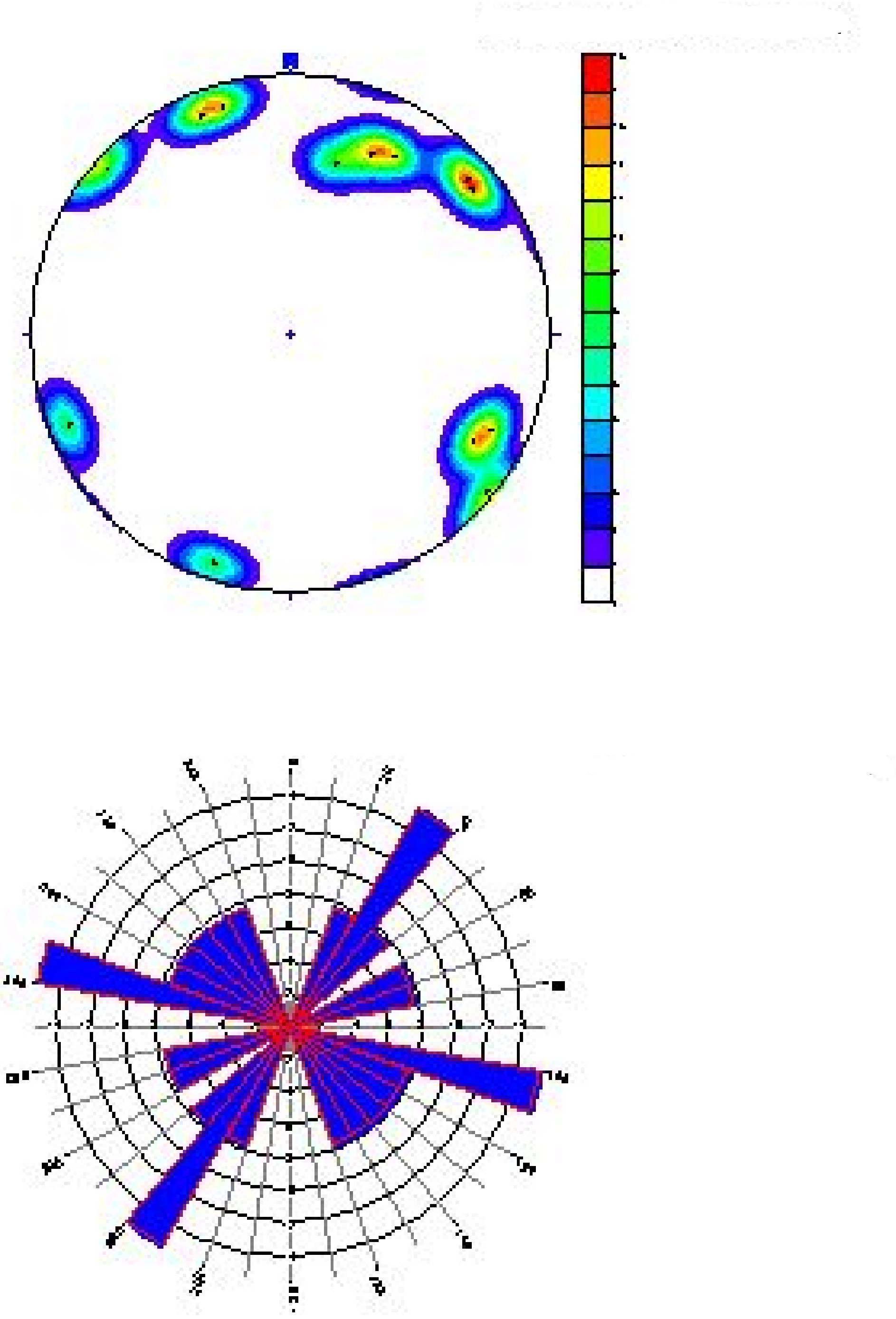


Figure 21. A stereonet and bi-directional rose diagram showing joint orientations in well 14FF59 from 375 to 400 ft bgs.

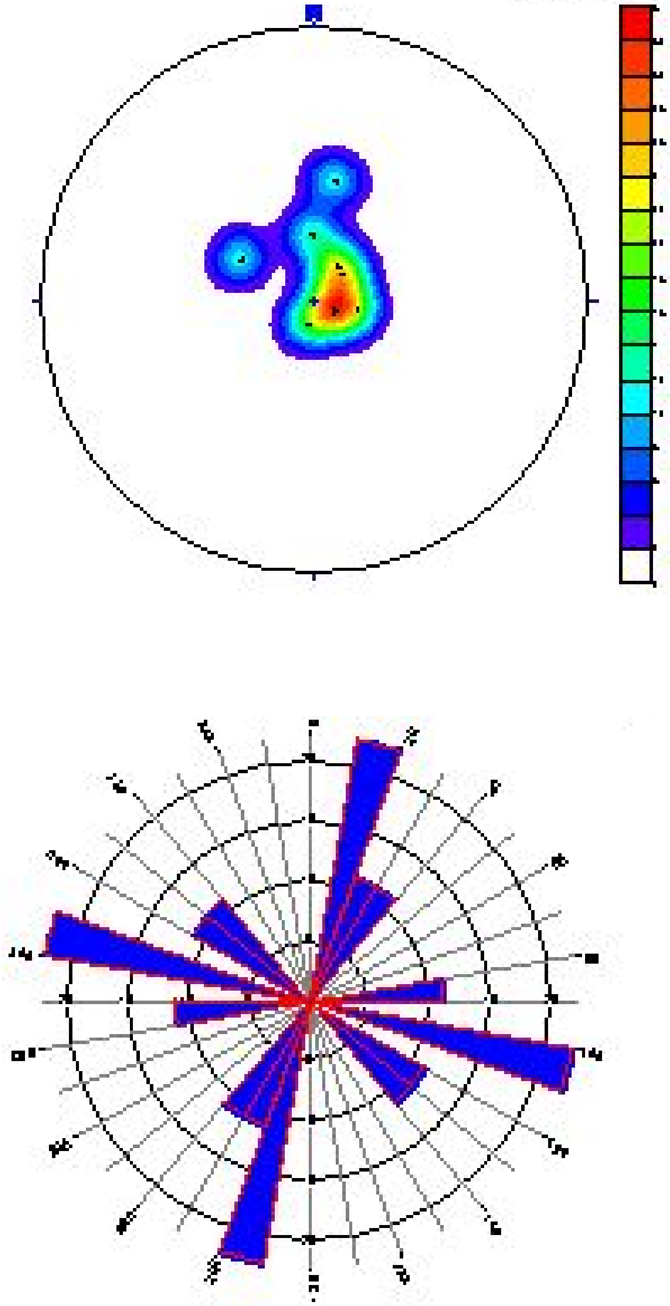


Figure 22. A stereonet and a bi-directional rose diagram showing the foliation orientations in well 14FF59 between 0 and 100 ft.

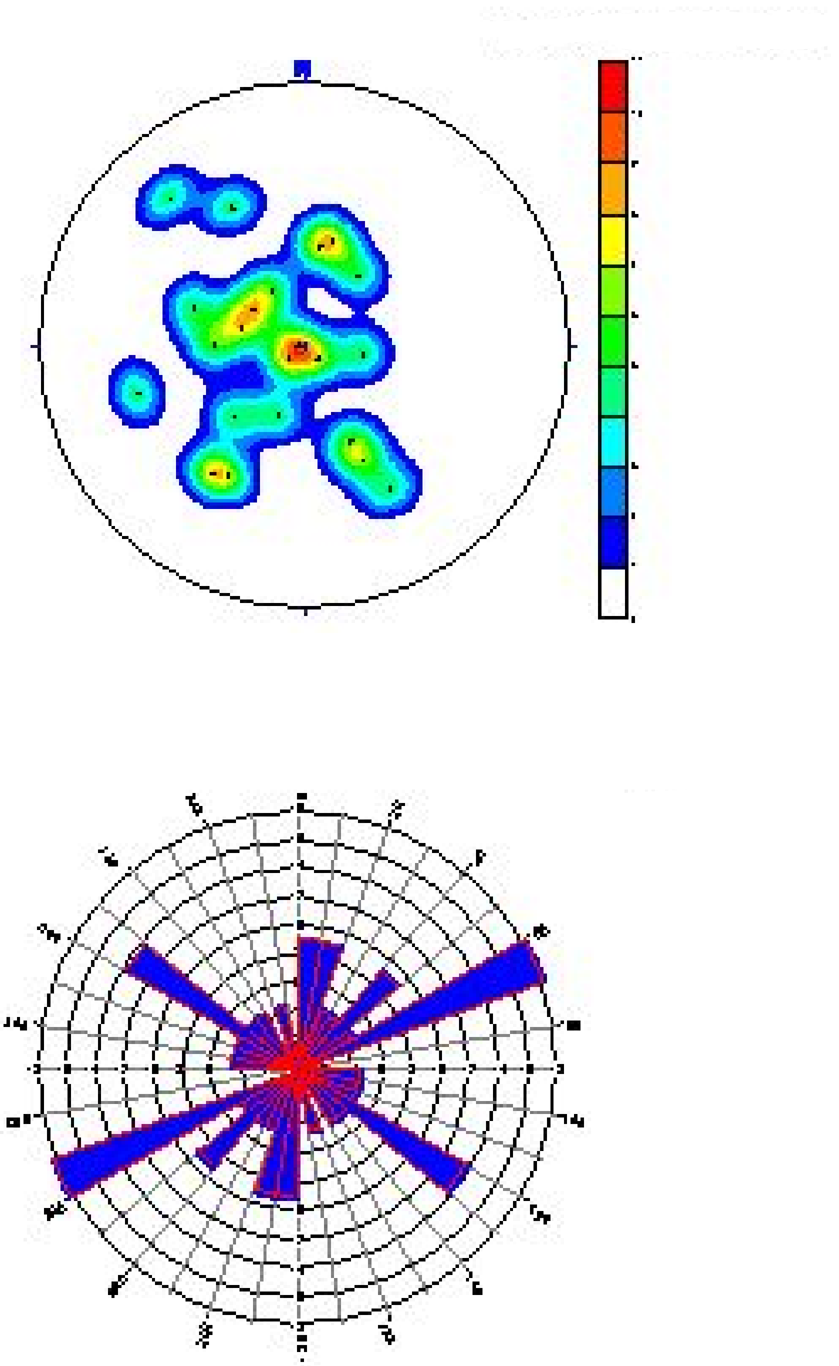


Figure 23. A stereonet and a bi-directional rose diagram showing the foliation orientations in well 14FF59 between 100 and 200 ft.

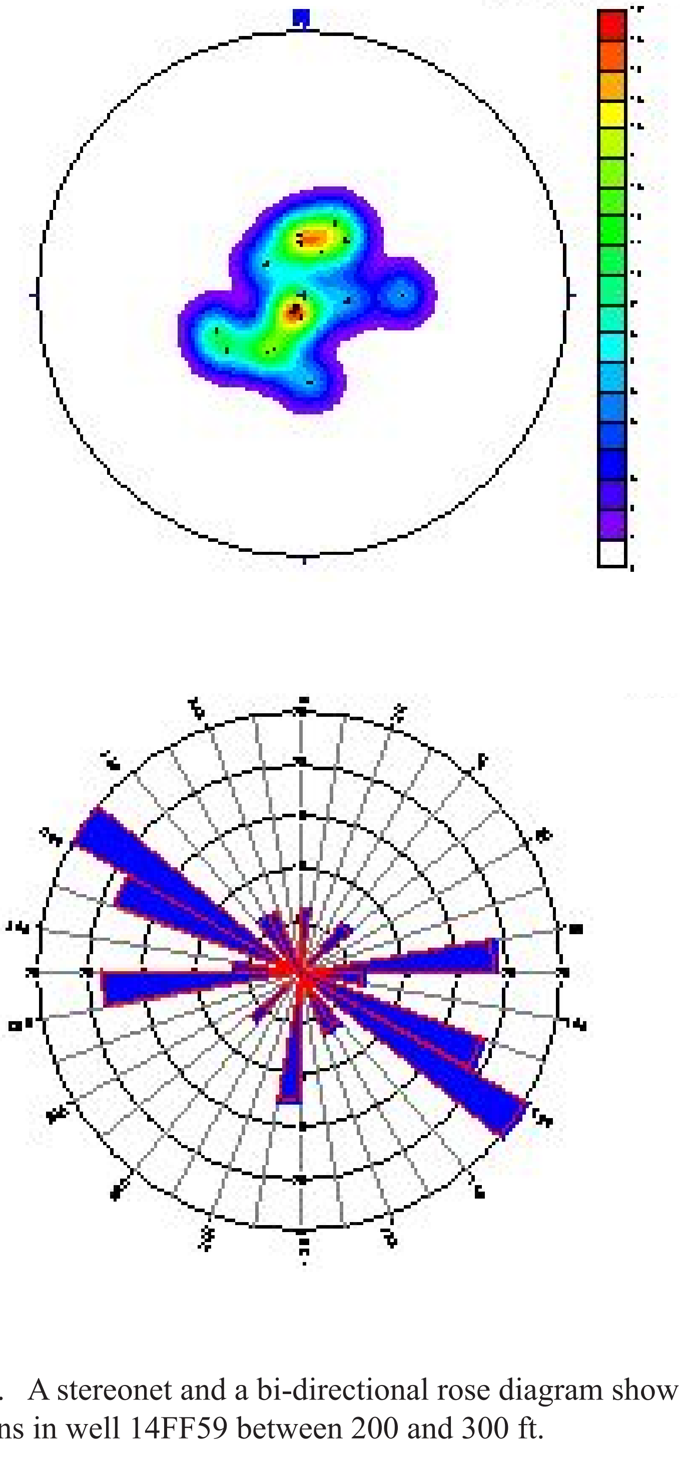


Figure 24. A stereonet and a bi-directional rose diagram showing the foliation orientations in well 14FF59 between 200 and 300 ft.

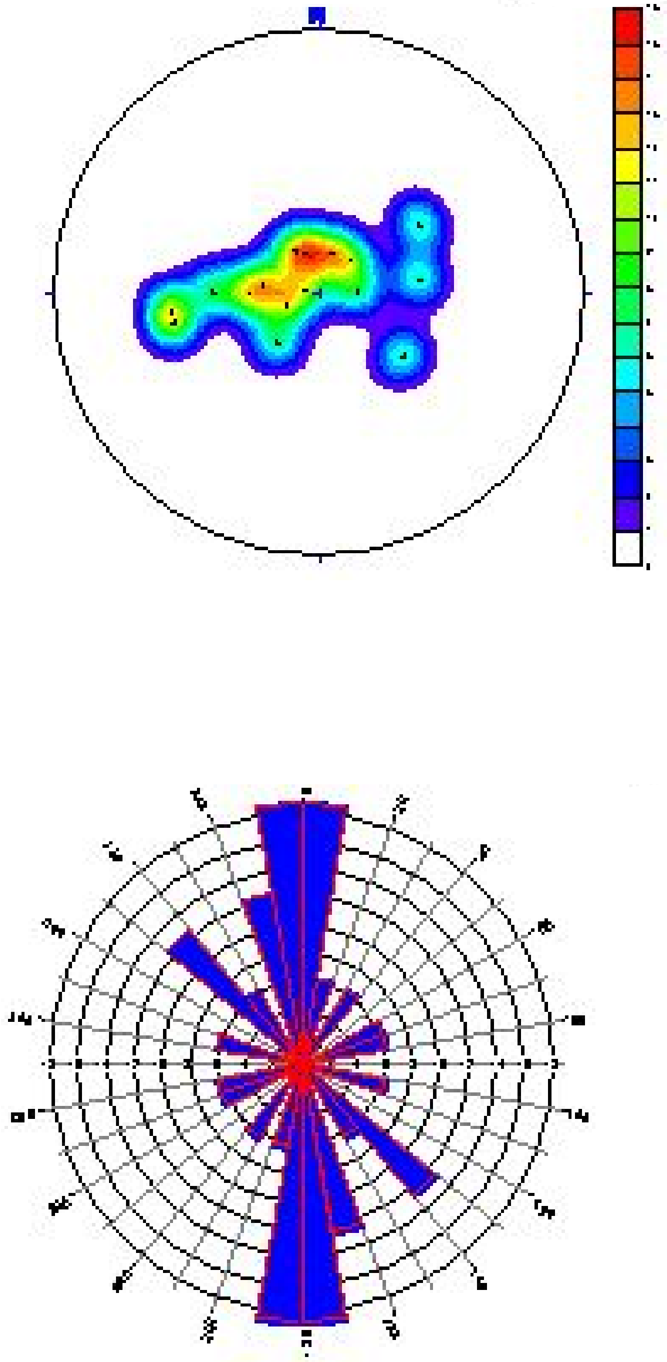


Figure 25. A stereonet and a bi-directional rose diagram showing the foliation orientations in well 14FF59 between 300 and 400 ft.

major trend. A strong north-south strike dominates the foliation orientations in the bottom section of the borehole.

Well 14FF59 is characterized by many sub-horizontal, open fractures. It has been observed in many areas of Lawrenceville that the open, sub-horizontal fractures parallel foliation/compositional layering. Stereonets and bi-directional rose diagrams of the fractures and surrounding foliations are used to demonstrate several instances where this can be observed.

One of the first fractures where this observation can be seen in well 14FF59 is located at 131.5 ft bgs. The diagrams in Figure 26 show the orientation of the fracture and the orientation of the foliation from 115 to 132 ft bgs. Even though the foliation is variable in the seven-foot interval, the foliation measurement taken closest to the fracture is near parallel. The diagrams in Figure 26 illustrate that one of the foliations from the interval (the foliation measurement taken closest to the fracture) closely parallels the orientation of the major fracture.

Another area where this can be seen is at the fracture encountered at 241.15 ft bgs. The stereonets and rose diagrams shown in Figure 27 compare the orientation of the fracture with the orientation of the foliation. The diagrams in Figure 27 show that several of the surrounding foliations closely parallel the orientation of the major fracture.

The four water-bearing fractures in well 14FF59 best illustrate the aforementioned observation. The fractures located at 294.61 and 297.02 ft bgs best illustrate the observation that the open, sub-horizontal fractures parallel foliation/compositional layering. Only one of the two fractures (297.02 ft bgs) is a major water-bearing fracture, but both are shown in Figure 28. Three foliation orientations were plotted from the depth

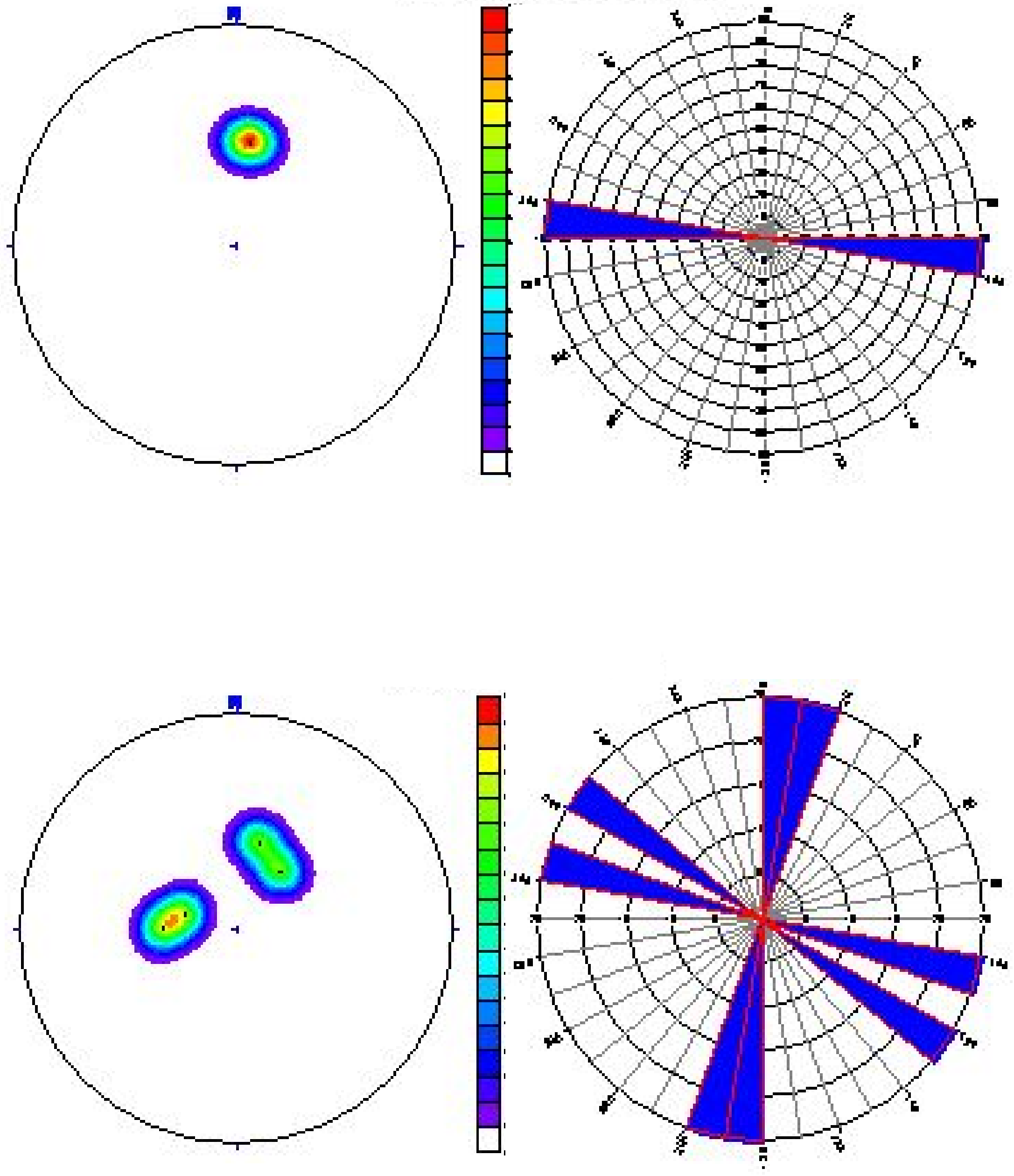


Figure 26. Stereonet and rose diagram of major fracture at 131.5 ft bgs (top pair of diagrams) and stereonet and rose diagram of surrounding foliation from 115 to 132 ft bgs (bottom pair of diagrams).

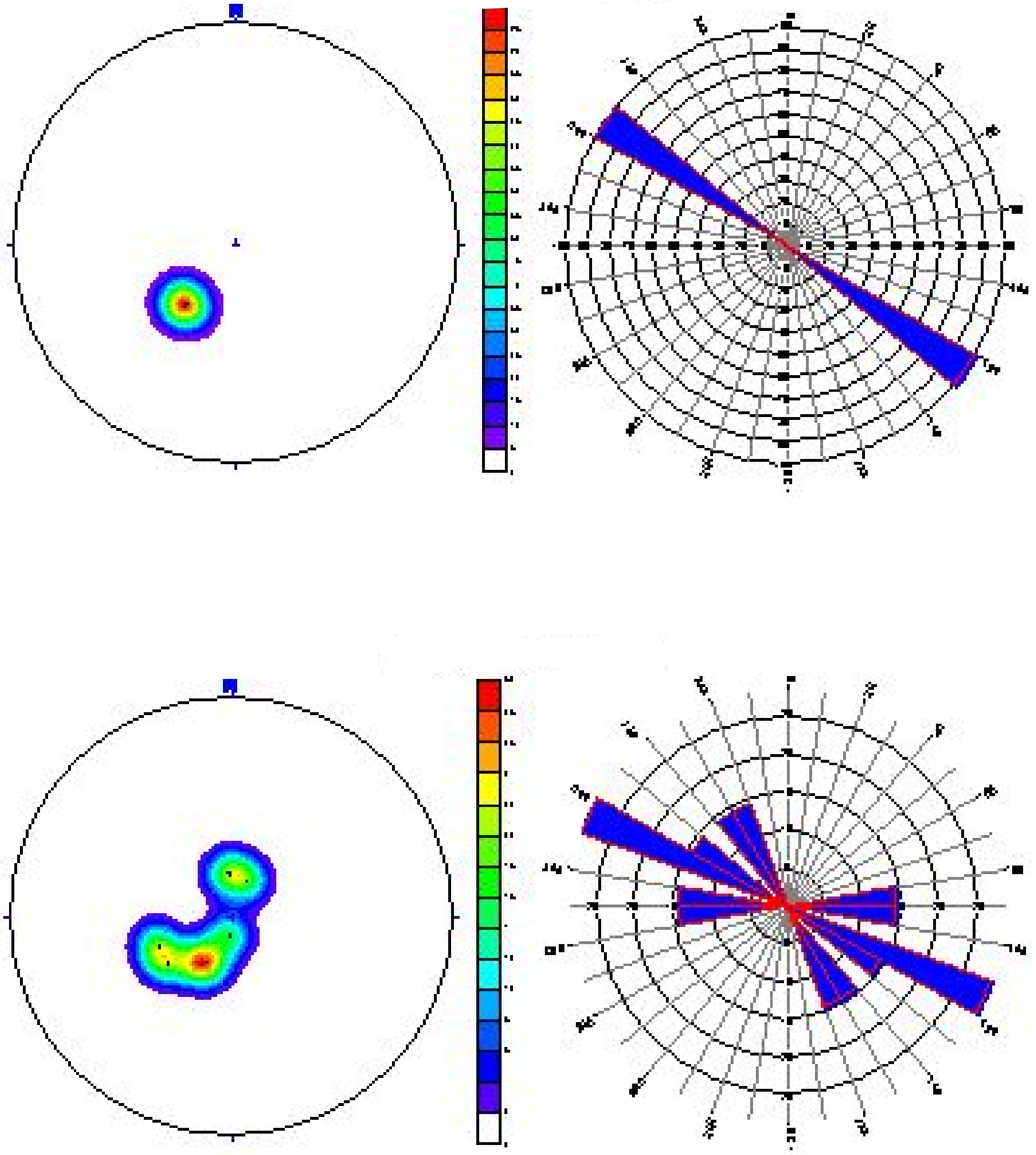


Figure 27. Stereonet and rose diagram of major fracture at 241.15 ft bgs (top pair of diagrams) and stereonet and rose diagram of surrounding foliation from 225 to 265 ft bgs (bottom pair of diagrams).

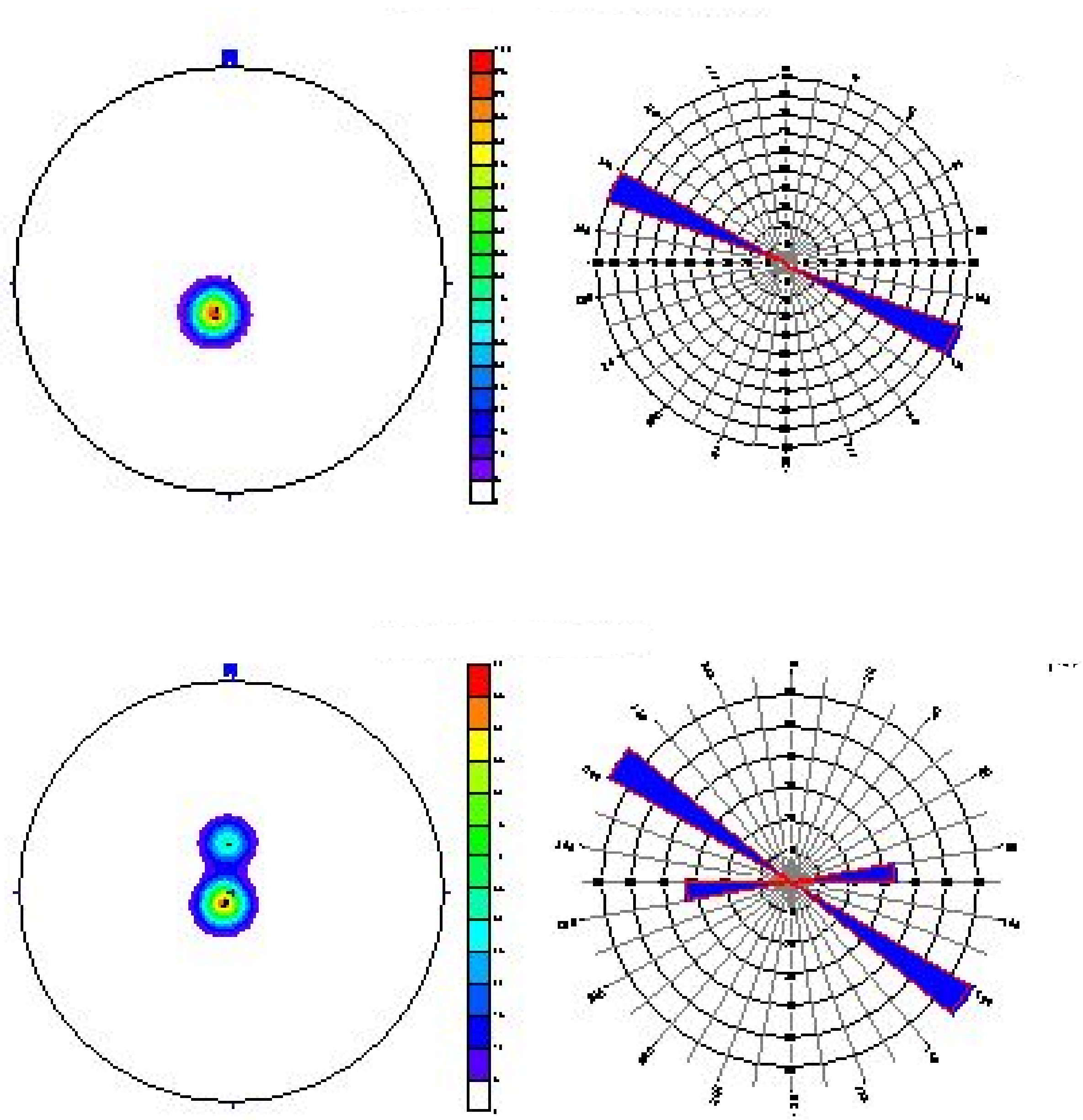


Figure 28. Stereonet and rose diagram of major fractures at 294.61 and 297.02 ft bgs (top pair of diagrams) and stereonet and rose diagram of surrounding foliation from 290 to 300 ft bgs (bottom pair of diagrams).

interval of 290 to 300 ft bgs. One of the foliation measurements clearly does not parallel the fractures, but that foliation measurement is the furthest away from the two fractures. The remaining two foliation measurements taken close to the structural features closely parallel both of the major fractures.

All of the major water-bearing fractures in well 14FF59 occur at or near lithologic contacts, thus indicating a degree of lithologic control on these zones. The four main water-bearing fractures are located at the following depths: 267, 282, 297, and 348 ft bgs. The fracture at 267 ft bgs is located near the contact between interlayered biotite gneiss and button schist and an amphibolite with layers of biotite gneiss. The fractures observed at 282 and 297 ft bgs are located within a finely interlayered amphibolite biotite gneiss unit. The fracture at 348 ft bgs is located near the contact between biotite gneiss with layers of amphibolite and an amphibolite with layers of biotite gneiss.

The origin of the open, sub-horizontal fractures parallel to foliation/compositional layering appear to be the result of differential weathering along layering. The differential weathering process combined with tectonic expansion of the rock along foliation weaknesses from the processes of stress-relief could also explain the presence of the sub-horizontal system of foliation fractures observed at well 14FF59.

Unlike well 14FF59, the bedrock at well 14FF42 appears to be relatively unfractured. Fractures were picked from 14FF42 using a BIPS log, which is a higher resolution imaging log than the ATV log used to pick fractures from well 14FF59. Eleven joints were identified from the entire 600-ft log. This number is compared to the 80 joints, which were identified from well 14FF59. Not only is the number of joints low for well 14FF42, but the joints are also widely spread and unconcentrated throughout the entire length of the borehole. The diagrams in Figure 29 show the orientations of all the joints measured in well 14FF42. The stereonet and rose diagram in Figure 29 illustrate that while the joints are high-angle, the strikes tend to focus in the northeast-southwest direction. This dominating trend hinders the development of a well-connected, extensive fracture network, which is more common when the joint orientations are more varied.

The foliations measured in well 14FF42 are highly variable as seen in well 14FF59. Figure 30 illustrates this variation. Foliation measurements in metamorphic terrain are highly variable due to numerous deformational events. This variation is clearly shown in Figure 30. The only consistency to the foliations is the low-angle dips.

Many foliation partings were observed in the high-resolution BIPS log, although many of these are probably not water bearing. Foliation partings in well 14FF42 are hairline fractures that are differentiated from the larger foliation fractures observed in well 14FF59. Foliation partings were not identified in wells that were logged using the ATV since the imagine resolution did not allow them to be readily distinguished. Figure 31 shows the orientations of the foliation partings measured in well 14FF42. The foliation partings identified in well 14FF42 closely parallel the surrounding foliation in the borehole. It is surmised that foliation partings are formed by the same mechanism that forms the major fractures in well 14FF59 but lack the development needed to transmit groundwater due to their relatively tight aperture. In core samples, many of the foliation partings appeared to be filled with pyrite, zeolite and other minerals.

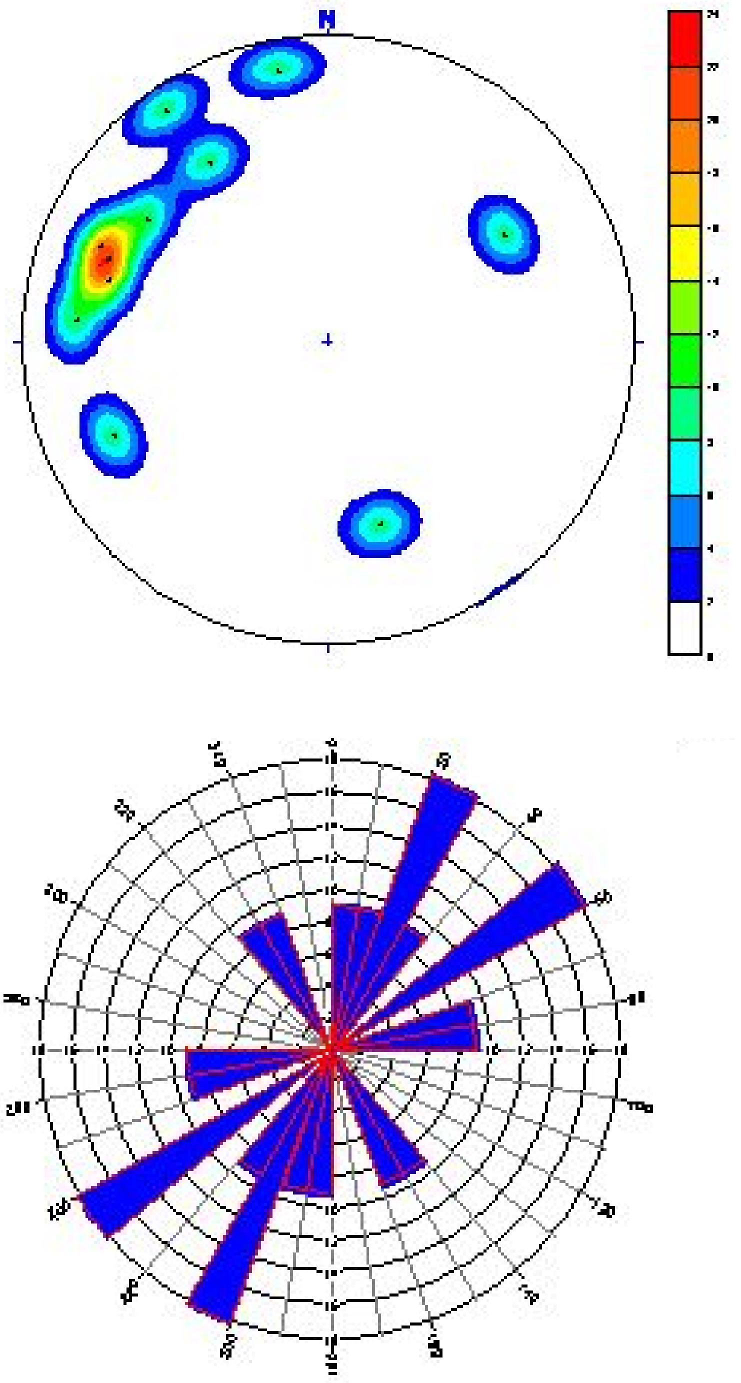


Figure 29. Stereonet and bi-directional rose diagram of all joints identified in well 14FF42.

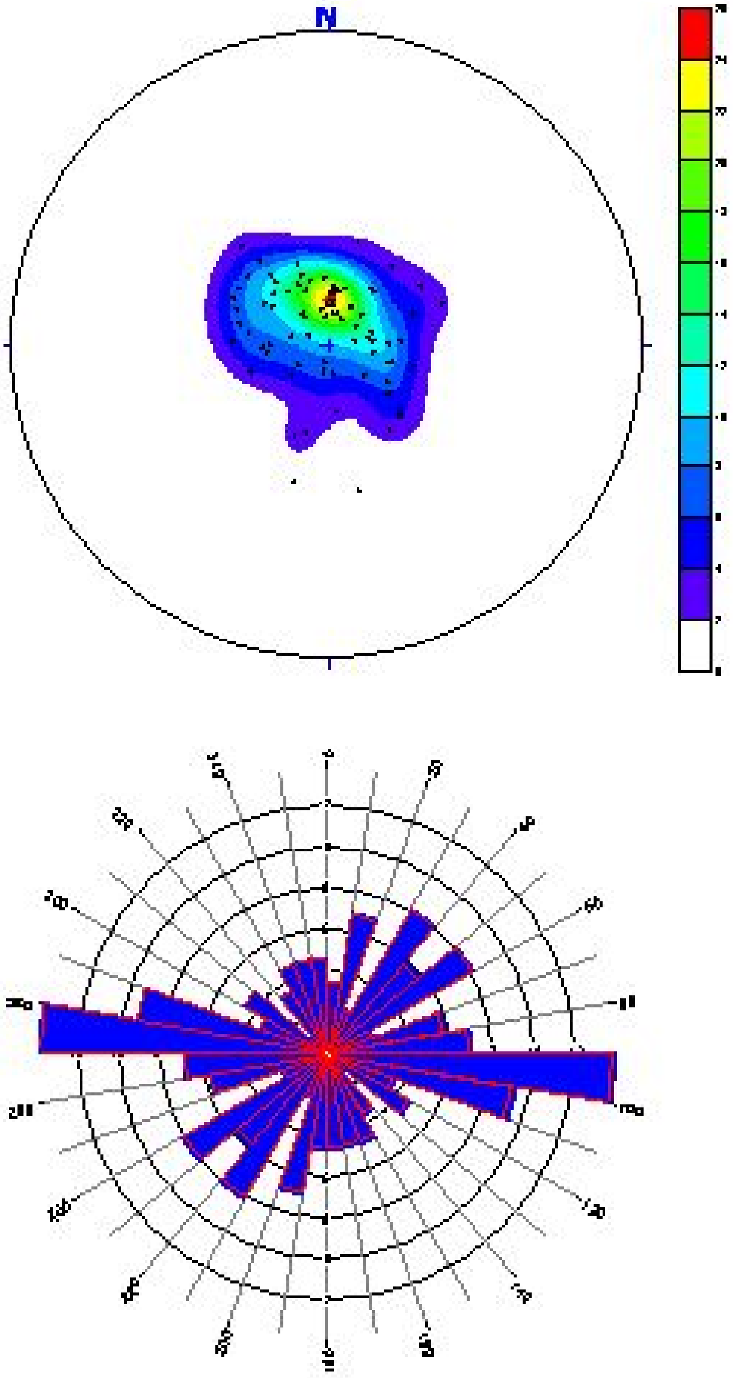


Figure 30. Stereonet and bi-directional rose diagram of all the foliation measurements in well 14FF42.

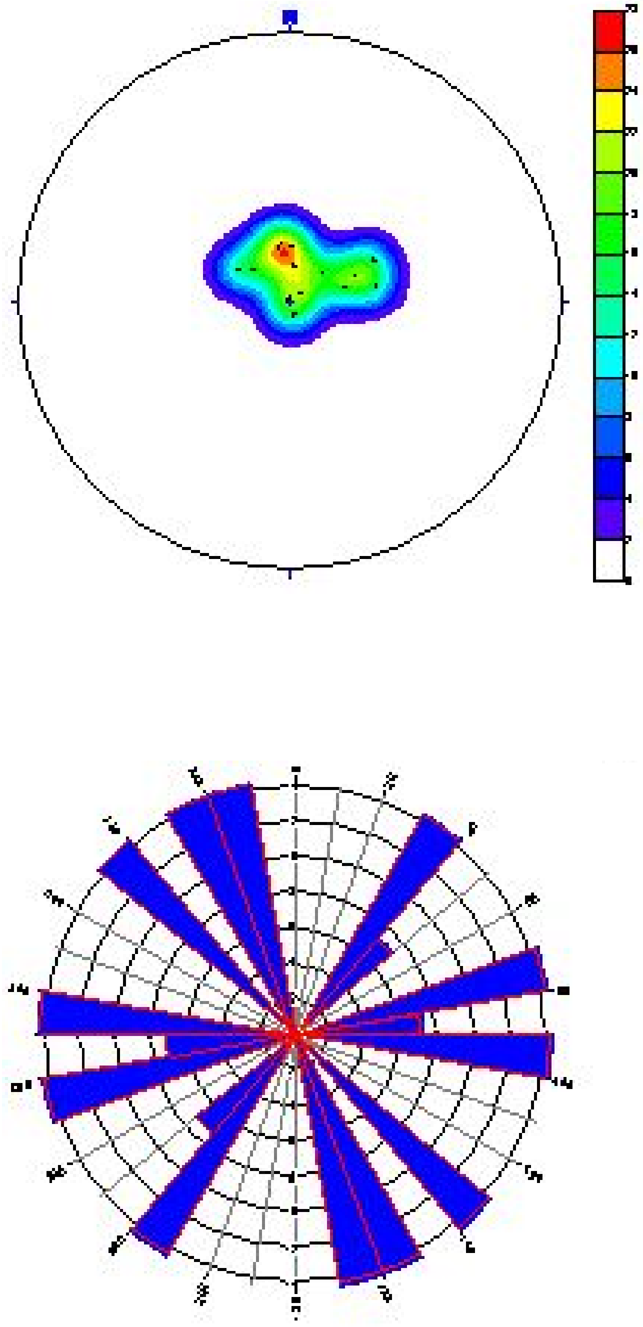


Figure 31. Stereonet and bi-directional rose diagram of all the foliation fracture orientations in well 14FF42.

Collins Hill Road Vicinity

This section of the report presents data from the Collins Hill Road vicinity (CHRV) and well 14FF58. Data is presented from 1:12,000-scale geologic mapping and various borehole logs.

Geologic Mapping (CHRV)

Key geologic features identified during all mapping included: (1) massive, non-layered rock having poorly developed foliation; (2) joints and zones of concentrated jointing; (3) apparent deep saprolite development and, (4) layered rocks deep in the subsurface dipping toward the well site. The test well (14FF58) was drilled in a position in the basin to intercept the layers of biotite gneiss and amphibolite based on the geologic map (Figure 32), however the test well was not drilled deep enough to intercept these rocks. One of the key considerations given in selecting this site was the possible presence of concentrated jointing in the subsurface. Abundant jointing was observed along the area's topographic lineament on nearby outcrops. An example of jointing in the granite gneiss, but not along the topographic lineament described above, is shown in photographs in Figure 33. Deep weathering of the granite gneiss made it difficult to locate extensive exposures where joints could be measured.

West of Collins Hill Road, where the layered rocks outcropped, similar geologic structures to those seen in the GCAA are present. The biotite gneiss exhibited very deep weathering and most of this unit was mapped using saprolite exposures. The button schist is resistant and forms distinct and easy to map exposures along the north part of the University of Georgia property (Figure 3). Jointing in the button schist was rare.

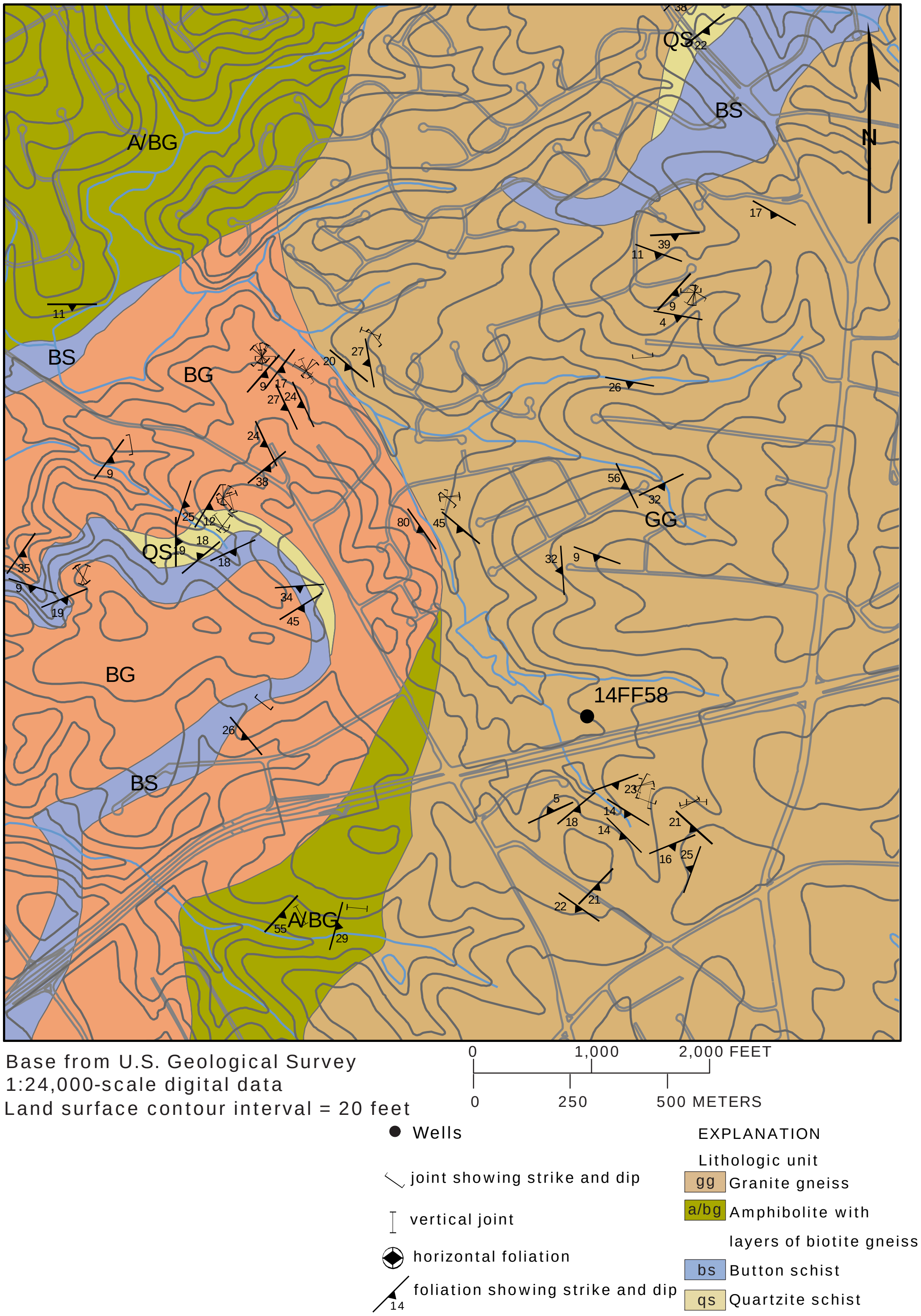


Figure 32. Geologic map for Collins Hill Road area. Mapping done by the USGS (R. Kath, T. Crawford, M. Higgins, L. Willams, J. Lawson and others).

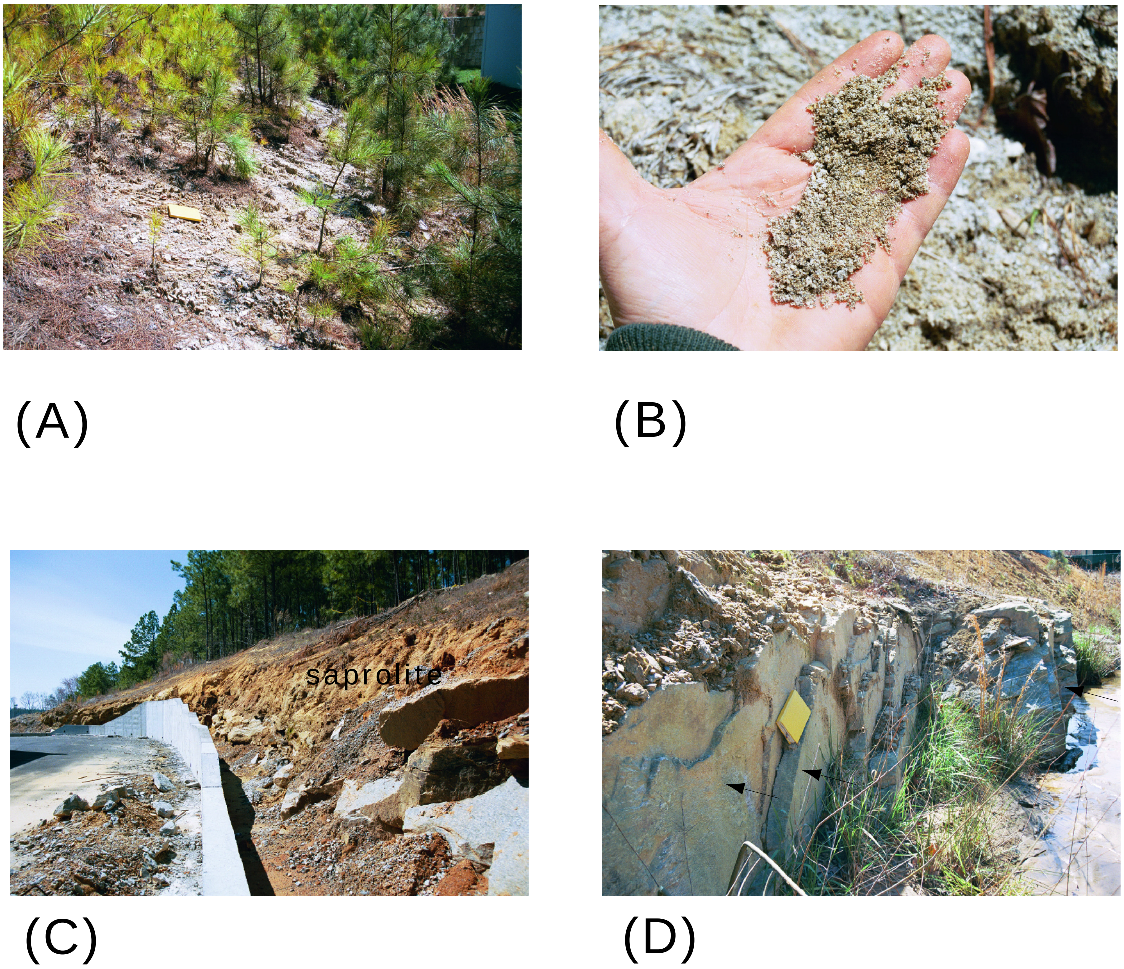


Figure 33. Photographs of granite gneiss showing (A) grayish-white granite gneiss saprolite exposed on hillside, (B) close up of granite gneiss saprolite, (C) brownish saprolite formed over granite gneiss, view looking west and, (D) granite gneiss outcrop (Collins Hill Rd. vicinity) exhibiting closely spaced joints (arrows point to near vertical planar joints), view looking west. Notebook for scale.

Borehole Lithologic Units in the Collins Hill Road Vicinity

Well 14FF58 was drilled to a depth of 550 ft bgs. Geologic logs indicate that this well penetrates one lithologic unit: granite gneiss (Figures 34A and 34B).

The granite gneiss unit at well 14FF58 extends to a depth of greater than 550 ft bgs. Throughout the borehole, the granite gneiss is poorly foliated to massive and in some sections well jointed. The upper 140 ft of the borehole is relatively unjointed although there are some well-developed joints shallow beneath the saprolite. There are two areas of concentrated jointing between the depths of 140 to 160 and 170 to 205 ft bgs. An area of highly concentrated jointing was encountered between the depths of 210 to 230 ft bgs. A high degree of jointing is observed for the remainder of the borehole except for an area of relatively low jointing between 310 and 385 ft bgs. No major water-bearing fractures were encountered during the drilling of well 14FF58. The total yield is estimated at less than one gpm.

Four 10-foot composite samples and one 20-foot composite sample were selected for XRD-analysis. These samples represent the varying compositions of the granite gneiss unit. The results of XRD-analysis indicate that the granite gneiss unit is primarily composed of biotite, chlorite, feldspar, and quartz (Table 5).

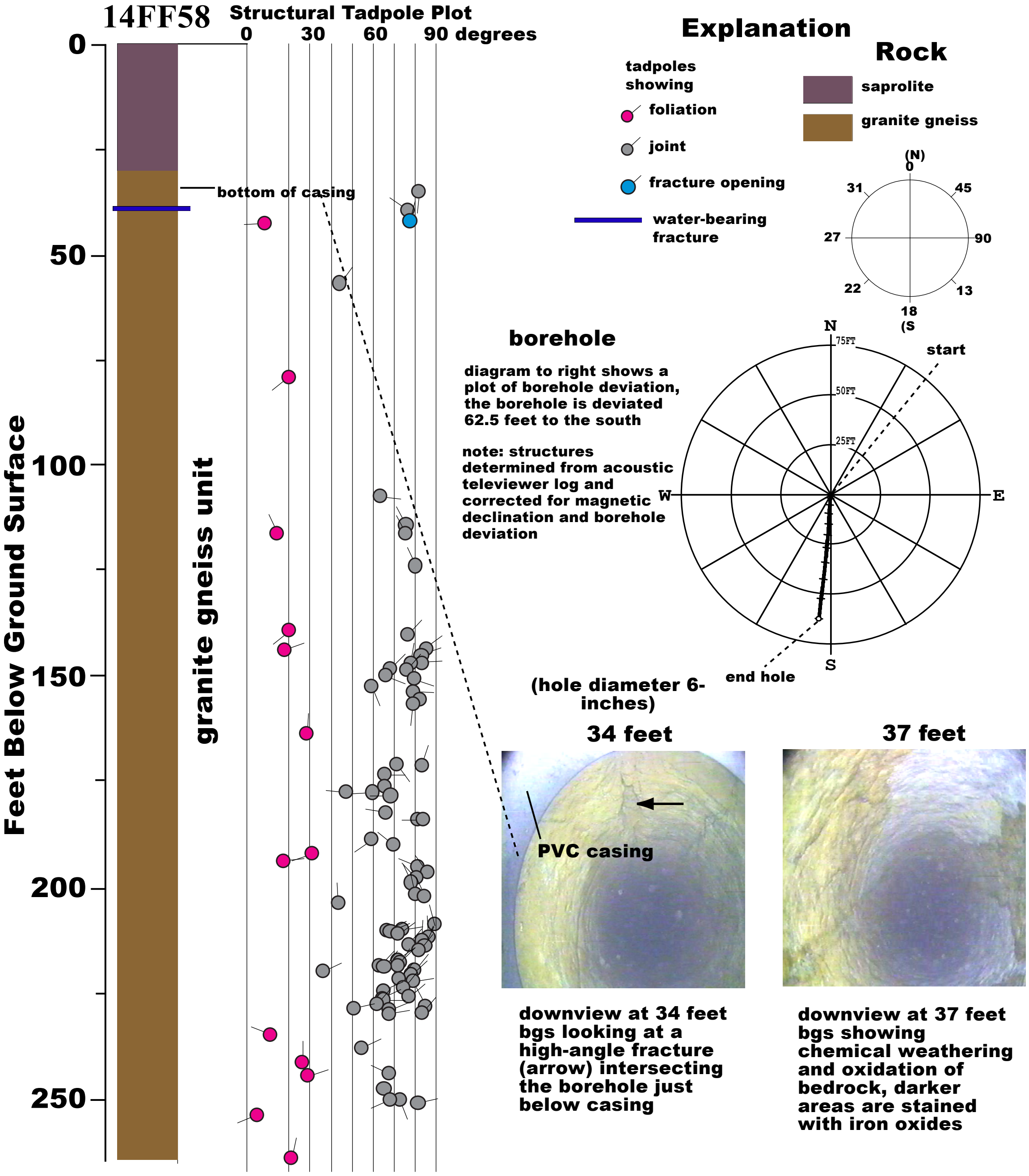


diagram to right shows a plot of borehole deviation, the borehole is deviated 62.5 feet to the south

note: structures determined from acoustic televiewer log and corrected for magnetic declination and borehole deviation

(hole diameter 6-inches)

downview at 34 feet bgs looking at a high-angle fracture (arrow) intersecting the borehole just below casing

downview at 37 feet bgs showing chemical weathering and oxidation of bedrock, darker areas are stained with iron oxides

Figure 34A. Structural tadpole plot and downhole camera images for well 14FF58.

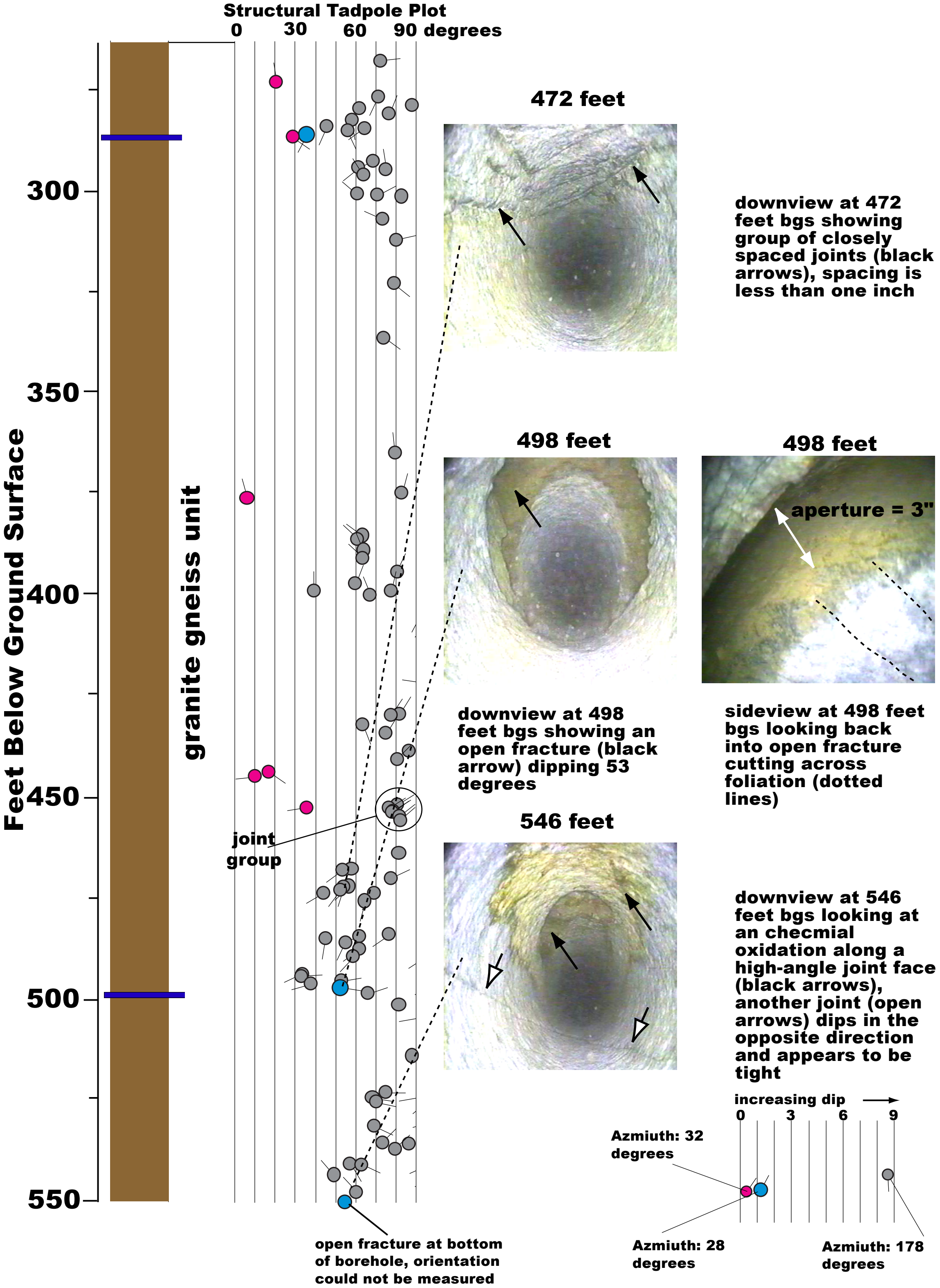


Figure 34B. Structural tadpole plot and downhole camera images for well 14FF58.

Table 5. Quantitative/qualitative mineralogy of the five samples collected from the granite gneiss unit in well 14FF58.

Depth Interval (ft)	**Lithologic Unit**	**Mineral Percent Weight**	**ΔμS**
30 to 50	Granite Gneiss	33.12% quartz, 21.21% orthoclase, 21.08% albite, 16.98% limonite, 4.34% epidote, 2.11% chlorite, 1.16% biotite	0
100 to 110	Granite Gneiss	49.88% anorthite, 20.03% quartz, 14.90% orthoclase, 12.52% albite, 2.67% biotite	-37.03
140 to 150	Granite Gneiss	47.66% quartz, 28.35% albite, 16.38% orthoclase, 7.62% chlorite	2.41
200 to 210	Granite Gneiss	60.90% quartz, 37.51% albite, 1.58% biotite	-6.67
440 to 450	Granite Gneiss	34.98% quartz, 32.21% albite, 22.35% orthoclase, 6.30% muscovite, 3.12% chlorite, 1.04% biotite	5.25

A ΔμS of ±5.00 is needed to establish a good quantitative analysis. Analyses that record a ΔμS over ±5.00 should be considered qualitative and not quantitative.

The granite gneiss is composed of quartz, feldspar, biotite, chlorite, muscovite, and epidote. Quartz is the most abundant mineral. The granite gneiss commonly has two feldspars present. Most of the feldspars were identified as albite during XRD analysis but are more likely oligioclase or andesine. Orthoclase was also identified in several of the samples. The micas present included biotite, chlorite, and muscovite. Some samples had only one mica constituent, while others had all three. Micas were in small amounts (<10%) when present. Epidote was identified in one sample, but was a small component.

Lithology and Fracture Characterization of Borehole in the CHRV

Well 14FF58 is the only well being characterized in the CHRV. Structurally, well 14FF58 is highly jointed: 159 joints in total. There are twelve areas of concentrated jointing in well 14FF58. Figure 35 shows the orientations of all 159 joints measured in the borehole. The stereonet in Figure 35 shows that the majority of the joints are high-

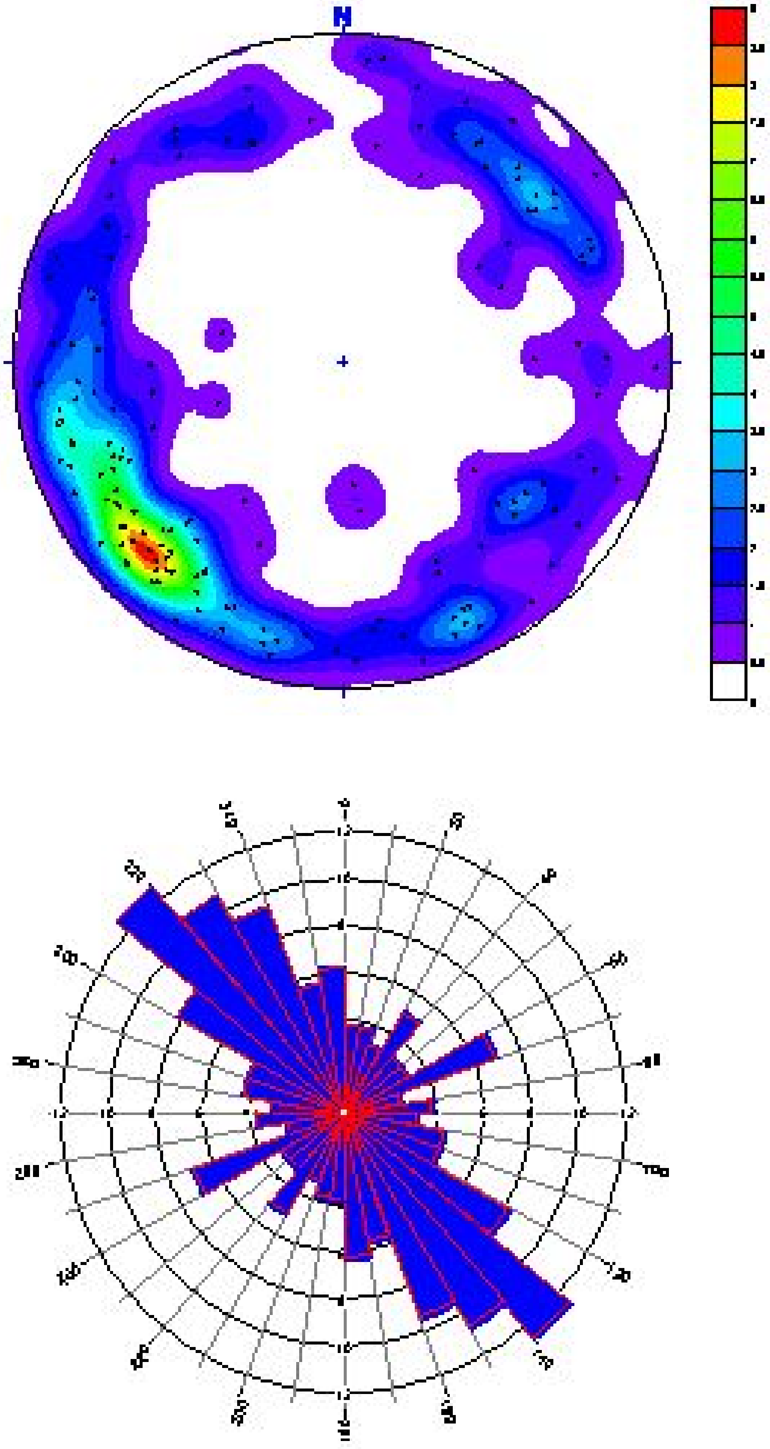


Figure 35. Stereonet and bi-directional rose diagram showing all joints measured in well 14FF58.

angle (>45 degrees) and that there is one predominant tight grouping in the bottom left quadrant of the stereonet. The rose diagram in Figure 35 shows a clear prevailing trend of northwest-southeast. This dominant strike also parallels the topographic lineament identified in the CCRV.

If joint trends are compared between well 14FF58 (< 1 gpm) and 14FF59 (300 gpm) (Figure 36), the reader can see that well 14FF58 lacks the joint orientation variation needed to better promote the development of a well-connected fracture network. The presence of a single dominant strike direction for all the joints reduces the likelihood of a well-connected fracture network.

There are two open fractures in well 14FF58. The stereonet diagram in Figure 37 shows that, compared with the major fractures in 14FF59 and the foliation fractures in 14FF42, these two fractures have much higher angles. The two open fractures in well 14FF58 are high-angle joints with apertures capable of transmitting groundwater. The granite gneiss encountered in 14FF58 is poorly foliated to massive, which further supports the belief that the open fractures are joints. In addition, there are no contacts between rock types or interlayered units present to promote the development of sub-horizontal, open fractures.

Foliation orientations are not presented for well 14FF58 due to the poorly foliated, massive nature of the granite gneiss.

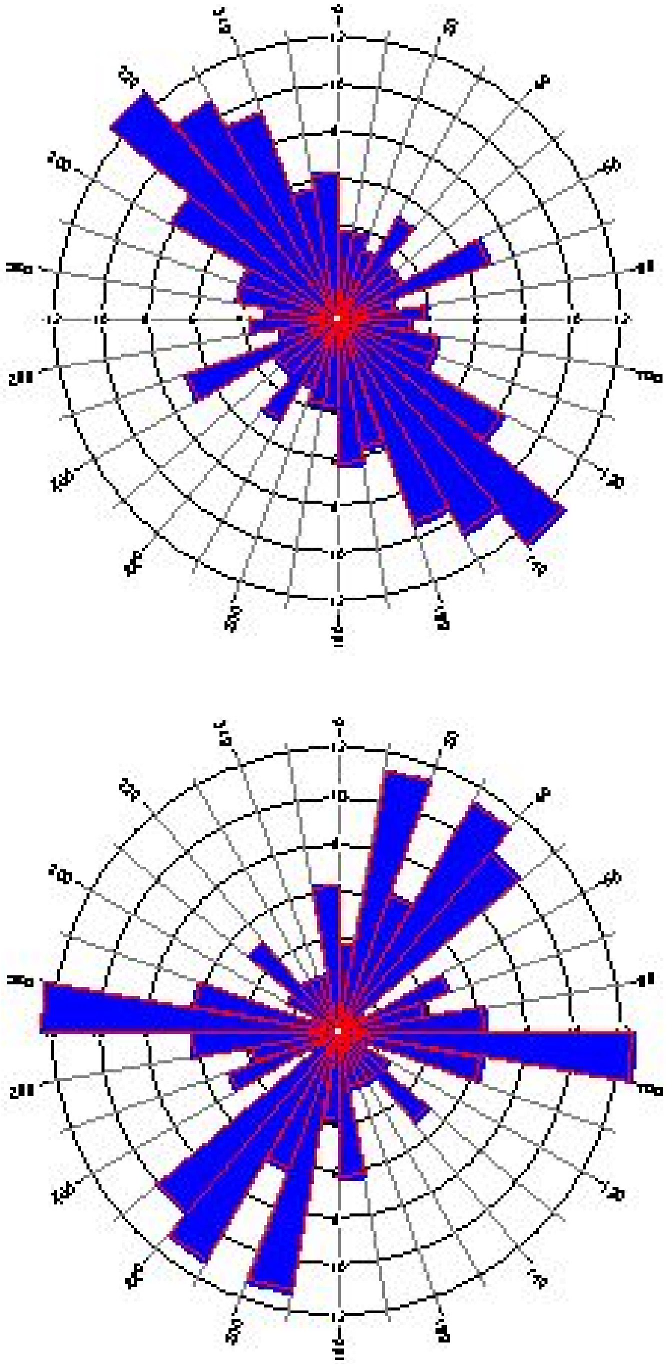


Figure 36. Bi-directional rose diagrams of all joints for wells 14FF58 (top) and 14FF59 (bottom).

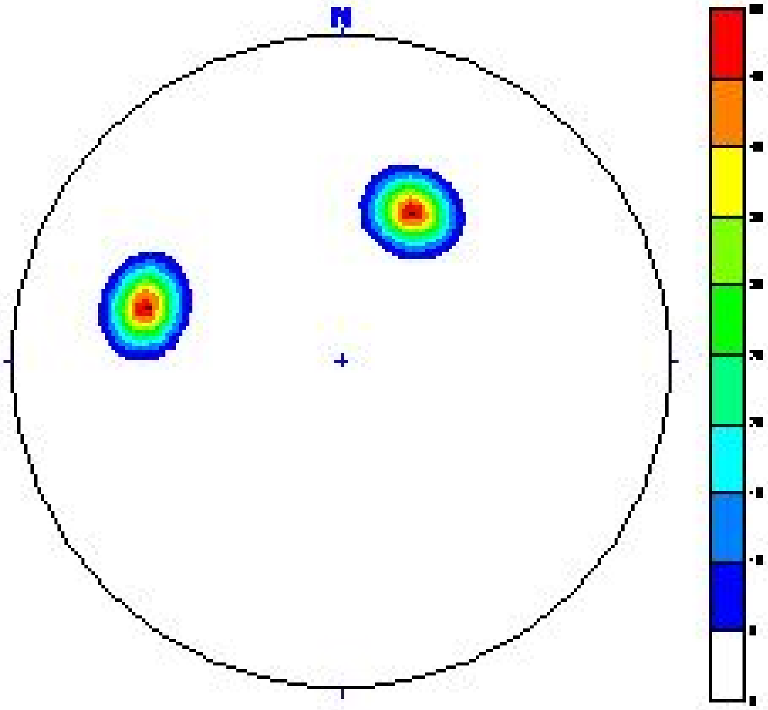


Figure 37. Stereonet diagram showing the poles for the two open fractures in 14FF58.

CHAPTER 4

DISCUSSION

Rock Type

The USGS found that rock type appears to be the most important factor in obtaining high groundwater yields in Lawrenceville (LJ Williams, personal comm., 2002). High groundwater yields in the area are obtained exclusively from the layered rocks while relatively low-yields are obtained from massive rocks.

This study provides two excellent examples of different scenarios where rock type influences the potential groundwater yield of three bedrock wells.

Well 14FF58 was sited in an area of massive granite gneiss. This rock type was not viewed as a potential groundwater-bearing rock during mapping for two reasons. The granite gneiss is poorly foliated and not found thinly interlayered with other rocks. Weak to absent foliation reduces the likelihood that sub-horizontal fractures will form along foliation. The granite gneiss is not interlayered with any other rock types and is found massive in the study area. This lack of interlayering eliminates the potential development of fractures along contacts. The granite gneiss, when encountered as massive and not interlayered or near contacts with other rock types, is an example of a rock type that does not have a high potential to yield sufficient amounts of groundwater.

Wells 14FF42 and 14FF59 are both located in the same sequence of rocks: amphibolite interlayered with biotite gneiss (amphibolite) sitting atop button schist, which in turn is sitting atop biotite gneiss interlayered with amphibolite (biotite gneiss). Of the three rock types encountered in both wells, two of the rock types (amphibolite and biotite gneiss) were believed to be potential groundwater bearing rocks. Prior to test drilling, the amphibolite unit was believed to be the most productive rock type in the Lawrenceville area. The amphibolite is well foliated, resistant to weathering and thinly interlayered with biotite gneiss. Subsequent test drilling revealed that the biotite gneiss found beneath the button schist was the most productive rock type penetrated by the test wells. The button schist is foliated, resistant to weathering, and not interlayered with other rock types. The biotite gneiss is well foliated, not resistant to weathering, and thinly interlayered with amphibolite. The button schist was not considered to be a potential groundwater bearing rock during mapping, but contacts along this unit with the amphibolite and biotite gneiss units provided potential areas for development of openings capable of transmitting groundwater. Both the amphibolite and biotite gneiss were viewed as potential groundwater bearing rocks during mapping. Both units are well foliated, allowing for the potential development of fractures along foliation. The units also weather at different rates, allowing for the potential development of openings along the contacts within the interlayered units. Both the amphibolite and biotite gneiss units are good examples of rock types that have a high potential to yield significant amounts of groundwater especially when the units are encountered in contact with other rock types with different weathering rates.

Structure

Geologic structure plays a major role in potential groundwater yield at the wells studied. Geologic structure, as it pertains to this study, is defined as any subsurface feature that creates secondary porosity within the underlying rocks (i.e. high-angle joints, foliation fractures, etc.) All three wells discussed in this paper have varying types and quantities of subsurface structure.

Well 14FF58 is dominated by high-angle jointing. This well was sited because abundant jointing was noted during mapping along a topographic lineament near the well location. Due to the weakly foliated nature of the granite gneiss, it was not believed that the rock type would have developed sub-horizontal, subsurface fracturing parallel to foliation. Subsequent borehole logging revealed that well 14FF58 lacked a horizontal fracture component needed to develop a fracture network that could transmit significant amounts of groundwater, and that almost all of the high angle joints were tight. Borehole logging did reveal that there were a few high angle joints with apertures capable of transmitting groundwater.

High-angle jointing at the surface is a good indication that there is a potential for substantial groundwater yields in the area, but high-angle jointing alone typically only transmits small amounts of groundwater. Well 14FF58 is a good example of a how a high-yielding fracture network is difficult to develop with only high-angle jointing. Geologic mapping indicated significant vertical fracturing, but the rock type did not promote the development of horizontal fracturing.

Well 14FF42 provides an example of a well that encounters very minimal subsurface structure. Outcrops south of well 14FF42 lack structure capable of transmitting significant amounts of groundwater. Subsequent borehole logging revealed that this well encountered very few high-angle joints and where foliation fractures were present, they had negligible apertures.

The presence or lack of structure at the surface is a good indication of whether structure will be present in the subsurface. Well 14FF42 provides a good example of how the lack of structure at the surface correlated with the lack of structure in the subsurface. Without a vertical structural component transmitting infiltrated water into the bedrock beneath, the openings parallel to foliation/compositional layering do not develop through differential weathering.

Well 14FF59 provides an example of the ideal combination of subsurface structure needed to create a well-developed fracture network capable of transmitting significant amounts of groundwater. Geologic mapping in the area recorded the presence of abundant jointing in the rocks exposed in stream valley near well 14FF59. Geologic mapping also determined that the shallow dipping sequence of rocks in the area was dipping down basin (Alcovy River basin), which would favor the development of sub-horizontal openings along the contacts between the major units. Subsequent borehole logging confirmed that the abundant jointing noted at the surface persisted into the subsurface. Borehole logging also confirmed that there were sub-horizontal openings along shallow dipping contacts as well as along contacts within the thinly interlayered rock types (amphibolite and biotite gneiss).

The combination of high-angle jointing and sub-horizontal openings creates a fracture network that can apparently transmit substantial amounts of groundwater. The high-angle joints may serve as conduits through which groundwater is transmitted from the soil-bedrock interface into the underlying bedrock and the laterally extensive sub-horizontal openings. This combination not only allows for the effective transmission of groundwater, but it potentially creates significant groundwater storage if these sub-horizontal openings are laterally extensive.

The mapping conducted prior to drilling well 14FF59 provides an excellent example of how surface structure provided insight into the nature of subsurface structure. One of the main reasons well 14FF59 was sited was because of the structure and lithology noted during geologic mapping.

Topography

All three wells in this study are located in different topographic positions. Well 14FF58 is located on a shallow slope within the drainage basin of a spring-fed stream. Well 14FF42 is located on a ridge top and well 14FF59 is located in the stream valley of the Alcovy River. In the terms of geologic setting and well site location, topographic lows are viewed as more favorable locations as opposed to topographic highs. This view is mainly based on the effects of topographic position on depth of weathering and recharge potential.

Depth of Weathering

The relative depth of weathering in increasing order in the Lawrenceville area is generally granite gneiss, amphibolite and biotite gneiss. Overall, the depth of weathering in the study area is sufficient to produce a soil/saprolite capable of sufficient groundwater storage. Depth of weathering immediately around a well is not considered important since high-yield wells probably derive their recharge from large areas.

The weathered soil/saprolite sitting atop the rocks in the area is believed to act as a sponge, which stores and recharges groundwater to the fractured bedrock system. None of the wells in this study had a thick soil/saprolite cover. The highest yielding well, 14FF59, had less than 10 ft of soil/saprolite above the soil bedrock interface. Thin soil/saprolite layers in the immediate well area do not serve as a deterrent to potential high groundwater yields. Since fracture networks have the potential, if well connected, to extend far beyond the immediate well area, thick soil/saprolite distant from the well location can serve as the "sponge". An additional aspect of depth of weathering is differential weathering between rock types. Beyond the differences in depths of weathering at the outcrop scale, extensive preferential weathering can occur in layered rocks, especially in the amphibolite-biotite gneiss sequences. Preferential weathering along the more susceptible biotite gneiss layers leads to layers of saprolite within layers of rock. This process may enhance or be responsible for the development of the sub-horizontal foliation fracture systems observed in layered rocks like those at well 14FF59.

Recharge Potential

Recharge potential is controlled by several other factors including topographic position, structure, and depth of weathering and implies the potential of recharge to a selected well site. Recharge probably occurs all over the Piedmont. The amount in any given area is dependent on the vegetation cover, slope, soil type, etc. When a well pumps water from a fractured bedrock system, the recharge comes from a very local area. This differs from coastal plain aquifers for example, whose recharge could be received from many 10's or 100's of miles away. The rocks in the Lawrenceville area are generally shallow dipping and therefore openings along contacts between major units have the potential to be laterally extensive. Even with the shallow dipping contacts, recharge potential to a single well is generally thought to be within one or possibly several drainage basins surrounding the well (LJ Williams, personal comm., 2002).

When evaluating an area for a groundwater supply well, recharge potential is estimated by looking at the topographic position, systematic structures or geologic controls that could act as recharging mechanisms and depth of weathering in the area of the potential well site. Well 14FF58 appeared to have a good recharge potential. This is based mainly on its favorable position within a drainage basin and apparent structure (joints) in the area that promote downward migration of infiltrated water into the bedrock. The depth of weathering immediately around well 14FF58 was relatively deep. The rock in the upstream area of well 14FF58, on the other hand, does not promote a good recharge potential. The upstream areas have thin soil/saprolite coverage and were therefore considered poor sources of recharge.

Well 14FF42 provides an example where more than one factor promotes a poor recharge potential. Topographically, well 14FF42 sits atop a ridge, and significant structures in the area, such as joints, are generally lacking.

Well 14FF59 appeared to have a good recharge potential prior to drilling the well. Topographically, well 14FF59 is located in the stream valley of the Alcovy River. Structure in the area is abundant, and the sequence of rocks beneath the well location is dipping down-basin toward the well location. The depth of weathering is relatively thin, but this may not be indicative of soil/saprolite thicknesses away from the well location.

Interrelationship Between all Factors

The key to understanding the potential for high-yielding wells in any given area is believed to be the interrelationship of all the previously mentioned factors (Crawford and Kath, 2001; Kath and others, 2001). Crawford and Kath use a qualitative approach in site evaluation that requires experience in understanding the significant interplay of each of the above-mentioned factors. This interrelation can be extremely complicated depending on the complexity of the geology and the main factors controlling groundwater in the bedrock. Each of the factors alone play a role, but the success of well locations is based on the interrelationship of all the factors for any given well location.

Well 14FF58 yielded less than 1 gpm. Many of the factors considered in siting fractured bedrock wells promoted a much higher yield for well 14FF58, but all the factors combined support this low yield. Topographic position, depth of weathering and for the most part structure all promoted the potential for a high groundwater yield. Rock type and structure to some extent were the factors that controlled the low yield of well 14FF58. Structurally, the area where well 14FF58 was sited had one of the needed subsurface components but lacked the key subsurface component that produces high groundwater yields in the Lawrenceville area. The shallow dipping nature of the rocks in Lawrenceville allows openings along contacts and foliation, which tends to be low-angle as well, to be laterally extensive. The contact with the underlying biotite gneiss was targeted, but when it was not encountered during drilling, the major sub-horizontal component to the fracture network was eliminated. Without a major contact present, rock type controlled the remainder of the potential to yield significant amounts of groundwater. The granite gneiss was noted during mapping as being weakly foliated and not thinly interlayered with any other rock types. These two observations significantly decreased the possibility of encountering any sub-horizontal fractures. The interrelationship of all the factors, in turn, promotes the low yield of well 14FF58.

Well 14FF42 also has a yield of less than 1 gpm but is situated in a geologic setting that is almost opposite of the geologic setting of well 14FF58. Two of the three rock types (amphibolite and biotite gneiss) in the area of well 14FF42 are favorable rock types for yielding high amounts of groundwater, but all the remaining factors do not promote high groundwater yields. Topographically, the well location is on a ridge. Structurally, the area is lacking both surface and subsurface structure. Depth of weathering and recharge potential as well do not promote high groundwater yields.

Well 14FF59 is situated in a geologic setting that promotes high groundwater yields in every aspect. Two of the three rock types (amphibolite and biotite gneiss) are favorable rock types for yielding high amounts of groundwater. Structurally, the area is characterized by abundant high-angle jointing along with the potential for sub-horizontal openings along major and minor contacts and along foliation. Topographically, the well site is located in a stream valley, and both the depth of weathering and recharge potential are favorable as well. The interrelationship of these factors defines a good geologic setting for obtaining high groundwater yields. The rock types interact with the structure of the area to create a well-developed fracture network capable of transmitting high amounts of groundwater. The rock types and structure interact with the topographic position, depth of weathering and, in turn, with the recharge potential to create a setting of open sub-horizontal contacts dipping down basin and abundant high angle joints, which are potentially being recharged by thick soil/saprolite covers away from the well location. This combination of factors can recharge significant amounts of groundwater to well 14FF59. A sustainable yield of approximately 250 gpm was determined for well 14FF59 by a pumping test performed by the City of Lawrenceville independent of this study.

Collectively, the factors recognized by Crawford and Kath explain the outcomes of all three wells discussed in this thesis. The massive nature of the granite gneiss at well 14FF58 controls the low groundwater yield. The lack of structure and high topographic position controls the low groundwater yield at well 14FF42. The high groundwater yield at well 14FF59 is controlled by the interlayered rock types, abundant structure, differential weathering within the interlayered rock types and low topographic position.

CHAPTER 5

CONCLUSION

The goal of this study was to evaluate three different wells located in different geologic settings to demonstrate the importance of geologic setting in developing high groundwater yields from fractured metamorphic bedrock aquifers. Due to the limited number of wells studied during this project, no conclusions can be drawn on the accuracy of the methods used in this study. The five factors believed to control well yield in igneous and metamorphic rocks are: (1) rock type, (2) structure, (3) topographic position, (4) depth of weathering and (5) recharge potential. None of these factors alone can characterize an area as having a high groundwater potential. An area is believed to be characterized as having a high groundwater potential when many if not all of the above factors interplay to create a geologic setting capable of transmitting groundwater to a bedrock well.

The study involved constructing detailed geologic maps in each area, drilling wells and documenting lithology and bedrock fractures and comparing well yield characteristics to the actual factors believed to be related to high-yielding wells in igneous and metamorphic rocks.

For the most part, the majority of these factors can be determined with site-specific geologic mapping. Site-specific geologic mapping can determine the distribution of rock types, provide a qualitative sense of the frequency and type of structures that may be encountered in the subsurface and document site specific information (i.e. depth of weathering, recharge potential, etc.) about the local geologic setting. Subsequent borehole logging can produce information regarding the nature of subsurface structure, which can be difficult to determine with geologic mapping alone. Borehole imaging allowed for greater interpretation as to the source or mechanism responsible for the sub-horizontal, water-bearing fractures encountered in well 14FF59. Because the high-yield fractures were found parallel to foliation it indicated the potential importance of lithologic and structural controls on groundwater occurrence and availability.

Crawford and Kath conduct groundwater exploration and development projects without the use of geophysical logging and have had great success. Even though geophysical borehole logging is not necessary to conduct successful explorations, a combination of site-specific geologic mapping, pilot hole installation and borehole logging is believed to be the most favorable methodology for developing groundwater supplies.

Rock type was observed as the most important factor of geologic setting controlling the yields of the wells studied in Lawrenceville, Georgia. Rock type has an affect on almost all of the other factors used in determining potential high yielding well locations. Rock type is intimately related to structure and in essence, rock type controls structure in many aspects. The major aspects of rock type that control groundwater yields are the degree of foliation, the degree of fracturing and the nature of the contacts between the rock types. The degree of fracturing is also considered when analyzing structure but, the more structures such as joints, foliations and layering within a given rock type the more likely that the rock type will be considered favorable. Within any given area, one or more rock types typically will be considered more favorable than the other. Well 14FF59 encountered several rock types that were considered favorable due to their abundance of subsurface structures and topographically low structural position.

Recharge potential and depth of weathering are closely related to topographic position and also interrelated with structure and rock type. Each of the five factors analyzed during this study are not stand-alone factors. Even the most important factor, rock type, is dependent on other factors like topographic position and recharge potential. In order to better determine groundwater potential for any given area, all five factors should be analyzed and viewed as interrelated.

In conclusion, the three wells studied during this project behave consistently with what would be predicted based on the rock type(s), structure, topographic position, depth of weathering and recharge potential identified for each well location. This study demonstrates that learning the geologic setting prior to drilling can provide insight into the outcome of a bedrock well. The methods for conducting groundwater exploration projects discussed in this study and practiced by Crawford and Kath are not commonly used in the Piedmont, but their more practical widespread use could increase the success rate of groundwater exploration projects in the Piedmont and potentially in other igneous and metamorphic rock settings.

REFERENCES

Atkins, R.L., and Higgins, M.W., 1980, Superimposed folding and its bearing on geologic history of the Atlanta, Georgia, area; *in* Frey, R.W., ed.: Excursions in southeastern Geology: American Geological Institute, v. 1, p.19-40.

Atkins, R.L., and Morris, L.J., 1982, Luxomni quadrangle, Georgia: Georgia Geologic Survey Open-File geologic map, scale 1:24,000.

Chapman, M.J., Crawford T.J., and Tharpe W.T., 1999, Geology and Ground-Water Resources of the Lawrenceville Area, Georgia: U.S. Geological Survey Water-Resources Investigations Report 98-4233, p. 46.

Chapman, M.J., Hicks, D.W., Peck, M.F., and Tharpe, W.T., 1997, Characterization of a crystalline-rock aquifer near Lawrenceville, Georgia-Application of advances in borehole and surface geophysical methods: *in* Proceedings of the Fifth Biennial Georgia Water Resources Conference, March 20-22, 1997, Athens, Ga., p. 369-372.

Chapman, M.J. and Lane, J.W., Jr., 1996, Use of directional borehole radar and azimuthal square-array d.c. resistivity methods to characterize a crystalline-bedrock aquifer: *in* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 28-May 2, Keystone, Co., p. 833-842.

Clark, W.Z., Jr., and Zisa, A.C., 1976, Physiographic map of Georgia: Georgia Geologic Survey State Map 4, 1 sheet, scale 1:2,000,000.

Crawford, T.J., Higgins, M.W., Crawford, R.F., Atkins, R.L., Medlin, J.H., and Stern, T.W., 1999, Revision of Stratigraphic Nomenclature in the Atlanta, Athens, and Cartersville 30’ x 60’ Quadrangles, Georgia, Georgia Department of Natural Resources Environmental Protection Division Georgia Geologic Survey, Bulletin 130, p. 45

Crawford, T.J., and Kath, R.L., 2001, Ground-Water Exploration and Development in Igneous and Metamorphic Rocks: Part I: Influencing Factors and Considerations in Adams, D. Briane, Burke, Katrina, Hemingway, Bruce, Keay, Jeff, and Yurewicz, Michael, comps., U.S. Geological Survey Appalachian Region Integrated Science Workshop Proceedings, Gatlinburg, Tennessee, October 22-26, 200l: U.S. Geological Survey Open-File 01-406, p. 106.

Cressler, C.W., Thurmond, C.J., and Hester, W.G., 1983, Ground water in the greater Atlanta region, Georgia: Georgia Geological Survey Information Circular 63, p. 144

Dooley, R.E., Lawrenceville, quadrangle, Georgia: unpublished, Georgia Geological Survey Open-File Geologic Map, scale 1:24,000.

Herrick, S.M., and LeGrand, H.E., 1949, Geology and ground-water resources of the Atlanta area, Georgia: Georgia State Division of Conservation Department of Mines, Mining and Geology, Bulletin 55, p. 124

Higgins, M.W., Atkins, R.L., Crawford, T.J., Crawford, R.F., III, Brooks, Rebekah, and Cook, R.B., 1988, The structure, stratigraphy, tectonostratigraphy, and evolution of the southernmost part of the Appalachian orogen: U.S. Geological Survey Professional Paper 1475, p. 173

Higgins, M.W., Crawford, T.J., Atkins, R.L., and Crawford, R.F., 1998, Geologic Map of the Atlanta 30' x 60' Quadrangle, Georgia, U.S. Geological Survey, Open-File Report 98-245, p. 18

Kath, R.L., Crawford, T.J., and Williams, L.J., 2001, Ground-Water Exploration and Development in Igneous and Metamorphic Rocks: Part II: Case Histories from the Southeastern Piedmont/Blue Ridge Province in Adams, D. Briane, Burke, Katrina, Hemingway, Bruce, Keay, Jeff, and Yurewicz, Michael, comps., U.S. Geological Survey Appalachian Region Integrated Science Workshop Proceedings, Gatlinburg, Tennessee, October 22-26, 2001: U.S. Geological Survey Open-File Report 01-406, p. 120.

Kath, R.L., Spilde, M.N., Davis, B.L., and Smith, D.K., 1991, Reference Intensity Ratio and Mass Absorption Measurements of Eleven Biotites, Powder Diffraction, Vol. 6, No. 4, p. 183-186.

McConnell, K.I., and Abrams, C.E., 1984, Geology of the Greater Atlanta region: Georgia Geologic Survey Bulletin 96, Dept. of Natural Resources, Environmental Protection Division, Georgia Geologic Survey, p. 127

Prowell, D.C., 1988, Cretaceous and Cenozic tectonism on the Atlantic coastal margin; *in Sheridan, R.E., and Grow, J.A., eds., The Geology of North America, Volume I-2, The Atlantic Continental Margin, U.S.*: Geological Society of America, Chapter 29, p. 557-564.

Radzieta, David, 1993, The characterization of a layered saprolite/fractured bedrock aquifer: *in Proceedings of the Third Biennial Georgia Water Resources Conference, April 20-21, 1993 Athens, Ga.*, p. 204-208.

Special Environmental Services, Inc., 1991, Hydrogeologic investigation for municipal water well data, City of Lawrenceville: unpublished, prepared for the City of Lawrenceville and Hayes, James, & Associates, p. 50

Williams, L.J., R.L. Kath and J.L. Lawson, 2002, in press, Methods Used to Identify Geologic Structures That Affect Ground-Water Occurrence and Availability in Igneous and Metamorphic Rocks in the Gwinnett County Airport and Collins Hill Road Areas, Gwinnett County, Georgia.

Zoback, M.L, and Zoback, M.D. 1989, Tectonic stress field of the Continental United States, *in Pakiser, L.C., and Mooney W.D., Geophysical framework of the continental United States*: Boulder, Colorado, Geological Society of America Memoir 172, p. 523-539.