Groundwater Resources of the Blue Ridge Geologic Province, Virginia

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Cover: View from the Priest Mountain in Nelson County, Virginia looking east toward the Virginia Piedmont. (Photograph by Brad White, Virginia Department of Environmental Quality, November 2010)

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NOTE: ***Appendixes available for download as Microsoft® Excel files at the following web site:***
http://www.deq.virginia.gov/Programs/Water/WaterSupplyWaterQuantity/GroundwaterCharacterization/ReportsPublications.aspx

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GROUNDWATER RESOURCES OF THE BLUE RIDGE GEOLOGIC PROVINCE, VIRGINIA

ABSTRACT

A comprehensive regional description presents hydrogeologic and geochemical characteristics and the water-bearing potential of major rock types in the Blue Ridge Geologic Belt of Virginia. Stream and groundwater-level records are presented and described to help illustrate groundwater recharge and discharge processes. Groundwater pumping records are presented and discussed to describe the variability in groundwater storage in fractured crystalline rock aquifers. Regional structural outcrop and borehole measurements and reported water bearing fracture depth information are presented and analyzed to describe regional trends in fracture orientation and depth of groundwater circulation.

A total of 45 rock type pairs among 10 major rock types were compared for differences in hydrogeologic and geochemical characteristics recorded from well drilling reports and groundwater samples. Statistically significant differences were observed between pairs of rock types for most hydrogeologic and some geochemical characteristics.

Reported depth to bedrock and reported well depth were the two hydrogeologic characteristics exhibiting the highest percentages of statistically significant differences between rock type comparisons (62% and 60%, respectively), followed by depth to lowest reported water bearing zone (49%) and first reported water bearing zone (44%), well yield (42%), and depth to water (22%). No statistically significant differences were observed between viable populations for non-domestic well yield, pumping well yield (reported well yield after at least 24 hours of pumping), and specific capacity, but several populations were not compared due to insufficient data in the specific capacity and pumping well yield categories. Layered Granulites, rocks of the Lynchburg Formation and late Proterozoic shallow water facies, and rocks of the Ashe Metamorphic Suite have the greatest percentages of wells having non-domestic well yields of more than 50 and 100 gallons per minute.

Statistical analyses of selected groundwater geochemical characteristics show no statistically significant difference between groundwater samples for most pairs of rock types, with the exception of rock type pairs associated with the Catoctin Formation of the rift related volcanics group. Statistically significant differences between groundwater geochemical parameters for rock type pairs associated with the Catoctin occurred most frequently with magnesium, bicarbonate, and specific conductance (8 of 9 possible pairs), followed by filtered residue, hardness, calcium, and potassium (6 of 9 possible pairs), and pH (5 of 9 possible pairs). With the exception of potassium, values for these parameters were elevated in the Catoctin when compared with other rock types. Values for potassium were notably lower in groundwater samples from the Catoctin than in samples from other rock types. Other notable differences in groundwater geochemical parameters between rock type pairs occurred for lower concentrations of sodium in the Ashe Metamorphic Suite

and Alligator Back formations (6 of 9 and 3 of 9 pairs, respectively), higher concentrations of potassium in the foliated crystalline rocks pairs (5 of 9), and lower concentrations of aluminum in the Lynchburg (4 of 9 pairs), Ashe Metamorphic Suite, and Alligator Back Formation (both with 6 of 9 possible pairs). No statistically significant differences were observed between pairs for iron.

When considered as percentages of total ion charge, major cations in groundwater samples taken from the major rock types are uniformly dominated by calcium, followed by sodium and then magnesium with the exception of samples taken from the Catoctin Formation, Chilhowee Group, and Candler Formation which have magnesium as the next most abundant percentage, followed by sodium. Potassium makes up the smallest percentage of the total major cation charge for all major rock types. Trends in percentages of total anion charge within groundwater sampled from all major rock types are similar, and are dominated by bicarbonate, similar percentages of chloride and sulfate, with fluoride as the lowest percentage of total major anion charge.

Groundwater-level, streamflow, and precipitation data indicate that groundwater recharge is diminished when evapotranspiration is active during the summer. Timing of recharge to fractured rock aquifers is further controlled locally by the orientation of transmissive fractures and their resulting degree of hydraulic connection with overlying regolith through which infiltrated meteoric water is transmitted and stored. Stream discharges vary directly with groundwater levels, but correlations between these variables are dependent on the locations of hydraulic head represented by groundwater levels. Observed hydraulic heads within shallow fractures vary closely with observed streamflows, whereas observed hydraulic heads within deeper fractures vary more independently.

Among wells with all reported water bearing zones restricted to a single 100 foot fracture interval, median and average well yield trends decrease with depth of fracturing, but this trend may be governed by the lack of transmissive fractures higher in the borehole. Median well yields decreased from a high of 12 gallons per minute for wells with 100 foot fracture intervals occurring between 100 to 300 feet, to 4 gallons per minute for wells with 100 foot fracture intervals occurring greater than 600 feet.

An analysis of reported water bearing zones from well drilling reports indicate that wells completed in mylonitic rocks of the Blue Ridge basement and the Ashe Metamorphic Suite of the Blue Ridge cover have the highest frequency of water bearing zones, and drillers logs indicate that foliated crystalline rocks of the Blue Ridge basement and the Candler Formation of the Blue Ridge cover show the greatest percentage of deeper water bearing zones (deeper than 300 feet).

Based on outcrop and borehole measurements, joints in rocks of the Blue Ridge Basement Complex exhibit distinct trends only locally but not regionally. By contrast, regional trends are distinct among the foliation and schistosity of basement rocks. Likewise, for Blue Ridge Cover Rocks, regional trends are distinct among foliation, schistosity and cleavage, as well as joints.

This investigation entailed compilation by personnel of the Virginia

Department of Environmental Quality of archived digital water-well construction records and groundwater geochemical data from databases of the Environmental Protection Agency (STORET), United States Geological Survey (GWSI and NWIS), Virginia Department of Health (VENIS and SDWIS), Virginia Division of Mineral Resources, Virginia Department of Environmental Quality, and Albemarle, Fauquier and Loudoun counties. In conjunction with the Virginia Division of Mineral Resources GIS version of the Virginia State Geologic Map (Virginia Division of Mineral Resources, 1993), hydrogeologic and geochemical characteristics and the water-bearing potential of major formations and rock types in the Virginia Blue Ridge Geologic Belt were evaluated and described. Water level and streamflow records also were compiled from observation wells and streamflow gages in the USGS/DEQ real-time surface-water and groundwater networks to describe variable timing of groundwater recharge and temporal relations between changes in groundwater storage and stream discharge. A conceptual description of groundwater storage was developed based on data from 48-hour pump tests of wells in fractured rock aquifers, geophysical logging, and analysis of groundwater level records. Regional differences and similarities in schistosity, cleavage, and fracturing were compared and contrasted based on structural geologic outcrop measurements by VDMR and USGS personnel and structural borehole geophysical measurements by DEQ personnel.

INTRODUCTION

Background

Concern over the lack of available groundwater related information coupled with the severe impacts of the 2002 drought has highlighted the need to better understand the occurrence and dynamics associated with the groundwater resource. In 2005, the Virginia General Assembly enacted legislation to allow for the creation of a Groundwater Characterization Program within the Virginia Department of Environmental Quality Office of Water Supply. Information collected by the Program is made available for water supply planning and educational purposes.

Purpose and Scope

The purpose of this report is to describe the occurrence, movement, and geochemical character of groundwater within the portion of the Piedmont and Blue Ridge Physiographic Provinces of Virginia known as the Blue Ridge Geologic Province. This report is intended to refine previous work by examining the groundwater components of distinct rock types within the Blue Ridge Geologic Province based on the assumption that the unique mineralogy and metamorphic history of each group are integral to its hydrogeologic and geochemical characteristics. The report is also intended to review the conceptual model of groundwater flow and storage in the Blue Ridge Geologic Province by examining the major groundwater components of the hydrologic cycle: recharge, discharge, and storage. Lastly, it is hoped that this report will serve as a resource to those wishing to seek additional references pertaining to the geology and groundwater resources of the Blue Ridge Geologic Province.

Previous Hydrogeologic Investigations Conducted in the Blue Ridge Geologic Province of Virginia

The following table organizes published hydrogeologic studies conducted in the Blue Ridge Geologic Province of Virginia at the local, county, and regional levels. There are undoubtedly additional published works on this topic that are not known to the author.

Table 1. List of groundwater related publications by size of study area, date, and author.

Scale	Author and Date	Title	Report Description
LOCAL	(Furcron, 1939)	Geology and Mineral Resources of the Warrenton Quadrangle	Section on groundwater in publication. Discussion of occurrence and movement and description of groundwater productivity and quality by rock type in the study area. Brief discussion of municipal water supplies and mineral springs in the area.
	(Leonard, 1962)	Ground-Water Geology Along the Northwest Foot of the Blue Ridge Between Arnold Valley, and Elkton, Virginia	Description of geology and water bearing characteristics of formations in study area. Description of groundwater quality and geologic influences on groundwater chemistry.
	(Toewe, 1966)	Geology of the Leesburg Quadrangle, Virginia	Section on groundwater in publication. Discussion of occurrence and movement and description of groundwater productivity and quality by rock type in the study area. Utilizes well records to describe average yield by rock type, as well as trends in well yield with depth for rock types in the study area.
	(Dekay, 1972)	Development of Ground-Water Supplies in Shenandoah National Park, Virginia	Description of geology, spring flow characteristics for 30 springs, drilling sites, and test wells drilled in the Shenandoah National Park between 1961 and 1971.
	(Luckert and Nuckols, 1976)	Geology of the Linden and Flint Hill Quadrangles, Virginia	Section on groundwater in publication. Discussion on occurrence and movement and geologic controls on groundwater quality and quantity in study area. Summarizes yield and depth data by formation for 135 wells drilled in the study area.
	(Hopkins, 1984)	Ground-Water Availability Along the Blue Ridge Parkway	Description of geology, spring flow characteristics, drilling sites, and test wells drilled along the Blue Ridge Parkway. Identifies potential drilling sites for future groundwater development. Inventory of well and spring records, streamflow, water quality data, and site locations.
	(Lynch, 1987)	Hydrologic Conditions and Trends in Shenandoah National Park, Virginia, 1983-84	Describes (1) the amount and variability of precipitation, surface water, and groundwater and (2) long-term trends in groundwater levels in relation to climate and groundwater withdrawals within the Shenandoah National Park.
	(Southworth, 1990)	Hydrogeologic Setting of Springs on Short Hill Mountain, Loudoun County, Northern Virginia	Describes the hydrogeologic settings of springs and potential geologic controls on groundwater flow and storage on Short Hill Mountain in Loudoun County, Virginia.
	(Seaton and Burbey, 2000)	Aquifer Characterization in the Blue Ridge Physiographic Province Using Resistivity Profiling and Borehole Geophysics: Geologic Analysis	Development of conceptual groundwater flow model in the Blue Ridge based on borehole geophysical logging and surface electrical resistivity profiling at a field site in Floyd County Virginia .

Scale	Author and Date	Title	Report Description
LOCAL	(Sutphin et al., 2000).	Characteristics of Water-Well Yields in the Blue Ridge of Loudoun County, Virginia	Variography of well yields in the Blue Ridge Province of Loudoun County. ANOVA statistical analysis of well yield by rock type within the county.
	(Plummer et al., 2001)	Ground Water Residence Times in Shenandoah National Park, Blue Ridge Mountain, Virginia, USA, A multi-tracer approach.	Multiple environmental tracers used to estimate the residence times of shallow groundwater discharging from 34 springs and 15 wells in the Shenandoah National Park.
	(Gentry and Burbey, 2004)	Characterization of Ground Water Flow From Spring Discharge in a Crystalline Rock Environment	Describes the sources and relative contributions of groundwater discharging from a spring in a crystalline rock setting of the Blue Ridge Province.
	(Seaton and Burbey, 2005)	Influence of Ancient Thrust Faults on the Hydrogeology of the Blue Ridge Province	Development of conceptual groundwater flow model in the Blue Ridge based on borehole geophysical logging, surface electrical resistivity profiling, and aquifer testing at a field site in Floyd County Virginia .
	(White and Burbey, 2007)	Evidence for Structurally Controlled Recharge in the Blue Ridge Province, USA	Investigation of the geologic controls on groundwater recharge at a field site in Floyd County, Virginia using surface electrical resistivity, moisture content profiling, and matric potential measurements.
	(Rugh and Burbey, 2007)	Using Saline Tracers to Evaluate Recharge in Fractured Rocks, Floyd County, Virginia, USA	Investigation of the geologic controls on groundwater recharge at a field site in Floyd County, Virginia using saline tracer techniques.
COUNTY	(Cross, 1960)	Water-Well Data, Western Part of Albemarle County	Inventory of approximately 300 water well records for the western portion of Albemarle County.
	(Legrand, 1960)	Geology and Ground-Water Resources of Pittsylvania and Halifax Counties	Describes geology and groundwater conditions in Pittsylvania and Halifax Counties. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.
	(Nelson, 1962)	Geology and Mineral Resources of Albemarle County	Section on groundwater in publication. Description of groundwater productivity by rock type or formation.
	(Allen, 1963)	Geology and Mineral Resources of Greene and Madison Counties	Section on groundwater in publication. Description of groundwater productivity by rock type or formation.
	(Breeding and Dawson, 1976a)	Botetourt County Groundwater. Present Conditions and Prospects	Describes geology and groundwater conditions in Botetourt County by utilizing well construction and location information and groundwater sample data. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.
	(Breeding and Dawson, 1976b)	Roanoke County Groundwater, Present Conditions and Prospects	Describes geology and groundwater conditions in Roanoke County by utilizing well construction and location information and groundwater sample data. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.
	(Comer, 1976)	Prince William County Groundwater	Describes geology and groundwater conditions in Prince William County by utilizing well construction and location information and groundwater sample data. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.

Scale	Author and Date	Title	Report Description
COUNTY	(Hinkle and Sterrett, 1978)	Groundwater Resources of Augusta County, Virginia	Describes geology and groundwater conditions in Augusta County by utilizing well construction and location information and groundwater sample data. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.
	(Dawson and Davidson, 1979)	Groundwater Resources of Henry County, Virginia	Describes geology and groundwater conditions in Henry County by utilizing well construction and location information and groundwater sample data. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.
	(Murphy, 1979)	Groundwater Resources of Loudoun County Virginia	Describes geology and groundwater conditions in Loudoun County by utilizing well construction and location information and groundwater sample data. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.
	(Sterrett and Hinkle, 1980)	Groundwater Resources of Albemarle County, Virginia	Describes geology and groundwater conditions in Albemarle County by utilizing well construction and location information and groundwater sample data. Provides guidance on groundwater development in the area. Appendix of well construction and water quality data.
	(Loudoun, 1993)	Statistical Analysis of Groundwater in Loudoun County, Volume 1: Groundwater Quantity	Describes hydrogeology, geology, and trends of water well data in Loudoun County. Includes statistical summary of historical groundwater data.
	(Nelms and Moberg, 2010a)	Hydrogeology and Groundwater Availability in Clarke County, Virginia	Describes hydrogeologic conditions and geology of Clarke County, Virginia, and provides a statistical analysis of historical groundwater data generated from well construction records. Utilizes streamflow and groundwater level records to describe climatic influences on groundwater availabiality and storage. Presents a conceptual model for groundwater flow in the geologic setting described in the report.
	(Nelms and Moberg, 2010b)	Preliminary Assessment of the Hydrogeology and Groundwater Availability in the Metamorphic and Siliciclastic Fractured-Rock Aquifer Systems of Warren County, Virginia	Describes hydrogeologic conditions and geology of Warren County, Virginia, and provides a statistical analysis of historical groundwater data generated from well construction records. Utilizes streamflow and groundwater level records to describe climatic influences on groundwater availabiality and storage. Presents a conceptual model for groundwater flow in the geologic setting described in the report.
IN-STATE REGIONAL	(Cady, 1933)	Preliminary Report on Ground-Water Resources of Northern Virginia	Describes the geology and the water bearing properties of rock types occuring in Frederick, Clarke,Loudoun,Fairfax, and Prince William Counties. Provides a description of how rock type and geologic structure can control the occurrence and movement of groundwater in the study area. Presents well yield data to describe the availability of groundwater within the differing rock types in the study area.
	(Cady, 1938)	Ground-Water Resources of Northern Virginia	Describes the geology and the water bearing properties of rock types occuring in Frederick, Clarke, Loudoun, Fairfax, and Prince William Counties. Provides a description of how rock type and geologic structure can control the occurrence and movement of groundwater in the study area. Presents continuous record groundwater level data from several wells within the study area. Describes hydrogeologic conditions within the study area on a county by county basis and presents tables of water well construction data and groundwater sample data collected and used in the report.

Scale	Author and Date	Title	Report Description
IN-STATE REGIONAL	(Geyer, 1955)	Ground Water in Piedmont, Virginia	A short publication providing a description of the occurrence and movement of groundwater in fractured crystalline rocks of the Piedmont.
	(Latta, 1956)	Public and Industrial Ground-Water Supplies of the Roanoke-Salem District, Virginia	Provides an inventory and well site location map of groundwater wells and springs used for public or industrial water supply in the Roanoke-Salem District. Discusses the water bearing characteristics of the different rock types occurring in the study area.
	(DeBuchananne, 1968)	Ground-Water Resources of the James, York, and Rappahannock River Basins West of the Fall Line	Map of the variation in major ion geochemistry of groundwater in the study area. Depicts locations of known high yielding wells in the study area. Table provides a lithologic description and general description of the water bearing characteristics of the rock types in the study area.
	(Gathright and Wilson, 1968)	Ground-Water Fluctuations in Virginia	Short publication describing the different kinds of groundwater level fluctuations observed on continuous record hydrographs from a number of observation wells throughout Virginia.
	(Trainer and Watkins, 1975)	Geohydrologic Reconnaissance of the Upper Potomac River Basin	Utilizes pump test data, water level data, and streamflow hydrographs to estimate average transmissivities and storage coefficients for crystalline and carbonate rocks in the Upper Potomac river Basin.
	(Waller, 1976)	Geohydrology of the Upper Roanoke River Basin, Virginia	Presents streamflow and baseflow characteristics of sub-basins in the Upper Roanoke River Watershed. Analysis of well construction characteristics by rock type in the Upper Roanoke River Watershed. Analysis of low-flow surface and groundwater quality by rock type. Water resources planning, development, and management recommendations.
	(Powell and Abe, 1985)	Availability and Quality of Ground Water in the Piedmont Province of Virginia	Describes the occurrence and movement of groundwater in the crystalline rocks of the Piedmont Province of Virginia. Describes the influence of topography and landscape morphology on well yield. Description of groundwater quality in the Piedmont Province of Virginia.
	(Hayes, 1991)	Low-Flow Characteristcics of Streams in Virginia	Presents low-flow characteristics of gaged stream sites in Virginia, and techniques for estimating low-flow characteristics at gaged and ungaged sites.
	(Nelms et al., 1997)	Base-Flow Characteristics of Streams in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia	Describes the base-flow characteristics of streams within the Valley and Ridge, Blue Ridge, and Piedmont provinces of Virginia, identifies regional differences in these characteristics, and if possible, describes the potential surface-water and groundwater yields of basins on the basis of base-flow characteristics.
	(Nelms et al., 2003)	Aquifer Susceptibility in Virginia, 1998-2000	Presents determinations of aquifer susceptibility to contamination from near-surface sources for the regional aquifer systems of Virginia. The investigation involves the use of multiple environmental tracers to calculate apparent groundwater ages and percentage of young water, and compares these values to the occurrence and concentrations of chemical constituents to help classify regional aquifer systems in terms of susceptibility.

Scale	Author and Date	Title	Report Description
IN-STATE REGIONAL	(Heller, 2008)	Trends in the Depth, Yield, and Water Quality of Wells in Virginia Related to Geologic Conditions	Well records were grouped by geologic province and by rock type for statistical analysis of well construction characteristics and water quality parameters. Results were compared and contrasted across rock types and provinces.
REGIONAL	(Legrand, 1967)	Ground Water of the Piedmont and Blue Ridge Provinces in the Southeastern States	Brief summary of groundwater conditions in the Piedmont and Blue Ridge provinces of the Southeastern United States. Relates well yield to soil thickness and topographic position, discusses recommended drilling depths, fracture trends in bedrock, and provides a brief synopsis of groundwater quality.
	(Swain et al., 1991)	Plan of Study for the Regional Aquifer-System Analysis of the Appalachian Valley and Ridge, Piedmont, and Blue Ridge Physiographic Provinces of the Eastern and Southeastern United States, With a Description of Study-Area Geology and Hydrogeology	Describes the geology and hydrogeology of the Valley and Ridge and Piedmont and Blue Ridge provinces. Hydrogeologic terranes and conceptual flow systems are described within the Valley and Ridge and Piedmont and Ble Ridge. Study needs and future study objectives are defined.
	(Rutledge and Mesko, 1996)	Estimated Hydrologic Characteristics of Shallow Aquifer Systems in the Valley and Ridge, Blue Ridge, and the Piedmont Physiographic Provinces Based on Analysis of Streamflow Recession and Base Flow	Uses streamflow records to enhance the understanding of shallow groundwater systems in the Appalachian Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces.
	(Briel, 1997)	Water Quality in the Appalachian Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces, Eastern United States	Presents groundwater geochemical data and trends from the Appalachian Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces. Compares and contrasts trends in groundwater geochemistry between these provinces.
	(Trapp and Horn, 1997)	Ground Water Atlas of the United States, Segment 11	Describes the general hydrogeologic conditions and controls on the occurrence and movement of groundwater occuring in the crystalline rock aquifers of the Piedmont and Blue Ridge. Describes general trends in groundwater quality and water use.
	(Focazio et al., 1997)	Preliminary Estimates of Residence Times and Apparent Ages of Ground Water in the Chesapeake Bay Watershed, and Water Quality Data From a Survey of Springs	Presents apparent age values for a number of springs sampled in the Chesapeake Bay Watershed. Most apparent ages were indicative of shallow groundwater flow systems. High nitrate concentrations in several of the springs indicate that contaminated groundwater can be a source of nutrients to surface water bodies.
	(Mesko et al., 1999)	Hydrogeology and Hydrogeologic Terranes of the Blue Ridge and Piedmont Physiographic Provinces in the Eastern United States	Groundwater productivity was analysed by hydrogeologic terrain using data from well records. Trends in well yield vs depth were analyzed for 7 areas within the Piedmont Province.
	(Lindsey et al., 2003)	Residence Times and Nitrate Transport in Ground Water Discharging to Streams in the Chesapeake Bay Watershed	Presents information about the factors affecting the discharge, nitrate concentration, and residence time of groundwater in the Chesapeake Bay Watershed.

Scale	Author and Date	Title	Report Description
REGIONAL	(Lindsey et al., 2006)	Factors Affecting Occurrence and Distribution of Selected Contaminants in Ground Water From Selected Areas in the Piedmont Aquifer System, Eastern United States, 1993-2003	Describes factors affecting the occurrence and distribution of nitrate, selected pesticides, selected volatile organic compounds (VOCs), and radon in groundwater of the Piedmont Province of the southeastern United States.

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DESCRIPTION OF STUDY AREA

Physiography and Extent of Study Area

The Blue Ridge Geologic Province encompasses approximately 8,250 mi^2 and extends for approximately 270 miles as an elongate, northeast - southwest trending feature occupying the central portion of the Commonwealth (from Lat. 39° 19′ in Loudon County to Lat. 36° 35′ where it extends from Grayson County into North Carolina). The Blue Ridge Geologic Province is commonly subdivided into two sections based on distinct differences in physiography and geologic structure: northern and southern (figure 1).

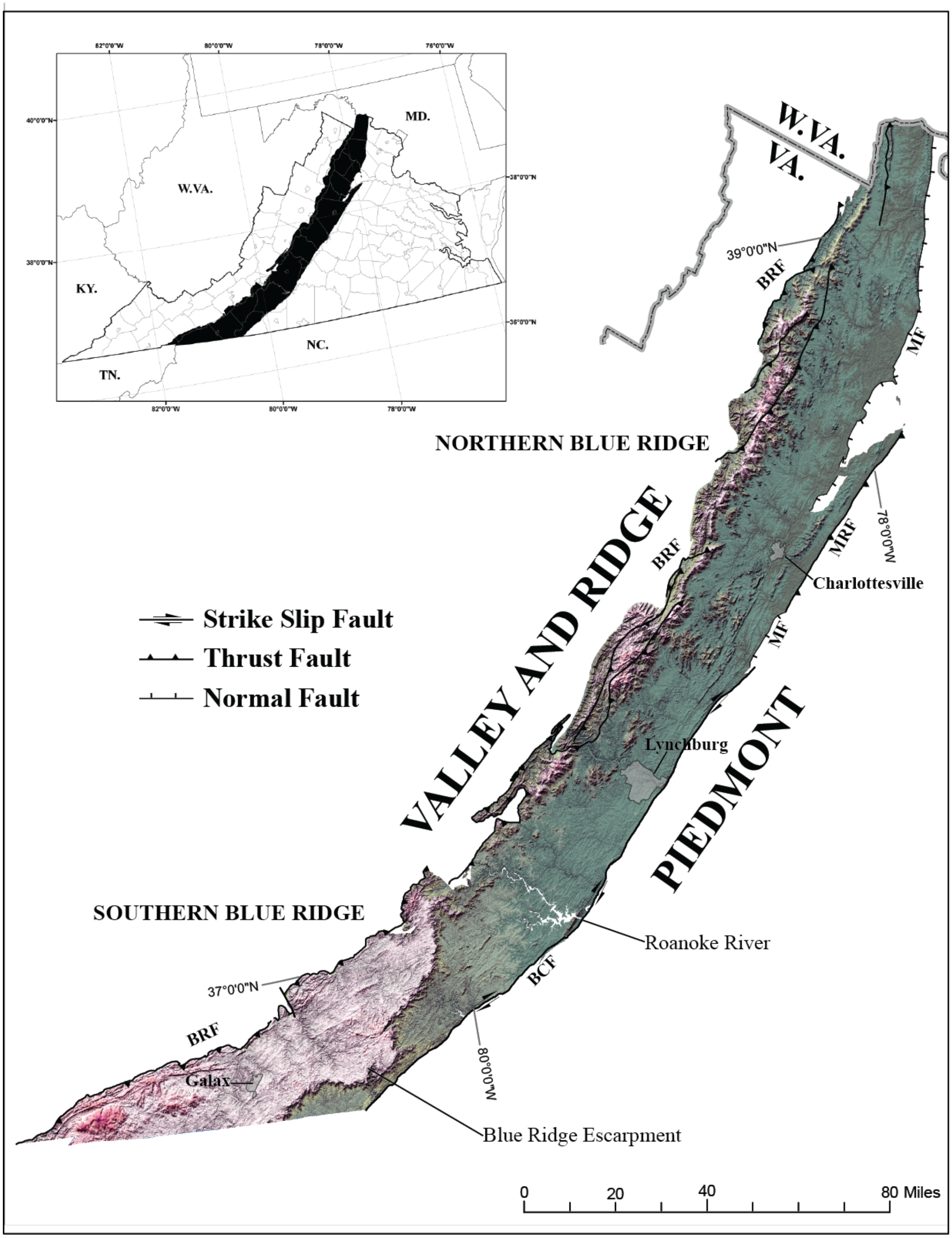


Figure 1. Digital elevation model of the Blue Ridge Geologic Province. Locations of fault boundaries were modified from Hibbard et.al. (Hibbard et al., 2006). Blue Ridge Fault (BRF), Bowens Creek Fault (BCF), Mesozoic Fault (MF), and Mountain Run Fault (MRF).

North of the Roanoke River, the Blue Ridge Geologic Province ranges in width from approximately 15 to 30 miles. An extensive normal fault system marks the structural and physiographic break between the eastern margin of the Blue Ridge Geologic Belt and the Culpeper Early Mesozoic Basin, extending from Maryland, through portions of Loudon, Prince William, Fauquier, Culpeper, Madison, and Orange Counties. South of the Culpeper Early Mesozoic Basin, the Mountain Run Fault Zone, a small normal fault system associated with the western margin of the Scottsville Early Mesozoic Basin, and the Bowens Creek Fault Zone mark the eastern limits of the Northern Blue Ridge Geologic Province. Discontinuous mountain chains run longitudinally along the eastern margin of this portion of the Blue Ridge Geologic Province. Notable mountain ranges include the Catoctin and Bull Run Mountains in northern Virginia, Southwest, Carters, and Green Mountains in Central Virginia, and Candler and Johnson Mountains in the southern portions of the northern section. The longitudinal axis of the northern Blue Ridge Geologic Province is occupied by eroded lowland situated between the Blue Ridge Mountain Chain to the west and the mountains along the eastern margin. This section contains discontinuous mountains and gently rolling hills cross cut by a dendritic network of shallow to deeply incised streams. Elevations of the hills and mountains in the central portion of the belt rarely exceed 1,000 feet (ft). The western portion of the northern Blue Ridge Geologic Province is marked by a sharp transition in slope that defines the lowest elevations of a rugged and continuous mountain chain extending the length of the western border of the belt. North of the Roanoke River, this mountain chain is irregular in elevation, and relative to the southern section of the belt, quite narrow. Small, higher gradient drainages in the western portion of the northern section of Blue Ridge Geologic Province commonly cut across the regional strike, draining in an easterly or southeasterly direction. Lower gradient, higher order streams in the eastern section of the lowland tend to flow in a NE-SW direction, parallel to the regional strike. Summit elevations for the mountains in the northern section of the Blue Ridge Geologic Province range from approximately 1,100 ft. above NGVD 29 near the Potomac River in Loudon County to a little over 4,000 ft. above NGVD 29 for a number of peaks. The western boundary of the Northern Blue Ridge Geologic Province is marked in places by the Blue Ridge Fault, which places rocks of the Blue Ridge in fault contact with the younger rocks of the Valley and Ridge Physiographic Province. Where rocks are in conformable contact, the western margin of the Blue Ridge Anticlinorium is marked by a formational transition (from Chilhowee to Tomstown Formation or Shady Dolomite).

South of the Roanoke River, the Blue Ridge Geologic Province becomes progressively wider, ranging in width from approximately 30 miles in the Roanoke area to approximately 75 miles at the Virginia - North Carolina border. The southern section of the Blue Ridge Geologic Province varies in elevation from its highest point at Mount Rogers (5,719 ft. above NGVD 29) to the lowest point along the Roanoke River where it crosses the Bowens Creek Fault along the eastern border of the belt (approx. 540 ft. above NGVD 29). The Blue

Ridge Fault is the western boundary of the southern Blue Ridge Geologic Province.

Hack (Hack, 1982) provided a detailed physiographic description of the southern Blue Ridge Province by dividing the province into 5 distinct sub-provinces. From east to west they are: (1) The Blue Ridge Escarpment – the narrow strip of steep land that drains southeastward to the Piedmont and Atlantic Ocean; (2) The Southern Blue Ridge Highlands – high mountain ranges typically running parallel with the regional strike of the rocks on the northeast and southwest sides of the sub-province, and exhibiting orientations in the center that appear to be governed more by drainage patterns rather than structural controls; (3) The New River Plateau – the northeastern portion of the Southern Blue Ridge having comparatively low relief relative to the rest of the Southern Blue Ridge, broken intermittently by isolated, low mountains.; (4) Chilhowee-Walden Creek Belt – located on the northeastern side of the Southern Blue Ridge Province and forming a belt of elongate mountain ridges typically composed of resistant quartzite. The elevations of the mountains in the Chilhowee-Walden Creek Belt are typically lower than the elevations of the mountains in the Southern Blue Ridge Highlands, but they exhibit high local relief between valley floor and ridge top; (5) Mount Rogers Area – a localized area (Mount Rogers and White Top Mountain) of high relief in Grayson County, Virginia. The high relief is attributed to the presence of the resistant rhyolite in the Mount Rogers Formation. Adjacent to the rhyolitic component of the Mount Rogers formation are less resistant, more highly eroded meta-sedimentary and epiclastic rocks and lower relief quartzite ridges of the Iron Mountains that contribute to the discrepancy in local relief.

The Southern Blue Ridge Geologic Province includes a portion of the southern Virginia landscape extending westward from the Bowens Creek Fault to the Blue Ridge Escarpment designated Piedmont Province by geographers. The Physiography of this region is characterized by a plateau eroded into a fabric of numerous northeast/southwest trending hills and mountains. Local relief within this area is more subdued than the Southern Blue Ridge described by Hack (Hack, 1982), but structurally it constitutes a portion of the Blue Ridge Geologic Province. Many drainages in this portion of the Blue Ridge Geologic Province are oriented Northeast to southwest along the regional strike of the rocks, but cut in many places through gaps in the ridges and hills to drain ultimately in a southeastern (to the Smith or Mayo Rivers) or eastern (to the Roanoke River) direction.

Climate

The distribution of temperature and precipitation throughout the Blue Ridge Geologic Province is heavily influenced by topography. The areas of highest rainfall are coincident with the steepest slopes and higher elevations in the Blue Ridge Mountains, and occur along the crest of the Blue Ridge Anticlinorium from northern Rappahannock County to central Bedford County, along the Blue Ridge escarpment in eastern Floyd/ western Patrick and eastern Carroll Counties, and in the vicinity of Mount Rogers in western Grayson County. Annual parameter-elevation regressions on independent slopes model (PRISM) rainfall estimates in these areas are often in excess of 55 inches – almost a foot more precipitation than PRISM estimated annual precipitation totals in the less mountainous regions of the Blue Ridge (figure 2). The section of the Blue Ridge Geologic Province from southern Bedford to central Floyd County lacks the conspicuous ribbon of higher estimated annual precipitation due to the lack of an abrupt topographic shift provided by a prominent ridge line or escarpment, and highlights the influence of morphology and geologic structure on the orographic contribution to total rainfall amounts within the region. Average monthly precipitation totals for selected climatic stations within the Blue Ridge Geologic Province (figures 3 and 4) do indicate that the annual distribution of precipitation throughout the Blue Ridge is fairly uniform, but small differences in the temporal distribution of precipitation exist due to seasonal differences. More rainfall can be expected to occur during the warmer months of the year (May –October), but the relative contribution of monthly rainfall to the annual precipitation total for any one area varies among climatic stations, as does the distribution of higher precipitation months during the warmer times of the year. Frequently, much of the precipitation occurring in the warmer months of the year is lost to evapotranspiration. Figure 5 plots total annual rainfall and effective precipitation (total annual rainfall minus potential evapotranspiration - potential evapotranspiration rates were calculated using the Thornwaite method), for the Big Meadows and Charlottesville Climatic stations, and illustrates the significance of late fall through early spring precipitation events for groundwater systems in the Blue Ridge. Although both of these stations receive their highest average annual rainfall totals in the summer, the net flux of water to the groundwater reservoir is negative or negligible due to high evapotranspiration rates during the summer months. Potential evapotranspiration rates are usually lower at higher elevations due to the moderating effect of elevation on temperature and total water demand, but small variations in local climatic conditions (shade, aspect, vegetation type, etc.) can have large influences on evapotranspiration rates (and climates) at the local scale.

Temperature data taken from selected climatic stations throughout the Blue Ridge (figures 3 and 4) show that seasonal temperature variations within the Blue Ridge Geologic Province vary between the mid to upper 30s (degrees Fahrenheit) in the colder months of the year to the lower to upper 80s (degrees Fahrenheit) during the warmer months. As with precipitation, mean annual temperature values are influenced by topography, with slightly cooler annual temperatures occurring at higher elevations. Differences between the average seasonal highs and lows for a particular locale can be expected to vary by 18 to 25 degrees Fahrenheit. The differences between seasonal highs and lows are usually slightly lower in the cooler months of the year.

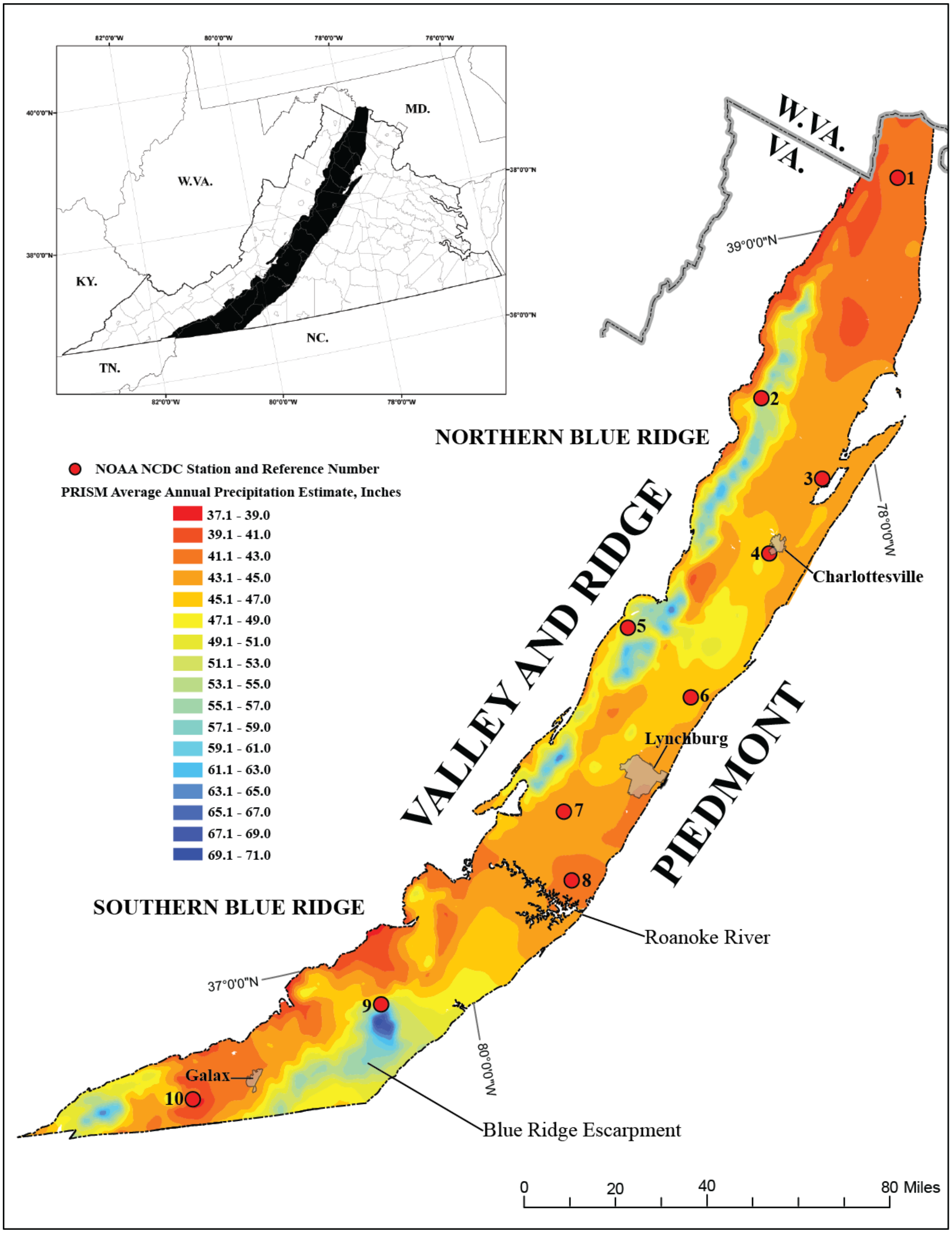


Figure 2. Average annual precipitation based on parameter –elevation regressions on independent slopes model (PRISM) and locations of selected NOAA NCDC climatic stations for the Blue Ridge Geologic Province. The normal values are based on the National Weather Service's current normal climatological period from 1971 to 2000. Data from PRISM Climate Group, Oregon State University.

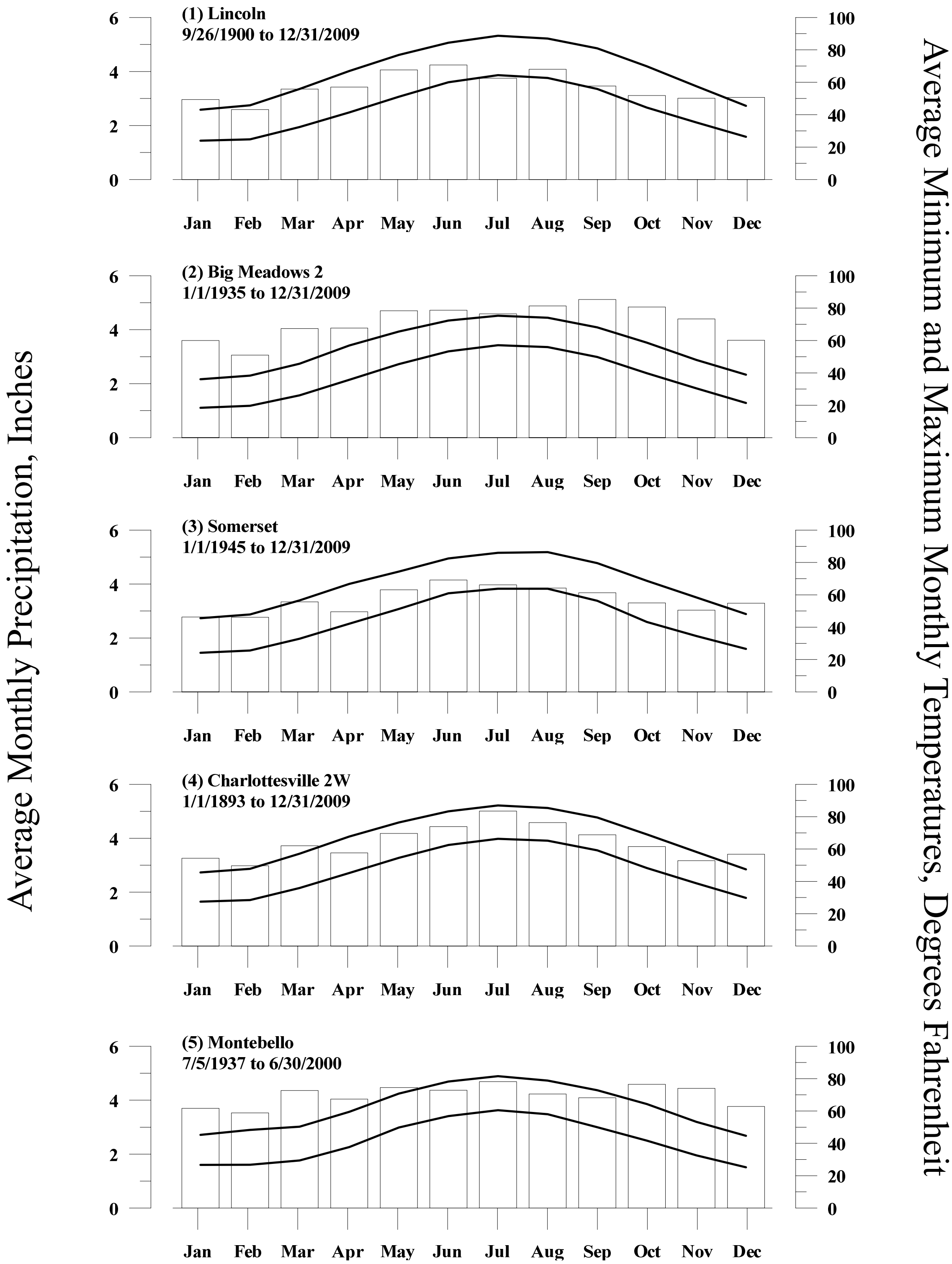


Figure 3. Average monthly precipitation (bars), average monthly minimum, and average monthly maximum temperatures calculated from long term climatic observations at selected NOAA/NCDC climate observation stations within the Blue Ridge Geologic Province. See figure 2 for station locations.

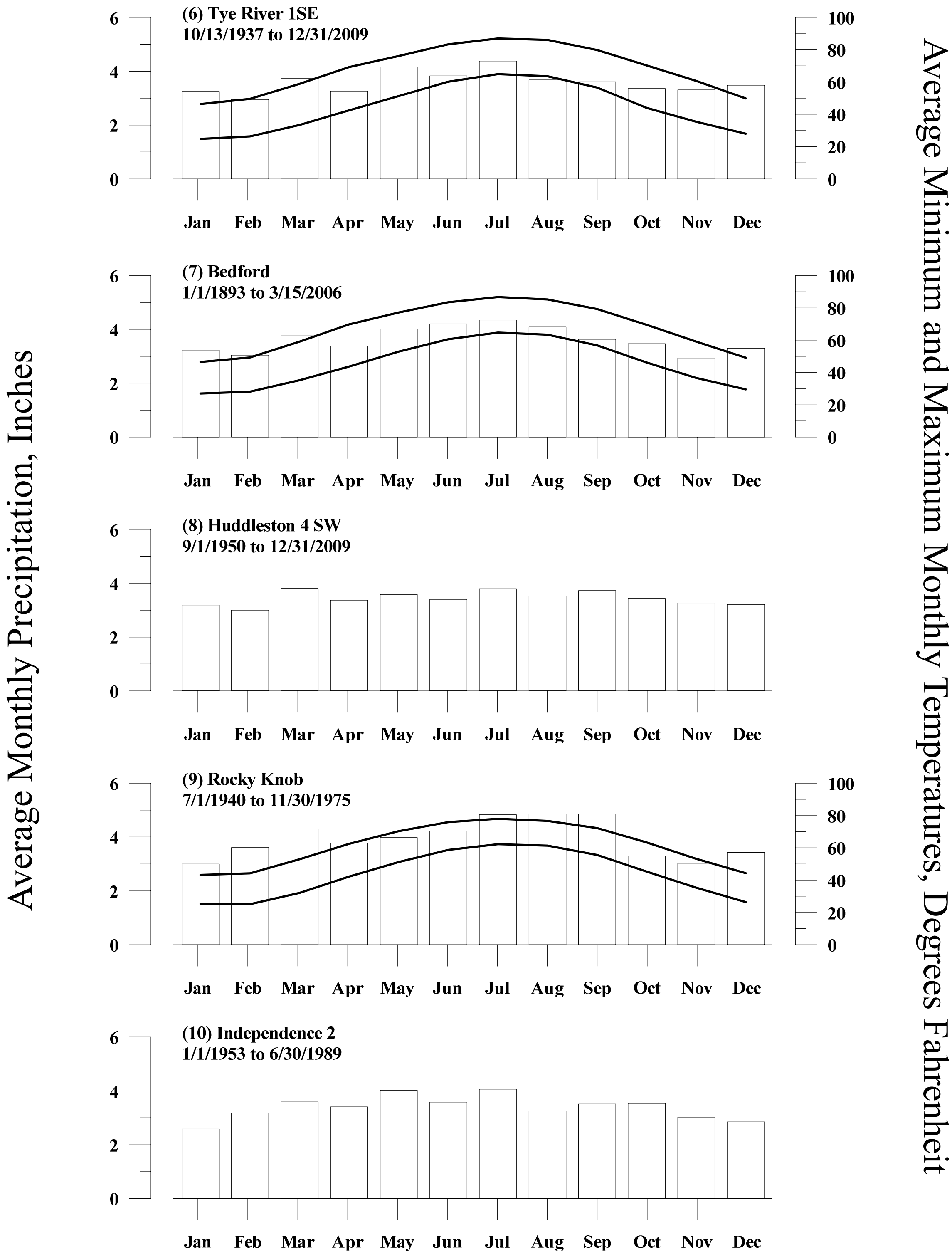


Figure 4. Average monthly precipitation (bars), average monthly minimum, and average monthly maximum temperatures calculated from long term climatic observations at selected NOAA/NCDC climate observation stations within the Blue Ridge Geologic Province. See figure 2 for station locations.

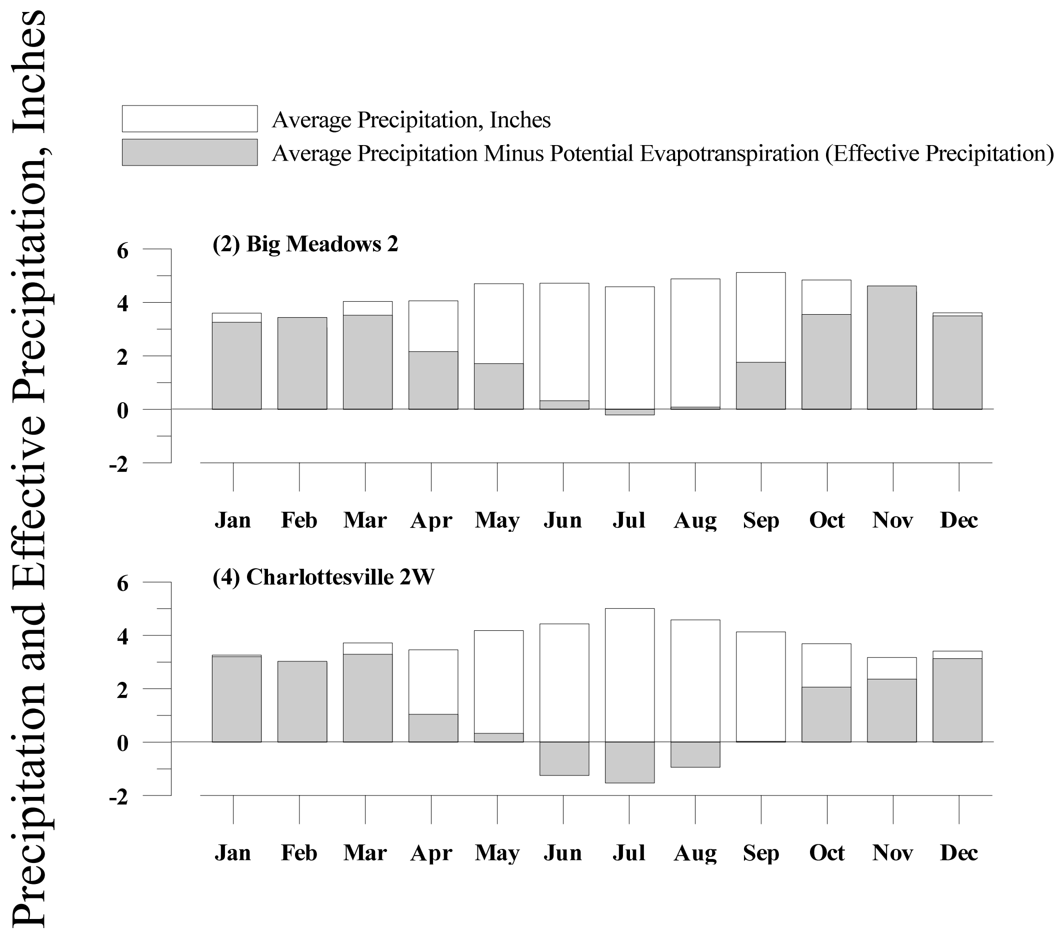


Figure 5. Average monthly precipitation and average monthly precipitation minus potential evapotranspiration (effective precipitation) calculated from long term climatic observations at the Big Meadows 2 and Charlottesville 2W NOAA/NCDC climate observation stations. See figure 2 for station locations.

Hydrogeologic Setting

The Blue Ridge Geologic Province encompasses the western most unit of the Blue Ridge and Piedmont terrane/belt assemblage, and in Virginia it is commonly separated into northern and southern sub-provinces to account for the physiographic and geologic features that are unique to each section (figure 1). In the northern and central portions of Virginia, the Blue Ridge is comprised of a fault bounded stack of thrust sheets in a northeast to southwest striking anticlinorium that is moderately overturned toward the northwest (Bailey et al., 2006; Southworth et al., 2009b). The core of the anticlinorium consists of highly metamorphosed, mid to late Proterozoic (basement) rock. This core is flanked on the northwest and southeast sides by late Proterozoic to Cambrian sequences of variably metamorphosed, Grenvillian rift related metasedimentary and metavolcanic crystalline (cover) rocks. The Blue Ridge Anticlinorium extends northward from the Roanoke River (northern border of Franklin County and northwestern border of Pittsylvania County) into south-central Pennsylvania. The Southern section of the Blue Ridge Geologic Province is composed of complexly faulted imbricate stacks of westward-vergent thrust sheets extending westward from the Bowens Creek Fault (figure 1) to the Blue Ridge Fault (Hatcher and Goldberg, 1991). The rocks of the southern Blue Ridge extend from the Roanoke River into northern Georgia, and are predominately late Proterozoic sequences of rift related meta-sedimentary and meta-volcanic cover rocks that are now preserved as variably thick units of schist, gneiss, amphibolite, and metagraywacke. Along the western limb of the southern Blue Ridge in Virginia, exposures of basement rock occur. Distributions of the major rock types and in the Blue Ridge Geologic Province and generalized cross sections are shown in figure 6.

Continual exhumation and weathering and stresses related to the structural deformation of Blue Ridge crystalline rock have imparted fracture systems of various magnitudes and orientations. The density and distribution of fracture sets in crystalline rock are controlled by the mineralogy and the metamorphic history of the rock. Because crystalline rocks can not uniformly expand to accommodate the reduction in pressure that occurs during exhumation, the rocks often part (or joint) where the fabric of the rock can accommodate reductions in the local stress field. Joints occur primarily in portions of otherwise massive rock at a variety of scales and orientations, and are one of the major components of storage and transmissivity in fractured rock groundwater systems. Other types of fractures in crystalline rock occur along cleavage planes, along zones of preferential weathering, and within or adjacent to zones of deformation (shear zones, faults, intrusive contacts, and folds).

In the very near surface, the weathering of the rocks within the Piedmont and Blue Ridge Provinces has created a layer of regolith comprised of weathered bedrock (saprolite) and soil that mantles almost all bedrock. The thickness and permeability of the regolith are variable and dictated by the weathering rates and mineralogical and structural characteristics of the underlying rocks. The total thickness of regolith can exceed 200 feet in some cases, or can be absent in areas where weathered material is readily transported. The saprolitic component of the regolith originates from the in-situ weathering of the parent bedrock and is characterized by a semi-competent matrix of more weathering resistant minerals that often exhibit the relict structural features of the parent bedrock, such as grain orientation and the strike and dip of foliation and bedding (Daniel and Harned, 1998). The saprolitic component of the regolith grades upward into soil, where the structural matrix of the underlying saprolite has been obliterated and broken into the most basic textural components of clays, silts, and sands. The relative percentages of clay, silt and sand in the soil and subsoil are a key component in determining the timing and quantity of recharge to the subsurface (Legrand, 1960), and the structural orientation of the saprolitic matrix plays an important role in directing groundwater recharge preferentially to the deeper bedrock fracture networks (Rugh and Burbey, 2007; White and Burbey, 2007). Both the soil and saprolite are capable of storing and transmitting substantial quantities of groundwater to the bedrock fracture networks.

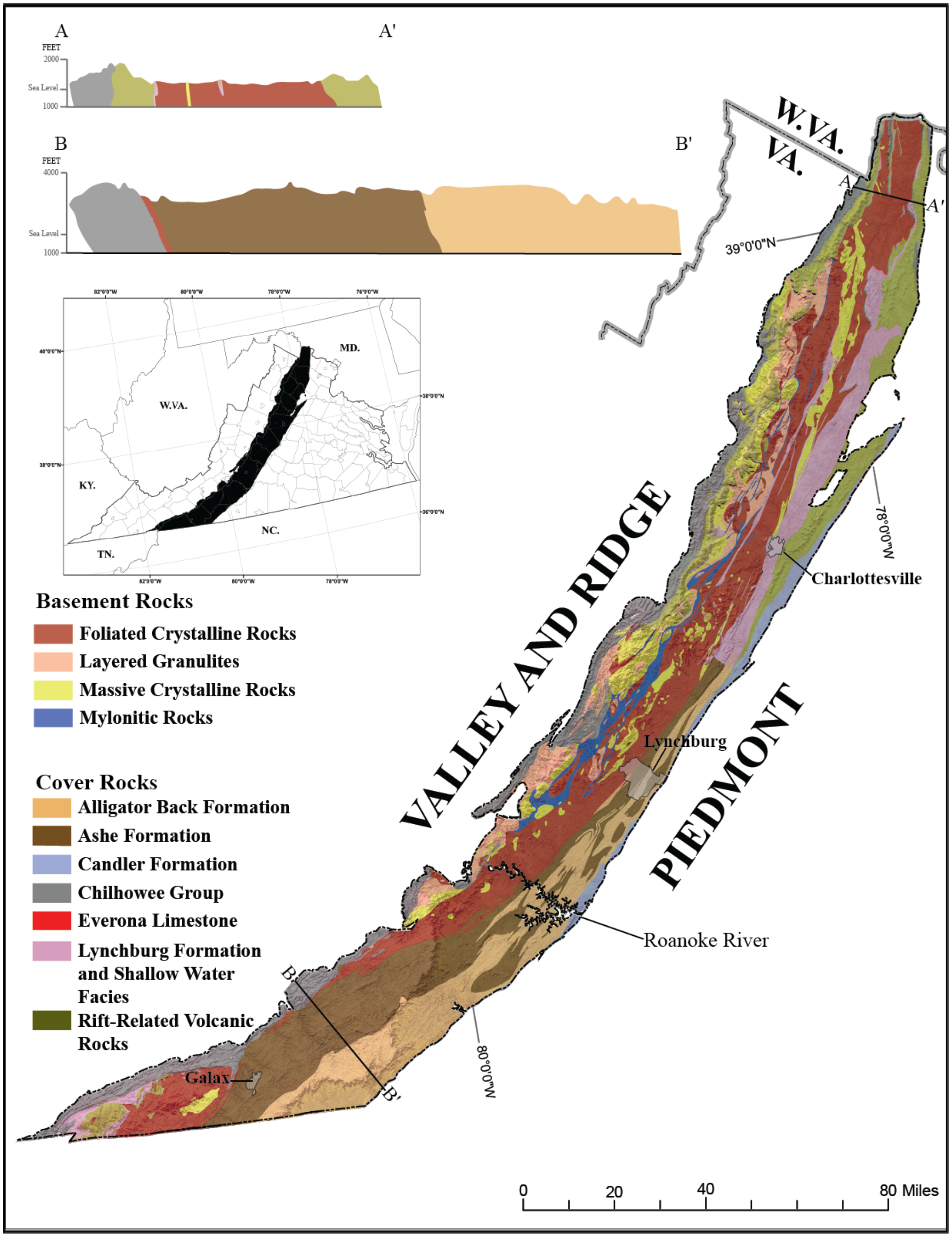


Figure 6. Distribution of major rock types, and generalized cross sections of the northern and southern portions of the Blue Ridge Geologic Province. Rocks of the Blue Ridge basement are flanked on the east and west by metasedimentary and metavolcanic cover rocks in the northern section, and largely covered by southeast-dipping stacks of metasedimentary and metavolcanic cover rocks in the southern section. Cross section A to A' modified from Southworth (Southworth, 1994; Southworth et al., 2006) and Gathright and Nystrom (Gathright and Nystrom, 1974). Cross section B to B' modified from Espenshade (Espenshade et al., 1975). Both cross sections at 2x vertical exaggeration. Base map modified from Virginia Division of Mineral Resources, 1993.

GENERAL WATER BEARING PROPERTIES AND GEOCHEMICAL CHARACTERISTICS OF GROUNDWATER

MID TO LATE PROTEROZOIC ROCKS

The mid to late Proterozoic rocks of the Blue Ridge are identified by a characteristic crystalline structure and by their stratigraphic position within the Blue Ridge Anticlinorium. These rocks are commonly referred to as "Basement Rocks" or the "Basement Complex" because they are, in many places, overlain by younger rift related metasedimentary and metavolcanic rift related sequences (or "cover rocks"). Much of the basement has been subjected to multiple periods of deformation during the Proterozoic, Ordovician, and Mesozoic Eras and consequently, the rocks of the Blue Ridge Basement Complex rank among the oldest and most structurally complex rocks in North America. The Basement is primarily exposed in the core of the Anticlinorium in the northern portion of the Blue Ridge Geologic Province, and to a lesser extent along the western margin of the Blue Ridge Geologic Province in the southern section (figure 7).

Blue Ridge Basement rocks are segregated into four different categories based on textural differences that are thought to have an influence on the occurrence and movement of groundwater within the scale of this investigation: foliated crystalline rocks, massive crystalline rocks, mylonites, and layered granulites (figure 6 and figure 7). Table 2 lists the map units from the 1993 geologic map of Virginia (Virginia Division of Mineral Resources, 1993) comprising the mid to late Proterozoic rock types described in this report.

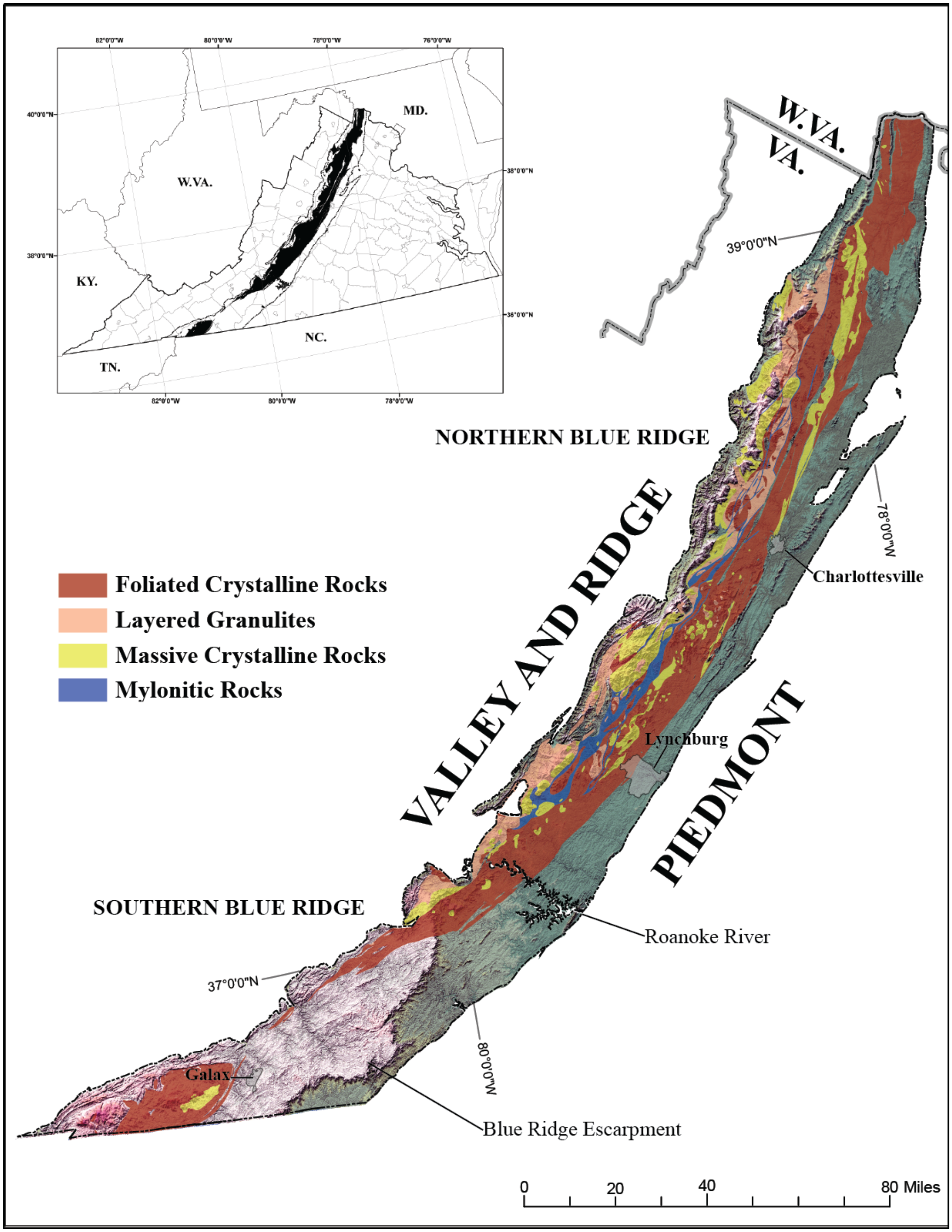


Figure 7. Extent and distribution of mid to late Proterozoic "basement" rock types of the Blue Ridge Geologic Province (geology modified from the VDMR 1993 State Geologic Map of Virginia).

Table 2. Map units described in the 1993 Geologic Map of Virginia (Virginia Division of Mineral Resources, 1993) grouped by major rock type.

foliated crystalline rocks:

Map Unit Symbol and Map Unit Name:

Yal; alkali-feldspar leucogranite
Ybg; porphyroblastic biotite-plagioclase augen gneiss
Yblg; biotite-muscovite leucogranite gneiss
Ybp; porphyroblastic granite gneiss
Ybr; border gneiss
Ycm; charnockite gneiss
Yec; Elk Park Plutonic Group - quartz monzonite, quartz monzonite flaser gneiss, quartz monzomite gneiss
Yep; Elk Park Plutonic Group - augen gneiss and porphyritic gneiss
Yfh; Flint Hill Gneiss
Yg; leucocratic metagranite
Ygb; layered biotite granulite and gneiss
Ygbt; biotite granite
Ygg; layered leucocratic granite gneiss
Ygh; hornblende gneiss
Ygn; leucocratic granulite and gneiss
Ygr; biotite granite gneiss
Ygt; garnetiferous leucocratic metagranite
Yma; layered quartzofeldspathic augen gneiss and flaser gneiss
Ymc; Marshall Metagranite - coarse-grained metagranite
Ymg; two-mica granite
Ymm; Marshall Metagranite - medium-grained biotite metagranite
Yn; metanorite and metadiorite
Yp; garnet graphite gneiss
Yq; quartzite and quartz-sericite tectonite
Yt; metatrondhjemite
Yum; metaperidotite, hornblende, metagabbro and metapyroxenite
Zgd; biotite granodiorite or biotite gneiss

massive crystalline rocks:

Map Unit Symbol and Map Unit Name:

Yc; charnockite
Ycz ;Crozet granite
Yhd; biotite-horneblend granodiorite
Yhg; megacrystic charnockite
Yl; leucocharnockite
Yor; Old Rag granite
Ypc; porphyritic leucocharnockite
Yra; Roseland anorthosite
Ysh; Schaeffer Hollow granite
Zgdm; Mobley Mountain granite
Zgdr; Rockfish River pluton
Zgds; Striped Rock granite
Zra; Robertson River Igneous Suite - Amissville Alkali Feldspar Granite
Zram; Robertson River Igneous Suite – Arrington Mountain Alkali Feldspar Granite
Zrbf ;Robertson River Igneous Suite - felsite
Zrbg; Robertson River Igneous Suite - granitoid
Zrc; Robertson River Igneous Suite - Cobbler Mountain Alkali Feldspar Quartz Syenite
Zrh; Robertson River Igneous Suite - Hitt Mountain Alkali Feldspar Syenite
Zrl; Robertson River Igneous Suite - Laurel Mills Granite
Zrr; Robertson River Igneous Suite - Rivanna Granite
Zrw; Robertson River Igneous Sute- White Oak Alkali Feldspar Granite

layered granulite:

Map Unit Symbol and Map Unit Name:

Ypg; layered pyroxene granulite
Ypp; layered porphyroblastic pyroxene granulite

mylonitic rocks:

Map Unit Symbol and Map Unit Name:

my; mylonite

Foliated Crystalline Rocks of the Blue Ridge Basement

Figure 8 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the foliated crystalline rock hydrogeologic group. Figures 9 and 10 provide photographs of selected rock types within the foliated crystalline rocks hydrogeologic group.

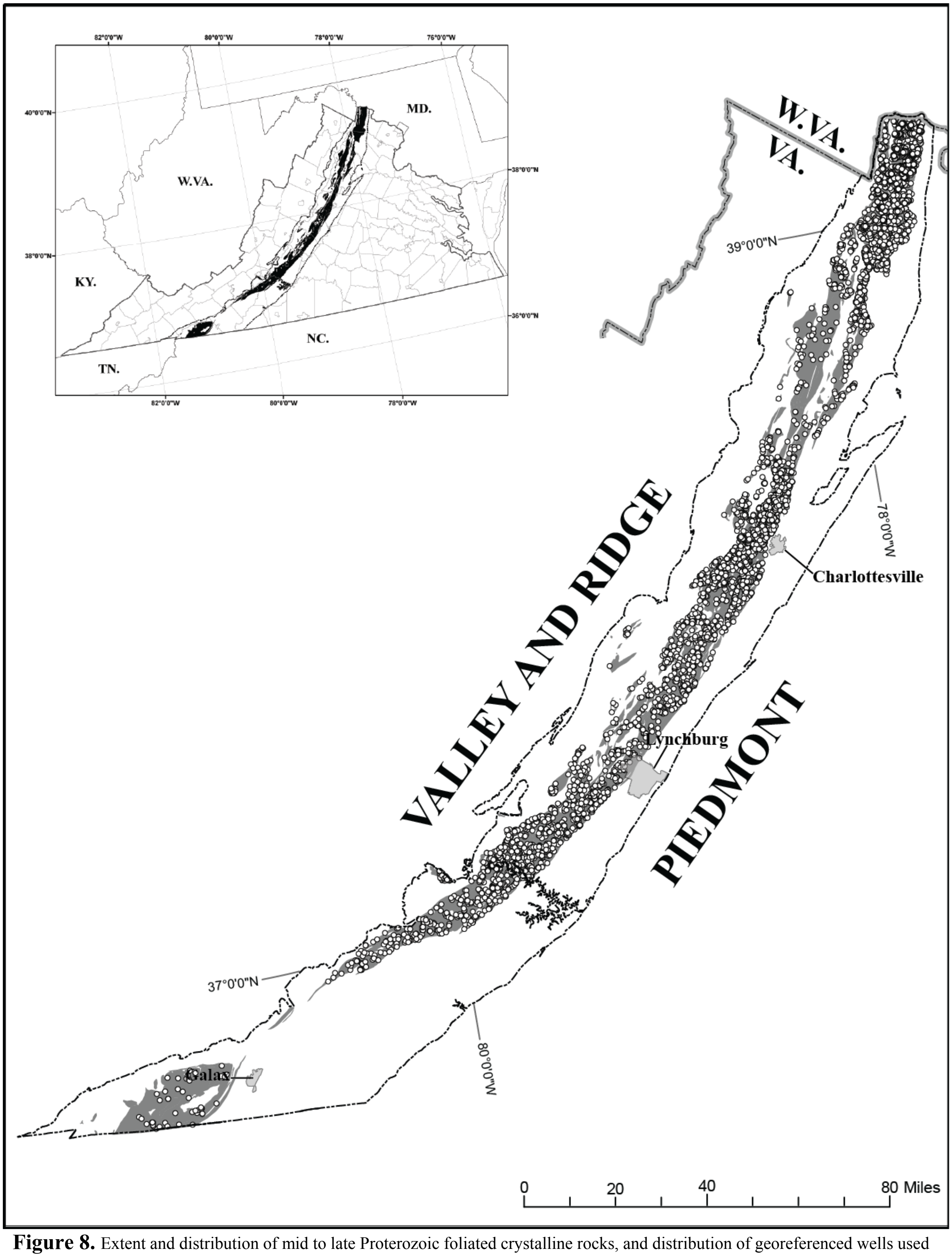


Figure 8. Extent and distribution of mid to late Proterozoic foliated crystalline rocks, and distribution of georeferenced wells used to generate gydrogeologic and groundwater geochemical observations pertaining to the foliated crystalline rocks group.

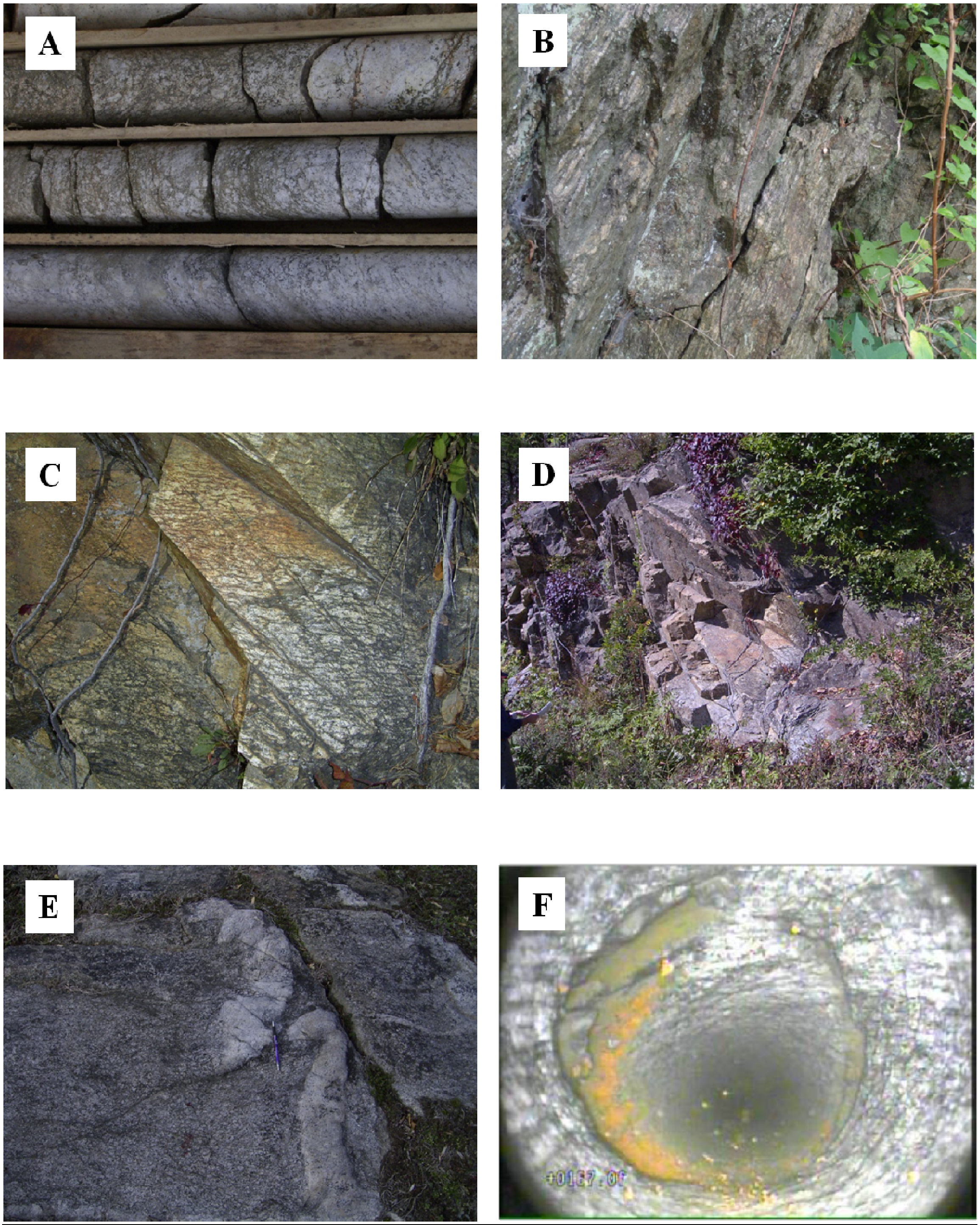


Figure 9. Photographs of foliated crystalline rock within the Blue Ridge Basement Complex. A) 2” rock core (56 to 73 feet) extracted from biotite-plagioclase augen gneiss near Ivy, Virginia - note presence of nearly horizontal fractures and fractures along foliation; B) Biotite Granitoid Gneiss near Thaxton, Va – fracturing is parallel to foliation; C) Leucogranitoid Gneiss near Skyline Drive in Central portion of Shenandoah National Park – jointing is orthogonal to predominate foliation; D) Leucogranitoid Gneiss near Skyline Drive in Central portion of Shenandoah National Park – predominate joint set in outcrop; E) Biotite granite gneiss in mylonitic section of Suck Mountain Pluton near Otterville, Virginia – note the folded dike originally intruded into the pluton, which is now strongly foliated and sheared in places at this locality ; F) Water bearing joint in 6” well bore drilled in Biotite granite gneiss of Suck Mountain Pluton – joint is orthogonal to foliation and yielded approximately 60 gal/minute during air lift test.

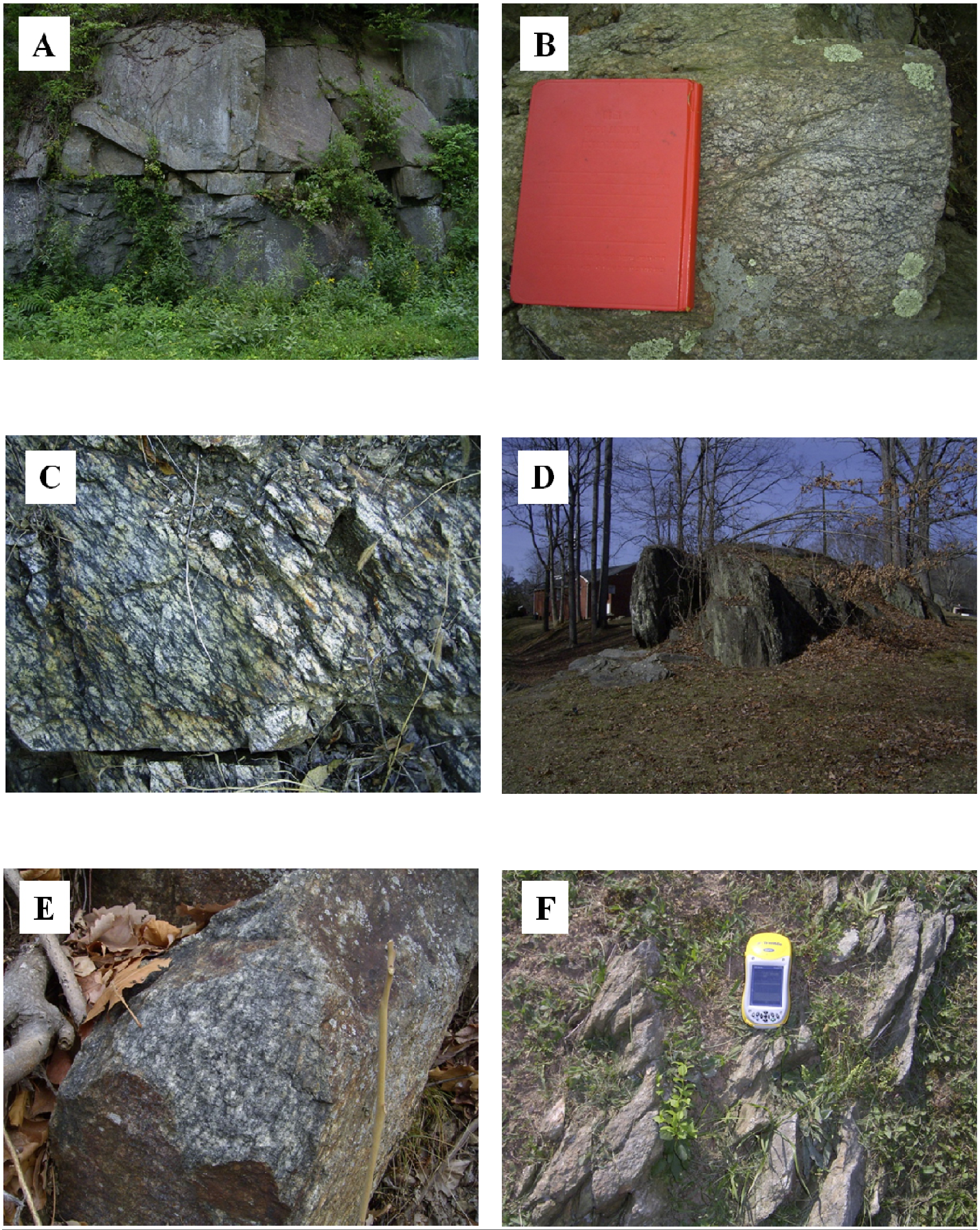


Figure 10. Photographs of foliated crystalline rock within the Blue Ridge Basement Complex. A) Jointed massive biotite augen gneiss near Rockfish, Virginia; B) Foliated Gneiss near Rock Mills, Virginia; C) Sheared Charnockite gneiss near Naff, Virginia; D) Layered Biotite Gneiss near Goode, Virginia – fracturing parallel to strongly developed schistosity; E) Foliations in porphyroblastic gneiss north of North Creek Campground near Arcadia, Virginia; F) Marshall Meta-Granite near Marshall, Virginia. Fracturing in outcrop is primarily sub-parallel to foliation.

Geologic Description and Hydrogeologic Characteristics

The mappable units within this group of rocks can be separated based on stratigraphic position, lithology, and mineralogy. These rocks are predominately moderately to well foliated gneisses, but the regional scale of this investigation has required the incorporation of smaller mappable inclusions of massive crystalline, mylonitic, and granulitic textures into this group.

These rocks exhibit prevalent megascopic foliation imparted by at least one period of ductile deformation and are commonly referred to as gneisses, granitic gneisses, and meta-granites. These rocks are derived from either mid to late Proterozoic plutonic rock or less commonly, from the pre-existing country rock intruded by the mid to late Proterozoic plutons.

The metamorphic pressures and temperatures associated with ductile deformation in the mid to late Proterozoic imparted a discernible fabric with prevalent mineral and structural orientation to much of the basement rock. Directional stresses imparted to the rock during deformation established non-uniform stress fields within the rock that currently act in conjunction with its mineralogical and structural characteristics to control the formation of joints during exhumation and weathering. Contrasting mineralogies between foliations as well as the preferential orientation of mineral grains within the foliations can promote fracturing within or parallel to foliation planes (Crawford and Kath, 2003; Johnston, 1964; Williams et al., 2005). In other cases foliation is barely discernible or does not lend itself as a primary plane of fracturing. Within the zone of aeration and groundwater circulation, preferential weathering can further enhance secondary porosity. Horizontal or nearly horizontal sheet jointing commonly occurs in outcrop among the more massive rock types in this group. In places, crustal movement associated with brittle deformation has imparted local zones of concentrated fracture networks within foliated crystalline rock. On a local scale, dominant jointing trends can often be observed and mapped, but the structural complexities of the Blue Ridge Basement negates the dominance of any one jointing trend on a regional scale (Bailey et al., 2003; Southworth et al., 2009b). Joint densities and orientations in foliated crystalline rocks vary based on texture and mineralogy, structural orientation, and the degree of weathering to which the rock has been subjected.

Table 3 provides summary statistics pertaining to the geologic and hydrogeologic characteristics of wells completed in the foliated rocks of the Blue Ridge Basement.

Reported estimated yield values were recorded for 6652 wells in the foliated crystalline rocks hydrogeologic group. Estimated yield values were 20 gallons/minute (gal/min) or more for 28%, 50 gal/min or more for 8%, and 100 gal/min or more for 2% of the total well population. Estimated yield data were also analyzed for 284 municipal, commercial, and light industrial wells in the foliated crystalline rocks hydrogeologic group. Values of 20 gal/min or more were reported for 49%, 50 gallons/minute or more for 19%, and 100 gallons/minute or more for 7% of the non-domestic well population.

Reported water zone depth values for 900 wells drilled to or past 400 feet in the foliated crystalline rocks rock type were available for analysis. At least one water bearing fracture was reported by the driller to occur at depths of 400 feet or greater for 57% (512) of these wells. A total of 1504 fractures were reported among these wells and 39% (588) of them occurred below 400 feet. The deepest water bearing fracture reported in the foliated crystalline rocks was encountered at 1,235 feet below land surface and yielded 1 gal/min at the time of completion. This analysis suggests that water bearing zones below 400 feet in foliated crystalline rock are fairly common.

The highest yielding well in the foliated crystalline rock data set was drilled at the Route 17/66 Business Park in the Marshall Meta-Granite near the Town of Marshall, Virginia and had an initial air-lift yield of 800 gallons per minute after 2.5 hours of air lifting. The well was drilled to 400 ft. below land surface and water bearing zones were encountered at 160' below land surface (250 gal/min), 180' below land surface (225 gal/min), and at 260' below land surface (325 gal/min). The well was pumped at 150 gallons per minute for approximately 3 days with a total drawdown of 77 feet. During the pump test, the rate of drawdown increased with time, indicating that groundwater was being withdrawn from storage at a rate exceeding natural recharge to the well. A sudden increase in the rate of drawdown near 2,000 minutes into the test indicated the presence of a boundary condition an unknown distance from the pumping well.

Table 3. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in foliated crystalline rocks of the Blue Ridge Basement.

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

	Mean	Median	Maximum	Minimum	Number of Observations
Estimated Yield, All Wells (Gal/Min)	16.5	10	800	0.5	6,652
Estimated Yield, Non-Residential Wells (Gal/Min)	33.69	18	800	1	284
Pumped Yield (Gal/Min)[a]	37.22	25	164	2	49
Specific Capacity (Gal/Min/Ft Drawdown)[b]	0.36	0.23	1.45	0.05	24
Well Depth (Ft)	306	299	1,320	5	6,902
Depth to Bedrock (Ft)	28.6	23	140	1	2,797
Depth to First Water-Bearing Fracture (Ft)	210	165	1,025	13	2,427
Depth to Lowest Water-Bearing Fracture (Ft)	289	260	1,235	15	2,427
Water Level (Ft BLS.)	37.8	31.6	315	0.5	1,980

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Groundwater samples taken from wells and springs in the foliated crystalline rocks of the Blue Ridge Basement indicate that the natural groundwater chemistry is predominately of the calcium- magnesium-bicarbonate type or of the sodium-magnesium-bicarbonate type. Groundwater within foliated crystalline rock is typically soft, and slightly acidic. Table 4 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of selected secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in the foliated crystalline rocks unit.

Table 4. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the foliated crystalline rocks the Blue Ridge Basement.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.50	6.40	9.00	4.50	475
Temperature (˚C)	14.2	14.4	15.0	11.5	375
Temperature (˚F)	57.7	58.0	59.0	52.7	375
Specific conductance (µS/cm at 25˚C)	108	70.0	643	9.00	409
Filtered residue (mg/L)	116	79.0	2,500	1.00	165
Hardness (mg/L as $CaCO_3$)	56.4	37.0	999	1.00	215
Major Cations					
Calcium (mg/L)	14.9	8.30	87.0	0.90	225
Magnesium (mg/L)	3.48	1.47	120	0.10	325
Sodium (mg/L)	6.48	5.00	164	0.10	404
Potassium (mg/L)	3.57	2.30	119	0.01	224
Major Anions					
Bicarbonate (mg/L as HCO_3)	46.5	24.4	291	1.20	427
Sulfate (mg/L)	6.07	3.00	59.0	0.13	201
Chloride (mg/L)	6.79	4.20	104	0.80	410
Nutrients					
Nitrate (mg/L as N)	1.00	0.30	12.0	0.01	198
Ammonium (mg/L as N)	0.09	0.10	0.30	0.01	209
Phosphate (mg/L as P)	0.04	0.02	0.16	0.01	169
Secondary Constituents					
Silica (mg/L)	27.7	27.0	41.0	9.30	16
Aluminum (ug/L)	38.9	24.0	660	7.00	200
Iron (µg/L)	872	100	47,000	10.0	221
Manganese (µg/L)	54.9	17.5	1,000	2.00	380
Arsenic, total (µg/L)	1.12	1.00	4.30	1.00	72
Bromide (mg/L)	0.04	0.04	0.12	<0.01	133
Fluoride (mg/L)	0.19	0.10	3.14	<0.01	248
Radiochemical Constituents					
Uranium (µg/L)	0.05	0.02	1.26	<0.01	162

Figure 11 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anion milliequivalents are within 10% of total cation milliequivalents) collected from 82 different wells and springs within the foliated crystalline rocks unit. Major cations usually range between 40-80% calcium+magnesium and 20-60% sodium+potassium. Typical ranges for major anions are 5-40% chloride+fluoride+sulfate, and 60-95% bicarbonate+carbonate with almost all of that percentage being bicarbonate.

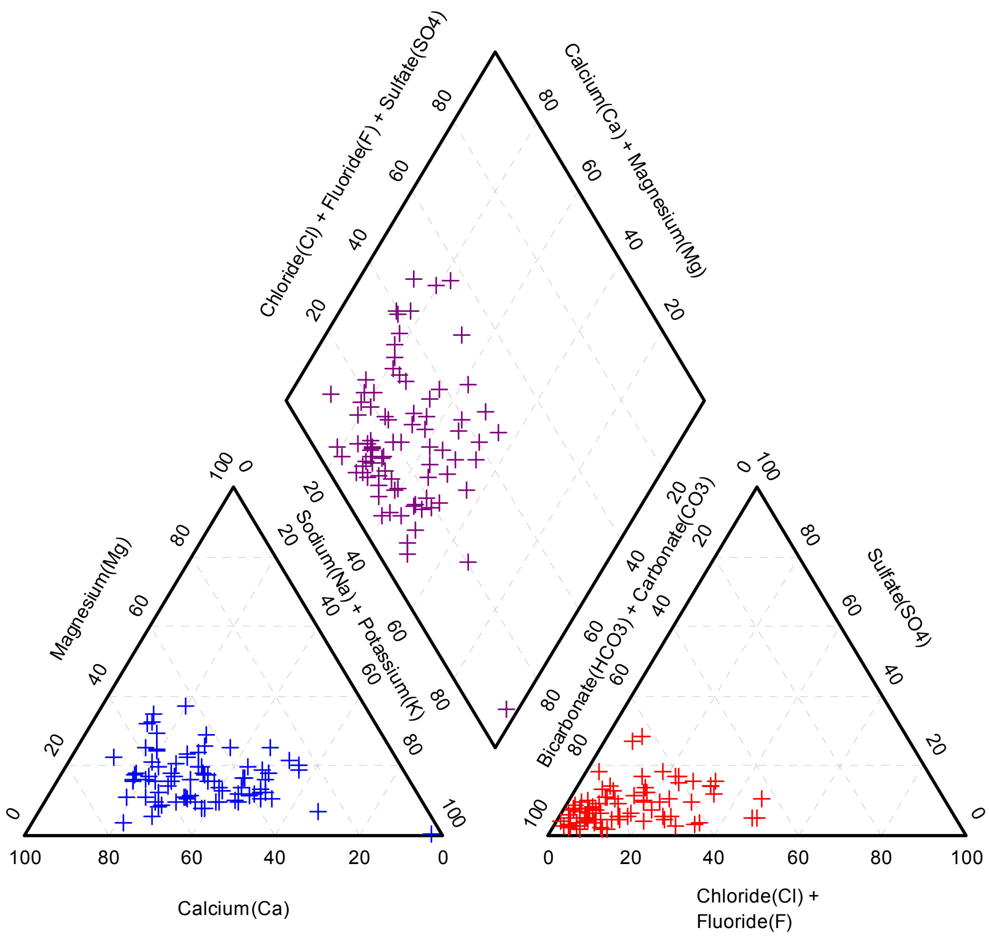


Figure 11. Piper diagram illustrating the relative distributions of major ions of groundwater samples collected from 82 different wells and springs within the foliated crystalline rocks unit.

Massive Crystalline Rocks of the Blue Ridge Basement

Figure 12 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the massive crystalline rock hydrogeologic group. Figure 13 provides photographs of selected rock types within the massive crystalline rocks hydrogeologic group.

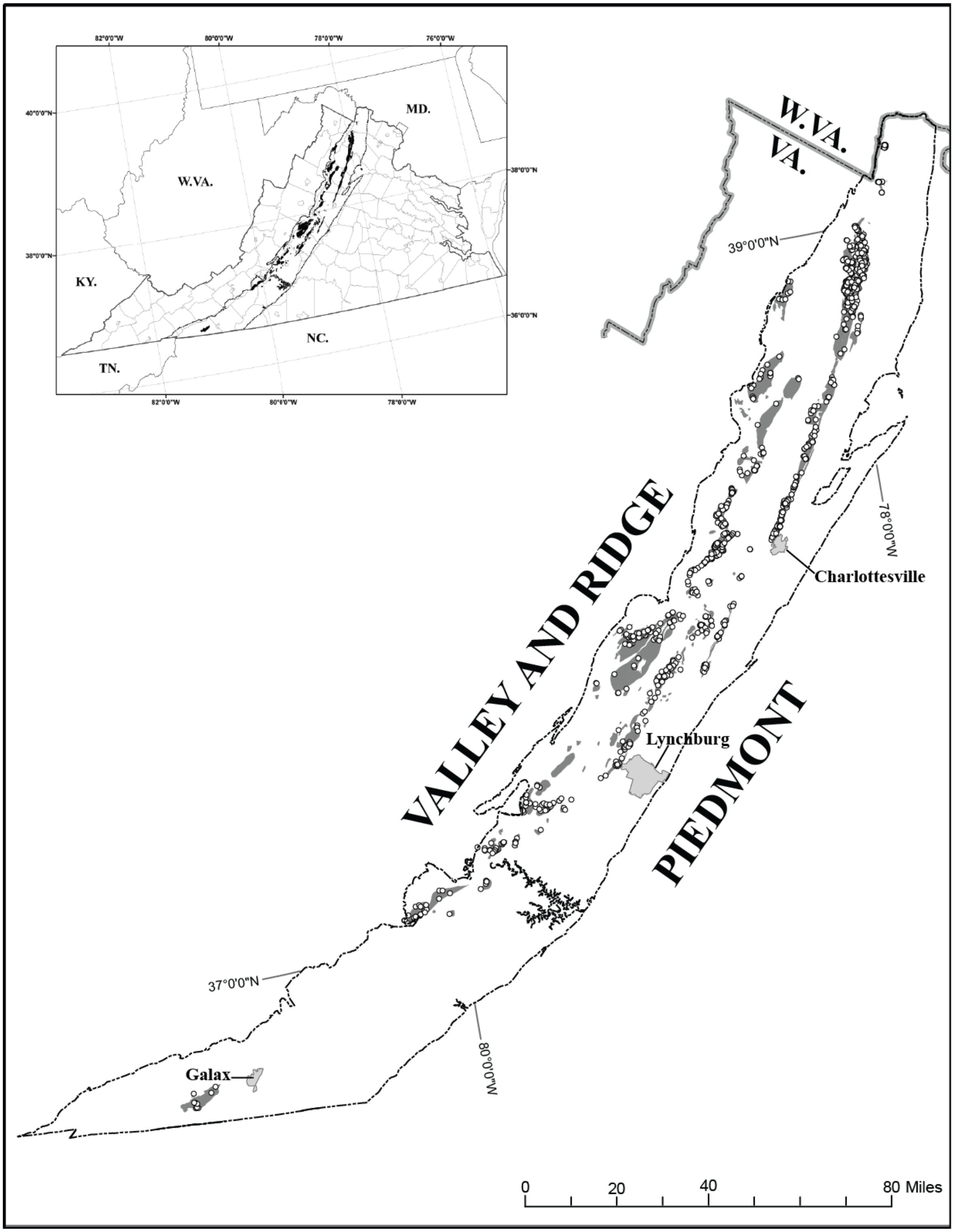


Figure 12. Extent and distribution of mid to late Proterozoic massive crystalline rocks of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

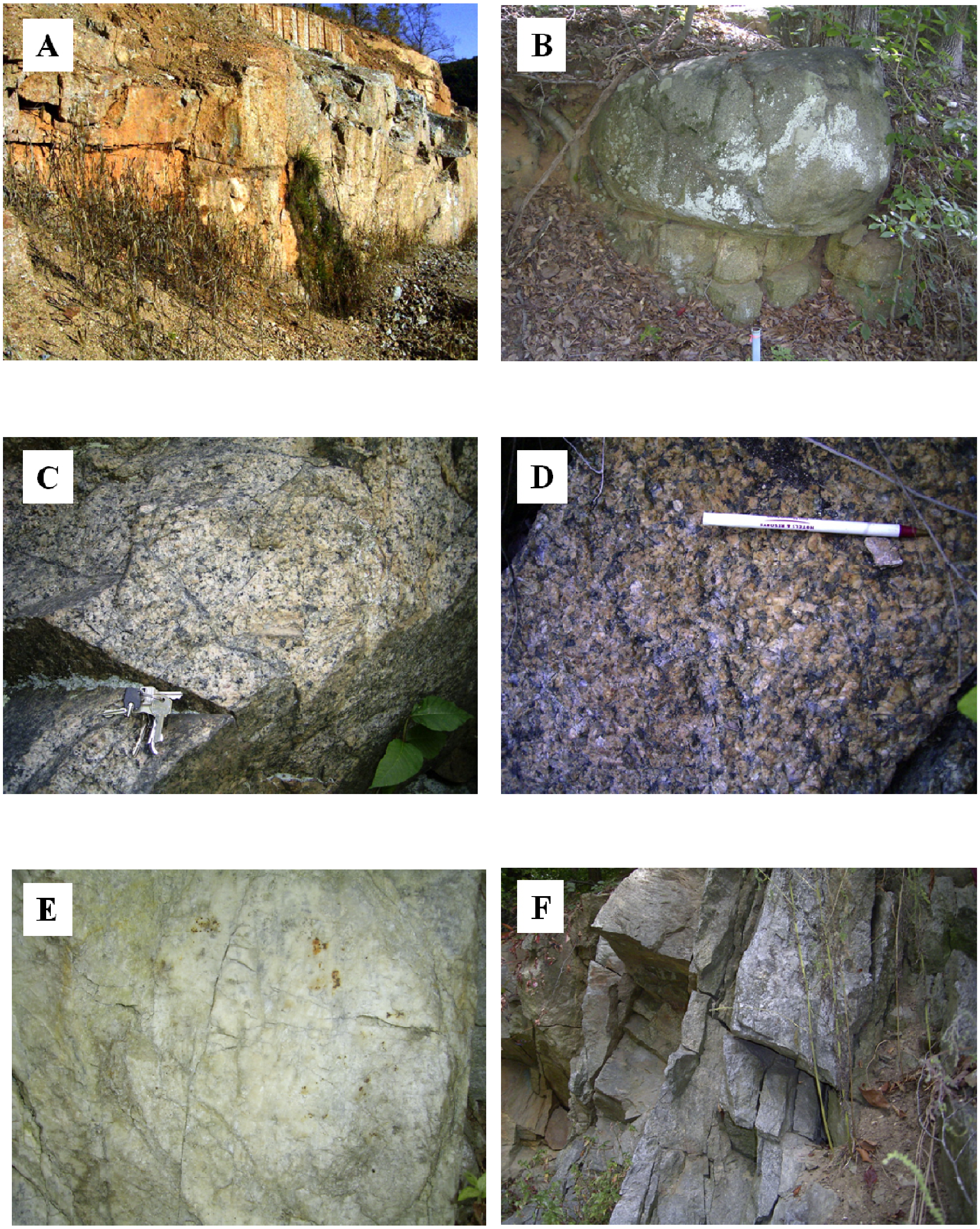


Figure 13. Photographs of massive crystalline rocks within the Blue Ridge Basement Complex. A) Leaky joint in Charnockitic rocks near Starkey, Virginia; B) Charnockite east of Rockfish Valley Fault System near Woods Mill, Virginia; C) Equigranular alkali feldspar granite of the Robertson River Igneous Suite near Haywood, Virginia; D) Biotite-hornblende granite of the Robertson River Igneous Suite near Laurel Mills, Virginia; E) Roseland Anorthosite near Roseland, Virginia; F) Roseland Anorthosite near Roseland, Virginia (outcrop).

Geologic Description and Hydrogeologic Characteristics

This unit includes the mid-Proterozoic charnockites and late Proterozoic granitoids associated with magmatism during Grenvillian orogenesis (1,160 to 1,050 Ma) and subsequent Iapetan rifting (705 to 735 Ma) (Tollo and Aleinikoff, 1996; Tollo et al., 2006). Despite the mid-to late Proterozoic ages of these rocks, the original igneous structures within them have been largely preserved. The charnockitic rocks occur primarily northwest of the Rockfish Valley fault system and as discontinuous lenses in the predominately gneissic bedrock to the southeast of the Rockfish Valley fault system (Bartholomew et al., 1981; Evans, 1991). The late Proterozoic granitoids occur primarily as northeast/southwest trending belts proximal to the eastern margin of exposed basement rock (Tollo and Lowe, 1994).

Jointing in massive crystalline rocks occurs parallel and perpendicular to primary flow lines, and in places where the igneous body has been offset, systems of joints diagonal to primary flow lines can occur in conjugate or single sets (Balk, 1937) (figure 15). Jointing can be more concentrated along the margins of the igneous body, in local zones of jointing imparted by stress reduction (such as unloading or faulting), along the margins of feeder dikes of contrasting mineralogy, and near contacts with the wall rock (Balk, 1937). Weathering of joints in the near surface environment tends to widen the apertures of the joint sets, thereby increasing the ability of fractures to store and transmit groundwater. Differential weathering and fracturing of intrusive bodies (dikes) in these granitic rocks can also result in increased groundwater storage and fracture transmissivity.

Table 5 provides summary statistics pertaining to the geologic and hydrogeologic characteristics associated with wells completed in massive crystalline rocks within the Blue Ridge Basement.

Reported estimated yield values were recorded for 1093 wells within the massive crystalline rock hydrogeologic group. Estimated yield values were 20 gal/min or more for 33%, 50 gal/min or more for 8%, and 100 gal/min or more for 2% of the total population. Reported well yield data for 83 municipal, commercial, and light industrial wells completed in the massive crystalline rock data set were also evaluated. Values of 20gal/min or more were reported for 43%, 50 gal/min or more for 17%, and 100 gal/min or more for 5% of the non-domestic well population in the massive crystalline rocks hydrogeologic group.

Reported water zone depth values for 96 wells drilled to or past 400 feet in massive crystalline rocks were available for water bearing zone depth analysis. At least one water bearing zone was reported by the driller to occur at depths of 400 feet or greater for 48% (46) of these wells. A total of 163 reported water bearing zones occurred among these wells and 32% (52) of them occurred below 400 feet. The deepest reported water bearing fracture in the massive crystalline rocks data set was reported at 941 feet below land surface and yielded 0.5 gallons per minute at the time of completion.

The highest yielding well on record in the massive crystalline rock data set was drilled in Madison County in the Robinson River Igneous Suite. This well is 187 feet deep, and at the time of completion was air lifted for 8 hours at a rate of 180 gal/min. Water-bearing fractures were encountered at 60 to 61 feet, and at 182 to 185 feet below land surface. A 48 hour pump test was later conducted with a 3 hp pump set at 160 feet below land surface. The average discharge during the pump test was 38 gal/min, with a total drawdown of 59 feet at the termination of the test.

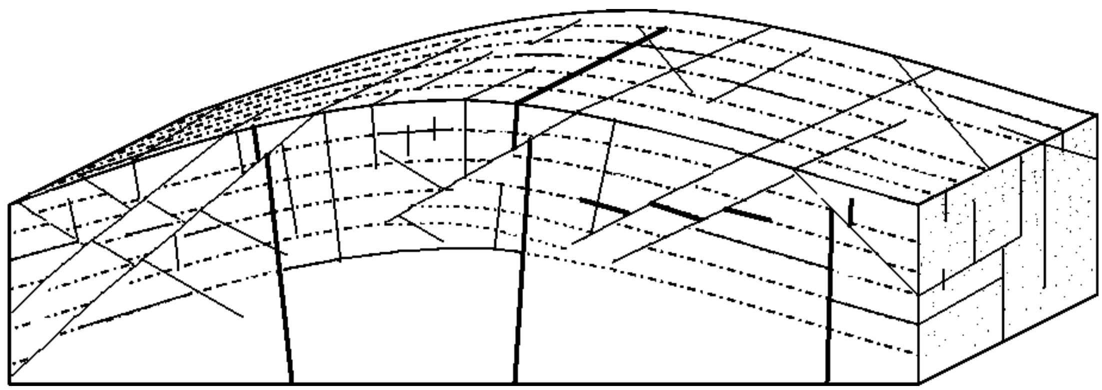


Figure 14. Jointing in an igneous body perpendicular and parallel to primary flow lines (dashed lines). Diagonal joints occur where the body has been offset or warped. Figure modified after Balk (1937).

Table 5. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in massive crystalline rocks of the Blue Ridge Basement.

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

	Mean	**Median**	**Maximum**	**Minimum**	**Number of Observations**
Estimated Yield, All Wells (Gal/Min)	17.3	10	180	1	1093
Estimated Yield, Non-Residential Wells (Gal/Min)	28.7	16.5	180	1	80
Pumped Yield (Gal/Min)[a]	42.6	22	165	5	6
Specific Capacity (Gal/Min/Ft Drawdown)[b]	0.3	0.08	1.18	0.03	6
Well Depth (Ft)	272	245	1300	16	1133
Depth to Bedrock (Ft)	28.7	25	150	1	481
Depth to First Water-Bearing Fracture (Ft)	164	140	895	14	410
Depth to Lowest Water-Bearing Fracture (Ft)	234	200	941	18	413
Water Level (Ft BLS.)	39.4	31	192	5	205

a Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
b Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Groundwater samples taken from wells and springs in the massive crystalline rocks of the Blue Ridge Basement indicate that the natural groundwater chemistry is predominately of the calcium-magnesium-bicarbonate type or of the sodium-magnesium-bicarbonate type. Groundwater within the massive crystalline rocks is typically soft, and slightly acidic. Table 6 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of selected secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in the massive crystalline rocks unit.

Table 6. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the massive crystalline rocks the Blue Ridge Basement.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.39	6.30	8.30	5.35	113
Temperature (˚C)	13.7	14.4	17.0	9.00	34
Temperature (˚F)	56.6	58.0	62.6	48.2	34
Specific conductance (µS/cm at 25˚C)	105	66.0	1280	10.0	103
Filtered residue (mg/L)	129	79.0	1200	26.0	45
Hardness (mg/L as $CaCO_3$)	78.6	34.0	999	1.00	43
Major Cations					
Calcium (mg/L)	15.3	7.00	154	<0.01	65
Magnesium (mg/L)	2.33	1.60	13.7	<0.01	86
Sodium (mg/L)	6.89	5.00	42.0	<0.01	97
Potassium (mg/L)	1.92	1.40	7.80	<0.01	56
Major Anions					
Bicarbonate (mg/L as HCO_3)	39.1	19.5	237	2.40	107
Sulfate (mg/L)	3.66	2.15	19.0	0.10	58
Chloride (mg/L)	6.61	4.00	60.8	0.50	104
Nutrients					
Nitrate (mg/L as N)	1.36	0.65	7.50	0.02	58
Ammonium (mg/L as N)	0.09	0.10	0.10	0.01	56
Phosphate (mg/L as P)	0.05	0.03	0.18	0.01	52
Secondary Constituents					
Silica (mg/L)	14.5	11.5	24.0	8.50	8
Aluminum (ug/L)	42.4	33.5	99.0	12.0	46
Iron (µg/L)	698	100	11,000	10.0	59
Manganese (µg/L)	70.7	18.0	920	3.00	87
Arsenic, total (µg/L)	1.00	1.00	1.00	1.00	17
Bromide (mg/L)	0.04	0.04	0.07	0.01	27
Fluoride (mg/L)	0.14	0.08	1.00	<0.01	63
Radiochemical Constituents					
Uranium (µg/L)	0.04	0.02	0.34	<0.01	35

Figure 15 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 21 different wells and springs within the massive crystalline rocks unit. The principal anions in these waters are uniformly dominated by bicarbonate. Major cations usually range between 40-80% calcium+magnesium and 20-60% sodium+potassium. Typical ranges for major anions are 5-20% chloride+fluoride+sulfate, and 80-95% bicarbonate+carbonate with almost all of that percentage being bicarbonate.

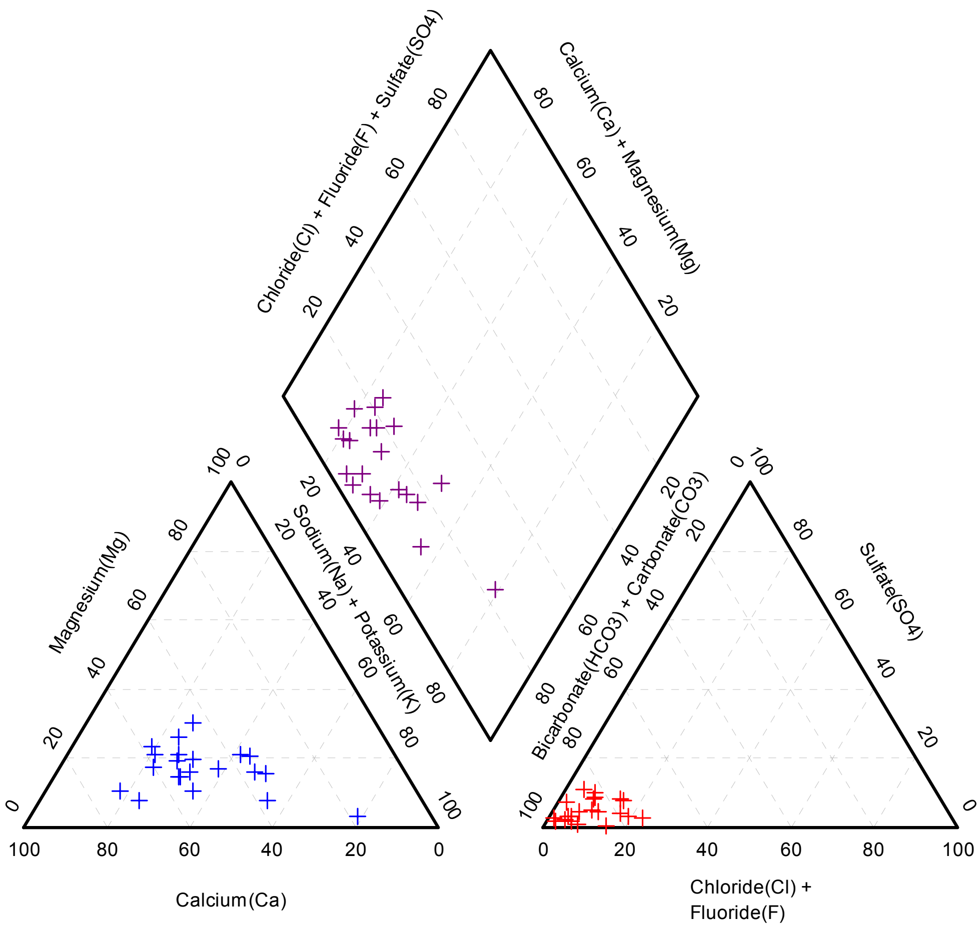


Figure 15. Piper diagram illustrating the relative distributions of major ions in groundwater samples collected from 21 different wells within the massive crystalline rocks unit.

Mylonitic Rocks of the Blue Ridge Basement

Figure 16 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the mylonitic rock hydrogeologic group. Figure 17 provides photographs of selected rock types within the mylonitic rock hydrogeologic group.

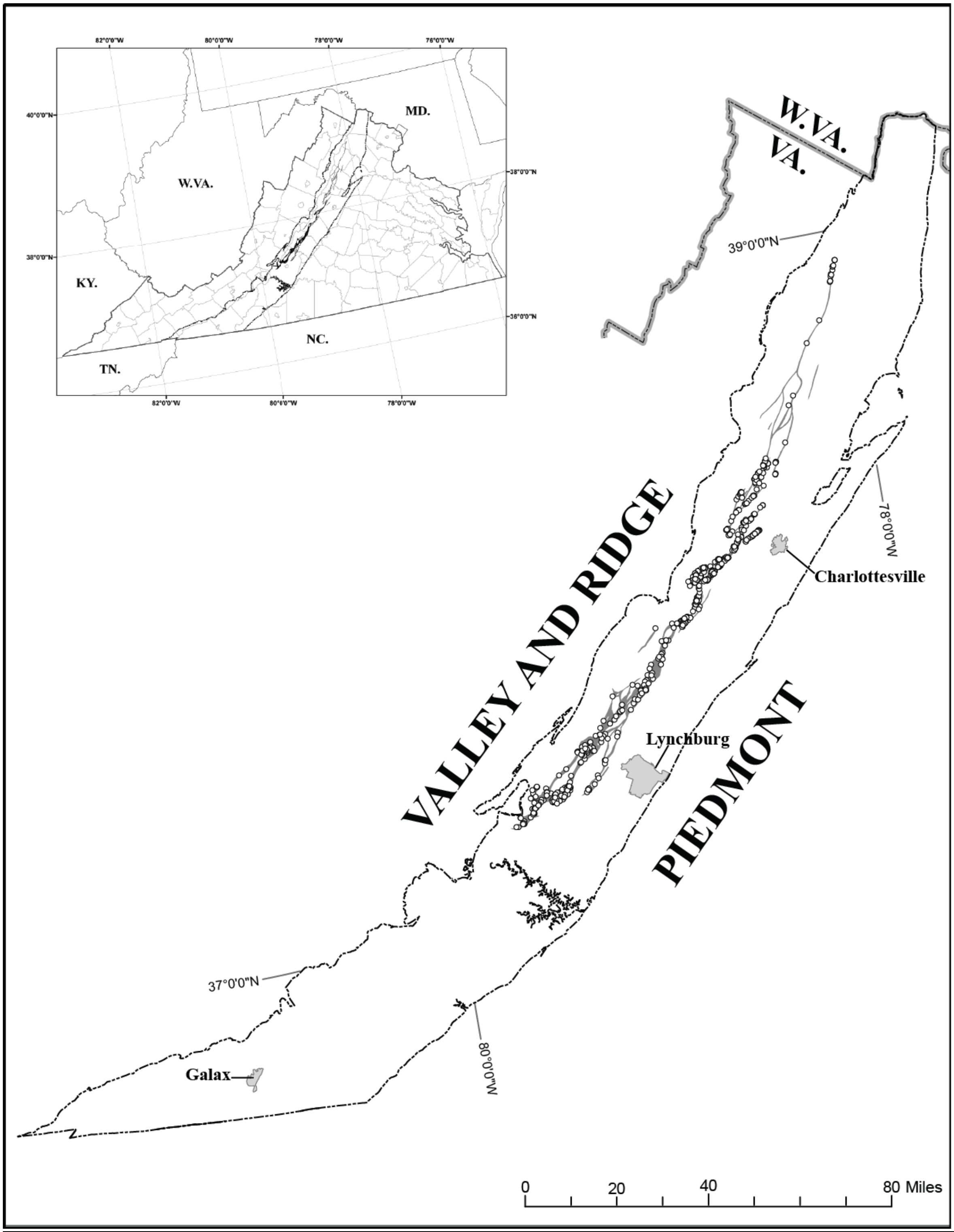


Figure 16. Extent and distribution of mid to late Proterozoic mylonitic rocks of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

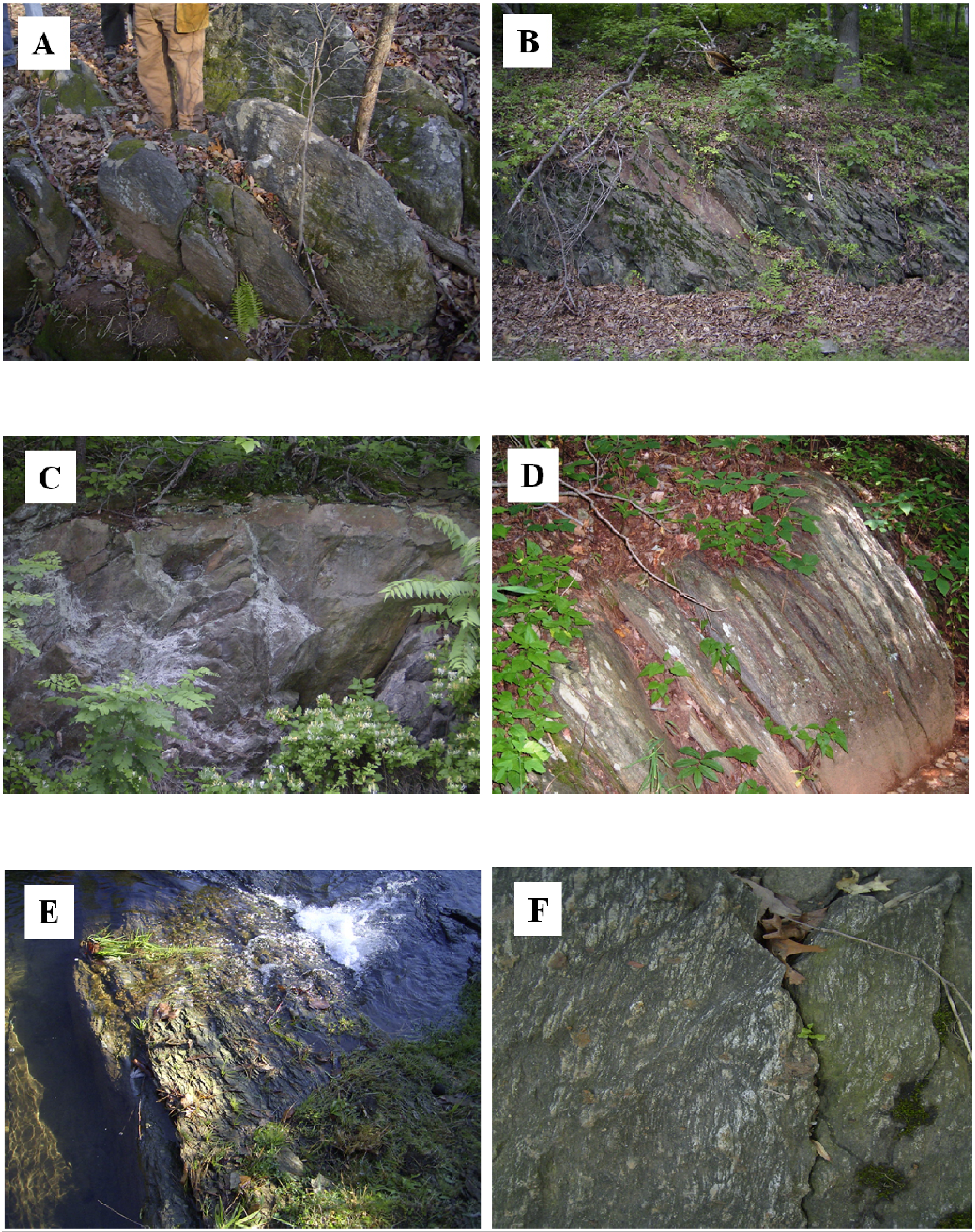


Figure 17. Photos of mylonitic crystalline rocks of the Blue Ridge Basement Complex. A) Mylonitic biotite augen gneiss near Sweetbriar College, Virginia; B) Mylonitic Biotite Gneiss west of Rockfish Valley Fault near Greenfield, Virginia ; C) Ultra-mylonite near Durrett Town, Virginia; D) Well developed fracture set parallel to foliation in mylonitic Charnockite near Tyro, Virginia; E) Mylonitic zone in Granulite Gneiss in bed of Maggodee Creek near Naff, Virginia. F) Proto-mylonite in creek bed near Sweetbriar College, VA.

Geologic Description and Hydrogeologic Characteristics

Mylonitic rocks within the basement complex of the Blue Ridge Geologic Province comprise a small percentage of total basement structure and are limited to discrete zones distinguished by metamorphic grade and fabric. Rocks within these zones often exhibit gradational metamorphic textures, with rocks of lower metamorphic grade along the perimeters (proto-mylonites) grading into rocks of higher metamorphic grade (interlayered mylonites, proto-mylonites, and ultra-mylonites or cataclastic rocks) within the very high-strain portions. Some of these mylonitic zones are thought to have been emplaced during the extensional movements associated with Laurentian rifting and in places re-activated during subsequent periods of crustal shortening or extension (Bailey and Simpson, 1993). Other mylonitic zones (namely the Rockfish Valley Ductile Deformation Zone) originated during Alleghanian thrusting (Bailey and Simpson, 1993; Bartholomew, 1977; Gathright et al., 1977). There are many mylonitic zones throughout the Blue Ridge Basement complex ranging in width from less than an inch to miles, but the scale of occurrence for many of these mylonitic zones precludes them from this report. Data generated from this investigation is limited to mylonitic zones large enough to be mapped on a 1:500,000 scale, and centers around the Rockfish Valley fault system.

Fracturing within strongly mylonitic rocks is pervasive at angles parallel or sub-parallel to the prevalent foliation planes characteristic of the mylonitic texture, and jointing at steep angles across foliation is common, which can cause the mylonitic rocks in many locales to have a platy or slaty appearance in outcrop (Gathright, 1976). In the ultramylonitic rocks, fracturing along or sub-parallel to the foliation planes is not as pervasive due to the nearly complete recrystallization and grain size reduction of the parent rock into a fine-grained, equigranular matrix. In proto-mylonites, fracturing can be more sub-parallel to foliation or absent due to the incomplete reorientation and flattening of mineral grains along foliation planes. On a regional scale, foliation and associated partings along foliation commonly dip to the southeast at steep to moderate dip angles. The strike of joints at steep angles to foliation are variable, but they often dip to the southeast or northwest. Abrupt textural and structural contrasts imparted by small scale mylonitic zones within foliated or massive crystalline rock can create areas of preferential fracturing and weathering and can enhance groundwater storage within and proximal to the zone(s) of mylonitization.

Table 7 provides summary statistics pertaining to the geologic and hydrogeologic characteristics of wells completed in mylonitic textures of the Blue Ridge Basement.

Data were recorded for 594 wells completed in mylonitic rock with estimated yield information. Estimated yield values were 20 gal/min or more for 24%, 50 gal/min or more for 6%, and 100 gal/min or more for 1% of the total well population. Estimated yield data were also analyzed for 41 municipal, commercial, and light industrial wells completed in mylonitic rock. Values of 20 gal/min or more for 44%, 50 gal/min or more for 22%, and 100 gal/min or more for 5% were reported for these non-domestic wells.

Due to a lack of available reported fracture depth information for wells completed in mylonitic rocks, a statistically significant data set is currently not available for quantitatively studying the incidence of fracturing below 400 feet in mylonitic rocks. Available fracture depth information for wells completed to depths of 400 feet or greater in mylonitic rock indicate that the bulk of the water bearing zones in these rocks occur at depths shallower than 400 feet. Only one in ten of the wells in this subset of data has fractures occurring below 400 feet, and of the total number of fractures among these wells, (23 fractures) only one occurs below 400 feet. The deepest reported water-bearing fracture in this sub-set was 473 feet below land surface. Although the yield of the individual fracture is not known, it is presumably less than 1 gallon per minute (this well had one other reported water bearing fracture and the reported yield of the well was 1 gallon per minute). Data from this small sub-set of wells suggest that water bearing zones within mylonitic rocks of the Blue Ridge Basement occur primarily within the upper 400 feet of rock, but more data are needed to substantiate this observation.

The highest yielding well on record in the mylonitic rock data set was drilled for the City of Bedford, Virginia approximately 0.5 mile south of Kelso Mill and 2.5 miles north-west of Bedford City limits. The well is 400 feet deep, and is sourced by numerous fractures in the top 240 feet of well bore. Complete pump test data were not available for this well, but the reported long-term pumping yield was 183 gallons/minute with a drawdown of 69 feet. VDH records indicate that the pump in this well is sized for production at 174 gallons per minute. This well is one of 5 that were drilled for Bedford City on a broad river terrace along the Big Otter River. These wells are all within a 600 foot radius of the center well, and have long-term pumping yield values of 183, 142, 78, 52, and 40 gallons/minute. The wells are drilled in the footwall of the Rockfish Valley Fault, and likely intersect similar, or the same structurally controlled fracture systems. The wells are favorably situated in a topographically low area with good alluvial cover for intercepting and storing groundwater recharge.

Table 7. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in mylonitic rocks of the Blue Ridge Basement.

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

	Mean	**Median**	**Maximum**	**Minimum**	**Number of Observations**
Estimated Yield, All Wells (Gal/Min)	14.6	10	191	1	593
Estimated Yield, Non-Residential Wells (Gal/Min)	29.8	12	191	1	41
Pumped Yield (Gal/Min)[a]	58.6	51	142	10	8
Specific Capacity (Gal/Min/Ft Drawdown)[b]	0.92	0.41	2.85	0.04	7
Well Depth (Ft)	269	265	900	60	606
Depth to Bedrock (Ft)	41	36	110	5	63
Depth to First Water-Bearing Fracture (Ft)	115	95	315	20	57
Depth to Lowest Water-Bearing Fracture (Ft)	166	139	473	46	57
Water Level (Ft BLS.)	35.7	30	120	1	66

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Groundwater samples taken from wells and springs in the mylonitic rocks of the Blue Ridge Basement indicate that the natural groundwater chemistry is predominately of the calcium-magnesium-bicarbonate type or of the sodium-magnesium-bicarbonate type. Groundwater within mylonitic rocks is typically soft, and slightly acidic. Table 8 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of selected secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in the mylonitic rocks unit.

Table 8. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the mylonitic rocks of the Blue Ridge Basement.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.63	6.50	8.24	5.80	56
Temperature (˚C)	13.2	13.3	14.5	12.0	3
Temperature (˚F)	55.9	56.0	58.1	53.6	3
Specific conductance (µS/cm at 25˚C)	82.0	64.0	225	18.0	52
Filtered residue (mg/L)	90.5	81.0	168	44.0	21
Hardness (mg/L as $CaCO_3$)	39.1	32.0	94.0	1.00	27
Major Cations					
Calcium (mg/L)	10.8	7.50	30.0	1.00	28
Magnesium (mg/L)	2.10	1.54	9.70	0.10	40
Sodium (mg/L)	7.34	4.96	62.0	1.02	54
Potassium (mg/L)	2.74	2.25	6.90	0.50	28
Major Anions					
Bicarbonate (mg/L as HCO_3)	38.8	23.2	174	1.60	142
Sulfate (mg/L)	4.68	3.40	14.7	0.20	29
Chloride (mg/L)	7.73	4.25	110	1.00	54
Nutrients					
Nitrate (mg/L as N)	0.60	0.16	6.75	0.04	26
Ammonium (mg/L as N)	0.09	0.10	0.10	0.04	27
Phosphate (mg/L as P)	0.04	0.03	0.18	0.01	21
Secondary Constituents					
Silica (mg/L)	28.7	26.0	46.0	14.0	5
Aluminum (ug/L)	49.0	33.0	128	11.0	25
Iron (µg/L)	606	100	9,060	10.0	29
Manganese (µg/L)	47.4	26.5	227	2.00	48
Arsenic, total (µg/L)	1.00	1.00	1.00	1.00	6
Bromide (mg/L)	0.03	0.03	0.07	<0.01	20
Fluoride (mg/L)	0.21	0.10	1.58	0.01	36
Radiochemical Constituents					
Uranium (µg/L)	0.04	0.03	0.09	<0.01	18

Figure 18 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 18 different wells within the mylonitic rocks unit. Major cations usually range between 55-80% calcium+magnesium and 20-45% sodium+potassium. Typical ranges for major anions are 5-40% chloride+fluoride+sulfate and 60-95% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate.

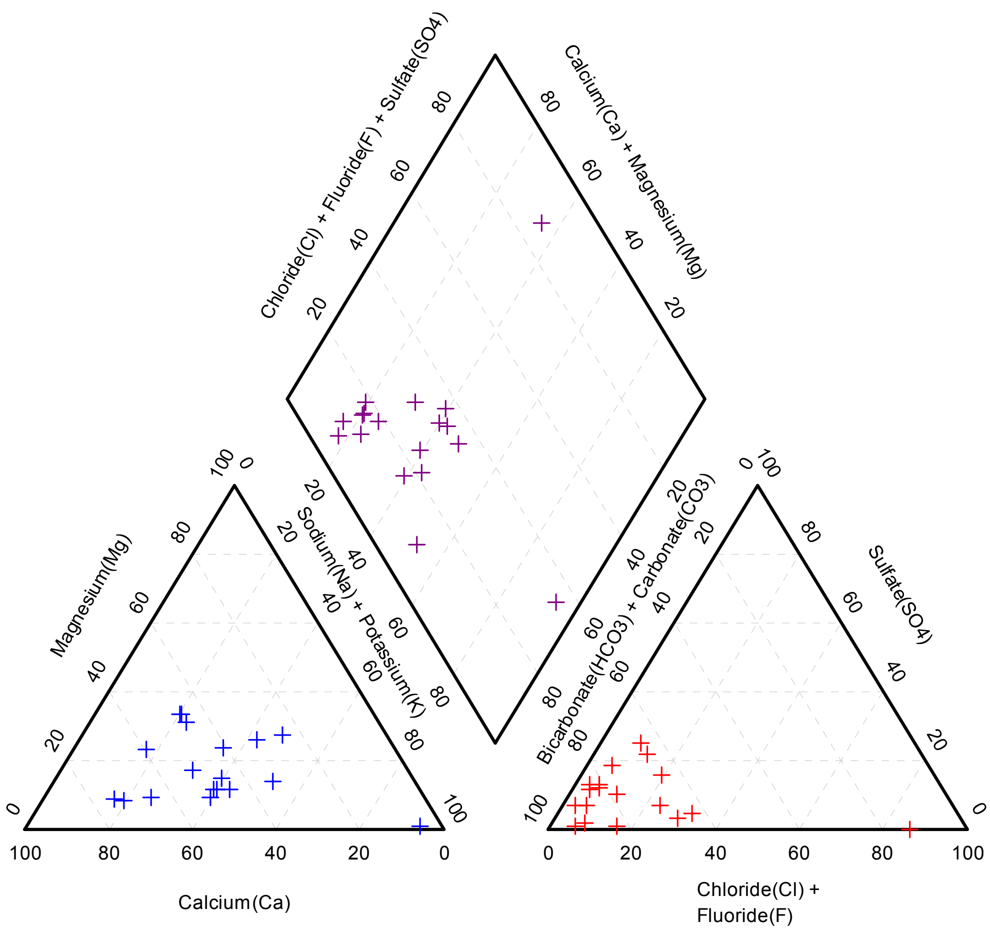


Figure 18. Piper diagram illustrating the relative distributions of major ions of groundwater samples collected from 18 different wells within the mylonitic crystalline rocks unit.

Layered Granulites of the Blue Ridge Basement

Figure 19 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the layered granulites hydrogeologic group. Figure 20 provides photographs of selected rock types within the layered granulites hydrogeologic group.

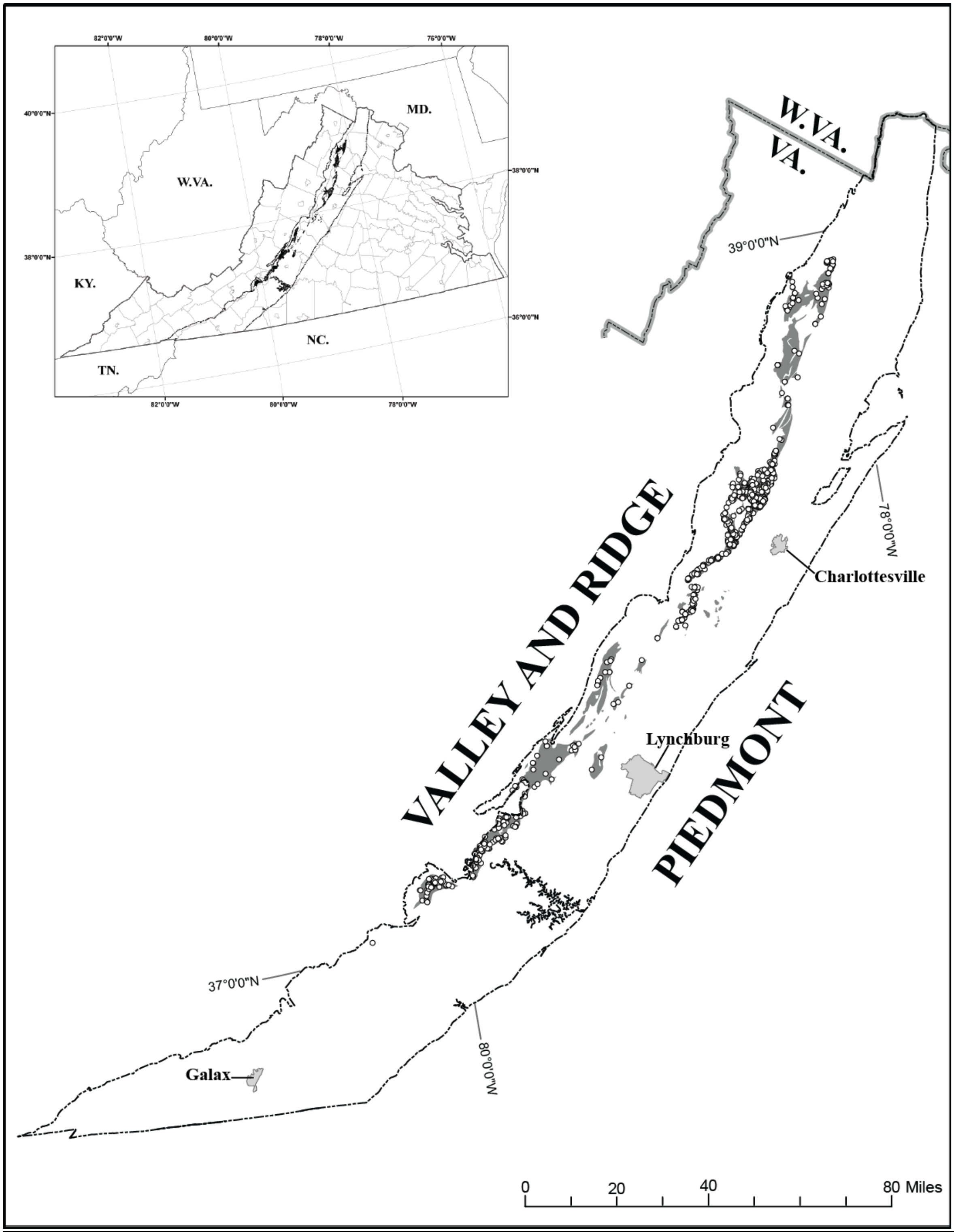


Figure 19. Extent and distribution of the layered granulites of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

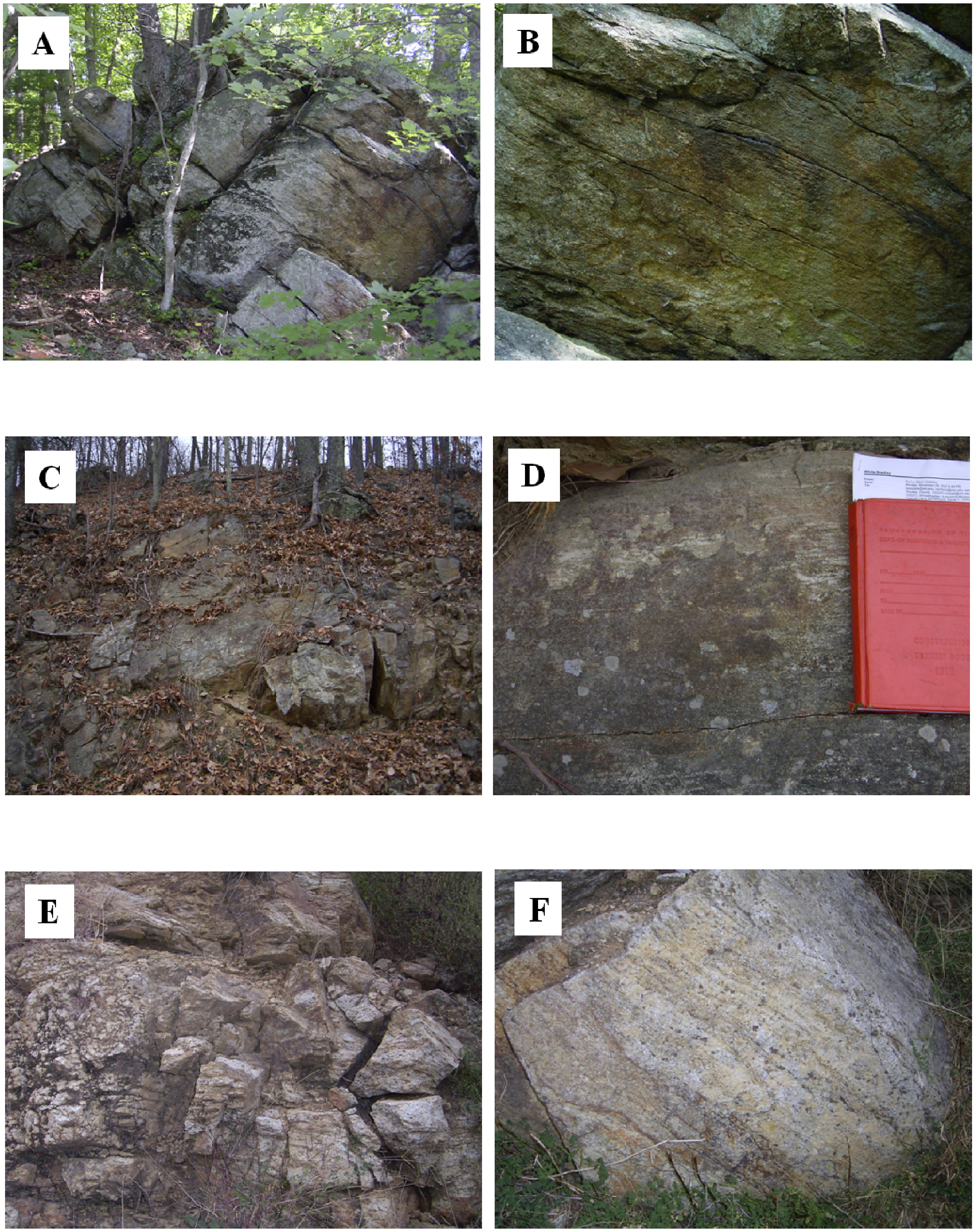


Figure 20. Photos of granulitic rocks of the Blue Ridge Basement Complex. A) Layered pyroxene granulite near Sperryville, Virginia (outcrop); B) Layered pyroxene granulite near Sperryville, Virginia; C) Laminated (granulite) gneiss near Arcadia, Virginia (outcrop); D) Laminated (granulite) gneiss near Arcadia, Virginia; E) Layered pyroxene granulite near Vinton, Virginia (outcrop); F) Layered pyroxene granulite near Vinton, Virginia.

Geologic Description and Hydrogeologic Characteristics

The granulite gneisses of the Blue Ridge Basement occur as mappable units at the 1:500,000 scale primarily west of the Rockfish Valley fault zone (Virginia Division of Mineral Resources, 1993). To the east of the Rockfish Valley fault zone, granulite gneisses are interlayered with younger gneisses throughout the Blue Ridge Basement complex. Granulites are interpreted as pre-existing country rocks that have been subjected to varying degrees of deformation and plutonism associated with Grenvillian through Alleghanian orogenesis and Mesozoic rifting. These rocks usually possess granular metamorphic textures and exhibit well to poorly developed segregation-layering of alternating mineral groups on the scale of less than an inch to several inches (Bartholomew, 1981; Bartholomew et al., 1981; Evans, 1991). They are among the oldest rocks in the Commonwealth.

Jointing within layered granulites can develop parallel to layering. In granulites with well developed layering, orthogonal joint sets roughly perpendicular to layering can give the rock a 'blocky' appearance in outcrop. Systematic jointing in more massive granulites with poorly developed layering is less prevalent. In many places, granulitic rocks are cross-cut by younger intrusive bodies. Differential weathering and jointing of intrusive bodies within the granulites can serve to enhance or diminish the secondary porosity of these rocks on a local scale.

Table 9 presents summary statistics for geologic and hydrogeologic characteristics associated with wells completed in granulites of the Blue Ridge Basement.

Reported estimated yield data were analyzed for 768 wells completed in layered granulites. Estimated yield values were 20 gal/min for 24%, 50 gal/min for 6%, and 100 gal/min or more for 2% of the total well population. Reported yield data were also analyzed for 89 municipal, commercial, and light industrial wells completed in the layered granulites. Values of 20 gal/min or more were reported for 49%, 50 gal/min or more for 28%, and 100 gal/min or more for 19% of the non-domestic well population. A large proportion of the wells reported to yield over 100 gal/min (10 of the 18 wells) had reported yields of over 200 gallons/minute, and draw on comparatively large stores of groundwater in the crystalline rocks in the vicinity of the Blue Ridge Fault in the Vinton/Roanoke/Salem metropolitan area. One of these wells (Bush Well #2) has a reported estimated yield of nearly 1,000 gal/min, making it the highest reported yield in the database for wells completed in the crystalline rocks of the Blue Ridge.

Reported water zone depth values for 28 wells drilled to or past 400 feet in the layered granulites rock type were available for analysis. At least one water bearing zone was reported by the driller to occur at depths of 400 feet or greater for 46% (13) of these wells. Within this subset of wells, 15 of the 43 total water bearing zones reported (34%) occurred below 400 feet.

The highest yielding well on record in the layered granulite gneiss data set was drilled in the town of Vinton, Virginia near the terminus of the Blue Ridge Fault. This well was drilled to a depth of 360 feet and has a reported stabilized yield of 1,000 gal/min. Water producing fractures were reported by the driller at the following depths: 85-87 feet (5gal/min); 90-95 feet (5 gal/min); 102-103 feet (10 gal/min); 110-111 feet (10 gal/min); 127-130 feet (20 gal/min); 145-148 feet (100 gal/min); 150-151 feet (25 gal/min); 308-309 feet (450 gal/min); 330-331 feet (350 gal/min). The well was pumped for 10 hours at 1000 gal/min with 44 feet of drawdown at the end of the test. Although stabilized drawdown conditions were not reached during the test, most of the drawdown in the well occurred within the first 10 minutes of pumping, indicating a rapid evacuation of water from storage within the immediate vicinity of the well-bore. Between the 10 minute and 600 minute period, water levels declined a total of 12 feet, as water demands were being met from storage further into the formation. During this test, water levels in Bush Well #1 and #3 (approximately 350 feet to the northwest and 1,000 feet to the southwest, respectively) were not measurably affected (written transmittal from contractor and personal communication with Vinton Public Works Personnel).

Table 9. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in layered granulites of the Blue Ridge Basement.

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

	Mean	Median	Maximum	Minimum	Number of Observations
Estimated Yield, All Wells (Gal/Min)	19.22	8	1000	1	768
Estimated Yield, Non-Residential Wells (Gal/Min)	83.49	20	1000	1	89
Pumped Yield (Gal/Min)[a]	30	59.6	170	9	13
Specific Capacity (Gal/Min/Ft Drawdown)[b]	4.31	1.14	22.7	0.01	11
Well Depth (Ft)	271	265	705	10	794
Depth to Bedrock (Ft)	41.7	38	157	2	147
Depth to First Water-Bearing Fracture (Ft)	165	116	630	20	122
Depth to Lowest Water-Bearing Fracture (Ft)	222	207	630	20	122
Water Level (Ft BLS.)	45.3	30	333	2	94

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Many municipal and industrial wells with yields in the hundreds of gallons per minute have been completed adjacent to the Blue Ridge Fault in the Vinton/Roanoke/Salem area, and exploit the high transmissivity and enhanced storage that are intrinsic to these rocks. Figure 21 depicts the location and magnitude of reported yield for wells on record in the Vinton/Roanoke area, and their proximity to the surface expression of the Blue Ridge Fault. Wells with higher reported yield values tend to cluster around the fault, in the carbonate rocks to the west of the fault, and in a cluster to the east of the fault in the Vinton area.

Detailed mapping, field investigations, and fracture trace analyses in the Roanoke area by (Bartholomew, 1981; Henika, 1981, 1997, 2007; Henika et al., 2004) have revealed at least three fracture systems within the crystalline and carbonate rocks that are transverse (NW to SE trending) to the Blue Ridge Fault and are thought to be related to Mesozoic extensional faulting. Transverse structures appear to be a favorable drilling target in this area, and are thought to play an important role in storing and conveying groundwater (Henika, 2008; Henika et al., 2004). Crystal Spring and several other high producing wells completed both in the head wall and foot wall of the Blue Ridge Fault are located along strike of transverse fracture systems that have been identified through field investigations and surface geophysics. It is currently not known if similar fracture/fault groundwater storage systems exist along other transverse structures in the Blue Ridge. Recently, additional transverse fault structures have been recognized and mapped in the Blue Ridge to the North (Southworth et al., 2009a).

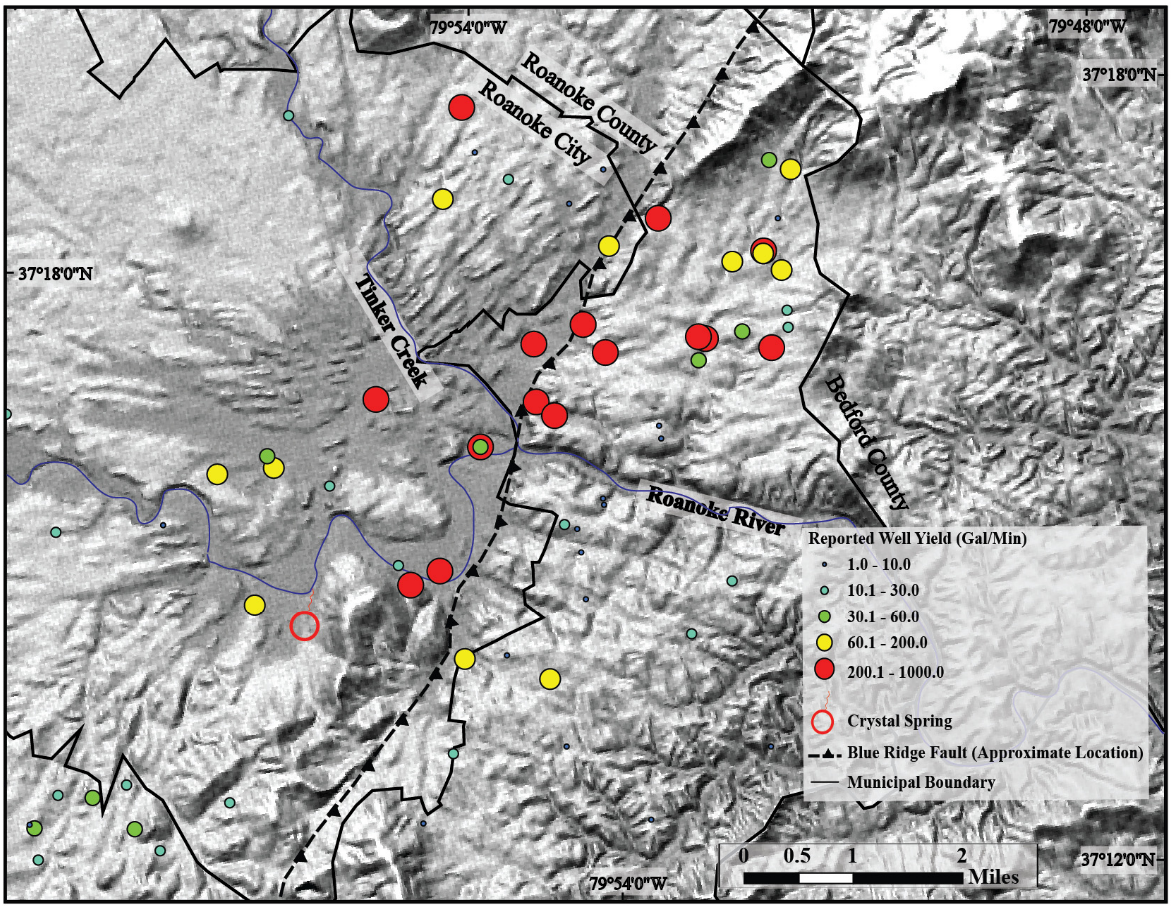


Figure 21. Well yield magnitude and location in relation to topography and structural position of the Blue Ridge Fault for wells on record for the Roanoke/Vinton area.

Groundwater Chemistry

Groundwater samples taken from wells and springs in the layered granulite gneisses of the Blue Ridge Basement indicate that the natural groundwater chemistry is predominately of the calcium-magnesium- bicarbonate type or of the sodium-magnesium-bicarbonate type. Groundwater within the layered granulite gneisses is typically soft, and slightly acidic. Table 10 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of selected secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in the layered granulite gneiss unit.

Table 10. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the layered granulites of the Blue Ridge Basement.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.62	6.60	8.20	5.00	91
Temperature (˚C)	13.2	13.3	18.3	10.0	29
Temperature (˚F)	55.9	56.0	65.0	50.0	29
Specific conductance (µS/cm at 25˚C)	97.1	63.4	972	10.0	88
Filtered residue (mg/L)	95.7	81.5	246	38.0	30
Hardness (mg/L as $CaCO_3$)	44.7	28.0	164	12.0	41
Major Cations					
Calcium (mg/L)	13.5	6.85	154	0.80	46
Magnesium (mg/L)	2.98	1.78	27.1	0.10	72
Sodium (mg/L)	6.79	5.00	35.0	0.37	83
Potassium (mg/L)	1.89	1.25	7.30	0.20	44
Major Anions					
Bicarbonate (mg/L as HCO_3)	43.6	29.0	146	2.40	91
Sulfate (mg/L)	13.0	2.00	411	0.31	47
Chloride (mg/L)	5.27	3.70	70.0	0.70	85
Nutrients					
Nitrate (mg/L as N)	0.90	0.60	7.00	0.04	42
Ammonium (mg/L as N)	0.09	0.10	0.10	0.04	40
Phosphate (mg/L as P)	0.05	0.04	0.16	0.01	37
Secondary Constituents					
Silica (mg/L)	19.2	20.8	32.3	5.50	6
Aluminum (ug/L)	57.4	35.0	278	3.00	43
Iron (µg/L)	367	100	4,000	10.0	41
Manganese (µg/L)	25.9	14.5	160	1.00	68
Arsenic, total (µg/L)	1.00	1.00	1.00	1.00	9
Bromide (mg/L)	0.03	0.03	0.10	<0.01	32
Fluoride (mg/L)	0.31	0.11	2.06	0.01	59
Radiochemical Constituents					
Uranium (µg/L)	0.05	0.02	0.24	<0.01	35

Figure 22 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 23 different wells within the layered granulite unit. Major cations usually range between 40-80% calcium+magnesium and 20-60% sodium+potassium. Typical ranges for major anions are 5-40% chloride+fluoride+sulfate and 60-95% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate.

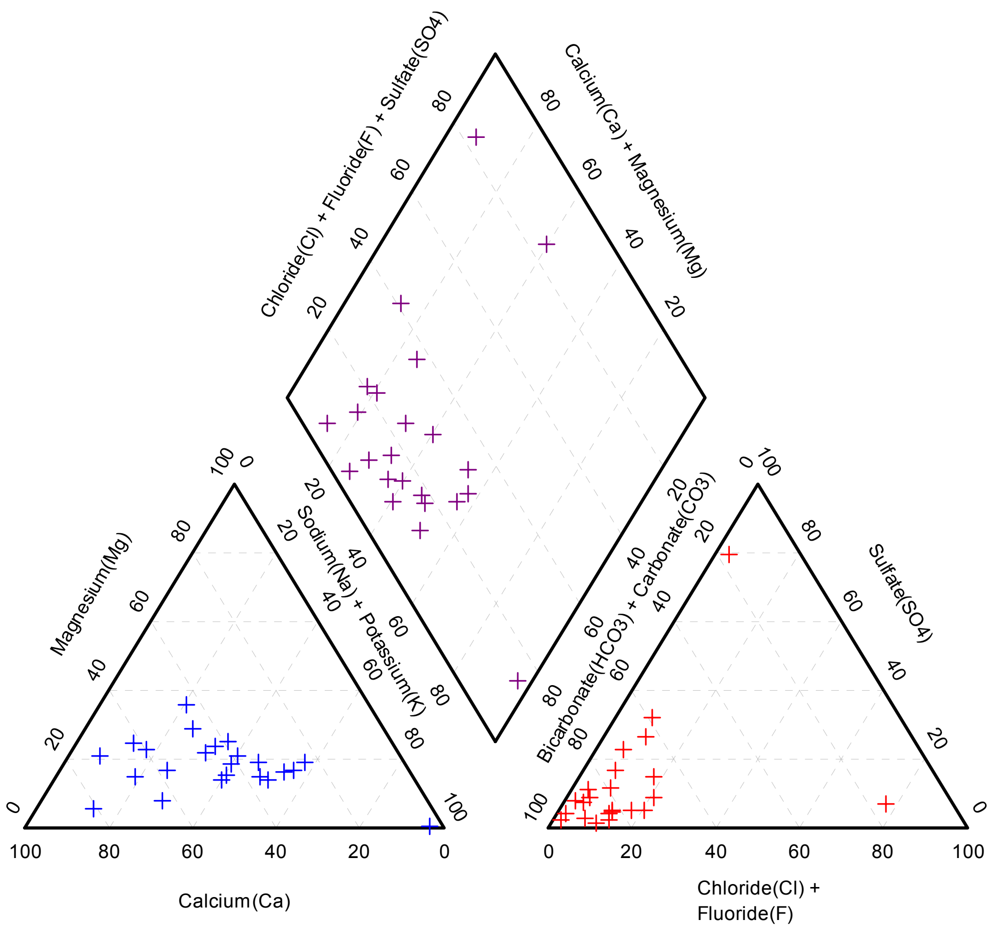


Figure 22. Piper diagram illustrating the relative distributions of major ions of groundwater samples collected from 23 different wells within the layered granulite unit.

LATE PROTEROZOIC AND EARLY ORDOVICIAN ROCKS

Late Proterozoic and early Ordovician rocks within the Blue Ridge Geologic Province consist of variably metamorphosed volcanic and clastic sequences that are stratigraphically above, and along strike with the basement rocks in the core of the Anticlinorium (Rankin, 1975; Southworth et al., 2009b; Wehr and Glover, 1985). In the northern portion of the Blue Ridge Geologic Province, the late Proterozoic/early Ordovician sequences flank the Basement Rocks on the eastern and western sides, forming the flanks of the Blue Ridge anticlinorium (Bartholomew et al., 1991; Southworth et al., 2009b). South of Roanoke, these rocks cover much of the basement sequence, accounting for the majority of mappable rock in the southern portion of Blue Ridge Geologic Province in Virginia (Bartholomew et al., 1994; Rankin et al., 1973) (figure 23). Table 11 lists the map units from the 1993 geologic map of Virginia (Virginia Division of Mineral Resources, 1993) comprising the late Proterozoic/early Ordovician rock types described in this report.

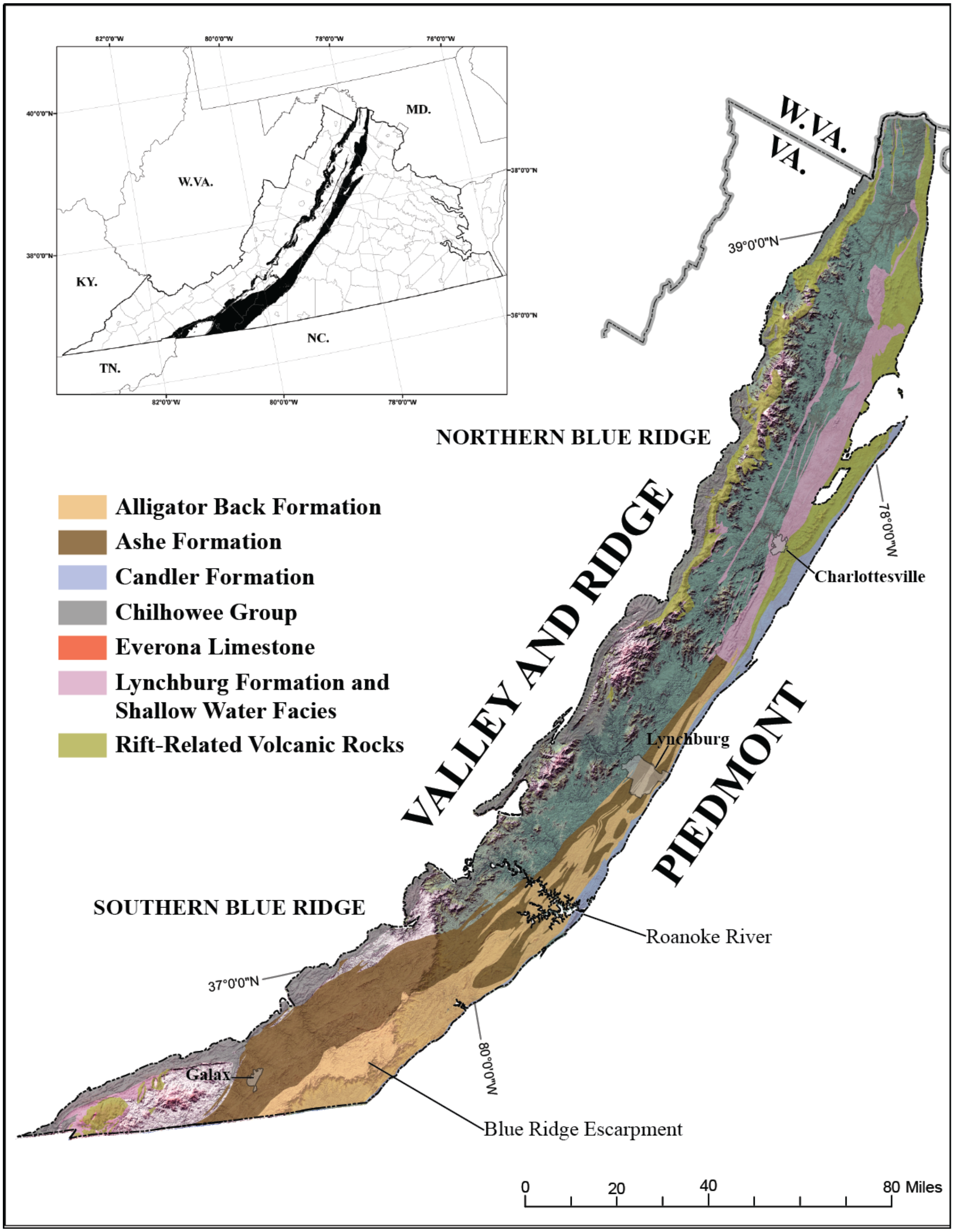


Figure 23. Extent and distribution of late Proterozoic to early Ordovician "Cover" Formations and Textural/Lithologic Classes of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map).

Table 11. Map units described in the 1993 Geologic Map of Virginia (Virginia Division of Mineral Resources, 1993) grouped by major rock type.

Ashe Metamorphic Suite:

Map Unit Symbol and Map Unit Name

Zaa; Ashe Formation - amphibolite

Zam; Ashe Formation - biotite gneiss

Zas; Ashe Formation - mica schist or phyllite

Zmg; Ashe Formation - Moneta Gneiss

[Zmd; metagabbro

[Zmi; mafic igneous complex

[Zum; ultramafic rocks

Alligator Back Formation:

Map Unit Symbol and Map Unit Name

Zac; Alligator Back Formation - banded marble

[Zas; Alligator Back Formation - actinolite schist

[Zmi; mafic igneous complex

[Zmy; Alligator Back Formation - feldspathic metagraywacke

[Zum; ultramafic rocks

Candler Formation:

Map Unit Symbol and Map Unit Name

[ca; Candler Formation - phyllite and schist

[cas; Candler Formation - laminated metasiltstone

Chilhowee Group:

Map Unit Symbol and Map Unit Name

ch; Chilhowee Group

[eh; Erwin and Hampton Formations

[t; Tomstown Dolomite

[u; Unicoi Formation

Lynchburg Formation and late Proterozoic shallow water facies

Map Unit Symbol and Map Unit Name:

[Zmd; metagabbro

[Zmi; mafic igneous complex

[Zum; ultramafic rocks

Zch; Lynchburg Group - Charlottesville Formation

Zfa; Fauquier Formation - arkosic metasandstone

Zfc; Fauquier Formation - metaconglomerate

Zfl; Fauquier Formation - laminated metasilstone and phyllite

Zfs; Fauquier Formation - meta-arkose and metasiltstone

Zkr; Konnarock Formation

Zlc; Lynchburg Group - conglomerate and metagraywacke

Zlf; Lynchburg Group - fanglomerate

Zlg; Lynchburg Group - graphitic phyllite and metasiltstone

Zlm; Lynchburg Group - metagraywacke

Zlq; Lynchburg Group - quartzite

Zm; marble

Zml; Mount Rogers Formation - graywacke conglomerate, graywacke, tuffaceous sandstone, laminated siltstone, shale and minor greenstone and rhyolite

Zmm; Lynchburg Group - Monumental Mills Formation

Zsr; Swift Run Formation

rift related metavolcanic rocks:

Map Unit Symbol and Map Unit Name:

[Zc; Catoctin Formation - metabasalt

[Zcb; Catoctin Formation - hyaloclastite pillow breccia

[Zcr; Catoctin Formation - metarhyolite

[Zcs; Catoctin Formation - metasedimentary rocks

[Zhb; Catoctin Formation - metabasalt breccia, high titanium

[Zlb; Catoctin Formation - metabasalt breccia, low titanium

[Zum; ultramafic rocks

Zgs; Mount Rogers Formation - greenstone and interbedded metasedimentary rocks

Zmf; Mount Rogers Formation - porphyritic felsite

Zmp; Mount Rogers Formation - porphyritic rhyolite

Zmr; Mount Rogers Formation - phenocryst-poor rhyolite

Despite the age and metamorphic history of these rocks, much of the stratigraphy of the late Proterozoic/early Ordovician rocks of the Blue Ridge Geologic Province is well preserved, and formation designations within this group of rocks are based largely on stratigraphic markers and textural characteristics that are convenient for use at the scale of this report. Consequently, divisions within these rocks for the purpose of hydrogeologic analysis was done at the formation scale, and resulted in the creation of seven different classes segregated largely by gross textural differences thought to influence the occurrence and movement of groundwater. When possible, correlated formations were combined. Formations with little well construction or geochemical information were combined with larger, texturally similar formations. The seven classes and associated formations are as follows: (1)Lynchburg Formation and late Proterozoic shallow water facies (Lynchburg Fm., Charlottesville Fm., Mechum River Fm., Fauquier Fm., Swift Run Fm., Monumental Mills Fm., Konnarock Fm.); (2) Ashe Metamorphic Suite; (3) Alligator Back Formation; (4) late Proterozoic rift-related volcanic rocks (Catoctin Fm., rhyolites of the Mount Rogers Fm.); (5) Chilhowee Group (Weverton Fm., Harpers Fm., Antietam Fm., Erwin Fm., Hampton Fm., Unicoi Fm.); (6) Candler Formation and (7) Everona Limestone

Lynchburg Formation and late Proterozoic shallow water facies

Figure 24 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the Lynchburg Formation and late Proterozoic shallow water facies hydrogeologic group. Figures 25 and 26 provide photographs of selected rock types within the Lynchburg Formation and late Proterozoic shallow water facies hydrogeologic group.

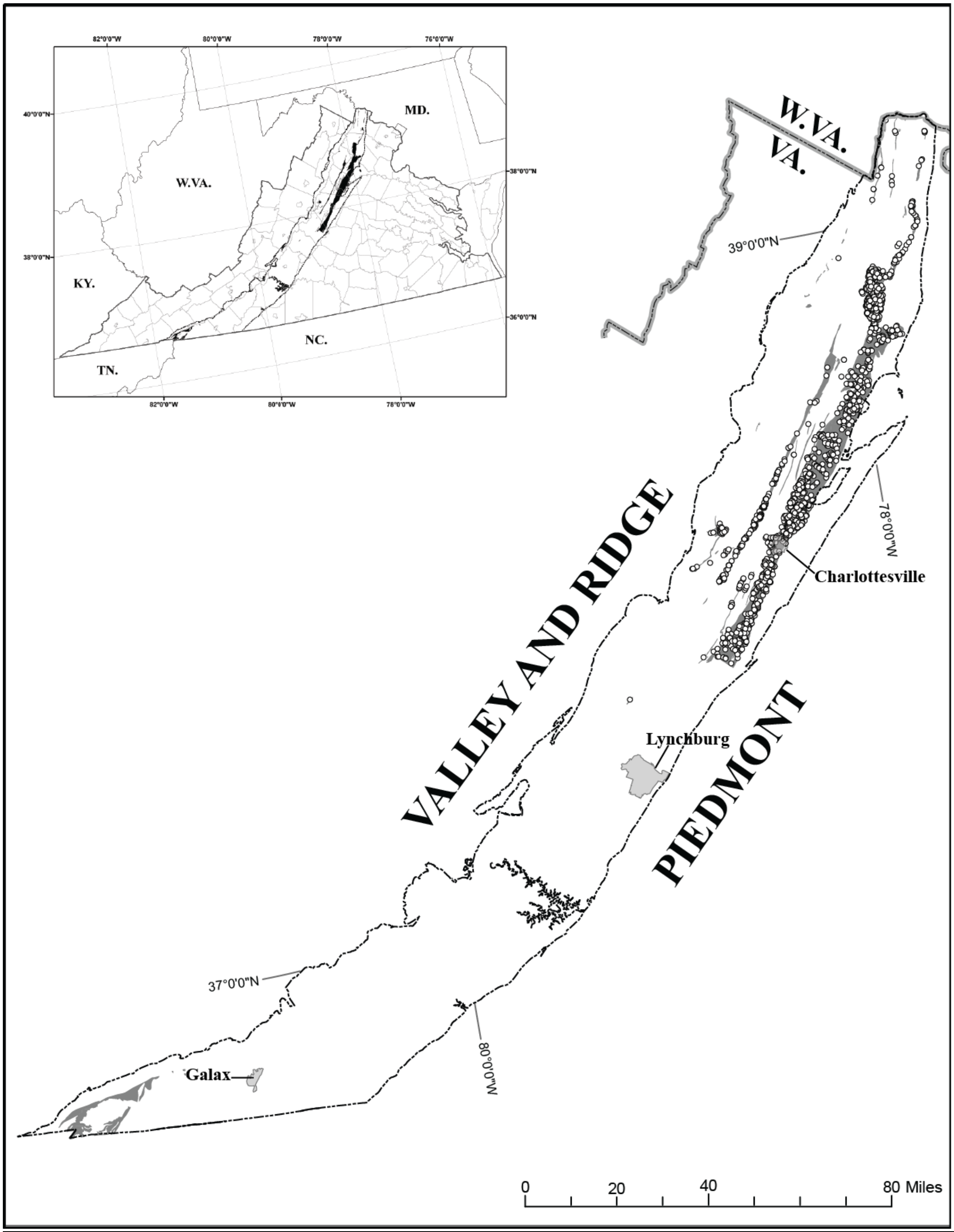


Figure 24. Extent and distribution of the Lynchburg Formation and late Proterozoic shallow water facies unit of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions. Wells in the Konnarock and Mount Rogers Formations (units in the southwestern portion of the Blue Ridge Belt) were not used in the statistical analyses but are cataloged in the data set used in this report (Appendixes 3 and 4).

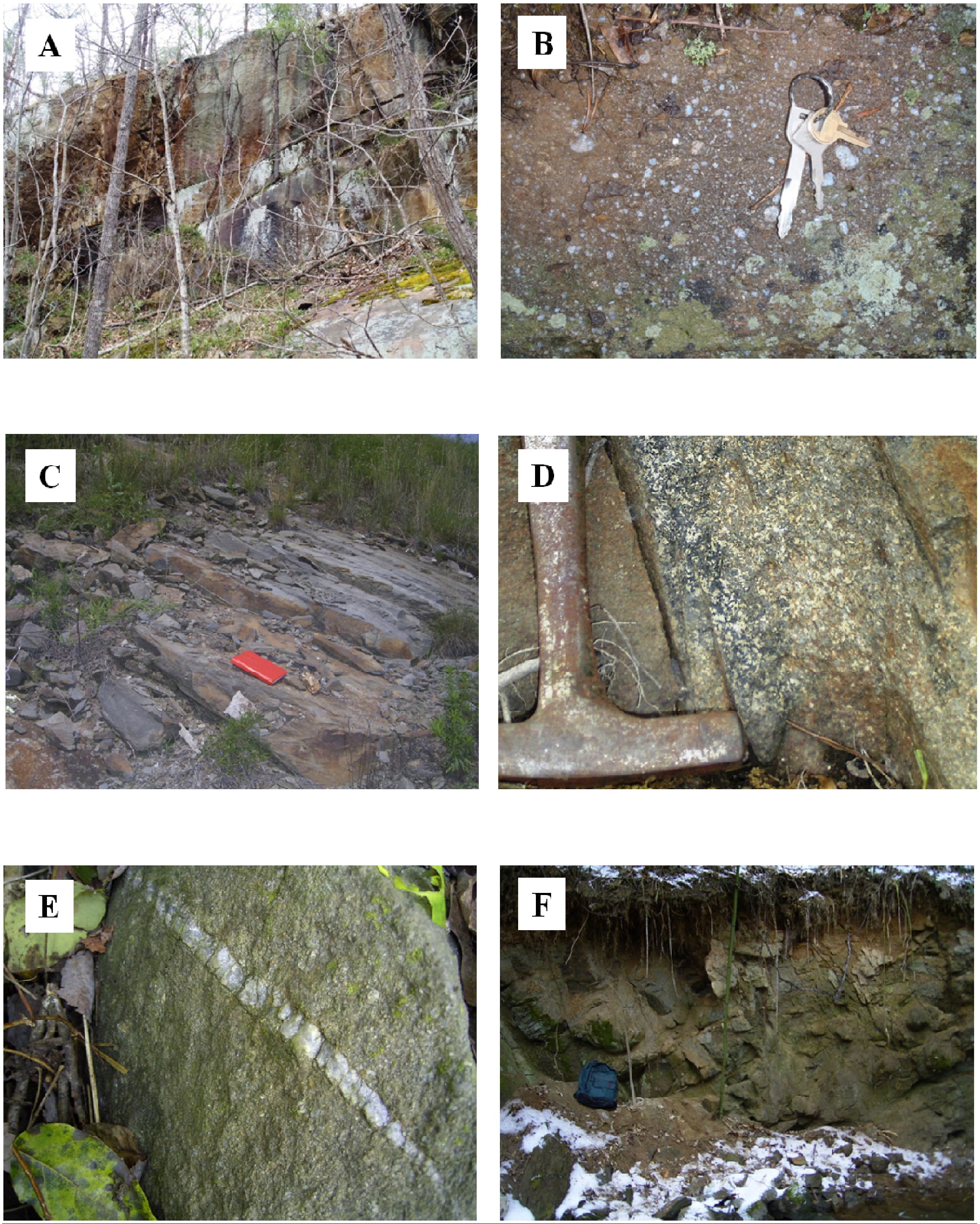


Figure 25. Photographs of Lynchburg Formation and late Proterozoic shallow water facies rocks of the Blue Ridge Cover Sequence. A) Jointing in conglomeratic metagraywacke near Schuyler, Virginia; B) Conglomeratic metagraywacke near Schuyler, Virginia; C) Cleavage in fine grained meta-arenite of Lynchburg Formation; D) Amphibolite dike south of Charlottesville, Virginia ; E) Metagraywacke cross cut by quartz vein near Charlottesville, Virginia; F) Saprolitic outcrop of metagraywacke near Charlottesville, Virginia.

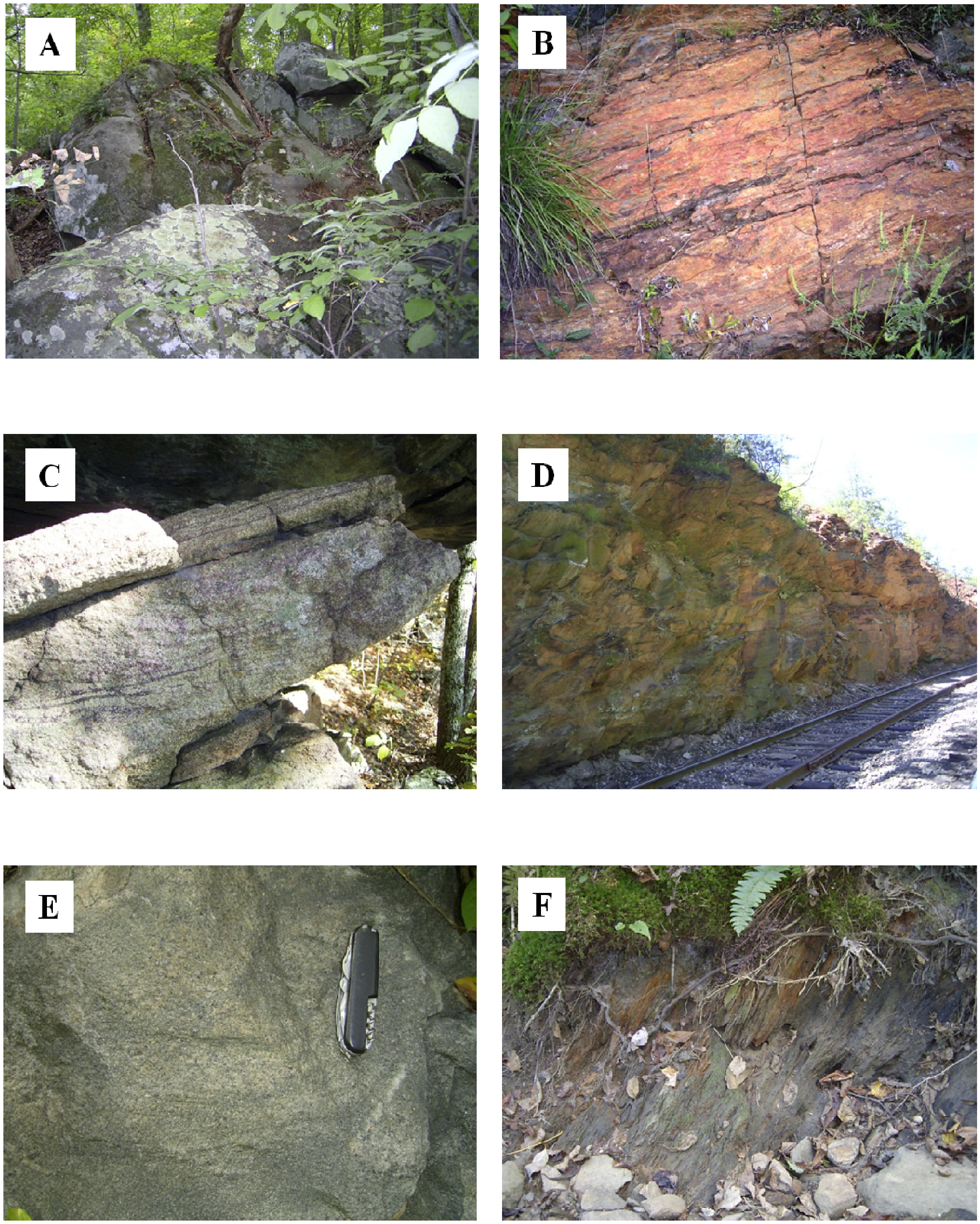


Figure 26. Photographs of Lynchburg Formation and late Proterozoic shallow water facies rocks of the Blue Ridge Cover Sequence. A) Metagraywacke outcrop of Lynchburg Formation near Leon, Virginia; B) Phyllitic interval in metagraywacke of Lynchburg Formation near Leon, Virginia; C) Cross-bedded arkosic metasandstone of Swift Run Formation near Skyline Drive in the central portion of Shenandoah National Park; D) Interbedded metasandstones and schists of Swift Run Formation near Afton, Virginia; E) Metagraywacke of Fauquier Formation near Scrabble, Virginia; F) Metamorphosed siltstone of the Ball Mountain (Lynchburg) Formation in a creek bed near South Wales Well 6, near Jeffersonton, Virginia.

Geologic Description and Hydrogeologic Characteristics

Rocks of the Lynchburg Formation unconformably overly the Blue Ridge Basement Complex and are in stratigraphic contact with the overlying Catoctin Formation along the eastern flank of the Blue Ridge Anticlinorium – where the Catoctin is absent, the Lynchburg Formation is in fault contact with the overlying Candler Formation (Bartholomew et al., 1991; Conley, 1978). Rocks of the Lynchburg Formation have been interpreted as late Proterozoic rift-related slope shelf sequences that were deposited along an ancient continental margin during Iapetian rifting (Wang and Glover, 1994; Wehr and Glover, 1985). At least 11 different formational names have been used at different times by multiple geologists to describe the stratigraphy of the Lynchburg Formation.

Rocks of the Lynchburg Formation have been lithified and strongly metamorphosed but primary features are frequently preserved. The overall stratigraphy of the Lynchburg Formation has been described as gradational from west to east (Wang and Glover, 1994) progressing from heterogeneous packages of coarser grained rocks (conglomerate and meta-arenite), eastward through finer grained sequences (interbedded meta-arenite, quartzite, and graphitic schist), into very fine grained sequences (interbedded fine grained arenite and mica schist). Mafic-ultramafic igneous dikes and schists exist in primarily conformable (along strike) relationships throughout the Lynchburg Formation (Wang and Glover, 1994). Post-depositional folding and faulting during Taconic, Acadian and Alleghanian orogenesis and the subsequent weathering of original depositional structures has left a present day erosional surface consisting of only portions of the original depositional sequence, expressed as a variably folded and faulted assemblage of crystalline metasedimentary rock.

Late Proterozoic shallow water facies rocks include the Swift Run Formation, Mechum River Formation, Fauquier Formation, and upper Mount Rogers Formation (Konnarock Formation). These formations contain rock types similar in texture and mineralogy to the Lynchburg Formation, but the environment of deposition appears to be chiefly terrestrial (alluvial and glaciogenic) with some evidence of shallow marine or lacustrine deposition in almost all formations (Wehr and Glover, 1985). Predominant lithologies for the formations in the shallow water facies are variable and include conglomerate, sandstone, tillite and a variety of fine grained rocks including argillite, mudstone, siltstone, slate, phyllite, schist, and marble. As with the rocks of the Lynchburg Formation, folding and faulting within this group of rocks is variable, and abrupt changes in lithology on a local scale are common.

Fracturing in the rocks of the Lynchburg Formation and late Proterozoic shallow water facies rocks is dependent on lithology, metamorphic grade, and local structural deformation. Finer grained lithologies often part along schistosity and bedding and are variably jointed, while coarser grained lithologies tend to form more massive structures with less frequent, but more open and extensive joints. Fracture sets in poorly sorted, coarser grained arenites and conglomerates with poorly defined bedding and schistosity exhibit uniform orientations at the local (outcrop) level but regionally, fractures in these rock types are not uniformly oriented. Schistosity is more pervasive in the finer grained and micaceous lithologies and has a dominant NE/SW strike and prevalent dip to the SE.

Table 12 displays summary statistics for the geologic and hydrogeologic characteristics of wells completed in the Lynchburg Formation and late Proterozoic shallow water facies group.

Reported estimated well yield data were compiled for 2027 wells completed in the Lynchburg Formation. Estimated yields were 20 gal/min or greater for 26%, 50 gal/min or greater for 7%, and 100 gal/min or greater for 2% of the total well population. Reported well yield information for 161 municipal, commercial, and light industrial wells completed in the Lynchburg Formation and late Proterozoic shallow water facies were also compiled. Estimated yield values for these wells were reported at 20 gal/min or greater for 48%, 50 gal/min or greater for 22%, and 100 gallons/minute or more for 9% of the non-domestic well population.

Reported water bearing zone depths were compiled for 59 wells drilled to 400 feet or more in the Lynchburg Formation and late Proterozoic shallow water facies. At least one water bearing zone was reported by the driller to occur at depths of 400 feet or greater for 46% (27) of these wells. Within this subset of wells, 31% (66) of the total number of water bearing zones (216 reported zones) occurred below 400 feet. Most of the wells in this depth interval produced less than 10 gallons/minute. The deepest reported water bearing zones for this unit occur in the Morton Frozen Foods Well #5 (DEQ Well #101-00674) which was drilled in a paragneiss underlying the Swift Run Formation to a depth of 1,100 feet. The well encountered water bearing zones at 1,040 and 1,071 feet below land surface, and reportedly yielded 80 gal/min at the time of drilling.

The highest yielding well on record in the Lynchburg Formation and late Proterozoic shallow water facies rocks was drilled for the South Wales Subdivision approximately 2 miles northwest of Jeffersonton in Culpeper County, Virginia. The well (South Wales Well #6; DEQ Well Number 123-00343) was drilled in fine-grained arenites and schists of the Lynchburg Formation, and is located near the mapped contact between the Ball Mountain and Monumental Mills Formations described by Wehr (Wehr, 1985). The well may have been drilled through a thrust fault contact between the two formations. The drillers log for this well reports water zones at 122 to 140 feet (60-70 gal/min), 195 to 215 feet (60 gal/min) and from 226 to 230 feet (145-155 gal/min). The depth of the main water bearing zone for this well is coincident with a change in rock color from gray/blue to green, and is consistent with Wehr's stratigraphic and structural descriptions of the detrital blue quartz wacke of the overlying Ball Mountain Formation and the dark gray to green upper siltstone member of the underlying Monumental Mills formations (Wehr, 1985). A long-term pumping test was conducted at a rate of 275 gal/min for 48 hours on March 1-3, 1988 and resulted in a total drawdown of nearly 122 feet. Four other wells were drilled within 2 miles of well 123-00343 that have estimated yields exceeding 100 gallons/minute.

Table 12. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Lynchburg Formation and late Proterozoic shallow water facies.

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

	Mean	**Median**	**Maximum**	**Minimum**	**Number of Observations**
Estimated Yield, All Wells (Gal/Min)	15.6	10	275	0.25	2027
Estimated Yield, Non-Residential Wells (Gal/Min)	29.5	15	275	1	161
Pumped Yield (Gal/Min)[a]	54.3	30	275	1	20
Specific Capacity (Gal/Min/Ft Drawdown)[b]	0.56	0.245	3.7	0.06	20
Well Depth (Ft)	259	245	1100	13	2075
Depth to Bedrock (Ft)	36.1	30	215	1	782
Depth to First Water-Bearing Fracture (Ft)	158	131	1040	19	587
Depth to Lowest Water-Bearing Fracture (Ft)	229	205	1070	20	587
Water Level (Ft BLS.)	39.9	30	390	-2	316

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Groundwater samples taken from wells and springs in the Lynchburg Formation and late Proterozoic shallow water facies rocks of the Blue Ridge Cover Rock Sequence indicate that the natural groundwater chemistry is predominately of the calcium-magnesium-bicarbonate type or of the sodium-magnesium-bicarbonate type. Groundwater within these rocks is typically soft, and slightly acidic. Table 13 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of selected secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in these units.

Figure 27 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 25 different wells within the Lynchburg Formation and late Proterozoic shallow water facies unit. Major cations usually range between 50-80% calcium+magnesium and 20-50% sodium+potassium. Typical ranges for major anions are 5-30% chloride+fluoride+sulfate and 70-95% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate.

Table 13. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the Lynchburg Formation and late Proterozoic shallow water facies.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	**Mean**	**Median**	**Maximum**	**Minimum**	**Number of Observations**
Physical Properties					
pH (standard units)	6.33	6.35	8.50	4.49	121
Temperature (˚C)	14.4	14.4	15.0	13.3	42
Temperature (˚F)	57.9	58.0	59.0	56.0	42
Specific conductance (µS/cm at 25˚C)	86.9	65.8	378	1.00	104
Filtered residue (mg/L)	90.9	80.0	288	29.0	49
Hardness (mg/L as $CaCO_3$)	54.3	38.0	480	0.60	54
Major Cations					
Calcium (mg/L)	11.8	7.00	59.0	1.00	58
Magnesium (mg/L)	2.41	1.70	12.0	0.06	92
Sodium (mg/L)	6.04	4.10	38.0	0.88	105
Potassium (mg/L)	2.24	1.80	6.10	0.10	57
Major Anions					
Bicarbonate (mg/L as HCO_3)	40.6	29.3	247.5	1.20	115
Sulfate (mg/L)	3.97	3.00	13.5	0.50	59
Chloride (mg/L)	6.03	4.00	54.0	1.00	110
Nutrients					
Nitrate (mg/L as N)	1.39	0.29	20.0	0.03	53
Ammonium (mg/L as N)	0.11	0.10	1.00	0.04	58
Phosphate (mg/L as P)	0.04	0.03	0.13	0.01	51
Secondary Constituents					
Silica (mg/L)	25.4	23.3	31.5	21.6	3
Aluminum (ug/L)	27.9	19.0	170	6.00	53
Iron (µg/L)	796	100	7,200	10.0	58
Manganese (µg/L)	45.2	14.0	810	0.02	100
Arsenic, total (µg/L)	1.85	1.00	10.0	1.00	14
Bromide (mg/L)	0.06	0.04	0.8	<0.01	39
Fluoride (mg/L)	0.11	0.07	0.95	0.01	61
Radiochemical Constituents					
Uranium (µg/L)	0.03	0.02	0.22	<0.01	49

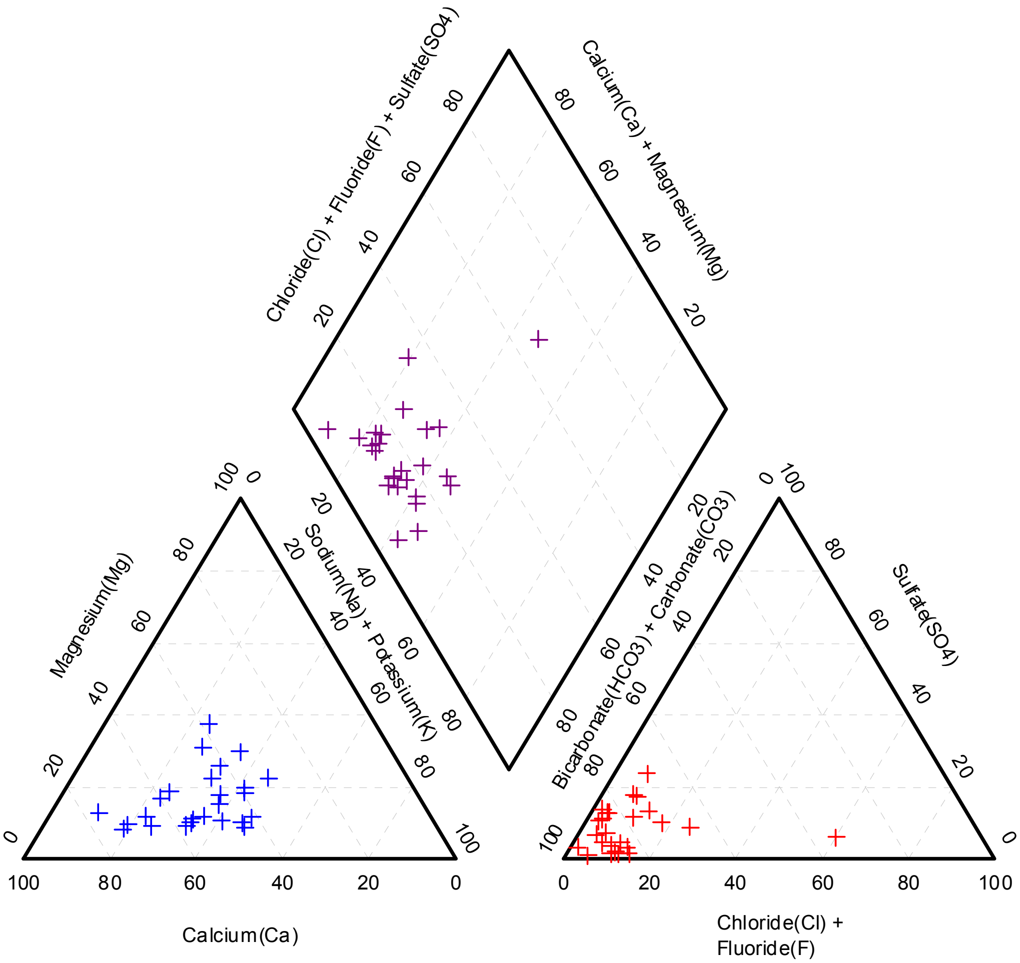


Figure 27. Piper diagram illustrating the relative distributions of major ions of groundwater samples collected from 25 different wells within the Lynchburg Formation and late Proterozoic shallow water facies unit.

Ashe Metamorphic Suite

Geologic Description and Hydrogeologic Characteristics

Figure 30 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the Ashe Metamorphic Suite. Figure 31 provides photographs of selected rock types within the Ashe Metamorphic Suite.

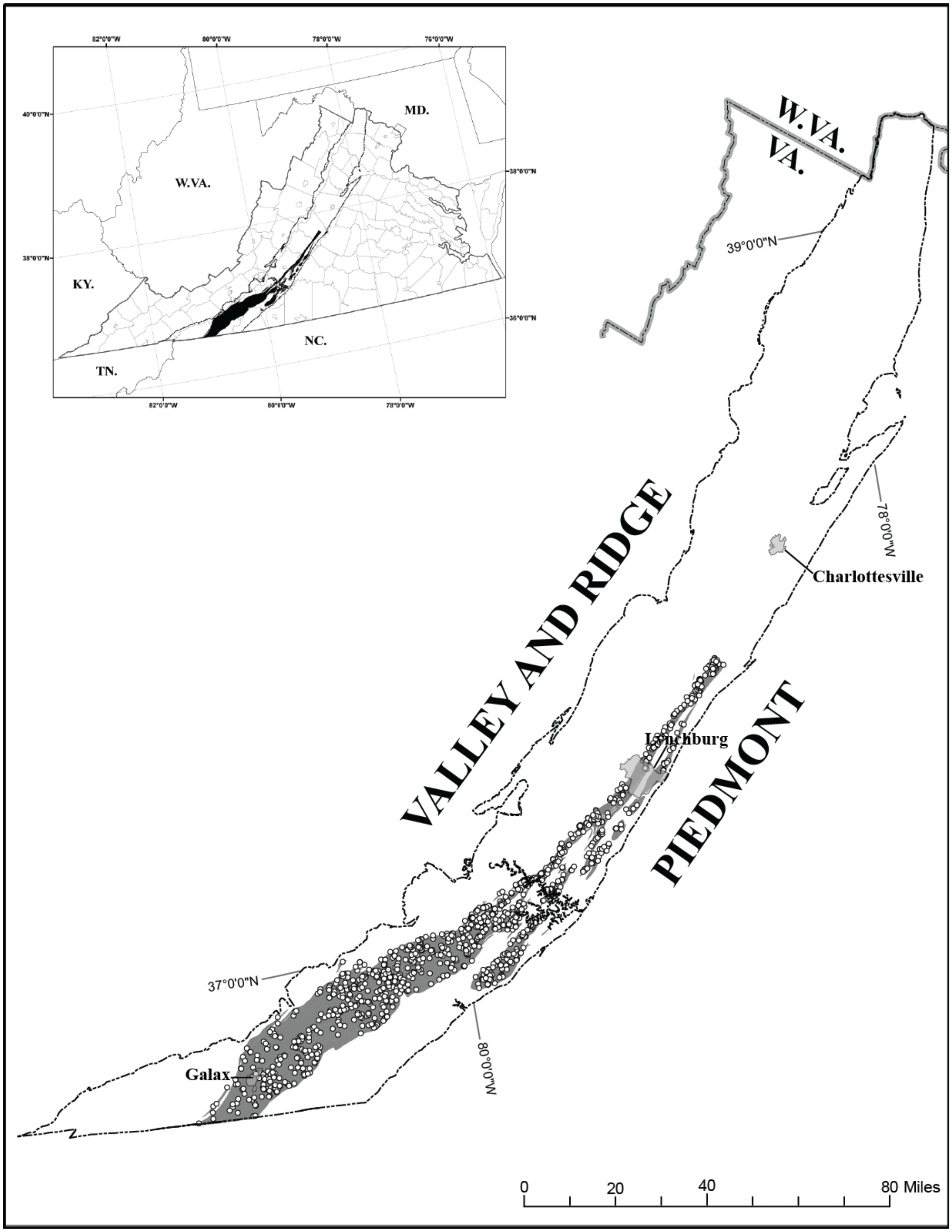


Figure 28. Extent and distribution of the Ashe Metamorphic Suite of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

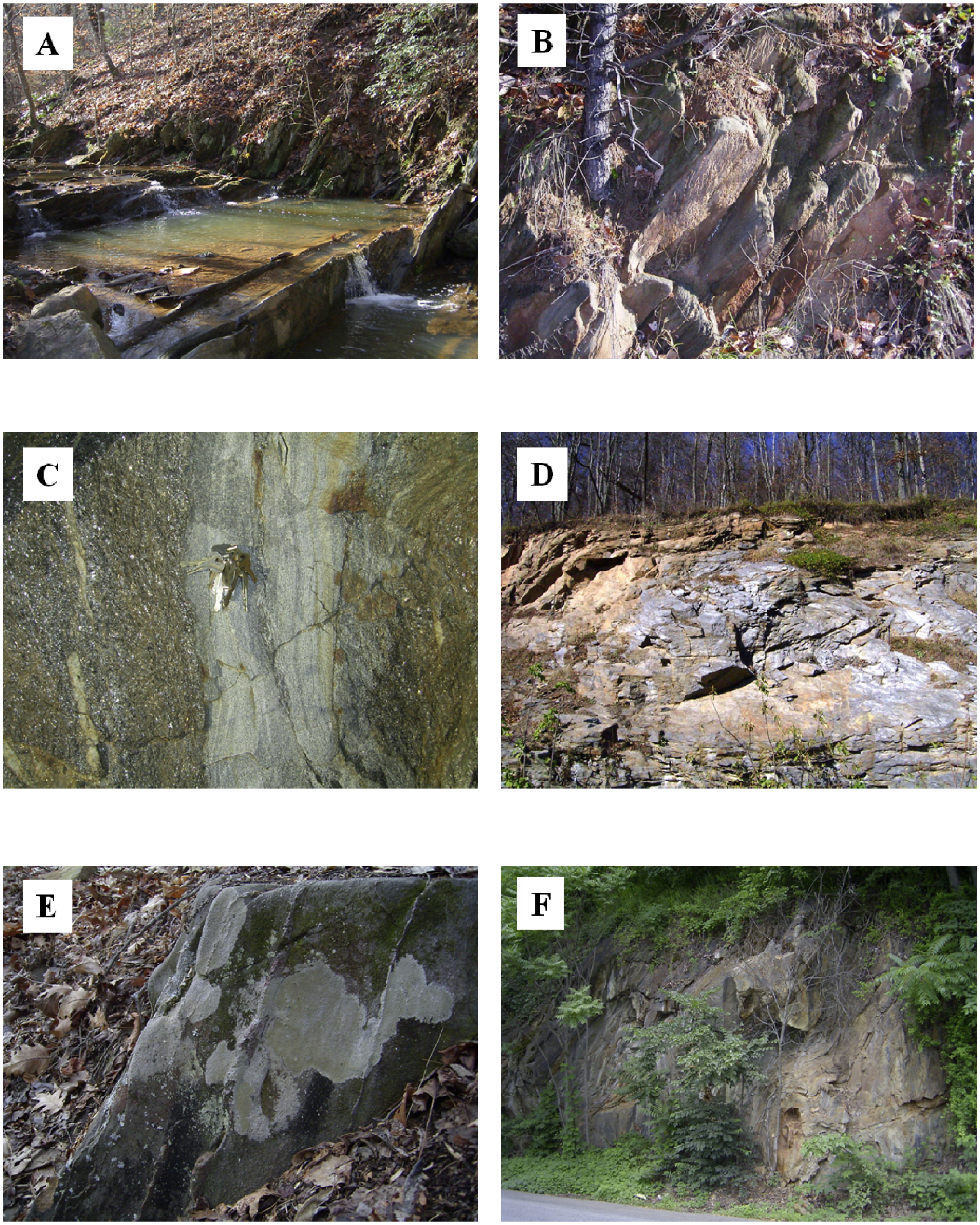


Figure 29. Photographs of rocks within the Ashe Metamorphic Suite – Blue Ridge Cover Sequence. A) Thinly bedded biotite-muscovite gneiss and schist in a tributary of the Blackwater River near Gogginsville, Virginia; B) Interbedded biotite-muscovite gneiss and schist in saprolitic outcrop near Rocky Mount, Virginia (note preferential weathering of less competent schistose beds); C) Fresh exposure of interbedded biotite-muscovite gneiss and schist in a road cut on Fivemile Mountain, Franklin County, Virginia; D) Interbedded biotite-muscovite gneiss and schist in a road cut on Fivemile Mountain, Franklin County, Virginia. Dip of predominate schistosity to SE; E) Metagraywacke beds near Sweet Briar Station, Amherst County, VA; F) Folded and interlayered graphitic schist and metagraywacke in an escarpment on the north side of the James River near Lynchburg, Virginia (type locality for the Lynchburg Formation named by Jonas and Stose in 1927).

Rocks of the Ashe Metamorphic Suite (AMS) consist of variably metamorphosed and interlayered sequences of muscovite-botite and quartzo-feldspathic gneiss (metagraywacke), mica schist, marble, amphibolite, and other ultra-mafic bodies that nonconformably overlie the Blue Ridge Basement along the eastern flank of the southern Blue Ridge Geologic Province (Hatcher and Goldberg, 1991; Rankin, 1970; Rankin et al., 1973). Although there is considerable variation among the lithologies of the Ashe Metamorphic Suite, the bulk of the AMS consists of a predominately fine grained, layered biotite-muscovite gneiss (metagraywacke) interlayered with varying amounts of mica schist, phyllite, and amphibolite, with metagraywacke beds ranging in thickness from inches to feet (Espenshade et al., 1975). The higher grade metamorphic rocks of the Ashe Metamorphic Suite are on strike with the coarse grained metasedimentary rocks and ultramafic packages of the stratigraphically equivalent lower Lynchburg Formation (Virginia Division of Mineral Resources, 1993). Outliers of the Ashe Metamorphic Suite have been mapped to the southeast of the main body as exposed cores of regional anticlines (most notably the Cooper Creek Anticline) flanked by the stratigraphically higher rocks of the Alligator Back Formation (Conley, 1989; Henika, 1997; McCollum, 1989). The northern contact between the Ashe Metamorphic Suite and the rocks of the lower Lynchburg Formation is intergradational. The State Map used for this study places the contact between the AMS and the structurally simpler conglomerates and coarse metasedimentary beds of the Lynchburg Formation in Nelson County, Virginia approximately 3.5 miles east of the town of Lovingston (Virginia Division of Mineral Resources, 1993).

Rocks of the Ashe Metamorphic Suite are thought to have originated as rift-related marine sedimentary and volcanogenic sequences that were metamorphosed into massive, to thinly bedded muscovite-biotite schist and gneiss (metagraywacke) and variably metamorphosed, lenticular ultra-mafic bodies that are on strike with regional foliation (Bartholomew et al., 1994; Hatcher and Goldberg, 1991; Rankin, 1975). Unlike the stratigraphically equivalent rocks of the Lynchburg Formation, primary depositional features within the Ashe Metamorphic Suite are often poorly preserved due to deformation and higher grade metamorphism (Abbott and Raymond, 1984; Bartholomew et al., 1994; Rankin, 1970).

Fracturing in the rocks of the Ashe Metamorphic Suite can occur along bedding planes (where present), parallel and sub-parallel to foliation (especially in rocks with aligned micas in the foliation planes), normal to foliation, along lithologic contacts, and can be concentrated in zones of deformation (axial cleavage, fault related fracturing). Regionally, rocks of the AMS have a fairly pervasive southeast dipping schistosity (Rankin et al., 1973). Differential weathering within the less competent (schistose) interbeds in the near-surface environment can enhance recharge and groundwater storage and circulation.

Table 14 presents summary statistics for selected geologic and hydrogeologic parameters for wells completed in the Ashe Metamorphic Suite of the Blue Ridge Cover Sequence.

Reported well yield data were compiled for 1,261 wells completed in the Ashe Metamorphic Suite. Estimated yields were 20 gal/min or more for 26%, 50 gal/min or more for 7%, and 100 gal/min or more for 1% of the total well population. Reported well yield estimates were available for 113 municipal, commercial, and light industrial wells completed in the Ashe Metamorphic Suite. Estimated yield values were 20 gal/min or more for 47%, 50 gal/min or more for 24%, and 100 gal/min or more for 5% of the non-domestic well population.

Reported water bearing zone data were available for only 9 wells having total depths of 400 feet or more in the Ashe Metamorphic Suite. The deepest reported fracture in this sub-set was 310 feet below land surface. The deepest reported fracture from the entire data set (all wells drilled in the Ashe Metamorphic Suite with reported fracture depth information) regardless of drilling depth was 350 feet below land surface.

The highest yielding well on record completed in the Ashe Metamorphic Suite within Virginia is located approximately 2,000 feet north of the intersection of Rt. 40 and Rt. 864 in Ferrum, Virginia. The well (Ferrum College Well #5, DEQ Well #133-00637) was drilled in 1967 to a depth of 330 feet below land surface and water bearing zones were encountered at 100 to 110 feet below land surface, 235 to 240 feet below land surface, and 293 to 300 feet below land surface. No pumping test data were available for Well #5, but the drilling record indicates that upon completion the well was air lifted for 12 hours at a rate of 425 gallons/minute. This well is one of four wells drilled to supply water for Ferrum College, each one of which initially yielded well over 100 gallons per minute. Currently, Well #5 is set at a consistent pumping rate of 230 gallons per minute, Well#1, DEQ Well#133-00635 (initially 156 gallons/minute after 50 hours of air lifting) is set at a consistent pumping rate of 80-85 gallons/minute, Well #4 (DEQ Well#133-00636, initially yielded 151 gallons/minute after 12 hours of air lifting) is set at a consistent pumping rate of 80-85 gallons per minute, and Well#6 (DEQ Well#133-00412, initially yielded 300 gallons/minute after 1 hour of air lifting) was taken off line in 2001 due to major production losses. Some time prior to being taken off line, Well #6 had been pumping consistently at approximately 160 gallons per minute. All wells in this system were drilled within 1,000 feet of each other and the degree of communication between these wells is currently unknown (personal communication with plant manager), so the loss in production from well #6 may be related to well interference.

Both the proximity of these wells to the mapped contact with the stratigraphically higher Alligator Back Formation, and the presence of amphibolite in the cuttings for two of these wells (noted on geologist's logs for Well #4 and Well #5) suggests that these wells may be drilled in a fairly persistent layer of amphibolite gneiss used as a formational break by geologists to separate the Ashe Metamorphic Suite from the overlying Alligator Back Formation (Bartholomew et al., 1994). The geologists log for Well 4 noted that many of the cuttings from the borehole showed evidence of intense fracturing and faulting, and supports field observations by other geologists regarding shearing within the amphibole rich sequence separating the Ashe Metamorphic Suite and the Alligator Back Formation (Conley, 1987). The degree to which favorable topographic setting, shear related fracturing, and contrasting lithologies play a role in the existence of high yielding wells in the Ferrum area is currently unknown.

Table 14. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Ashe Metamorphic Suite.

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

	Mean	Median	Maximum	Minimum	Number of Observations
Estimated Yield, All Wells (Gal/Min)	15	8	425	1	1,261
Estimated Yield, Non-Residential Wells (Gal/Min)	37.3	20	425	1	113
Pumped Yield (Gal/Min)[a]	46	26	160	6	17
Specific Capacity (Gal/Min/Ft Drawdown)[b]	1	0.63	3.16	0.04	20
Well Depth (Ft)	293	300	1,200	42	1,282
Depth to Bedrock (Ft)	60.4	57	145	1	91
Depth to First Water-Bearing Fracture (Ft)	132	111	335	10	70
Depth to Lowest Water-Bearing Fracture (Ft)	167	162	335	35	70
Water Level (Ft BLS.)	40.0	40	80	1	263

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Groundwater samples taken from wells and springs in the Ashe Metamorphic Suite of the Blue Ridge Cover Rock Sequence indicate that the natural groundwater chemistry is predominately of the calcium-magnesium-bicarbonate type or of the sodium-magnesium-bicarbonate type. Groundwater within these rocks is typically soft, and slightly acidic. Several of the groundwater samples taken within the Ashe Metamorphic Suite exhibit relatively high proportions of sulfate, which has been reported to originate from the oxidization and weathering of sulfide minerals (mainly pyrite) in some of the less competent schists within this unit (Stose and Stose, 1957). Sulfidic muscovite-biotite gneiss has also been reported to commonly occur within the Ashe Metamorpic Suite by several other workers mapping in this unit (Espenshade et al., 1975; Rankin et al., 1973). Although a number of groundwater samples within the data set contain higher percentages of sulfate, no samples in these data were above the sulfate Maximum Contaminant Level (MCL) of 250 mg/L. Table 15 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of selected secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in this unit.

Figure 30 is a piper diagram illustrating the relative concentrations and distributions of major ions within balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 38 different wells and springs within the Ashe Metamorphic Suite. Major cations usually range between 50-80% calcium+magnesium and 20-50% sodium+potassium. Typical ranges for major anions are 5-40% chloride+fluoride+sulfate and 60-95% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate. Although there were no groundwater samples from this data set with sulfate concentrations exceeding the EPA MCL of 250 ppm, several groundwater samples from wells and springs within the AMS data set indicate higher percent compositions of sulfate (20% – 35% of the total anionic composition).

Table 15. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the Ashe Metamorphic Suite.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.46	6.40	8.34	5.02	189
Temperature (˚C)	12.6	12.6	18.0	7.80	14.0
Temperature (˚F)	54.7	54.7	64.4	46.0	14.0
Specific conductance (µS/cm at 25˚C)	80.9	55.0	597	15.0	172
Filtered residue (mg/L)	83.7	70.0	331	13.0	64.0
Hardness (mg/L as $CaCO_3$)	41.6	29.0	244	0.25	68.0
Major Cations					
Calcium (mg/L)	12.0	8.40	50.1	1.00	79.0
Magnesium (mg/L)	2.57	1.60	17.0	0.10	158
Sodium (mg/L)	4.07	3.20	43.9	0.22	179
Potassium (mg/L)	2.42	1.50	18.0	0.11	79.0
Major Anions					
Bicarbonate (mg/L as HCO_3)	35.8	22.0	241	1.20	185
Sulfate (mg/L)	5.98	3.00	54.3	0.68	73.0
Chloride (mg/L)	5.45	3.80	130	0.60	180
Nutrients					
Nitrate (mg/L as N)	0.91	0.20	9.60	0.04	55
Ammonium (mg/L as N)	0.08	0.10	0.20	0.01	67
Phosphate (mg/L as P)	0.03	0.02	0.15	0.01	55
Secondary Constituents					
Silica (mg/L)	17.2	17.2	27.3	7.50	15
Aluminum (ug/L)	23.8	16.1	170	3.00	108
Iron (µg/L)	577	180	4,710	10.0	75
Manganese (µg/L)	40.0	20.0	328	1.00	156
Arsenic, total (µg/L)	1.76	1.00	10.0	1.00	17
Bromide (mg/L)	0.02	0.02	0.08	<0.01	71
Fluoride (mg/L)	0.08	0.07	0.48	<0.01	118
Radiochemical Constituents					
Uranium (µg/L)	0.06	0.02	2.16	<0.01	100

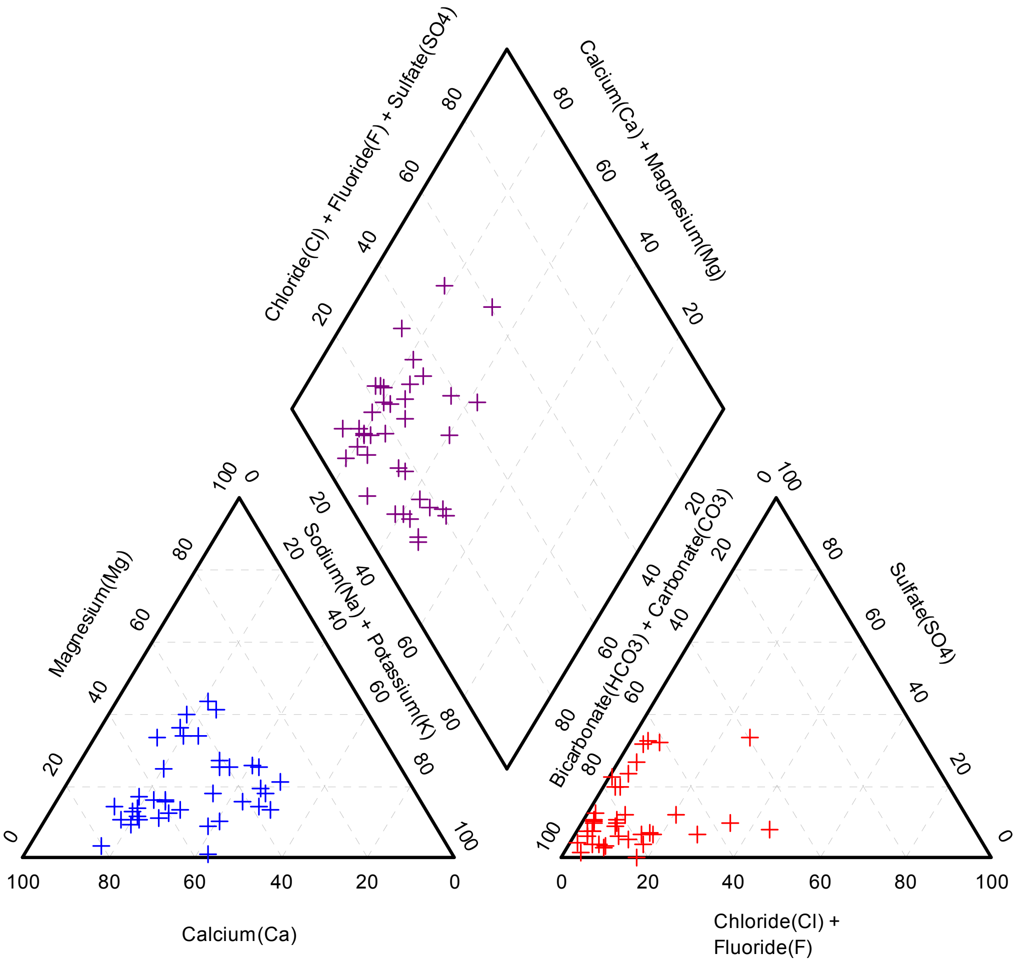


Figure 30. Piper diagram illustrating the relative distributions of major ions from groundwater samples collected from 38 different wells and springs within the Ashe Metamorphic Suite.

Alligator Back Formation

Figure 33 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the Alligator Back Formation. Figure 34 provides photographs of selected rock types within the Alligator Back Formation.

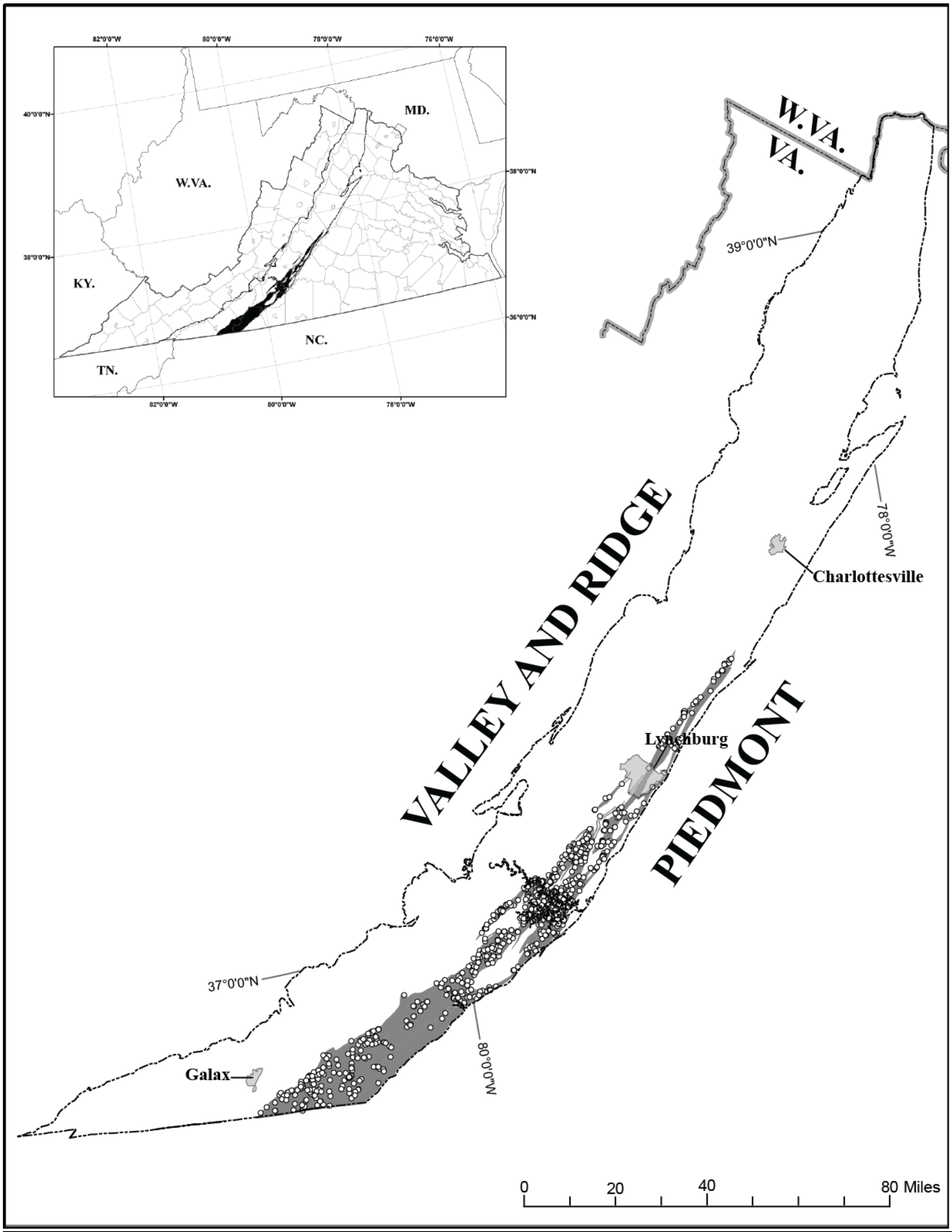


Figure 31. Extent and distribution of the Alligator Back Formation within the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

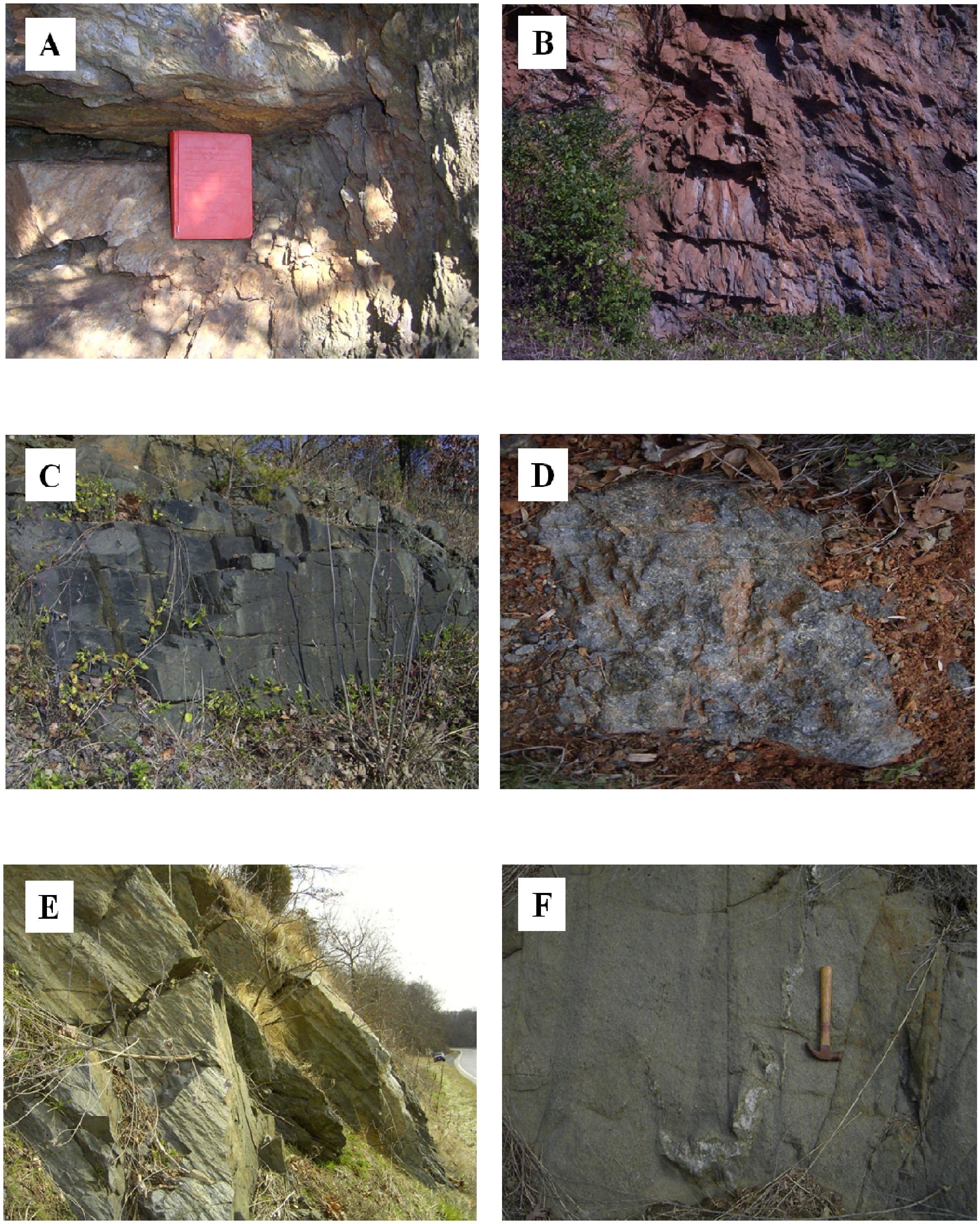


Figure 32. Photographs of rocks within the Alligator Back Formation – Blue Ridge Cover Sequence. A) Actinolite schist near Rocky Mount, Virginia; B) Actinolite Schist near Rocky Mount Virginia (outcrop); C) Amphibolite near Alligator Back/Ashe contact near Rocky Mount, Virginia ; D)Olivine Basalt near Coolwell, Virginia; E) Metagraywacke near Lynchburg, Virginia; F) Metagraywacke near Lynchburg Virginia – note folded vein and axial planar foliation.

Geologic Description and Hydrogeologic Characteristics

The Alligator Back Formation is primarily composed of thinly bedded micaceous gneisses (metagraywacke) and schist interspersed with more homogenous zones of schist, and micaceous or quartzo-feldspathic gneiss (metagraywacke), and layers of amphibolite and greenstone of variable thickness (Espenshade et al., 1975; Rankin et al., 1973). Lenses of marble have been mapped in the Alligator Back Formation, but are rare. The rocks of the Alligator Back Formation have been mapped as non-conformably overlying the rocks of the Ashe Metamorphic Suite (AMS), and are on strike with and equivalent to the finer grained sequences of the upper Lynchburg Formation to the northeast (Bartholomew et al., 1994; Conley, 1985). To the southeast, rocks of the Alligator Back Formation are in conformable contact with the overlying Candler Formation, or are in fault contact with the rocks of the Smith River Allochthon where the Candler has been truncated by faulting.

The rocks of the Alligator Back Formation (along with the rocks of the upper Lynchburg Formation) are thought to have originated as a younger depositional marine sequence along the Laurentian continental margin associated with a later phase of Iapetian rifting in the late Proterozoic and overlie much of the older marine rift-related rocks of the Ashe Metamorphic Suite (Henika et al., 2000). Unlike the stratigraphically equivalent portions of the upper Lynchburg Formation to the northeast, rocks of the Alligator Back Formation appear to have undergone a higher degree of metamorphism and structural deformation.

Fractures within the rocks of the Alligator Back Formation occur in similar fashion to the fractures in the rocks of the Ashe Metamorphic Suite. Parting parallel to micaceous foliation and schistosity in the rock are common, and pervasive jointing orthogonal to foliation often gives these rocks a flaggy or slaty appearance in outcrop. Regionally, foliations and schistosity in the Alligator Back Formation tend to dip to the south or southeast, but local fold and fault systems within this group can complicate field determinations. Preferential weathering of less competent schistose beds within the near surface environment or along preferential flow paths can enhance the storage capacity and the transmissivity of the fracture systems.

Table 16 presents summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Alligator Back Formation of the Blue Ridge Cover Sequence.

Reported yield data were recorded for 1,006 wells in the Alligator Back Formation. Estimated yields were 20 gal/min or more for 32%, 50 gal/min or more for 9%, and 100 gallons/minute or more for 2% of the total well population. Reported yield data were available for 222 commercial, municipal, and light industrial wells completed in the Alligator Back Formation. Estimated yields were 20 gal/min or more for 47%, 50 gal/min or more for 16%, and 100 gal/min or more for 5% of the non-domestic well population.

Reported water bearing zone data were compiled for 26 wells drilled to depths of 400 feet or more and completed in the Alligator Back Formation. At least one water bearing zone was reported by the driller to occur at depths of 400 feet or more for 31% of these wells. Approximately 15% of all reported fractures in this subset were below 400 feet. The deepest reported fracture was 680 feet below land surface, and the fracture yielded an estimated 1.5 gal/min.

The highest yielding well on record in the Alligator Back Formation was drilled near Woolwine, Virginia at the United Elastic Corporation plant in 1959. The well was drilled with a cable tool rig to a depth of 401 feet below land surface and reportedly yielded 517 gal/min at the end of a 60 hour pump test with 135 feet of drawdown. Two other wells at the plant yielded over 100 gal/min (DEQ well 170-00219 yielded 337 gal/min after 72 hours of pumping with 135 feet of drawdown, and although there is no pump test data available for well DEQ well 170-00229, it is fitted with a pump rated for 190 gal/min). These wells appear to be drilled in an amphibolite layer on strike with the regional foliation (Espenshade et.al.), although there is some speculation that these wells may have been drilled in or through a soluble, high calcium content marble in this area (noted as a possibility on the drilling report for well DEQ 170-00219). These wells are located on the edge of the Smith River flood plain, in a small valley favorably situated for accumulating topographically driven groundwater flow from adjacent hills and ridges. It is currently unknown if the groundwater flow and storage mechanisms associated with these wells are in hydraulic connection with the nearby Smith River.

Table 16. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Alligator Back Formation.

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

	Mean	Median	Maximum	Minimum	Number of Observations
Estimated Yield, All Wells (Gal/Min)	18.8	10	517	1	1006
Estimated Yield, Non-Residential Wells (Gal/Min)	30.8	18	517	1	222
Pumped Yield (Gal/Min)[a]	58.6	19	517	1	31
Specific Capacity (Gal/Min/Ft Drawdown)[b]	0.51	0.16	3.83	0.003	33
Well Depth (Ft)	312	300	1200	35	1026
Depth to Bedrock (Ft)	57.4	58	112	0	116
Depth to First Water-Bearing Fracture (Ft)	148	135	500	10	108
Depth to Lowest Water-Bearing Fracture (Ft)	203	180	680	10	108
Water Level (Ft BLS.)	47.8	46	155	3	171

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Groundwater samples taken from wells and springs in the Alligator Back Formation of the Blue Ridge Cover Rock Sequence indicate that natural groundwater chemistry is predominately of the calcium-magnesium-bicarbonate type, or of the sodium-magnesium-bicarbonate type. Groundwater within these rocks is typically soft, and slightly acidic. Table 17 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of selected secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in this unit.

Table 17. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the Alligator Back Formation.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.53	6.60	8.20	4.60	145
Temperature (˚C)	13.0	12.2	17.0	10.5	21
Temperature (˚F)	55.4	54.0	62.6	50.9	21
Specific conductance (µS/cm at 25˚C)	104	74.0	770	9.00	138
Filtered residue (mg/L)	88.6	71.5	263	14.0	40
Hardness (mg/L as $CaCO_3$)	50.9	40.0	140	0.68	41
Major Cations					
Calcium (mg/L)	13.7	8.00	68.0	0.60	43
Magnesium (mg/L)	4.01	1.90	87.7	0.30	107
Sodium (mg/L)	4.72	3.63	20.0	0.70	122
Potassium (mg/L)	2.08	1.70	8.60	0.40	43
Major Anions					
Bicarbonate (mg/L as HCO_3)	47.1	30.5	323	3.70	145
Sulfate (mg/L)	8.10	2.80	149	0.10	49
Chloride (mg/L)	5.02	4.00	45.0	0.60	128
Nutrients					
Nitrate (mg/L as N)	1.04	0.47	5.80	0.04	35
Ammonium (mg/L as N)	0.07	0.10	0.10	0.01	32
Phosphate (mg/L as P)	0.02	0.010	0.12	0.01	30
Secondary Constituents					
Silica (mg/L)	18.9	16.5	45.0	4.50	22
Aluminum (µg/L)	22.6	16.0	162	6.70	88
Iron (µg/L)	931	180	7,000	20.0	33
Manganese (µg/L)	92.4	30.0	2,200	3.00	106
Arsenic, total (µg/L)	2.63	1.00	10.0	1.00	11
Bromide (mg/L)	0.02	0.02	0.07	<0.01	70
Fluoride (mg/L)	0.07	0.06	0.27	<0.01	89
Radiochemical Constituents					
Uranium (µg/L)	0.11	0.04	0.81	<0.01	87

Figure 33 is a piper diagram illustrating the relative concentrations and distributions of major ions within balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 26 wells completed within the Alligator Back Formation. Major cations usually range between 50-90% calcium+magnesium and 10-50%

sodium+potassium. Typical ranges for major anions are 0-50% chloride+fluoride+sulfate and 50-100% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate.

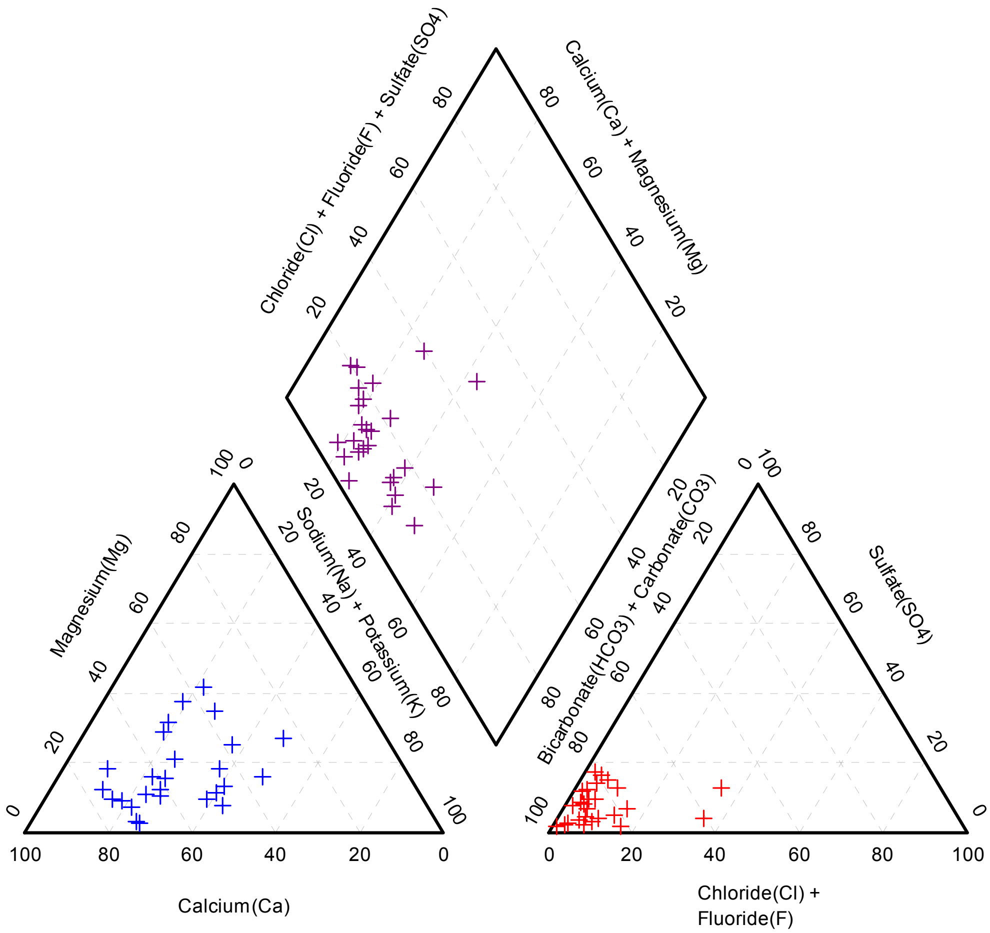


Figure 33. Piper diagram illustrating the relative distributions of major ions from groundwater samples collected from 26 different wells and springs within the Alligator Back Formation.

Late Proterozoic Rift Related Volcanic Rocks

Geologic Description and Hydrogeologic Characteristics

Figure 34 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the late Proterozoic rift related volcanic rocks. Figure 35 provides photographs of selected rock types within the late Proterozoic rift related volcanic rocks group.

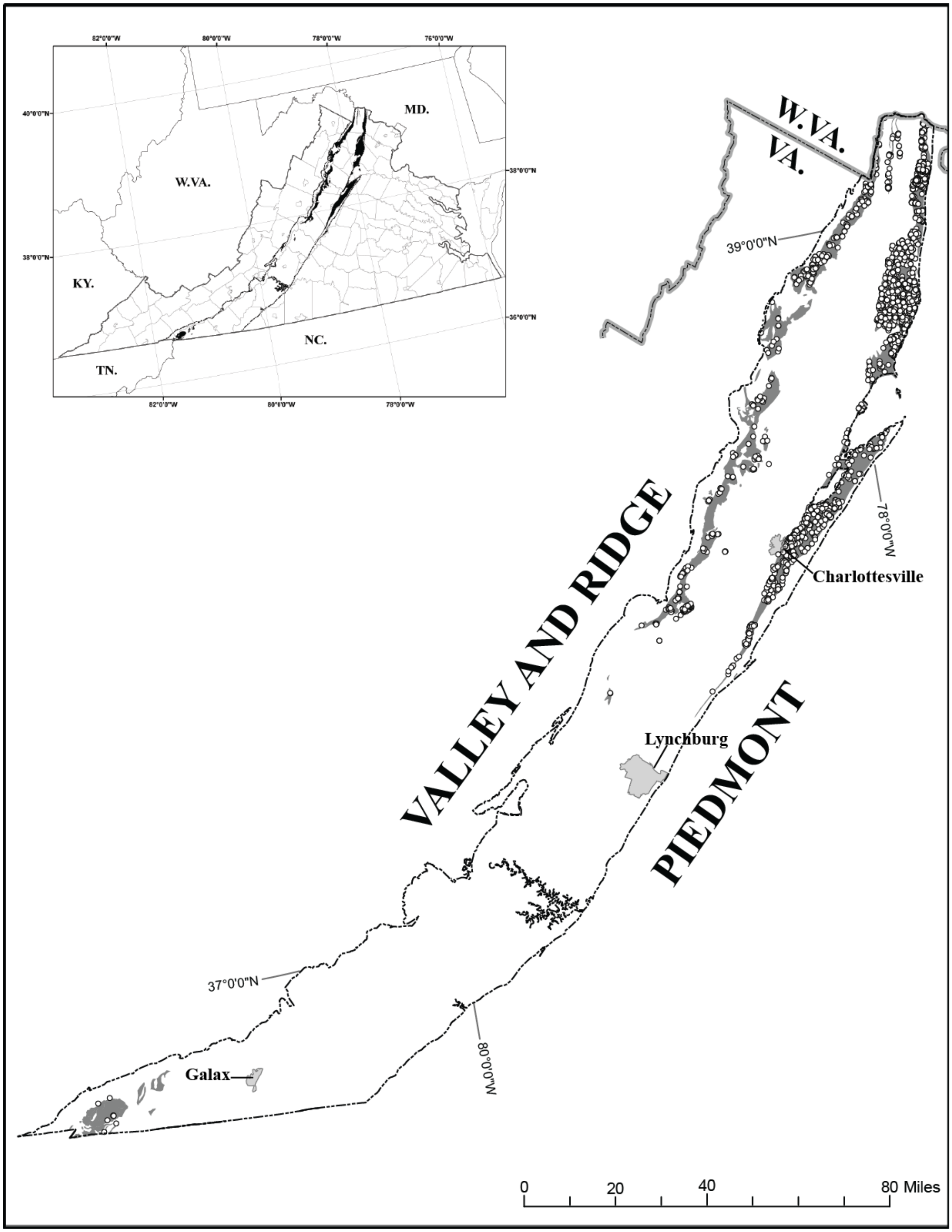


Figure 34. Extent and distribution of the late Proterozoic rift related volcanic rocks unit of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions. Wells shown in the Mount Rogers Formation (units in the southwestern portion of the Blue Ridge Belt) were not used in the statistical analyses but are cataloged in the GIS dataset of wells used in conjunction with this report (Appendixes 3 and 4).

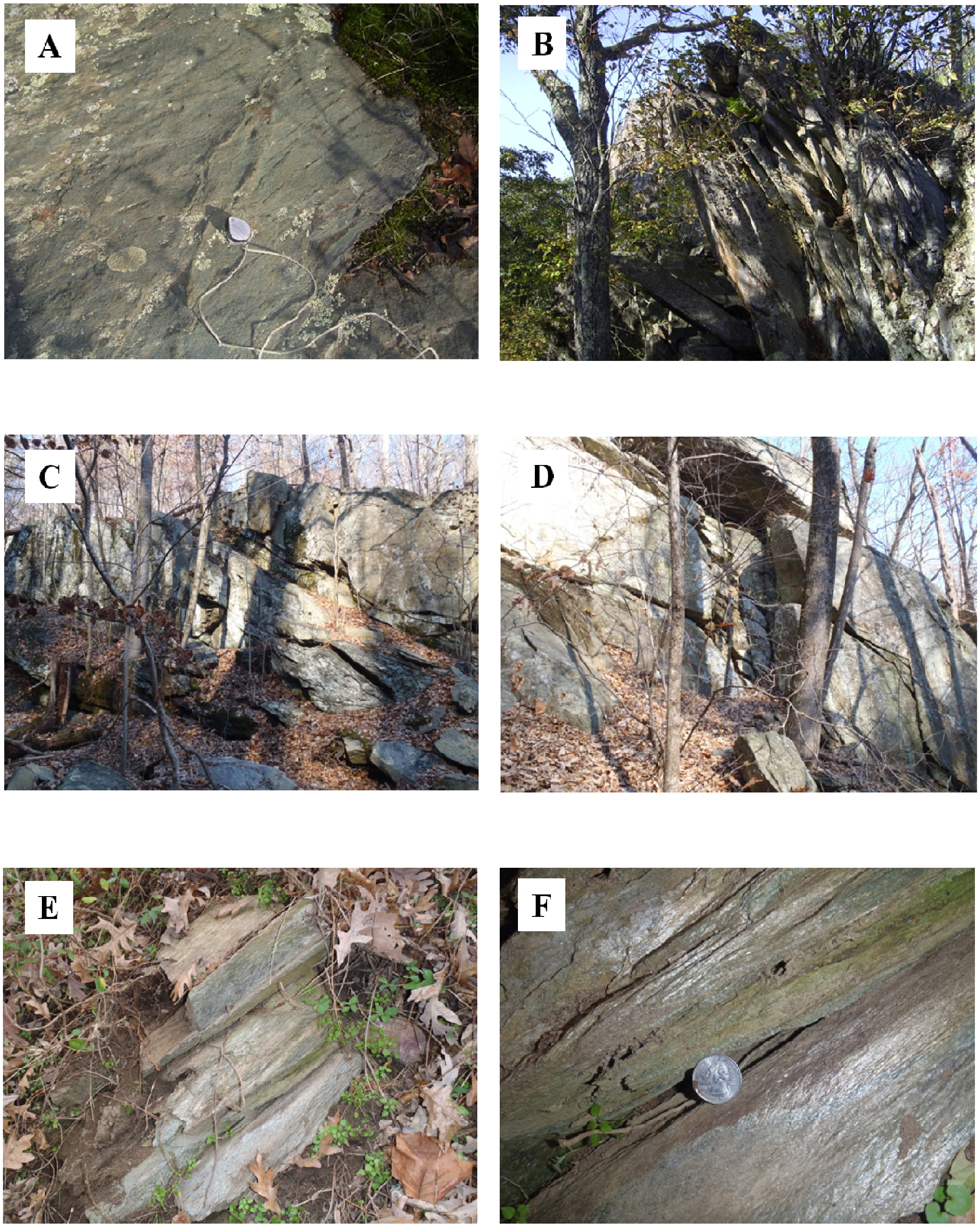


Figure 35. Photographs of rocks within the Catoctin Formation – Blue Ridge Cover Sequence. A) Massive metabasalt along Bearfence Mountain in the Shenandoah National Park.; B) Cleaved section of Catoctin Formation along Bearfence Mountain in the Shenandoah National Park.; C)Cleavage in the Catoctin Formation along Pauls Creek near Nellysford, Virginia.; D) Jointed section of Catoctin Formation along Pauls Creek near Nellysford Virginia.; E) Serecitic schist in outcrop near Warrenton Well #3, Town of Warrenton, Virginia.; F) Serecitic schist - close up near Warrenton Well #3, Town of Warrenton, Virginia.

Rocks of this group are comprised of the Catoctin Formation and the Mount Rogers Formation. These formations possess different textural characteristics and lithologies, and likely have distinctly different hydrogeologic characteristics.

The wells completed in the Mount Rogers Formation were not incorporated into the statistical hydrogeologic analysis due to a paucity of hydrogeologic and geochemical data in the Mount Rogers region. However, information for wells and groundwater samples that plot within the Mount Rogers Formation are included in the GIS dataset of wells used in conjunction with this report. The geologic characteristics of both formations are briefly discussed in the following paragraphs.

Catoctin Formation

The majority of the late Proterozoic rift related volcanic rocks unit are comprised of the Catoctin Formation - the metamorphosed remnants of an extensive volume of flood basalts and subordinate agglomerate and pyroclastic sedimentary deposits that were extruded through late Proterozoic rift-related fissures in the crystalline basement and cover rocks underlying the Catoctin (Gathright, 1976). The bulk of these rocks are comprised of fine grained amygdaloidal metabasalt that is in places interlayered with volcanic agglomerate, phyllitic beds of metamorphosed sediments, and schistose intervals of chloritic, metamorphosed volcanic tuff (Allen, 1963; Espenshade, 1986; Gathright, 1976; Reed, 1955). The Catoctin formation occupies both flanks of the Blue Ridge Anticlinorium and extends from the nose of the anticlinorium in Pennsylvania to western Nelson County, Virginia, where the formation pinches out between basement rocks and the overlying Chilhowee sequence on the western flank, and the Candler Formation and Lynchburg Formation rocks on the eastern flank (Rossman, 1991). Stratigraphically, the Catoctin Formation conformably overlies the rift related Late Proterozoic Metasedimentary rocks (Swift Run, Fauquier, and Charlottesville Formations) but in many places rests unconformably on basement rock. The top of the Catoctin transitions disconformably into the Chilhowee Group rocks in the northern and western portions of the Blue Ridge Anticlinorium (Southworth et al., 2009b), and into the Candler Formation on the eastern flank of the Blue Ridge Anticlinorium to the south of Culpeper County (Rossman, 1991).

Fracturing within the Catoctin Formation is highly dependent on lithology, texture, and geologic structure. Observations by several authors document a penetrative, spaced cleavage in the Catoctin with E-SE dip direction along both limbs of the Blue Ridge Anticlinorium (Gathright and Nystrom, 1974; Luckert and Nuckols, 1976; Reed, 1955; Southworth and Brezinski, 1996). Observations of outcrop in the vicinity of Luray, Virginia indicate that joints are often concentrated in the vicinity of abrupt textural changes within the formation, such as along the tops of volcanic flows and in the schistose intervals which are often sheared layers of metatuff that appear to have in many cases disproportionately accommodated displacement within the formation (Reed, 1955). Fracturing is usually less concentrated in more massive portions of the formation, but development of more hydraulically transmissive joints can still occur in this lithology. Weathering and groundwater circulation within these rocks in the near surface environment can promote and enhance cleavage aperture.

Mount Rogers Formation

The Mount Rogers Formation comprises a small percentage of the late Proterozoic rift related volcanic rocks group, and occupies a geographically distinct region along the western margin of the Blue Ridge Geologic Province in small portions of Grayson, Smyth, and Washington Counties. Unlike the Catoctin Formation, the rocks of the Mount Rogers Formation are primarily pyroclastic, and are composed largely of rhyolitic lava flows and welded rhyolitc tuffs and ash falls. The Mount Rogers Formation is composed of a lower, volcaniclastic sequence of folded sandstones, conglomerate, pelite, greenstones, and rhyolite, with clastic rocks making up about 80 percent of the sequence. The lower volcaniclastic sequence is capped by a thick sequence of variably metamorphosed rhyolitic lava flows and ash flow sheets, accounting for 50 to 60 percent of the entire formation (Rankin et al., 1994).

Fracturing within the lower portion of the Mount Rogers Formation is typically parallel and normal to bedding and can be concentrated in zones of localized deformation. Fracturing within the rhyolitic portions of the Mount Rogers Formation is often related to the presence of primary flow structures, and is consequently much less uniform on a regional scale than within the Catoctin Formation. Discernible joint and cleavage sets occur within shear zones, along flow layering, and the axial portions of flow folds, but vary locally due to the well preserved pyroclastic nature of the formation.

Table 18 presents summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Catoctin Formation of the Blue Ridge Cover Sequence.

Descriptive statistics for the characteristics presented in Table 18 were generated for wells drilled in the Catoctin Formation on each flank of the Blue Ridge Anticlinorium to observe hydrogeologic similarities or differences resulting from variation in geologic structure or lithology across the anticlinorium. A comparison of the results indicates that these hydrogeologic characteristics are remarkably similar regardless of position on the anticlinorium. A comparison of these hydrogeologic characteristics is presented in table 19.

Reported yield data were compiled and analyzed for 2,272 wells in the Catoctin Formation. Estimated yield values were 20 gal/min or more for 29%, 50 gal/min or more for 7%, and 100 gal/min or more for 4% of the total well population. Estimated yield values were 20 gal/min or more for 45%, 50 gal/min or more for 15%, and 100 gal/min or more for 4% of the non-domestic well population.

Reported water bearing zone information were compiled for 373 wells completed to depths of at least 400 feet in the Catoctin Formation. At least one water bearing zone was reported to have been encountered at depths of 400 feet or more by the driller for 50% of these wells (189 wells). A total of 578 water bearing zones were reported in this subset of wells and 36% (208) of the total were at depths of at least 400 feet. The deepest reported water-bearing fracture in this data set was at 889 feet below land surface, and produced an estimated 5 gallons per minute. This was the only reported fracture for the well, which was drilled to 1025 feet.

The highest yielding well completed in the Catoctin Formation according to available records, was drilled as a public supply well for the Town of Warrenton, Virginia in 1953 (Warrenton Well #3, DEQ Well #130-00058). The well is reportedly 412 feet deep, has water bearing zones at 233 feet, 257 feet, 282 feet, and 318 feet below land surface, and was pump tested at 400 gallons per minute with a total drawdown of 41 feet. The initial estimated yield for this well was 550 gallons per minute. Currently, the well is off line due to an elevated radiological count associated with a groundwater sample taken in the late 1990s. When the well was in production, it was pumped for about 13 hours/day at a rate of approximately 200 gallons/minute. The drilling log for this well indicates that it was completed in an arkosic metasedimentary rock and vein quartz. The description of the drilling log along with observations by the author of sparse, serecitic schist outcrop and abundant quartz float in the saprolite along the banks of the access road near the well suggest that the well may have been drilled along strike in a steeply dipping phyllitic or volcaniclastic package within the Catoctin Formation (figure 35E and 35F). This area was mapped as Loudon Formation by Furcron (Furcron, 1939), who noted that the metasediments in this area bore evidence of extensive shearing, and possessed distinctly different textural qualities from much of the Loudon Formation mapped elsewhere in the quadrangle. More recently, volcaniclastic and phyllitic intervals have been mapped as metamorphosed beds within the Catoctin on the eastern flank of the Blue Ridge Anticlinorium by a number of authors (Espenshade, 1986; Nelson, 1962; Rossman, 1991) although current geologic maps of this area do not include the lithology described by Furcron within the vicinity of this well.

Table 18. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Catoctin Formation of the Blue Ridge Cover Sequence.

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

	Mean	Median	Maximum	Minimum	Number of Observations
Estimated Yield, All Wells (Gal/Min)	16.1	10	550	0.12	2272
Estimated Yield, Non-Residential Wells (Gal/Min)	30.4	15	550	1	228
Pumped Yield (Gal/Min)[a]	35.7	25	106	3	44
Specific Capacity (Gal/Min/Ft Drawdown)[b]	0.88	0.25	13.1	0.02	32
Well Depth (Ft)	311	300	1125	6	2332
Depth to Bedrock (Ft)	34	30	185	1	1299
Depth to First Water-Bearing Fracture (Ft)	194	150	889	6	1093
Depth to Lowest Water-Bearing Fracture (Ft)	265	235	889	20	1094
Water Level (Ft BLS.)	46.0	36	379	0	551

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.

[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Table 19. Comparison of summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Catoctin Formation on the eastern and western flanks of the Blue Ridge Cover Sequence.

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

	Mean	Median	Maximum	Minimum	Number of Observations
Estimated Yield, All Wells *Eastern Flank* (Gal/Min)	16	10	550	1	1965
Estimated Yield, All Wells *Western Flank* (Gal/Min)	16.9	8	500	1	306
Estimated Yield, Non-Residential Wells *Eastern Flank* (Gal/Min)	30.7	15	550	1	157
Estimated Yield, Non-Residential Wells *Western Flank* (Gal/Min)	27.6	14.5	500	1	94
Pumped Yield *Eastern Flank* (Gal/Min)[a]	39.6	34	100	5	14
Pumped Yield *Western Flank* (Gal/Min)[a]	43.1	34.5	106	3	14
Specific Capacity *Eastern Flank* (Gal/Min/Ft Drawdown)[b]	0.46	0.28	1.76	0.02	14
Specific Capacity *Western Flank* (Gal/Min/Ft Drawdown)[b]	1.14	0.24	13.14	0.03	19
Well Depth *Eastern Flank* (Ft)	307	290	1125	25	2009
Well Depth *Western Flank* (Ft)	334	305	1001	6	320
Depth to Bedrock *Eastern Flank* (Ft)	34.6	30	320	1	1147
Depth to Bedrock *Western Flank* (Ft)	31.7	25	114	1	151
Depth to First Water-Bearing Fracture *Eastern Flank* (Ft)	194	150	910	20	957
Depth to First Water-Bearing Fracture *Western Flank* (Ft)	200	140	810	6	137
Depth to Lowest Water-Bearing Fracture *Eastern Flank* (Ft)	265	236	889	20	957
Depth to Lowest Water-Bearing Fracture *Western Flank* (Ft)	265	215	810	30	137
Water Level *Eastern Flank* (Ft BLS.)	38.3	33.1	251	0.91	633
Water Level *Western Flank* (Ft BLS.)	56.0	35.3	379	1	156

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Available groundwater samples taken from wells and springs in the Catoctin Formation are almost all of the calcium-magnesium-bicarbonate type. Groundwater within the Catoctin Formation is usually soft to moderately hard, and slightly acidic to slightly basic. The buffering capacities of the basaltic portions of the Catoctin Formation are higher than for most other rocks in the Blue Ridge Geologic Province, and result from the dissolution of calcium and magnesium oxides during the chemical weathering of the metabasalts. Dissolution of these minerals can also cause moderate hardness in these waters. The fine grained nature of the metabasalts and the lower abundance of silicate materials in these rocks promotes weathering and dissolution in the saturated portions of the formation. Table 20 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in the Catoctin Formation.

Table 20. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the Catoctin Formation.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.86	6.80	9.50	4.70	158
Temperature (˚C)	12.2	12.0	16.3	9.00	24
Temperature (˚F)	53.9	53.7	61.3	48.2	24
Specific conductance (µS/cm at 25˚C)	141	109	1,250	16.0	134
Filtered residue (mg/L)	135	115	338	31.0	50
Hardness (mg/L as $CaCO_3$)	83.8	66.0	292	14.0	75
Major Cations					
Calcium (mg/L)	24.1	18.0	200	1.10	89
Magnesium (mg/L)	6.97	4.99	39.8	<0.01	108
Sodium (mg/L)	6.49	5.68	32.0	0.10	130
Potassium (mg/L)	1.22	0.90	5.50	0.15	75
Major Anions					
Bicarbonate (mg/L as HCO_3)	77.5	62.8	262	3.70	152
Sulfate (mg/L)	9.47	3.50	201	0.10	75
Chloride (mg/L)	9.61	4.50	78.2	0.60	151
Nutrients					
Nitrate (mg/L as N)	0.87	0.45	6.5	0.04	68
Ammonium (mg/L as N)	0.09	0.10	0.20	0.01	72
Phosphate (mg/L as P)	0.03	0.02	0.30	0.01	74
Secondary Constituents					
Silica (mg/L)	21.0	16.0	55.0	7.50	11
Aluminum (µg/L)	38.8	26.0	277	8.00	57
Iron (µg/L)	532	100	11,000	5.00	77
Manganese (µg/L)	127	29.0	7,840	1.00	112
Arsenic, total (µg/L)	13.9	1.00	260	1.00	22
Bromide (mg/L)	0.04	0.03	0.23	<0.01	34
Fluoride (mg/L)	0.64	0.06	37.0	<0.01	68
Radiochemical Constituents					
Uranium (µg/L)	0.04	0.02	0.43	<0.01	45

Figure 36 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 33 different wells within the Catoctin Formation. Major cations usually range between 60-90% calcium+magnesium and 10-40% sodium+potassium. Typical ranges for major anions are 10-45% chloride+fluoride and sulfate and 45-90% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate.

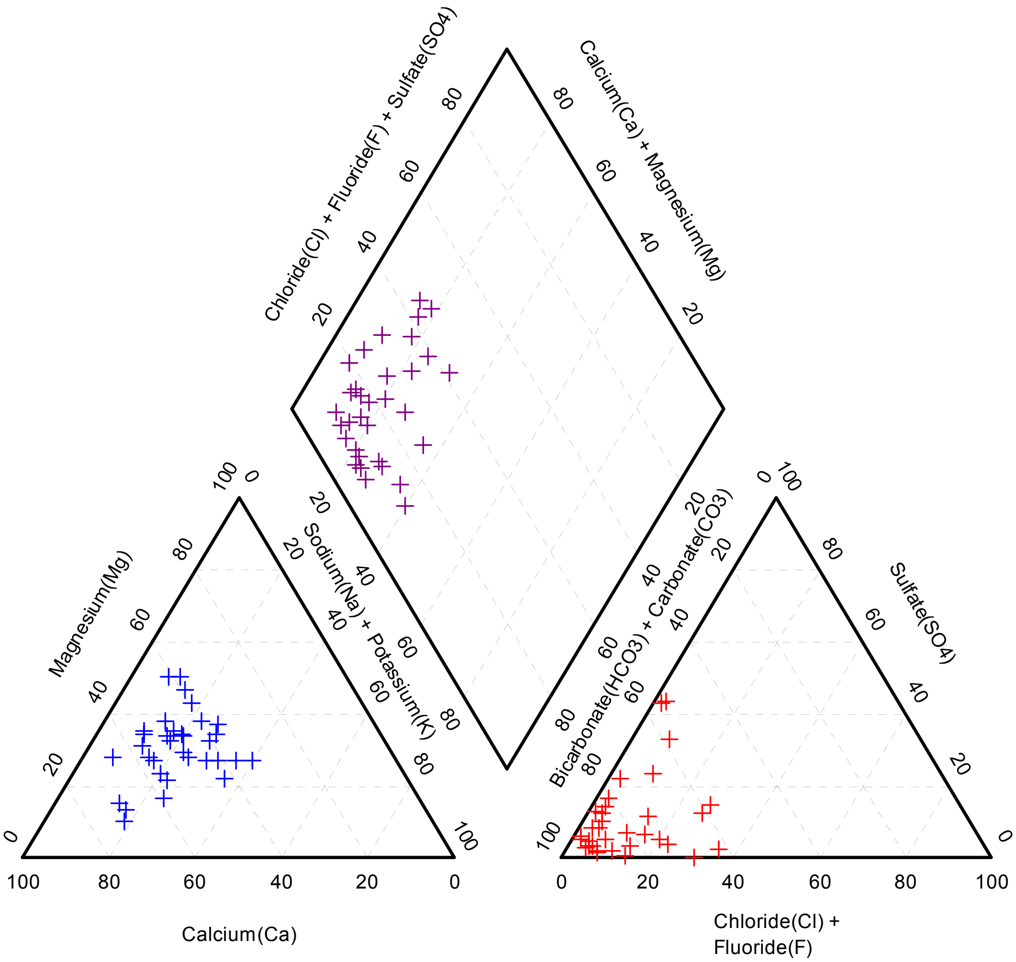


Figure 36. Piper diagram illustrating the relative distributions of major ions from groundwater samples collected from 33 different wells within the Catoctin Formation.

Chilhowee Group

Geologic Description and Hydrogeologic Characteristics

Figure 37 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the Chilhowee Group rocks. Figure 38 provides photographs of selected rock types within the Chilhowee Group.

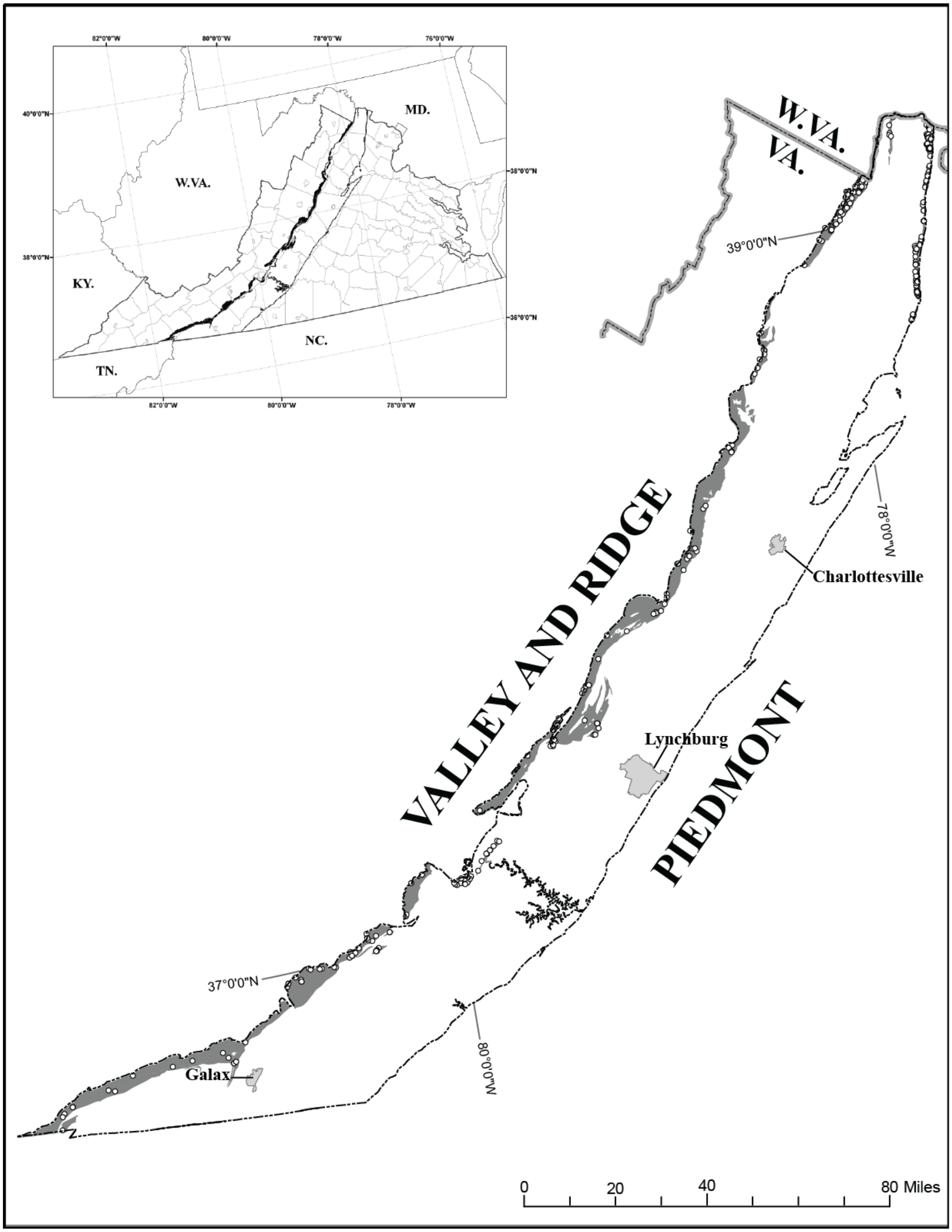


Figure 37. Extent and distribution of the Chilhowee Group of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

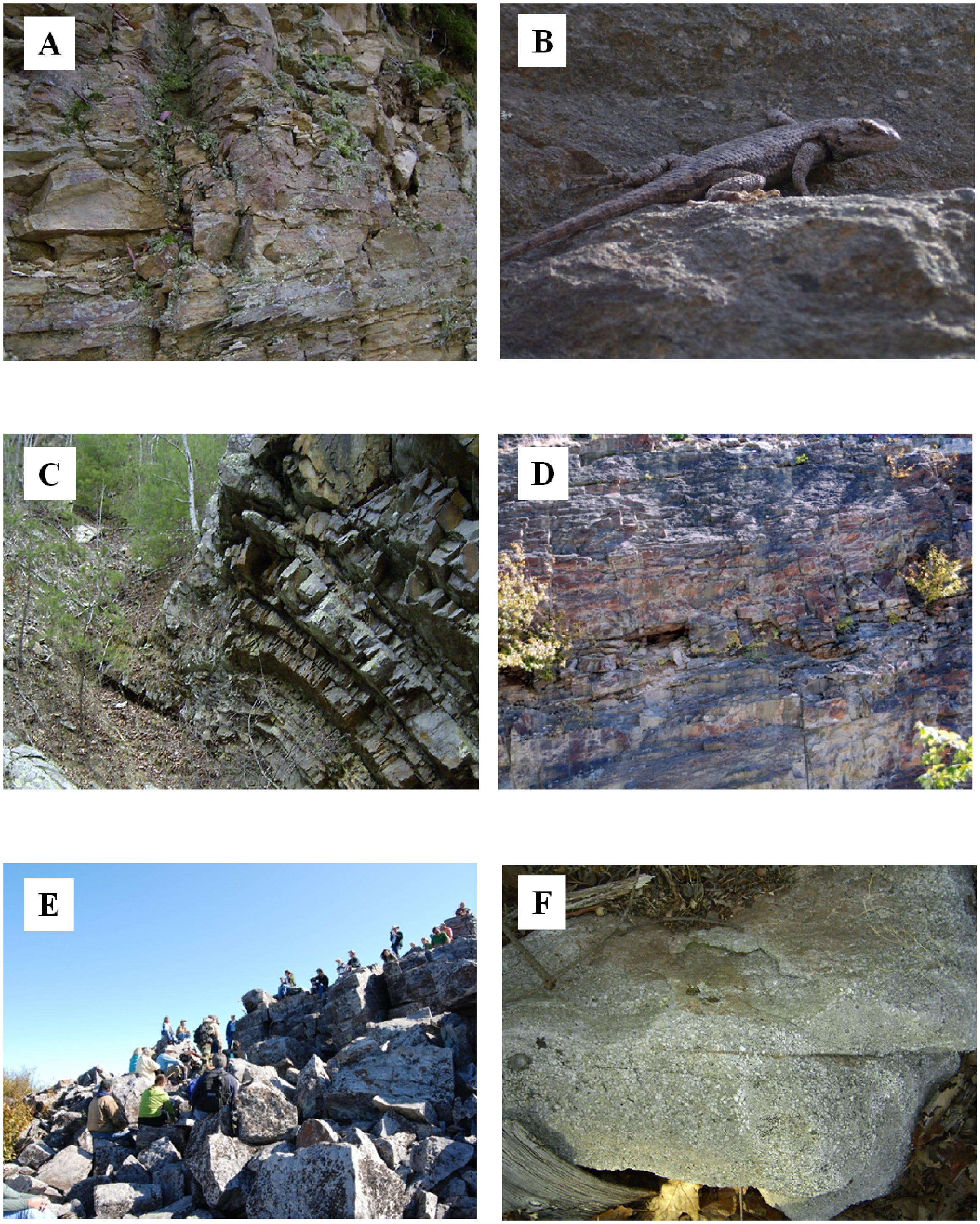


Figure 38. Photographs of rocks within the Chilhowee Group – Blue Ridge Cover Sequence. A) Blocky quartzite resting on top of siltstone in the Unicoi Formation near Roanoke, VA. ; B) Quartz conglomerate in the Unicoi Formation near Roanoke, VA.; C) Folded quartzite of the Hampton Formation near Arcadia, Virginia.; D) Intensely cleaved quartzite in the Harpers Formation-Shenandoah National Park, VA.; E) Talus field of blocky quartzite from Harpers Formation – Shenandoah National Park, VA. F) Boulder of Erwin Quartzite near Elliston, VA.

Rocks within the Chilhowee Group are composed primarily of metamorphosed siliciclastic deposits of varying texture and composition. These formations were deposited during the final stages of early Cambrian rifting during the formation of the Proto-Atlantic divergent continental margin (Rankin, 1975; Wehr and Glover, 1985). From the lowest stratigraphic position to the highest, these formations record the transition from primarily colluvial and fluvial active rift related sedimentary depositional environments, to passive coastal and shallow marine depositional environments that signify the end of late Proterozoic and early Cambrian rifting. Multiple names are used locally for these formations. The lithology within each formation, as well as the nature of the contacts between the formations, change along and across the regional strike of this group. The Chilhowee Group is typically separated into three distinct formations, each of which has at least two formation names in use within the Commonwealth, depending on where it is being mapped along strike.

The lowest stratigraphic unit in the Chilhowee Group is commonly referred to as the Weverton Formation along the northern and central sections where it rests unconformably on the Catoctin Formation, and the Unicoi Formation in the central to southern southern portions of the state where the Catoctin is absent. Rocks within this subdivision of the Chilhowee Group are composed of upward-coarsening sequences of metamorphosed siliciclastic rocks grading from metasiltstones and phyllites in the lower portions, to fine grained metasandstones and conglomerates near the top (Bartholomew, 1981; Espenshade et al., 1975; Gathright, 1976; Gathright et al., 1977; Henika, 1997; Southworth et al., 2009a). Discontinuous, sparse beds of metabasalt are present in the lower to middle portions of the Unicoi, and are usually associated with lenses of phyllitic or conglomeratic volcaniclastic rock (Espenshade et al., 1975; Henika, 1997).

The middle siliciclastic sequence of the Chilhowee Group is commonly referred to as the Harpers Formation in the northern to central extent and the Hampton Formation in the central to southern reaches. The Harpers/Hampton formation is heterogeneous, and is composed of interbedded sequences of varying lithology and thickness. Phyllite, metasiltstone, metasandstone, ferruginous metasandstone, and quartzite occur in varying proportions and positions within the sequence. Toward the top of the sequence, quartzite beds occur frequently. (Espenshade et al., 1975; Gathright, 1976; Henika, 1981; Southworth et al., 2009a; Southworth et al., 2009b). Cleavage within Harpers/Hampton formation is pervasive. Gathright (1976) reported that cleavage and related fracturing within portions of the Harpers/Hampton was so prevalent that it completely obscured bedding features.

The upper most siliciclastic sequence of the Chilhowee Group is commonly referred to as the Antietam Formation in the northern to central extent and the Erwin Formation in the central to southern reaches. The Antietam/Erwin Formation is composed predominately of gray to white, fine to medium grained orthoquartzite. The quartzites within the Antietam/Erwin are often cross bedded, and interbedded with thin, discontinuous, phyllitic sequences (Espenshade et al., 1975; Gathright, 1976; Henika, 1997). The massive quartzite within the Antietam is extremely hard and resistant to weathering. Both the quartzite facies of the Hampton/Harpers Formation and the Antietam Formation are predominate ridge and ledge formers, and commonly joint normal and perpendicular to bedding. The pronounced jointing pattern within the Hampton/Harpers and Antietam/Erwin formations result in the formation of large, angular quartzite blocks in the upper sections of more exposed portions of these formations. These blocks accumulate in extensive talus fields in depressions along the western margin of the Blue Ridge and the west slope of the Bull Run Mountains (Gathright, 1976; Southworth et al., 2009a; Southworth et al., 2009b).

Unlike crystalline basement rocks or the mid Proterozoic rift-related sequences, fracturing within the Chilhowee group tends to occur in a more systematic fashion. Bedding orientation is controlled by fold geometry, but commonly strikes northeast/southwest and typically dips to the southeast or the northwest along fold limbs. Fracturing within these rocks can occur along bedding, parallel or subparallel to foliation, or orthogonal to bedding and foliation, intersecting bedding at steep angles and dipping steeply to the northeast or southwest. Fracturing is often enhanced in the vicinity of fault zones and fold hinges. The heterogeneous nature of the lithologies within the lower formations of the Chilhowee Group (Weverton/Unicoi formations) and their position on a highly irregular and locally displaced erosional surface cause fracture geometries in the Weverton and Unicoi to be less systematic, although similar trends in regional fracturing are evident.

The structural and textural characteristics of the formations within the Chilhowee Group can have a substantial influence on the geometries of local and regional groundwater flow systems. Abrupt lithologic contrasts, bedding orientation, and pervasive cleavage and fracture trends at regional scales directly affect the recharge, movement, and storage of groundwater within these rocks. Observations of the relationship between geologic structure and the occurrence of springs on Short Hill Mountain by Scott Southworth (Southworth, 1990) in Loudon County Virginia, indicate that groundwater recharge and flow within the Weverton and Harpers formations is in places highly anisotropic, and can be largely controlled by the permeability differences that result from varying fracture densities within metamorphosed sedimentary beds of contrasting texture and mineralogy. Southworth's observations also described notable joint and fracture trends along and across strike that were theorized to enable the accumulation and movement of groundwater, as well as the occurrence of favorably oriented beds that may cause preferential groundwater recharge down dip into the deeper groundwater flow system.

Table 21 presents summary statistics for geologic and hydrogeologic parameters associated with wells completed in the Chilhowee Group.

Estimated yield data for 355 wells completed in the Chilhowee Group were compiled and analyzed. Reported estimated yield values were 20 gal/min or more for 27%, 50 gal/min or more for 6%, and 100 gal/min or more for 3% of the total well population. Reported yield data for 81 municipal, commercial, and light industrial wells completed in the

Chilhowee Group were also analyzed. Estimated yield values were 20 gal/min or more for 42%, 50 gal/min or more for 13%, and 100 gal/min for 7% of the non-domestic well population.

Descriptive statistics presented in Table 21 were generated to compare and contrast the hydrogeologic characteristics of the Chilhowee Group on the eastern and western flanks of the Blue Ridge Anticlinorium (Table 22). A comparison of these data indicate that wells in the Chilhowee Group on the western flank of the Anticlinorium tend to have higher yields, well efficiencies, and lower depths to water bearing zones, likely attributable to differences in structure and geomorphology spanning the Blue Ridge Anticlinorium. Structure along the eastern Flank of the Blue Ridge Anticlinorium where the Chilhowee Group rocks are present consists primarily of eastward dipping sequences of metamorphosed sedimentary rock that unconformably overly the Catoctin Formation and are in fault contact with the western border fault of the Culpeper Triassic Basin. The uniform dip directions of these beds, the tendency of fractures to form parallel or sub-parallel to bedding, and the tendency of the quartzites to form topographic highs over much of their eastern extent create conditions that are favorable for runoff and reduced infiltration, and establish substantial hydraulic gradients that direct groundwater down dip with limited structure for intercepting and storing groundwater. In places, groundwater storage can occur in joints that trend orthogonal to bedding and in fractures along strike where storage may be enhanced by the presence of low flow boundaries that can retard the movement of groundwater (such as lithologic contacts of lower permeability). In contrast, the Chilhowee Group along the western flank of the Blue Ridge Anticlinorium is variably folded and more frequently faulted, creating more favorable conditions for the storage and transmission of groundwater within fracture networks. Overall exposure of the Chilhowee sequence to meteoric inputs is much greater along the western flank of the anticlinorium, allowing for greater overall recharge to the rocks within this group. Large portions of the Chilhowee sequence along the Western slopes of the Blue Ridge Mountains are mantled by thick deposits of colluvium and sediment, providing an additional mechanism for groundwater storage and infiltration that is largely absent in the Chilhowee along the eastern flank of the Blue Ridge Anticlinorium.

Reported water bearing zone depth data for 68 wells drilled to at least 400 feet in the Chilhowee Group rocks were compiled and analyzed. At least one fracture was reported to occur at depths of at least 400 feet in 46% (31) of these wells. A total of 116 reported water bearing fractures were noted from this subset of data and 33% (38) of these reported water bearing fractures occurred at or below 400 feet. The deepest reported water-bearing fracture in the Chilhowee Group data set was at 853 feet below land surface, and produced an estimated 7 gallons per minute. The well was drilled to 900 feet below land surface.

The majority of fracture depth related data were acquired from wells drilled in the Chilhowee along the eastern flank of the Blue Ridge Anticlinorium. Only 8 wells drilled to depths of at least 400 feet with reported fracture depth information were available for analysis on the western flank of the anticlinorium, and all but 1 had fractures below 400 feet. A total of 16 reported water bearing zones were noted among these wells, and half of them were reported to occur below 400 feet. At least one water bearing zone was reported at or below 400 feet for 44% (24) of the 54 wells completed to depths of at least 400 feet on the eastern flank of the Blue Ridge Anticlinorium. A total of 93 fractures were reported for this subset of data, and 33% (31) were reported to occur at or below 400 feet.

The highest yielding well completed in the Chilhowee Group according to available records, was drilled in the Antietam/Erwin Quartzite as a public supply well for the City of Buena Vista, Virginia in 1956 (City of Buena Vista #1 – French Post Well, DEQ Well #181-00003). The well is located on an alluvial terrace adjacent to a small, northwest draining stream that cuts through a prominent quartzite ridge running to the west of and parallel to the central axis of the Blue Ridge Anticlinorium. This ridge is separated from the main axis of the Blue Ridge Anticlinorium by a narrow valley underlain by less resistant Harpers/Hampton Formation. The well is reportedly 207 feet deep, and was pump tested at rates varying from 632 gallons/minute to 800 gallons/minute over a 33 hour period with a total drawdown of 153 feet at the end of the test. Later pump tests indicate a drawdown of 142 feet after 72 hours with a pumping rate of 654 gallons/minute. The well is still in use, and is currently fit with a pump producing at approximately 375 gallons/minute. The drilling log indicates that the main water-bearing zone for this well occurred at 157 feet below land surface, and is located at the top of competent bedrock. The well is cased to 153 feet below land surface. Leonard (Leonard, 1962) reported that the water bearing zone for this well was originally plugged with clay, and did not start to yield water until approximately 20 hours after penetration. The well had a reported artesian flow of approximately 60 gallons per minute, indicating that the well is located in a favorable down gradient position for receiving stored water from the thick mantle of colluvium, and that the clays in the colluvial interval are likely responsible for creating confined conditions. Two other high yielding wells occur in the Antietam/Erwin Formation in the City of Buena Vista. All three of these wells are located at the mouths of small, northwest trending drainages that cut across a prominent ridge of Antietam/Erwin quartzite along the eastern edge of the city, and are along strike with the western terminus of the ridge coincident with the surface expression of the Blue Ridge Fault. The proximity of these wells to the Blue Ridge Fault and the occurrence of thick colluvial intervals in this region suggest fault related fracturing supplied by groundwater storage within the colluvial mantle as a possible mechanism for the occurrence of high yielding wells in this area. Drillers logs for these wells gave no indication that they penetrated into the underlying Shady Dolomite or Waynesboro Formation.

Table 21. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Chilhowee Group.

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

	Mean	**Median**	**Maximum**	**Minimum**	**Number of Observations**
Estimated Yield, All Wells (Gal/Min)	17.5	8	632	1	355
Estimated Yield, Non-Residential Wells (Gal/Min)	34.3	15	632	1	81
Pumped Yield (Gal/Min)[a]	97.5	28	632	4	14
Specific Capacity (Gal/Min/Ft Drawdown)[b]	0.86	0.45	4.13	0.004	13
Well Depth (Ft)	348	300	1300	21	400
Depth to Bedrock (Ft)	50.7	40	510	2	179
Depth to First Water-Bearing Fracture (Ft)	202	160	600	60	144
Depth to Lowest Water-Bearing Fracture (Ft)	281	250	780	70	143
Water Level (Ft BLS.)	55.1	40	450	-9.2	162

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Table 22. Comparison of summary statistics for selected geologic and hydrogeologic parameters of wells completed in the rocks of the Chilhowee Group on the eastern and western flanks of the Blue Ridge Cover Sequence.

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

	Mean	**Median**	**Maximum**	**Minimum**	**Number of Observations**
Estimated Yield, All Wells *Eastern Flank* (Gal/Min)	13.11	8	150	1	164
Estimated Yield, All Wells *Western Flank* (Gal/Min)	21.8	10	632	1	182
Estimated Yield, Non-Residential Wells *Eastern Flank* (Gal/Min)	16.5	8	75	1	17
Estimated Yield, Non-Residential Wells *Western Flank* (Gal/Min)	39.1	15	632	1	64
Pumped Yield *Eastern Flank* (Gal/Min)[a]	20	9	72	4	7
Pumped Yield *Western Flank* (Gal/Min)[a]	175	101	632	9	7
Specific Capacity *Eastern Flank* (Gal/Min/Ft Drawdown)[b]	0.5	0.11	1.79	0.02	4
Specific Capacity *Western Flank* (Gal/Min/Ft Drawdown)[b]	1.01	0.52	4.13	0.004	9
Well Depth *Eastern Flank* (Ft)	407	330	1300	21	191
Well Depth *Western Flank* (Ft)	294	260	1000	30	209
Depth to Bedrock *Eastern Flank* (Ft)	42.5	40	235	2	116
Depth to Bedrock *Western Flank* (Ft)	65.8	42	510	2	63
Depth to First Water-Bearing Fracture *Eastern Flank* (Ft)	215	173	580	70	98
Depth to First Water-Bearing Fracture *Western Flank* (Ft)	175	148	600	60	46
Depth to Lowest Water-Bearing Fracture *Eastern Flank* (Ft)	303	267	780	75	98
Depth to Lowest Water-Bearing Fracture *Western Flank* (Ft)	238	215	600	70	46
Water Level *Eastern Flank* (Ft BLS.)	48.3	35	250	-9.2	82
Water Level *Western Flank* (Ft BLS.)	62	45	450	4	80

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Available groundwater samples taken from wells and springs in the Chilhowee Group are predominately of the calcium –magnesium-bicarbonate type, with a small number of samples trending toward the calcium-magnesium-sulfate type and the sodium-bicarbonate type. Groundwater within the Chilhowee Group is usually soft, and slightly acidic to slightly basic. Due to the poor buffering capacities of the quartzites along the western edge of the Blue Ridge Geologic Province, acidic conditions can occur in shallow or rapidly circulating groundwater systems receiving acid precipitation. Further complications can occur in zones of concentrated iron or within abandoned iron mines in the quartzites where acid precipitation can dissolve exposed iron and manganese deposits and tailings. Elevated occurrences of sulfate and iron in these areas can be problematic. Table 23 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in the Chilhowee Group.

Table 23. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the Chilhowee Group.
[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.62	6.60	8.40	4.50	97
Temperature (˚C)	13.6	13.4	14.5	10.7	24
Temperature (˚F)	56.5	56.1	58.1	51.3	24
Specific conductance (µS/cm at 25˚C)	121	76.0	952	5.00	96
Filtered residue (mg/L)	97.1	82.0	544	3.00	25
Hardness (mg/L as $CaCO_3$)	73.0	50.0	440	0.10	35
Major Cations					
Calcium (mg/L)	14.8	5.00	118	0.01	47
Magnesium (mg/L)	4.39	1.82	28	<0.01	74
Sodium (mg/L)	4.39	2.77	37.0	0.02	91
Potassium (mg/L)	1.34	1.10	3.40	<0.01	47
Major Anions					
Bicarbonate (mg/L as HCO_3)	64.1	26.2	991	2.40	96
Sulfate (mg/L)	9.41	5.20	52.6	0.22	42
Chloride (mg/L)	4.58	3.20	31.0	0.60	91
Nutrients					
Nitrate (mg/L as N)	0.54	0.05	6.50	0.01	37
Ammonium (mg/L as N)	0.09	0.10	0.10	0.02	40
Phosphate (mg/L as P)	0.04	0.01	0.34	0.01	40
Secondary Constituents					
Silica (mg/L)	14.4	12.0	30.5	7.30	13
Aluminum (µg/L)	47.2	44.5	149	9.70	48
Iron (µg/L)	598	100	5,500	4.00	45
Manganese (µg/L)	86.8	24.0	860	1.00	78
Arsenic, total (µg/L)	0.88	1.00	1.00	0.30	6
Bromide (mg/L)	0.02	0.01	0.11	<0.01	24
Fluoride (mg/L)	0.10	0.10	0.85	<0.01	41
Radiochemical Constituents					
Uranium (µg/L)	0.09	0.03	1.08	<0.01	32

Figure 39 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 16 different wells within the Chilhowee Group. Major cations usually range between 60-90% calcium+magnesium and 10-40% sodium+potassium. Typical ranges for major anions are 10-60% chloride+fluoride and sulfate and 40-90% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate.

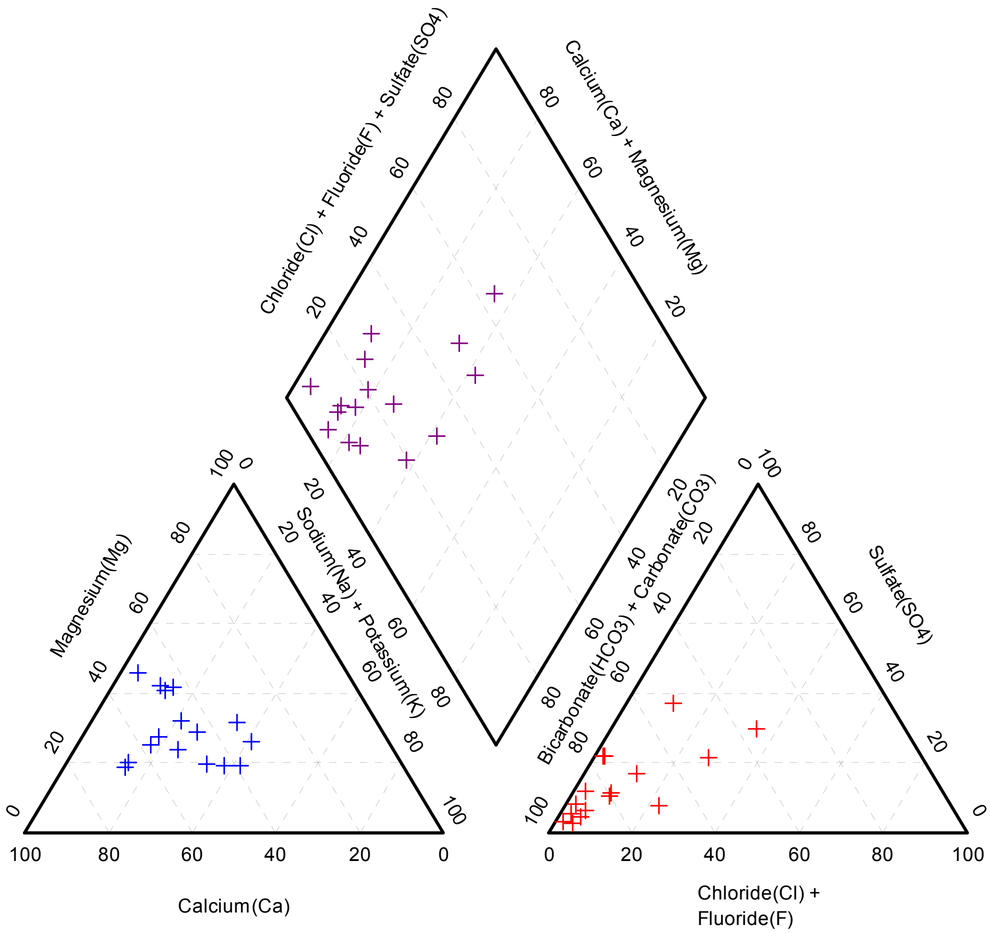


Figure 39. Piper diagram illustrating the relative distributions of major ions from groundwater samples collected from 16 different wells within the Chilhowee Group.

Candler Formation

Figure 40 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the Candler Formation. Figure 41 provides photographs of selected rock types within the Candler Formation.

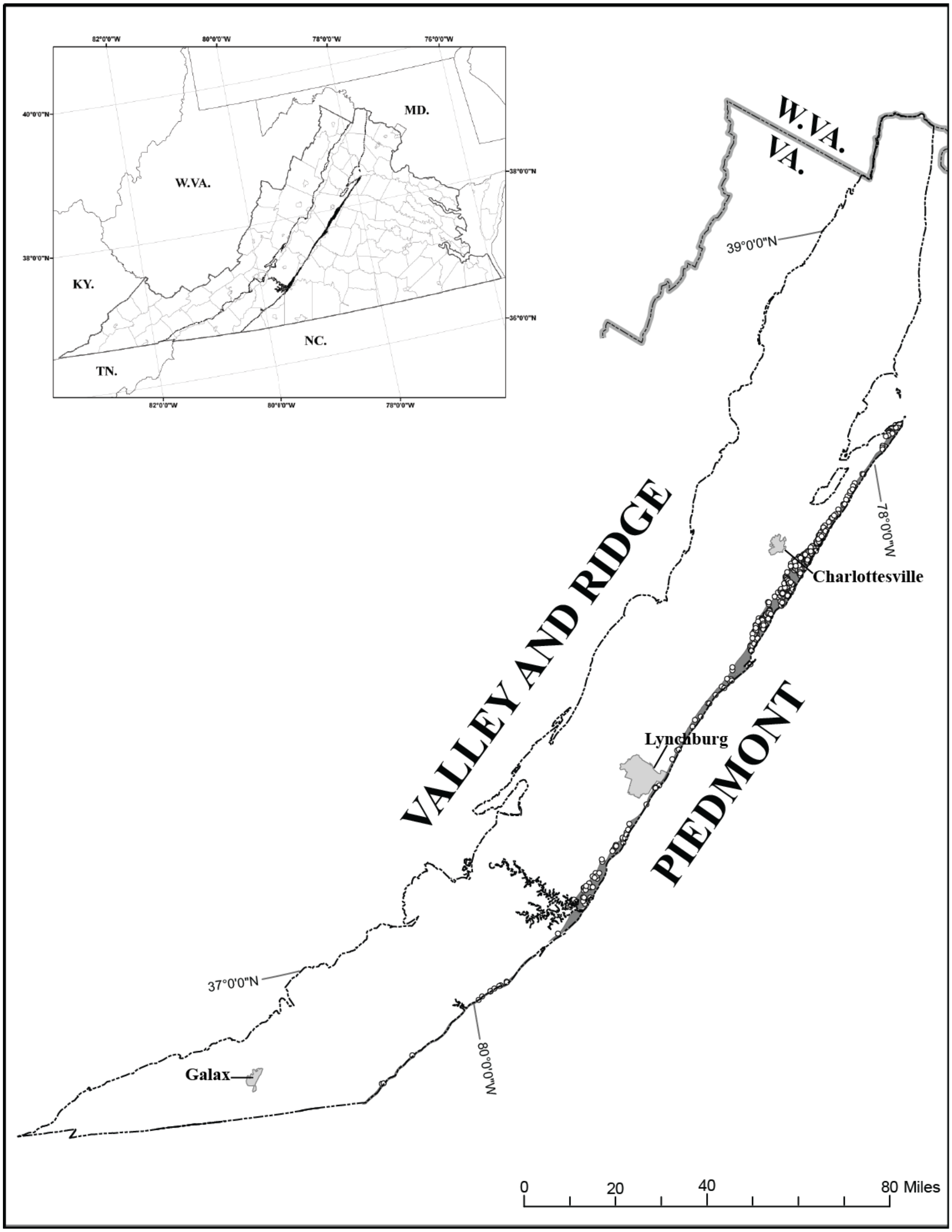


Figure 40. Extent and distribution of the Candler Formation of the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

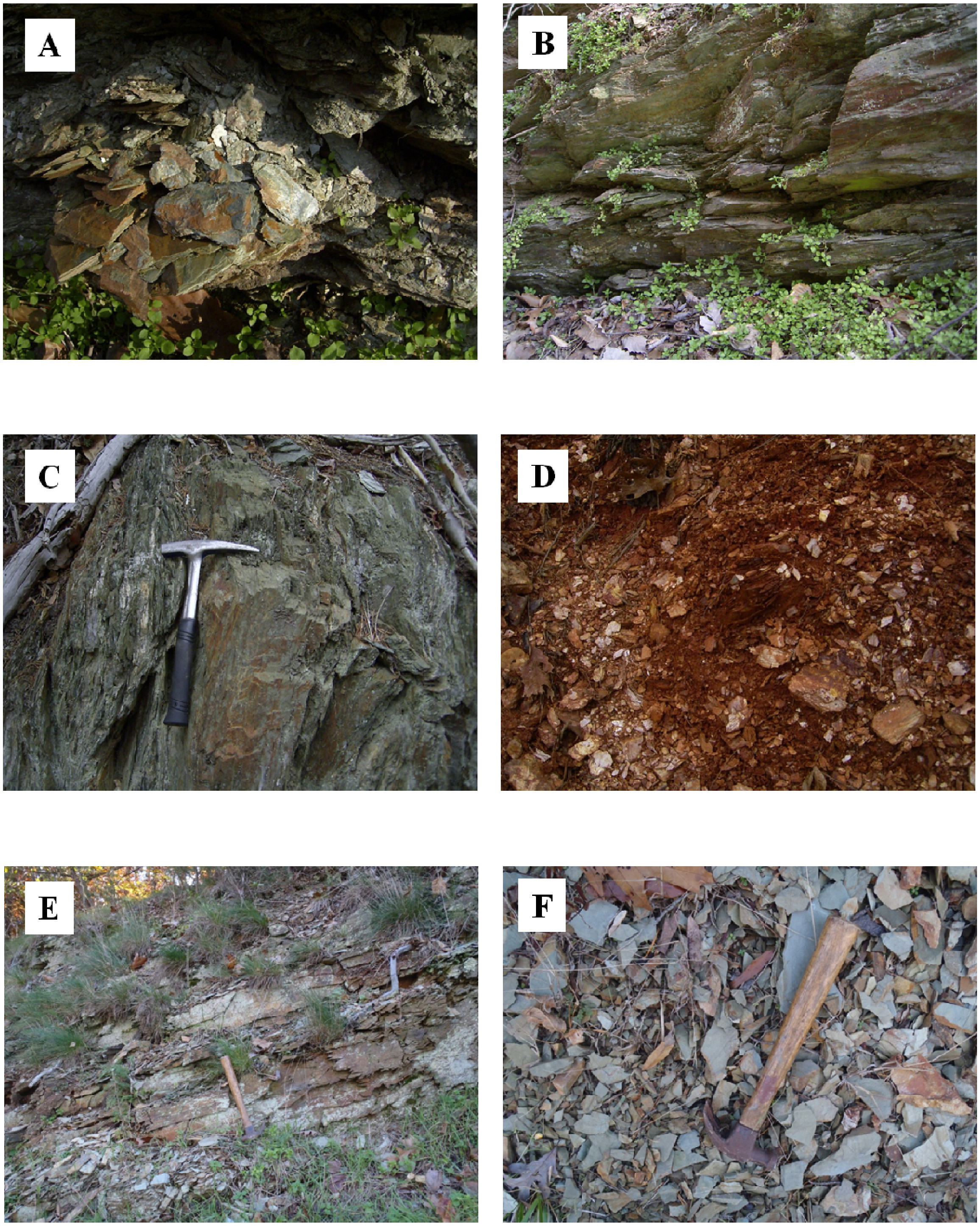


Figure 41. Photographs of rocks within the Candler Formation – Blue Ridge Cover Sequence. A) Phyllite of the Candler Formation near Wingina, VA. ; B) Phyllite of the Candler Formation near Wingina, Virginia (outcrop); C) Folded phyllite of the Candler Formation near Riverville, VA.; D) Phyllite of the Candler Formation on Buffalo Ridge near Amherst, VA.; E) Outcrop of laminated argillite in northern portion of Candler (True Blue Formation of Pavlides). Hammer handle is perpindicuar to bedding ; F) Chips of argillite weathered from outcrop shown in photo E. Note absence of luster or sheen when compared to phyllitic chips in photos A and D of this figure.

Geologic Description and Hydrogeologic Characteristics

The Candler Formation occupies a nearly continuous band of predominately fine grained metasediments along the easternmost flanks of the Blue Ridge Geologic Province and extends from a fault contact with the southeastern portion of the Culpeper Mesozoic Basin in Culpeper County to the Virginia/North Carolina border, where it is equivalent to portions of the Alligator Back Formation in North Carolina. The Candler is thought to be in conformable contact with the underlying Catoctin Formation in the northern and central portions of the Candler's Range. The Candler overlies the Alligator Back Formation and small portions of the Ashe Metamorphic Suite in the central to southern reaches of the Blue Ridge where the Catoctin is absent. To the East, the Candler is in fault contact with the Western Piedmont Terrane and in conformable contact with the Everona Limestone, where present.

The Candler Formation is thought to be the off shore marine equivalent to the upper portions of the Chilhowee Group, and was deposited as sands, silts and muds on a stable continental shelf in the early Ordovician (Pavlides, 1993; Wehr and Glover, 1985). The strata within this depositional environment were subsequently lithified and metamorphosed into folded and faulted sequences composed primarily of phyllite and schist with subordinate graywacke, slate, limestone, and marble interbeds. In the southern portions of the formation, the Candler has been described as predominately phyllitic (Brown, 1958; Carter, 2008a; Conley and Henika, 1970; Henika, 1971), but lithologic descriptions by geologists working in the northern portions of the Candler indicate that it may be more heterogeneous. Substantial beds of metasiltstone, graywacke, and slate have been mapped along the western edge of the Candler in conformable contact with the Catoctin at the 1:24,000 scale in Albemarle County (Evans, 1994; Rossman, 1991). These beds extend at least as far south as the Alberene quadrangle in southeastern Albemarle County, but are not present at a mappable scale in the vicinity of Amherst (Carter, 2008a). The stratigraphy of the Candler was described by Pavlides north of Albemarle County (Pavlides, 1993). Pavlides informally named the bulk of the rocks in his description the True Blue Formation – slaty to locally phyllitic metasiltstone and metamudstone with subordinate lenses of quartzite, greywacke, calcareous slate, limestone, black chert, and oxide ironstones. Two additional lenticular formations were used by Pavlides to describe small portions of the lower Candler: the Tomahawk Creek Formation (greywacke and phyllite) and the Nasons Formation (primarily quartzite).

Fracturing within the phyllitic sections of the Candler Formation tends to occur along and normal to schistosity, giving the rock a lenticular appearance in outcrop. The fine grained phyllites within the Candler Formation have accommodated much of the compressional deformation that occurred in the Acadian and Alleghanian orogenies through folding and shearing and consequently, schistosity within the Candler typically strikes NE/SW and has a predominate SE dip direction. Fold related fracturing along axial fold planes, and brittle deformation and concentrated fracturing within more competent schists, quartzite, limestone, and marble interbeds can allow for the concentration of groundwater in distinct zones within the Candler.

Most of the higher yielding wells within this data set (equal to or greater than 40 gallons/minute) occur in the northern portions of the Candler Formation. Structural features and lithologic contrasts within the more heterogeneous sections of the Candler may serve as important controls on groundwater storage and movement. Where the Candler is largely composed of phyllitic material, data indicate a diminished capacity of the formation to accumulate and transmit groundwater. Reported well yield data were available for analysis from 684 wells completed in the Candler Formation. Estimated yields were 20 gal/min or more for 16%, 50 gal/min or more for 2% and 100 gal/min or more for less than 1% of the total well population. Estimated yield values were 20 gal/min or more for 43%, and 50 gal/min or more for 4% of the 28 reported yield values for municipal, commercial and light industrial wells. There were no non-domestic wells on record with a reported yield of over 100 gallons/minute.

Fracture depth data were available for only 4 wells drilled to a depth of 400 feet or greater in the Candler Formation. One of these wells had a noted water bearing zone greater than 400 feet, and 2 wells had noted water bearing zones greater than 300 feet. A fracture frequency analysis for wells completed up to or greater than 300 feet follows: for the total number of wells drilled to or past 300 feet (12 wells), 4 of them had noted water producing fractures at or below 300 feet. Reported water bearing zone depths of 300 feet or greater occurred for 7 of the total number of water producing fractures for these wells (25 fractures)– 4 of them were in the same well.

The highest yielding well completed in the Candler Formation according to available records, was a residential well drilled in Orange County, Virginia in the lower portions of the Candler very near the contact with the Catoctin Formation. This well was 615 feet deep, and had a reported initial yield of 210 gallons per minute. Given the depth of the well and that the well was probably not being drilled to maximize water production, it is likely that water was not encountered until near the bottom of the hole. The proximity of this well to the Catoctin Formation and the deep completion depth for the well suggest that the well may have been drilled through the Candler Formation and into the Catoctin Formation.

Table 24 presents summary statistics for selected geologic and Hydrogeologic parameters of wells completed in the Candler Formation.

Table 24. Summary statistics for selected geologic and hydrogeologic parameters of wells completed in the Candler Formation.

[gal/min, gallons per minute; ft, feet; BLS, below land surface;"--" indicates no available data]

	Mean	**Median**	**Maximum**	**Minimum**	**Number of Observations**
Estimated Yield, All Wells (Gal/Min)	10.4	6	210	1	684
Estimated Yield, Non-Residential Wells (Gal/Min)	21	15	88	1	28
Pumped Yield (Gal/Min)[a]	37.4	36	88	10	7
Specific Capacity (Gal/Min/Ft Drawdown)[b]	--	--	--	--	--
Well Depth (Ft)	240	225	845	19	688
Depth to Bedrock (Ft)	37.4	30	204	1	37
Depth to First Water-Bearing Fracture (Ft)	101	95	300	30	26
Depth to Lowest Water-Bearing Fracture (Ft)	167	130	475	65	26
Water Level (Ft BLS.)	29.4	28	80	1	37

[a] Pumped Yield values are taken at the end of a constant-discharge pumping test of at least 24 hours duration.
[b] Specific Capacity values applied to wells that had been pumped for at least 8 hours and that had fracture depth information.

Groundwater Chemistry

Available groundwater samples taken from wells in the Candler Formation are predominately of the calcium –magnesium-bicarbonate type, with a small number of samples trending toward the calcium-magnesium-sulfate type and the sodium-bicarbonate type. Groundwater within the Candler Formation is usually soft and slightly acidic, however hard water and elevated ionic calcium levels do occur, and may be related to the local presence of calcium carbonate in the rock and or the fine grained and more soluble nature of some of the lithologies in the Candler. Table 25 provides statistical summaries for the general physical properties, major ionic concentrations, and concentrations of secondary constituents, nutrients, and radiochemical constituents of groundwater samples taken from wells and springs in the Candler Formation.

Figure 42 is a piper diagram illustrating the relative concentrations and distributions of major ions in balanced groundwater samples (total anoin milliequivalents are within 10% of total cation milliequivalents) collected from 10 different wells within the Candler Formation. Major cations usually range between 60-80% calcium+magnesium and 20-40% sodium+potassium. Typical ranges for major anions are 10-40% chloride+fluoride and sulfate and 60-90% bicarbonate+carbonate with almost all of the bicarbonate+carbonate fraction being bicarbonate.

Table 25. Summary of geochemical parameter values for groundwater samples taken from wells and springs in the Candler Fm.

[˚C, degrees Celsius; ˚F, degrees Fahrenheit; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; P, phosphorous; µg/L, micrograms per liter;"--" indicates no available data]

Constituent	Mean	Median	Maximum	Minimum	Number of Observations
Physical Properties					
pH (standard units)	6.79	6.65	8.90	5.30	36
Temperature (˚C)	--	--	--	--	--
Temperature (˚F)	--	--	--	--	--
Specific conductance (µS/cm at 25˚C)	123	79.0	435	18.0	35
Filtered residue (mg/L)	119	117	293	32.0	15
Hardness (mg/L as $CaCO_3$)	75.1	44.0	194	2.40	18
Major Cations					
Calcium (mg/L)	18.3	15.3	72.0	1.00	18
Magnesium (mg/L)	4.06	3.00	18.7	1.00	30
Sodium (mg/L)	7.47	4.96	41.0	0.94	34
Potassium (mg/L)	1.26	1.00	4.20	0.30	18
Major Anions					
Bicarbonate (mg/L as HCO_3)	68.3	39.0	244	0.60	35
Sulfate (mg/L)	9.44	4.00	54.0	2.00	17
Chloride (mg/L)	6.00	4.70	22.4	0.50	33
Nutrients					
Nitrate (mg/L as N)	0.81	0.09	10.2	0.04	18
Ammonium (mg/L as N)	0.09	0.10	0.10	0.04	18
Phosphate (mg/L as P)	0.02	0.01	0.01	0.12	18
Secondary Constituents					
Silica (mg/L)	--	--	--	--	--
Aluminum (µg/L)	39.0	20.0	119	0.80	19
Iron (µg/L)	1,260	140	11,000	20.0	19
Manganese (µg/L)	113	40.0	540	6.00	35
Arsenic, total (µg/L)	1.00	1.00	1.00	1.00	2
Bromide (mg/L)	0.05	0.05	0.14	0.01	13
Fluoride (mg/L)	0.11	0.08	0.45	0.01	16
Radiochemical Constituents					
Uranium (µg/L)	0.40	0.02	6.14	<0.01	17

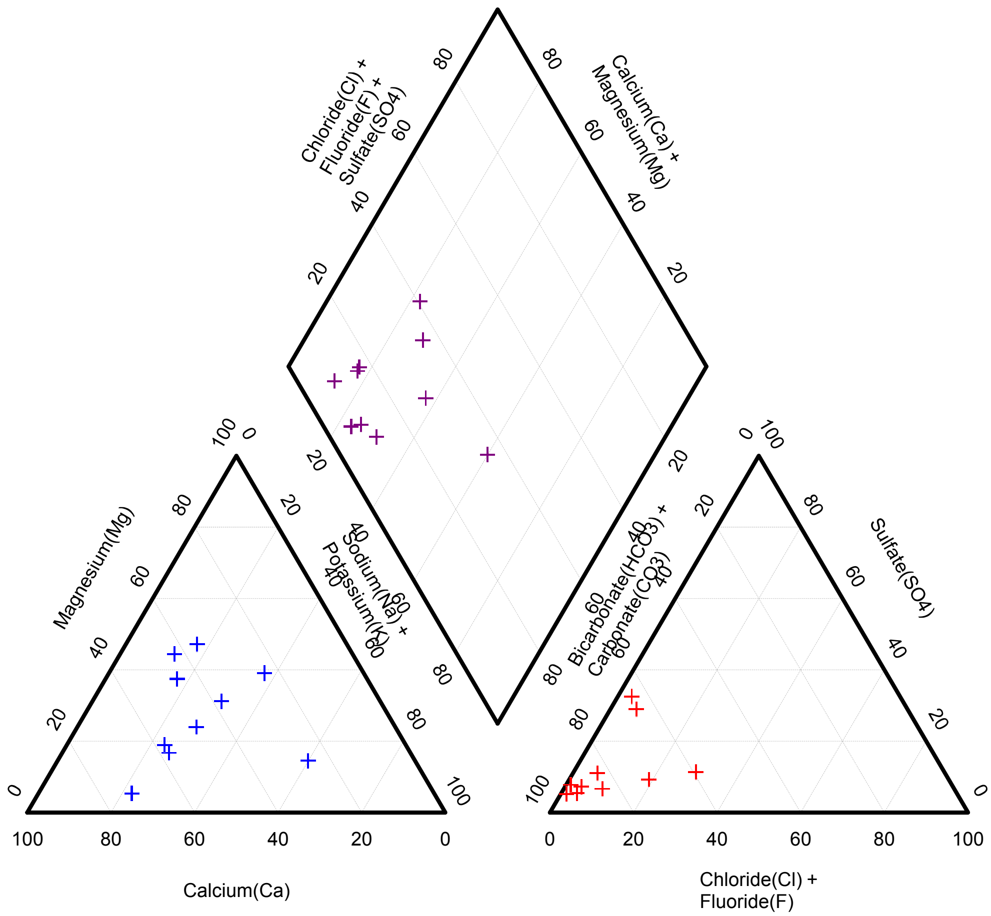


Figure 42. Piper diagram illustrating the relative distributions of major ions from groundwater samples collected from 10 different wells within the Candler Formation.

Everona Limestone

Figure 43 is a map depicting the location and extent of these rocks within the study area, and the location and distribution of wells used to document the hydrogeologic and groundwater geochemical characteristics of the Everona Limestone. Figure 44 provides photographs of outcrop within the Everona Limestone.

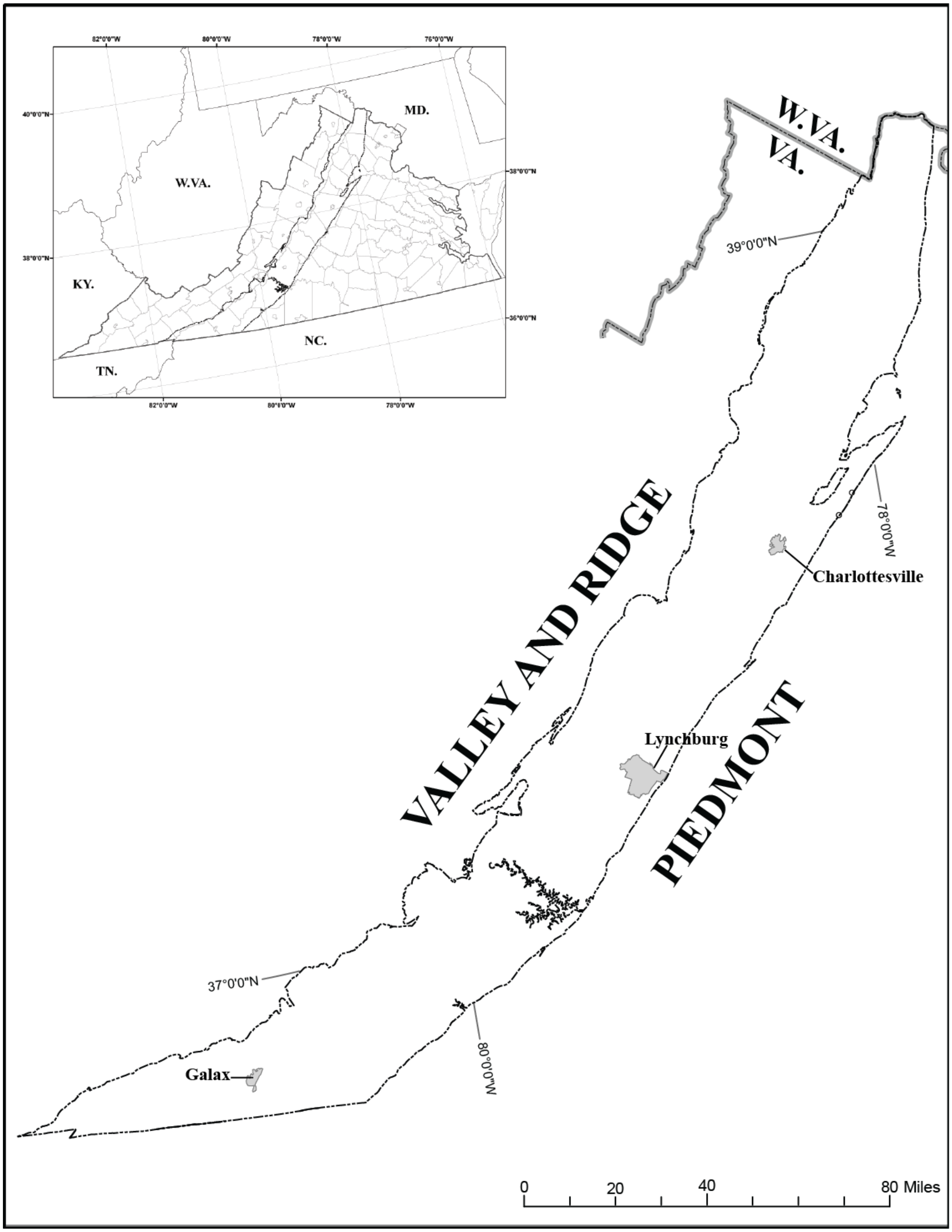


Figure 43. Extent and distribution of the Everona Limestone within the Blue Ridge Geologic Province (geology modified from VDMR 1993 State Geologic Map) and distribution of georeferenced wells used to generate hydrogeologic and geochemical descriptions.

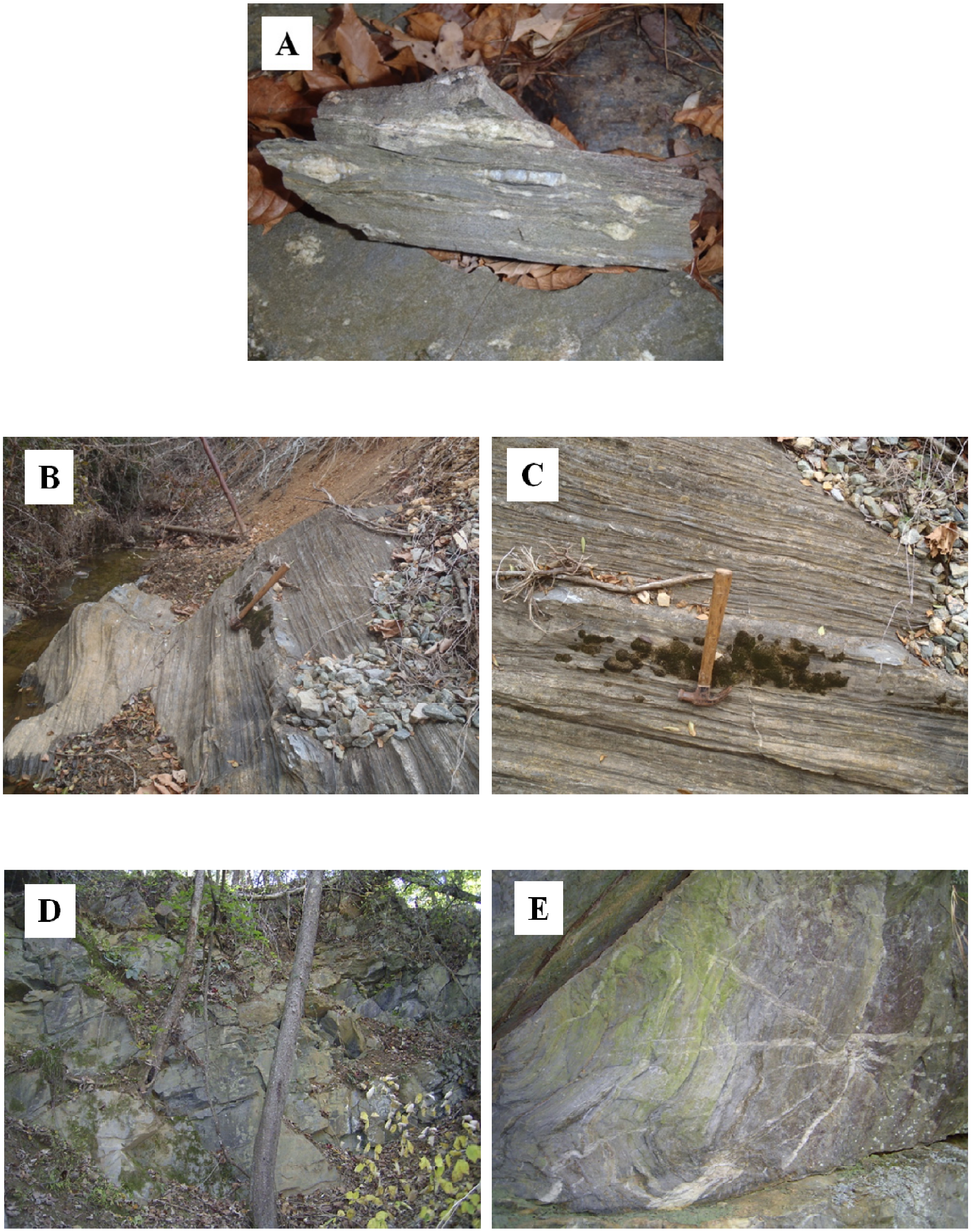


Figure 44. Photographs of the Everona Limestone – Blue Ridge Cover Sequence. A)Blue limestone 'float' in vicinity of abandoned quarry in Everona, Orange County, Va.. Abundant quartz and calcite stringers parallel to bedding.; B) Banded limestone of the Everona Formation in Railroad cut near Gordonsville in Orange County, Va. - photo oriented along strike of beds. ; C) Banded limestone of the Everona Formation in Railroad cut near Gordonsville in Orange County, Va. - photo oriented perpendicular to strike of beds. D) Fractured limestone in abandoned Hart Quarry near Woodridge, in Albemarle County, Va (outcrop).; E) Fractured limestone in abandoned Hart Quarry near Woodridge, in Albemarle County, Va. Note folded beds and abundant calcite veins cutting folds. Small displacements are evident along fold hinge in lower left section of photo.

Geologic Description and Hydrogeologic Characteristics

The Everona Limestone is a narrow ribbon of fine grained, gray-blue, (typically) laminated limestone occurring as discontinuous lenses along and near the top of the Candler Formation, extending from the Rockfish River in southern Albemarle County northeastward along the strike of the eastern margin of the Blue Ridge Anticlinorium to the southeastern onlap of Triassic sedimentary rock of the Culpeper Basin near Burr Hill, in Orange County (Mack, 1965; Pavlides, 1993). North of this onlap, the Everona is obscured by Triassic Sediments until very near its terminus near Kelly's Ford on the Rappahannock River in Fauquier County. Although Mack's delineation of the Everona Limestone extended northward to the Potomac River (Mack, 1965), the stratigraphic position of the northern section of the Everona Limestone (north from the Vicinity of Waterloo, in Culpeper County) described by Mack indicates that these rocks are late Proterozoic instead of Cambrian. Rocks in this northern section described by Mack are designated on the Virginia 1993 State Geologic Map as marble occurring at or near the contact between the Catoctin Formation and the late Proterozoic metasedimentary rocks. Smaller and more discontinuous lenses of limestone and marble in a similar stratigraphic position to the Everona Limestone have been mapped as far south as Lynchburg (Brown, 1958; Henika, 1997).

The Everona ranges in thickness from several feet in the northern and southern reaches to an estimated thickness of 1,500 feet in the central portions of the belt near Gordonsville, Virginia (Mack, 1965). Pavlides (Pavlides, 1993) theorized that the discontinuous nature of the Everona was due to both depositional and tectonic phenomena, and stated that the Everona Limestone was likely deposited in lenses that were subsequently pulled apart in places during pre-Mesozoic deformation.

Lithologic descriptions of the Everona provided by Mack (Mack, 1965), Pavlides (Pavlides, 1993), and Evans (Evans, 1994) indicate that the Everona Limestone can be massive to slaty in appearance, and that lithologic characteristics can change abruptly within the stratigraphic sequence. Fracturing within the slaty lithologies occurs primarily as parting along, and fracturing normal to schistosity. Fracturing within the more massive sections occurs primarily via jointing. In places, massive sections of the Everona are heavily fractured, and much of the Everona Limestone hosts occluded calcite veins and shears which bear testament to the active and complex tectonic history along the eastern margin of the Blue Ridge Anticlinorium.

The presence of several high yielding wells in the Gordonsville area (Louisa and Orange Counties) within and in close proximity to the mapped extent of the Everona indicate that the Everona Limestone can be a productive drilling target. The highest yielding well completed in the Everona Limestone according to available records, was Process Well 1, drilled at the Klockner Pentaplast Manufacturing Facility in Louisa County, Virginia. The Boswells Tavern 1:24000 Quadrangle Geologic Map (Rossman, 1991) indicates that this well was drilled in a heavily sheared phyllonite, a few hundred feet to the east of the inferred location of the Mountain Run Fault separating the easternmost limits of the Blue Ridge cover sequence from the Western Piedmont Terrane. However, the drilling log for this well notes the presence of blue slate from 95 to 245 feet closely resembling the description of the slaty limestone given by Pavlides (Pavlides, 1993) and the graphite slate with limestone interbeds unit described by Evans (Evans, 1994). The calcium content of the water sample associated with this well was 57.6 mg/L, and the alkalinity in terms of bicarbonate was 174 mg/L; both good indications of a calcareous source rock within the groundwater system associated with this well. This well was drilled to a depth of 245 feet, and encountered water from a single fracture zone between 110 to 113 feet below land surface. Total depth to bedrock for this well was 93 feet below land surface. The reported yield for this well was 270 gallons per minute at the end of a 48 hour pump test. A second well (Process Well 2) was drilled by the same driller a few days later approximately 20 feet to the south of Process well 1 and yielded a reported 200 gallons/minute at the end of a 48 hour pump test. Brown slate was noted in the drilling log from 7 to 112 feet, and blue, brown, and white slate was noted from 112 to 120 feet. Total depth to bedrock for this well was 112 feet below land surface. Water was encountered in a fracture zone from 116 to 118 feet below land surface. Although it has not been documented, these wells are likely sourcing water from the same fracture system. Along the strike of the Everona Limestone a few miles to the northeast of the Klockner Pentaplast Wells, a high yielding well was drilled in 1972 by Sydnor at what was then the Doubleday & Company Facility. This well was 400 feet deep, had a reported yield of 150 gallons per minute with 51 feet of drawdown at the end of a 48 hour pump test, and was reportedly drilled through blue limestone for the entire depth (top of bedrock was at 40 feet). Although no water bearing zones were reported on the completion report, the well is screened between 117 and 140 feet, 164 and 188 feet, and between 234 and 259 feet. Although this well was a good producer, the well pumped muddy water for the duration of the 24 hour test, and the water analysis indicates an extremely elevated iron content.

The Everona Limestone is locally intensely deformed. Cambro-Ordovician thrust faulting, Mesozoic strike-slip faulting, and Cenozoic reverse faulting events have in places fragmented and brecciated the Everona Limestone (Pavlides, 1993). The deformational forces these competent rocks have been subjected to have established local fracture networks within the Everona, and may be the reason for the occurrence of at least a few productive groundwater zones within these rocks.

Table 26 summarizes some of the key construction details and hydrogeologic characteristics for the Klockner Pentaplast and Doubleday & Company Wells, and Table 27 summarizes geochemical information for groundwater samples associated with these wells.

Table 26. Selected well construction and hydrogeologic information for wells completed in the Everona Limestone.

[gal/min, gallons per minute; ft, feet; BLS, below land surface;"--" indicates no available data]

General Parameters	Klockner Pentaplast Process Well 1	Klockner Pentaplast Process Well 2	Doubleday & Company Well 1
Total Depth (Ft.)	245	120	400
Diameter (In.)	8	8	10
Depth to Bedrock (Ft.)	93	112	25.5
Yield after 24 or 48 hour pump test (Gal/Min)	270	200	150
Specific Capacity (Gal/Min/Ft Drawdown)	--	--	2.96
Depth of Water Bearing Zones (Ft.)	110-113	116-118	screen at 117-140, 164-188, 234-259

Table 27. Groundwater geochemical parameters for water samples taken from wells completed in the Everona Limestone.

[µS/cm, microsiemens per centimeter; ˚C, degrees celcius; mg/L, milligrams per liter; CaCO3, calcium carbonate; N, nitrogen; µg/L, micrograms per liter;"--" indicates no available data]

Parameter	Klockner Pentaplast Process Wells 1&2 (blended sample)	Doubleday & Company Well 1
pH (standard units)	6.76	7.32
Specific Conductance (µS/cm at 25˚C)	327	--
Filtered Residue (mg/L)	188	--
Hardness (mg/L as $CaCO_3$)	144	195
Major Cations		
Calcium (mg/L)	57.6	57.7
Magnesium (mg/L)	--	12.47
Sodium (mg/L)	7.22	--
Major Anions		
Bicarbonate (mg/L as HCO_3)	174	142
Sulfate (mg/L)	--	6.60
Chloride (mg/L)	9.00	5.00
Nutrients		
Nitrate as N (mg/L)	--	9.52
Secondary Constituents		
Iron (µg/L)	--	42,400
Manganese (µg/L)	--	1.17
Arsenic (total - µg/L)	--	1.00

HYDROGEOLOGIC PROPERTIES OF ROCK UNITS

Local geologic and morphologic features are the chief controls governing the storage and movement of groundwater within fractured crystalline rock. However, certain parameters associated with groundwater can be meaningfully compared at the regional level. Features that appear to have the greatest variation across the different rock types outlined in this report are intrinsic to the mineralogy and crystalline structure of the host rock, and are closely associated with weathering processes: these include depth to bedrock, well completion depth, the depth to water-bearing zones, and depth to water and all exhibit notable variation across the rock types described in this report. Specific capacity values and sustained well yield values also exhibited notable, but lesser variations across rock types and it is likely that at least some of these differences are related to the lack of statistically significant data for a number of classes, as well as to a biased distribution of data within smaller data sets (most data for some groups coming from one or two municipalities, or in the case of the mylonites, one well field).

A Kruskal-Wallis one-way analysis of variance (ANOVA) test (Kruskal and Wallis, 1952) was run to determine if there were any statistically significant differences at the 95% confidence level between major rock types for each hydrogeologic property. For hydrogeologic properties where Kruskal-Wallis ANOVA testing indicated a statistically significant difference for at least one rock type, a Dunn's multiple comparison test (Dunn, 1964) was run to test for statistically significant differences between all possible pairs of major rock types. Results from these tests are briefly summarized in the following paragraphs. Complete results from the non-parametric ANOVA and Dunn's multiple comparison testing are displayed in Appendix 1. Descriptive statistics for all evaluated hydrogeologic properties are shown in Table 28.

Well Depth

Once a suitable supply of water has been obtained, it is common to drill past the location of the lowest water bearing fracture to allow for sediment accumulation below the pump and for storage of water in the wellbore. In cases where the driller has encountered low yielding fracture(s) higher in the borehole, the well may be drilled as much as several hundred feet deeper than the lower limit of the groundwater source so that groundwater may be stored in the wellbore reservoir for later use.

The evaluation of median well depth provides some indication as to the expected depth of readily attainable groundwater in the various rock types of the Blue Ridge. Wells completed in the massive crystalline, granulitic, and mylonitic textures of the basement rock, as well as in the Candler Formation and the Lynchburg Formation and late Proterozoic shallow water facies groups within the cover rocks all have median well depths of approximately 250 feet or less (figure 45). Median well depths are closer to 300 feet for the remainder of the lithologies. Statistically significant differences were found to occur between pairs within all rock types, and agree well with empirical observations of the box plots in figure 45. Wells completed in the Candler Formation had the greatest number of statistically significant differences when compared to wells completed in other rock types (8 of 9 pairs), and have the lowest median well depth (225 Ft.). Wells completed in the Alligator Back Formation shared the highest median well depth (300 Ft.) with wells completed in 3 other rock types (AMS, Catoctin Fm., and Chihowee Group), but had the highest number of statistically significant differences between these deeper groups (6 of 9 pairs). Statistically significant differences between a large number of pairs (27 of 45, or 60%) indicate that well depth is variable between rock types.

Lower median well depths within a particular rock type are indicative of the tendency for water bearing fractures to occur higher in the wellbore which often prompt the termination of drilling, especially if particularly high well yields are not needed. Shallower median well depth values do not necessarily indicate an absence of deeper groundwater flow – especially for the massive crystalline lithologies. Much of the well depth data evaluated for this report comes from domestic well reports where well drilling is often terminated shortly after the first appreciable water bearing zones are encountered.

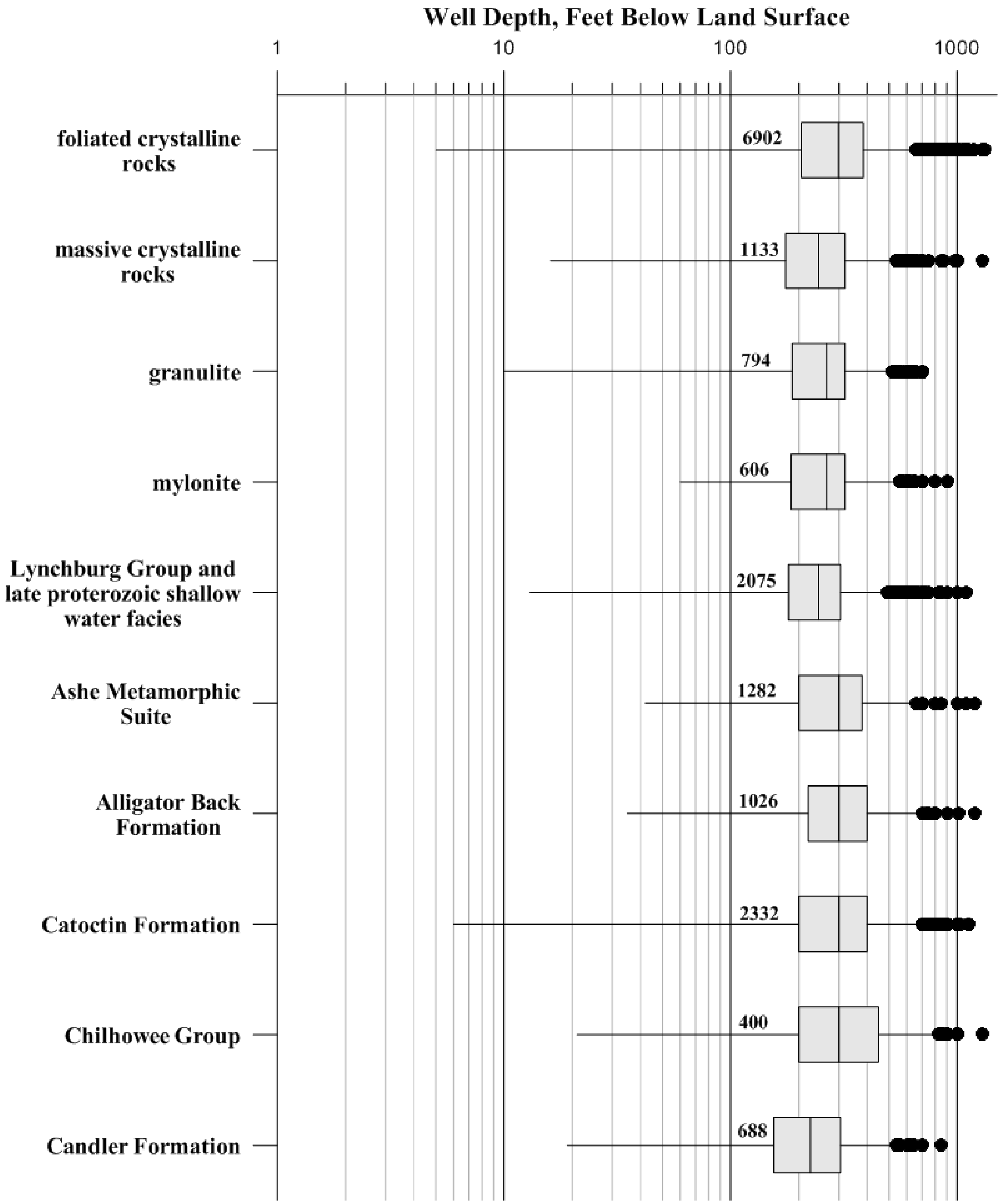


Figure 45. Distribution of well completion depth by rock type. Numbers denote number of observations occurring within each rock type.

Depth to Bedrock

Holding all other variables related to groundwater storage in regolith constant (local hydraulic gradients, storage capacity, precipitation, relict structural features), potential for groundwater storage in thicker regolith intervals is higher due to the obvious volumetric increase in the storage material. Swain, et.al. (1991) noted a positive relationship between median well yield and regolith thickness for the rocks in the Appalachian Valleys-Piedmont Regional Aquifer System Analysis (APRASA) study area.

Median regolith thicknesses vary by 35 feet between the lowest and highest median values among the rock types described in this report (figure 46). The Ashe Metamorphic Suite and Alligator Back Formation of the Southern Blue Ridge have the highest median regolith thicknesses of 57 and 58 feet respectively, and have statistically significant differences in regolith thickness with all other rock types. This characteristically deep weathering may be significant enough to have a regional influence on stream baseflow trends. A statistically significant difference was noted in median stream baseflow variability between the northern and southern Blue Ridge in the USGS Water Supply Paper 2457 (Nelms et al., 1997). The authors cited differences in structural controls on groundwater storage between the northern and southern sections of the Blue Ridge as a possible explanation, and it is possible that regional structural trends in the Southern Blue Ridge have played a significant role in the promotion of deeper weathering of the Ashe and Alligator Back formations. Weathering depths to bedrock tend to be shallower within the core of the Blue Ridge Anticlinorium – median depths to bedrock range between 23 and 25 feet for the foliated and massive crystalline rocks. These rock types show statistically significant differences in regolith thickness when compared to all other rock types, with the exception of the Candler Formation. Median weathering depths in the rocks flanking the anticlinorium (cover sequences), and the layered granulites and mylonites of the Blue Ridge basement range between 30 to 40 feet, with the meta-sedimentary formations of the Chilhowee Group tending to weather more deeply than the Lynchburg, Candler, or Catoctin formations.

Multiple comparison testing showed statistically significant differences in regolith thickness for 62% of the rock type pairs, and indicates that weathering depths are variable throughout the Blue Ridge Geologic Province. Although rock type (mineralogy) is a factor in controlling rates and depths of weathering, it is not the only factor. Regolith thickness in crystalline rock has been observed to be on average, thicker on hilltops than on side slopes and in drainage features (Johnston, 1962, 1964). Local variations in precipitation and temperature can also have large influences on erosion rates and depths of weathering.

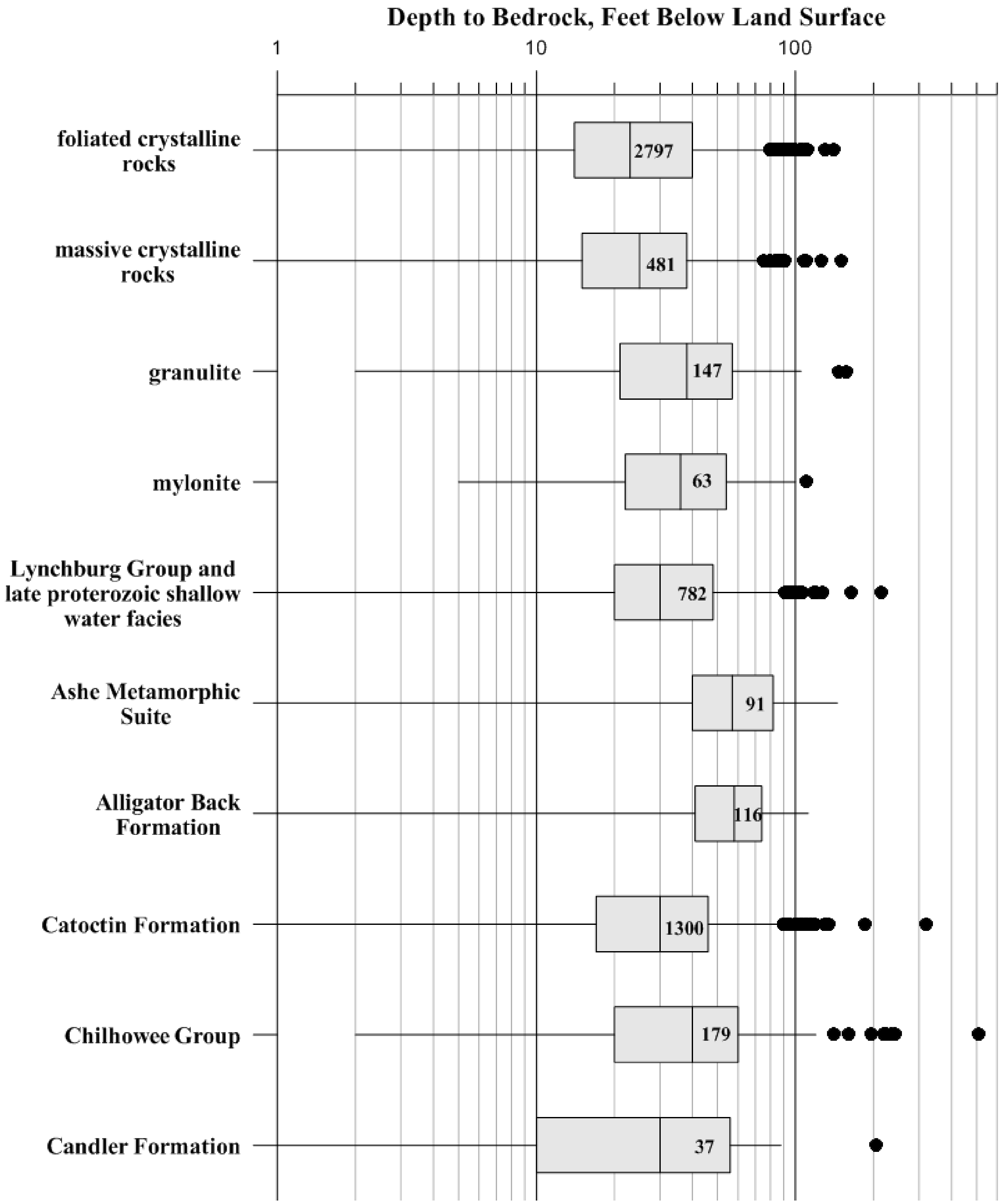


Figure 46. Distribution of depth to bedrock by rock type. Numbers denote number of observations occurring within each rock type.

Water Level

Groundwater levels are dependent on topographic position, recharge rates, and the geometry and structure of the groundwater flow system. On a regional scale, water level data provide some indication about the depths of groundwater circulation, and when taken in context with a reference datum (such as depth to bedrock), can provide clues about the dynamics of groundwater flow systems occurring within the various rock types or formations within the Blue Ridge Geologic Province.

Figures 47 and 48 display distributions of water levels in wells by rock type, and graphically show the variability in hydraulic head with respect to bedrock depth. These plots were generated by subtracting the reported depth to bedrock from the reported static water level – the result gives groundwater elevation with respect to bedrock depth as the reference datum. Assuming that water table (unconfined) conditions exist in the regolith for the majority of these wells and that reported water levels are representative of head values in the bedrock fractures, negative values on these plots indicate an unknown degree of overlap between unconfined head values in the regolith, and the potentiometric surface of the fractured bedrock groundwater system. Because the elevation of local water table conditions are not known from water well completion reports (depth to water in the regolith is not specified on well completion reports for drilled bedrock wells), any degree of overlap could indicate weak to moderate upward to weak to moderate downward hydraulic gradients between local water table conditions and the fractured bedrock system. More positive numbers on these plots indicate a stronger downward hydraulic gradient between local inferred water table conditions and the fractured bedrock system, and could also mean that the hydraulic conditions in the regolith are not well connected to the hydraulic conditions in the fractured bedrock system. Because many of these reported water levels were recorded shortly after drilling, positive (downward) values are likely over reported.

Figure 49 presents ranges in reported groundwater levels by rock type. Rocks of the Alligator Back Formation have the deepest median groundwater level value, and show the highest frequency of statistically significant differences with other rock types (6 of 9 pairs). Median groundwater levels are slightly deeper in the Ashe Metamorphic Suite and the Chilhowee Group (40 feet). Median groundwater depths for rock types in the northern section of the Blue Ridge are the shallowest, and fairly uniformly distributed (at or near 30 Ft. BLS).

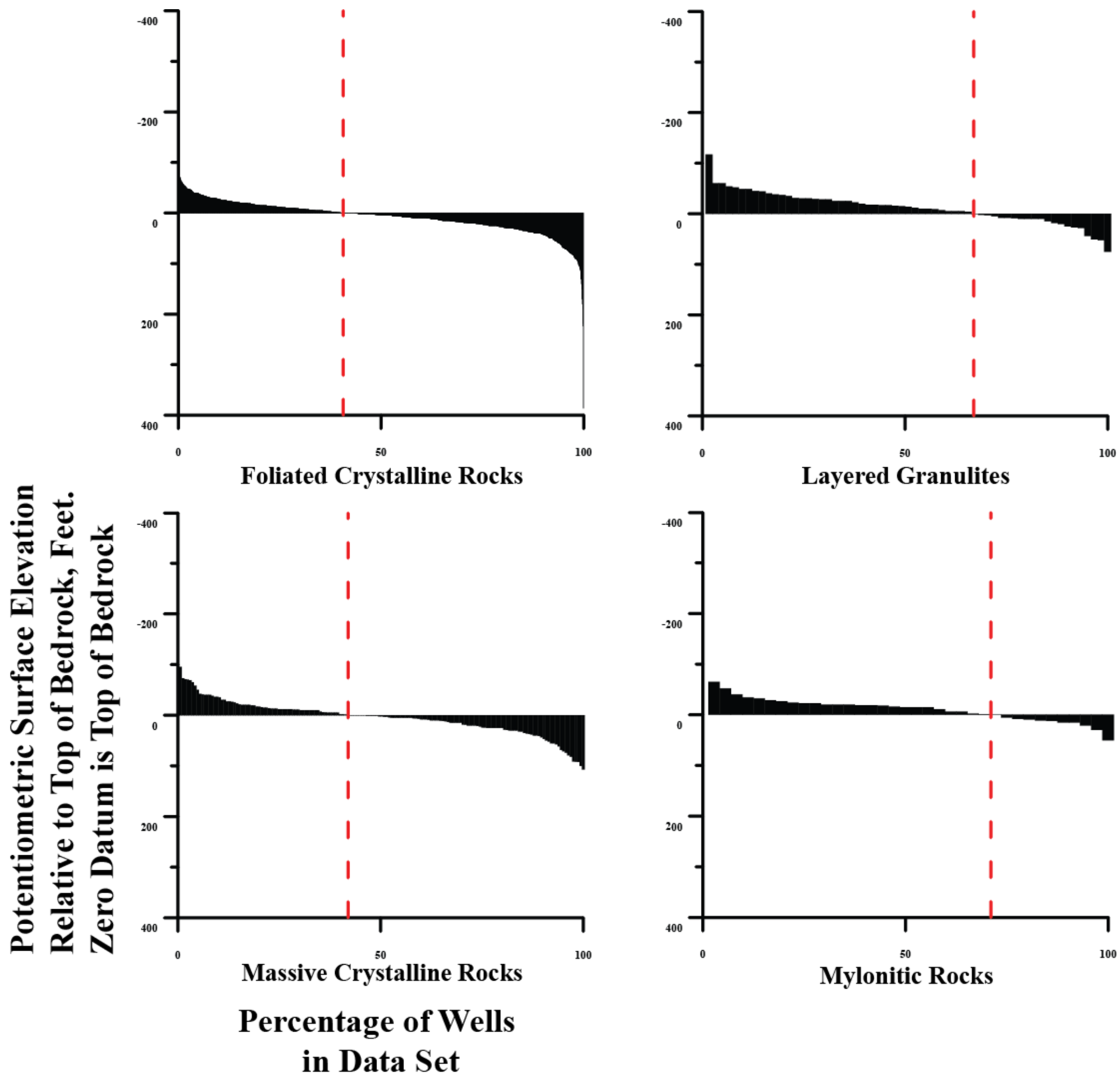


Figure 47. Potentiometric surface elevation relative to top of Bedrock, Feet. Zero datum is top of bedrock, dashed line designates groundwater level even with the top of bedrock: Blue Ridge Basement Rocks.

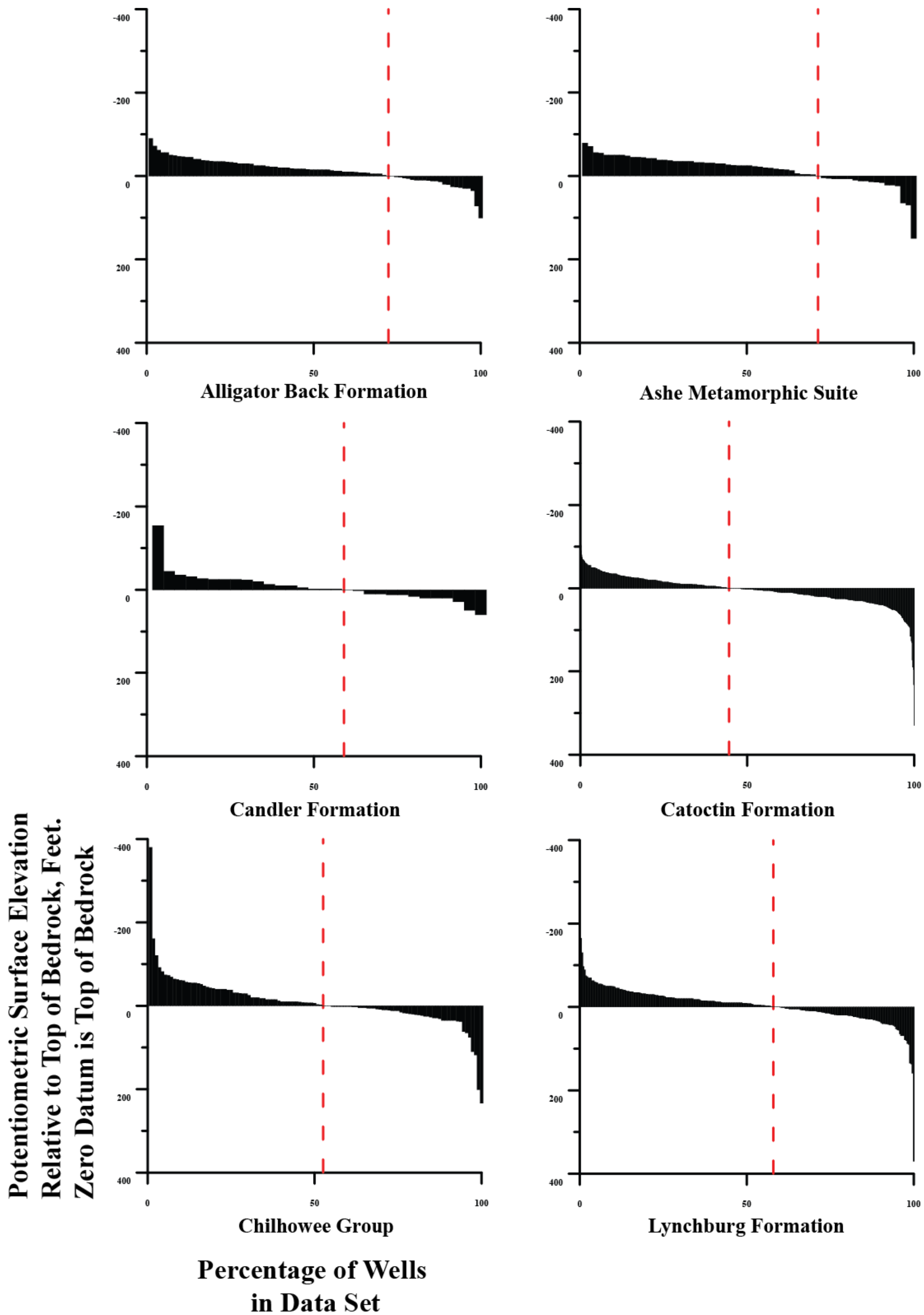


Figure 48. Potentiometric surface elevation relative to top of Bedrock, Feet. Zero datum is top of bedrock, dashed line designates groundwater level even with the top of bedrock: Blue Ridge Cover Rocks.

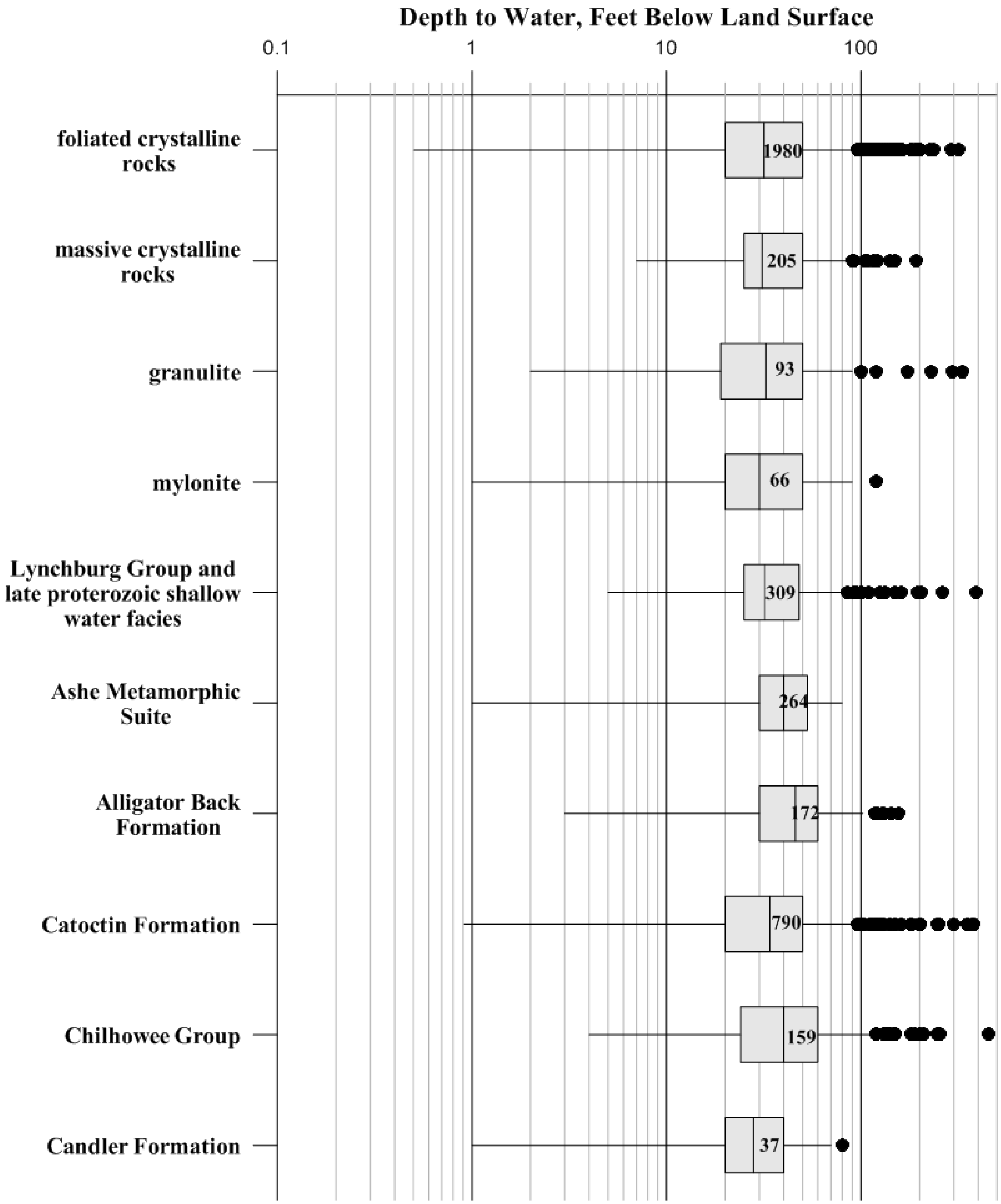


Figure 49. Distribution of depth to water by rock type. Numbers denote number of observations occurring within each rock type.

Depth to First Water Bearing Fracture

The depth to the first water-bearing fracture demarcates the uppermost portion of the groundwater flow system where it is intersected by the well in the fractured rock. Although there are little data available about the depth to the first water bearing zone and its relation to topographic position in the Blue Ridge Physiographic Province, authors have observed that median well depths on hilltops tended to be deeper than for wells drilled on slopes or topographic lows, and that median well depths for wells drilled in topographic lows tended to be the shallowest of the 3 topographic positions (Johnston, 1962; Legrand, 1960). These and other authors have noted that linear features coincident with local topographic lows such as draws and valleys can be the surface expressions of zones of concentrated fracturing where near surface fracturing in crystalline bedrock is likely to occur. In the highly stratified rocks of the Great Valley, Nelms and Moberg (Nelms and Moberg, 2010a) noted an opposite trend in the topographic position of the water table and attributed the occurrence of more shallow depths to water bearing zones to the presence of recharge areas along topographic divides, and the occurrence of greater depths to the first water bearing zone in draws and valleys to the structural controls imparted by down-dip features of highly stratified rocks. Although this has not been documented in the more stratified rocks (cover rocks) of the Blue Ridge Geologic Province, such trends are plausible.

Chemical and structural controls on bedrock weathering depths, rates, and styles are substantial influences on the depth of occurrence of the first water bearing zone. Examples of how the structure and mineralogy of a rock influence the formation of water bearing fractures include weathering within and along zones of altered mineralogy and or deformation (parting along schistosity, fractures within and adjacent to zones of deformation) and fracturing due to mechanical stresses imparted to the rocks such as vertical and sheet jointing or mechanical weathering processes.

Figure 50 displays the distribution of depth to first reported water bearing fracture for the rock types discussed in this report. Depths to first water bearing fracture in the rocks of the Chilhowee Group, foliated crystalline rocks, and the Catoctin Formation had the highest number of statistically significant differences between rock type pairs, and had the deepest median depth values (between 150 and 165 feet). Median values for depth to first water bearing fracture for other rock types ranged between 95 and 140 feet, with statistically significant differences occurring between the highest and lowest median values for these rocks (massive crystalline rocks and mylonites).

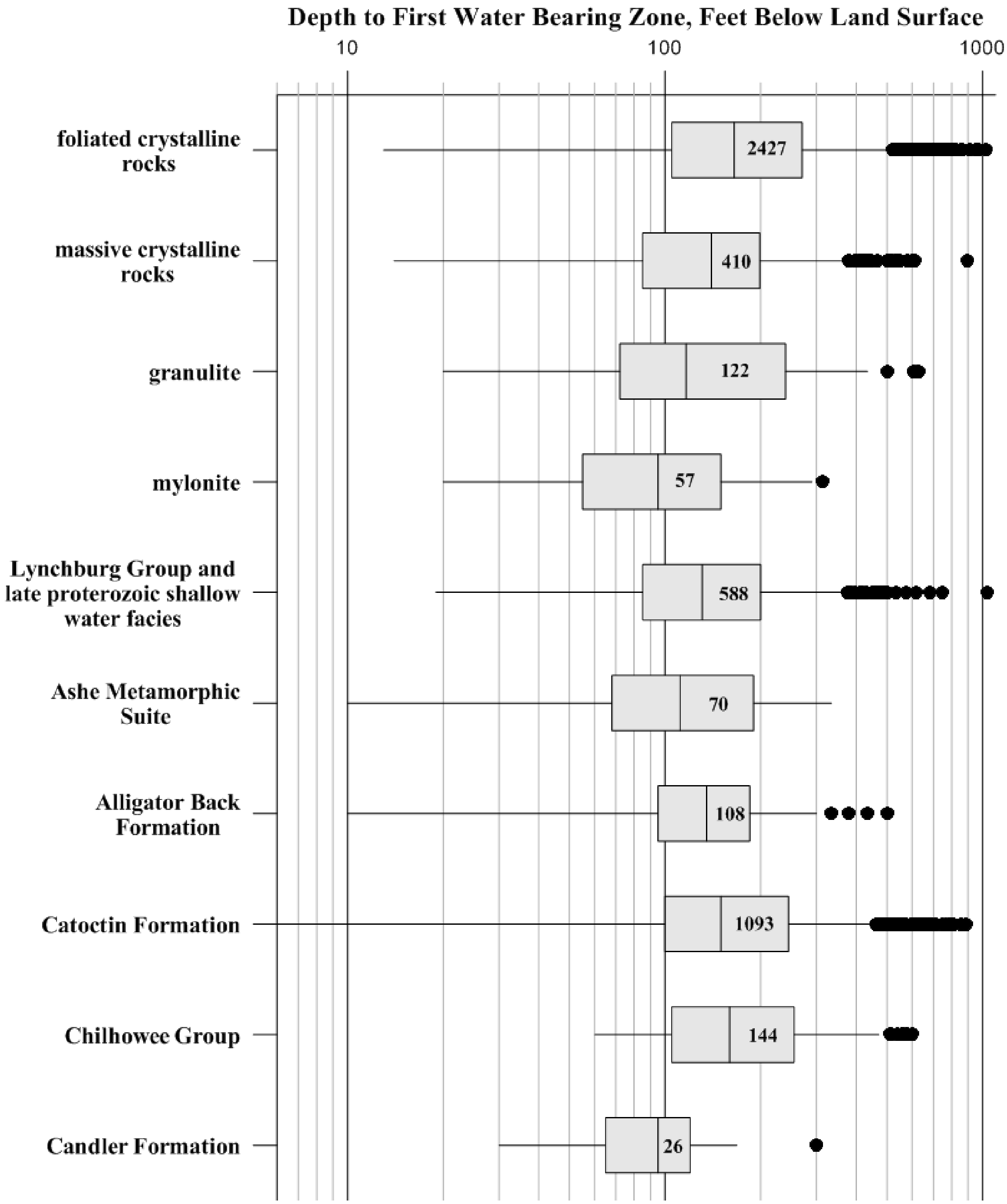


Figure 50. Distribution of depth to first water bearing zone by rock type. Numbers denote number of observations occurring within each rock type.

Depth to Lowest Water Bearing Fracture

Ranges between the median depth to first water bearing zone and median depth to lowest water bearing zone were less than 100 feet for all rock types. Such narrow ranges in median depths to top and lowest fractures indicate that water bearing zones often occur over closely spaced intervals within the first 250 feet of wellbore, and that adequate supplies of water for domestic use are typically encountered within this interval. Although lower fracture depth values are biased toward requirements for meeting domestic demands for water, numerous fractures at depths below 300 feet for all rock types are present in the data, and indicate that the groundwater resource is persistent at and below the 300 foot depth.

Available records indicate the presence of water bearing zones at depths exceeding 1,000 feet for several wells in the Blue Ridge Basement and for one well in a highly metamorphosed paragneiss. It is likely that there are wells with water bearing zones in excess of 1,000 feet scattered throughout the Blue Ridge, but reported water bearing zones for such depths are rare, due in part to the infrequency of drilling to such depths.

Figure 51 displays the distribution of depth to lowest reported water bearing fracture. As with median depth to first water bearing zone, foliated crystalline rocks, rocks of the Chilhowee Group, and rocks of the Catoctin formation had the highest number of statistically significant differences between pairs, and had the deepest median depth values to the lowest water bearing zone (ranging between 235 and 260 feet). Median values for depth to lowest water bearing zone ranged between 207 and 130 feet for the remainder of the rock types, with a slightly higher number of statistically significant differences occurring between the deeper and shallower values for those rocks.

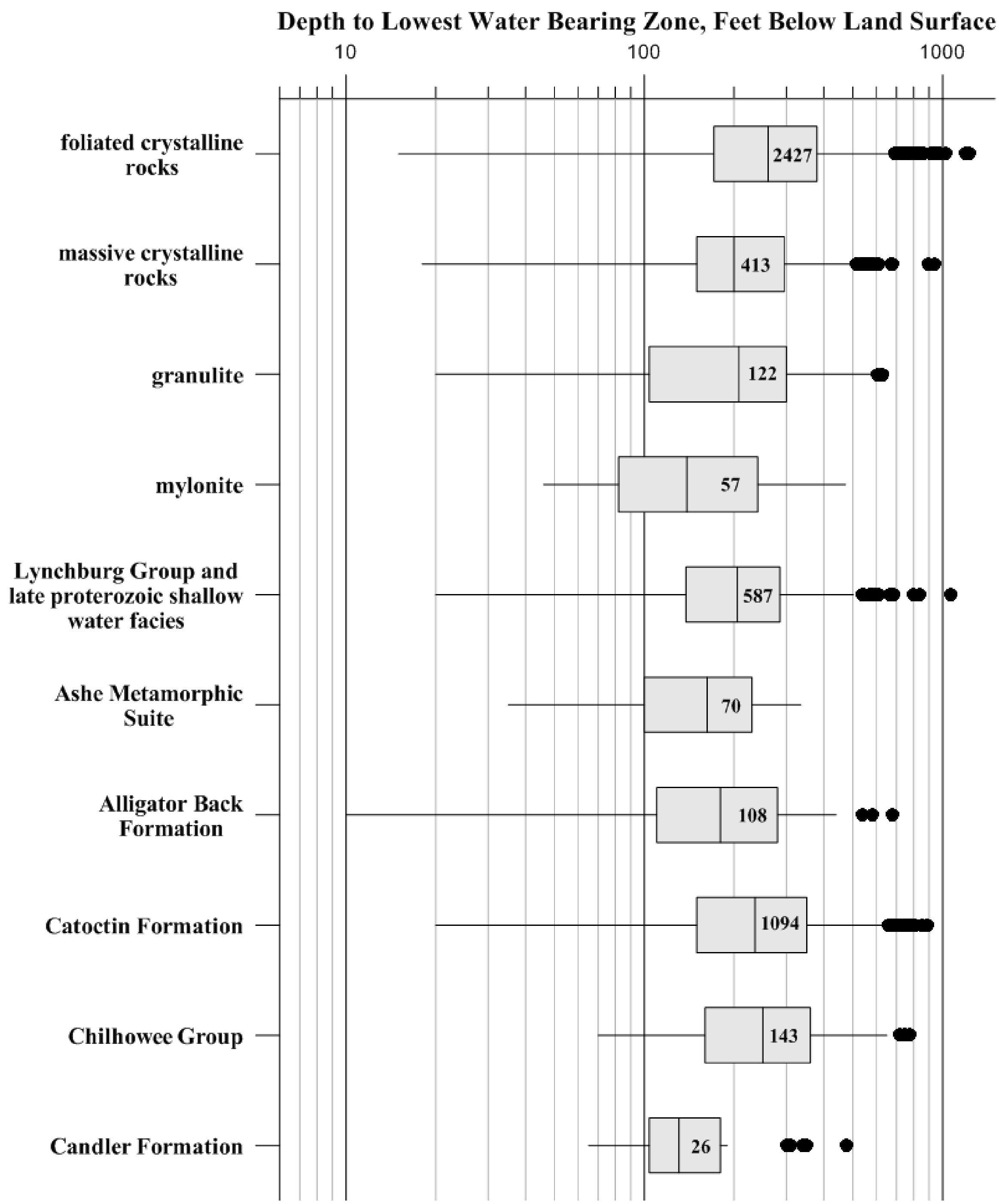


Figure 51. Distribution of depth to lowest water bearing zone by rock type. Numbers denote number of observations occurring within each rock type.

Estimated Yield, Non-Domestic Wells

Estimated well yield trends for non-domestic wells are useful for evaluating the propensity of a particular rock type to harbor productive groundwater systems. Because yields associated with non-domestic wells are often the end result of construction techniques employed to maximize well yield and reconnaissance efforts taken to locate favorable local groundwater production zones, these values can provide a realistic range of estimates of the potential for a particular rock type to yield groundwater. Although there is some variation among the groups for this category, median values for estimated non-domestic well yield are well within the same order of magnitude, as are the interquartile ranges. No statistically significant differences in non-domestic well yields occurred between rock types. This trend indicates that fracture systems across rock types at a regional scale in the Blue Ridge have about the same potential for yielding water, and it is the local occurrences of increased fracture density and fracture distribution that are primarily responsible for the occurrence of productive groundwater systems in the Blue Ridge Geologic Province. Figure 52 displays the percent of non-domestic wells in each rock type with estimated well yields equal to or greater than 20gallons/minute, 50 gallons/minute, and 100 gallons/minute, respectively. These data indicate that while trends are similar, on a regional level mylonitic and granulitic basement rocks may have the most frequent occurrence of productive (greater than 50 gallons/minute) water bearing fracture systems and in the cover sequences, rocks of the Lynchburg Formation and late Proterozoic shallow water facies and the rocks of the Ashe Metamorphic Suite appear to have higher incidence of favorably yielding water bearing fracture networks. The phyllitic rocks of the Candler Formation stand out as being the least productive rocks in the Blue Ridge Geologic Province. Figure 53 displays the distribution of reported well yield for non-domestic wells for the rock types discussed in this report.

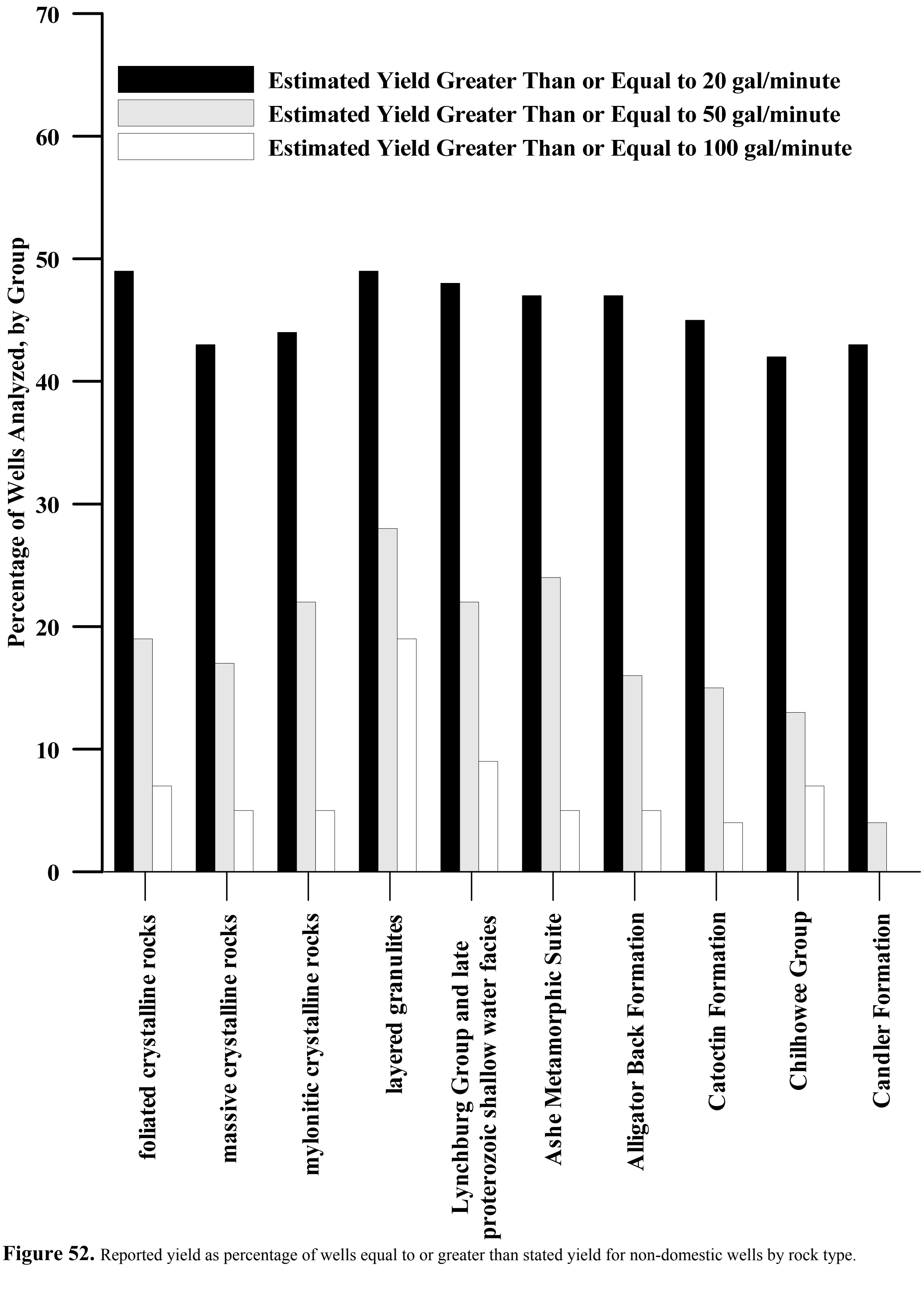


Figure 52. Reported yield as percentage of wells equal to or greater than stated yield for non-domestic wells by rock type.

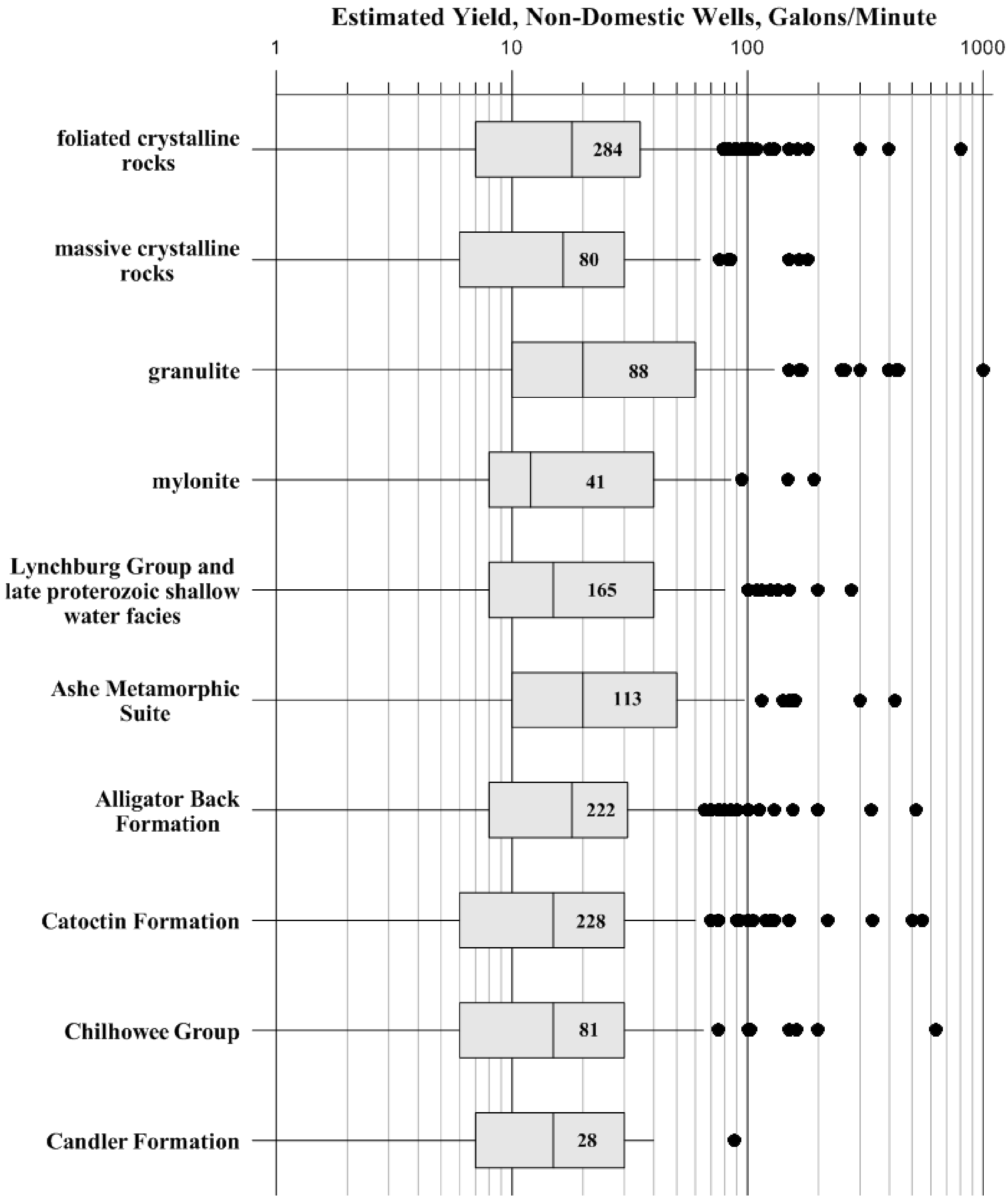


Figure 53. Distribution of estimated non-domestic well yield by rock type. Numbers denote number of observations occurring within each rock type.

Pumped Well Yield, Non-Domestic Wells

Pumped well yield derived from long term pump testing is an indicator of long-term well performance, and provides a means for assessing the capacity of a local fracture network to sustain a well. Pumped well yield values from 24 hour or greater duration pump tests on non-domestic wells were compiled and analyzed. Statistically significant populations were not available (at least 20 pump test results) for 6 of the 10 formations or textural/lithologic classes, but were reported as box plots if there were at least 10 values (figure 54). Among the groups with statistically significant populations, median values for sustained well yield varied between 19 and 30 gallons/minute, with interquartile ranges typically between 10 and 50 gallons/minute. Wells within the Alligator Back Formation had a slightly wider range in interquartile values, ranging between 4 and 50 gallons/minute. More long term pump test data are needed to establish statistically meaningful values for sustained well yields in the massive crystalline rocks, mylonites, granulites, Ashe Metamorphic Suite, Chilhowee Group, and Candler Formation. Non-parametric one-way ANOVA testing of pumped well yield among the viable populations yielded no statistically significant differences between populations.

Specific Capacity

Specific capacity data are used to numerically describe the efficiency of wells completed in local groundwater systems. Specific capacity is usually expressed as yield in gallons per minute per foot of drawdown and is obtained by dividing the stabilized yield of a well after pumping for a given time by the total drawdown in the well. Values of specific capacity were used in this report only if the pumping duration prior to the acquisition of the recorded drawdown and yield values for the well was at least 8 hours, and the locations of the water bearing zones were known. In the cases of wells where the pumping water level was drawn down below the bottom of the lowest reported water bearing zone, total drawdown was corrected to reflect the difference between initial static water level and the bottom of the lowest water bearing zone so as not to under report the true water bearing capacity of the rock at a particular well. Statistically significant data (at least 20 values) were compiled for 5 of the 10 rock types, and there appears to be variation both in median values of specific capacity as well as variation in the interquartile ranges among the statistically significant groups (figure 55). Ranges in median values of specific capacity for the statistically significant groups vary from 0.16 to 0.63 gallons/foot of drawdown. Interquartile ranges for statistically significant groups range from 0.2 to 1 log units. The effects of well diameter and pumping period on specific capacity were not examined by rock type in this analysis because statistically significant data were already limited, but these parameters are recognized as substantial influences on specific capacity. Despite the empirical observations of variation in specific capacity between rock types, non-parametric one-way ANOVA testing of specific capacity among the viable populations yielded no statistically significant differences between populations. Additional specific capacity data are needed to more effectively describe potential differences among rock types for this hydrogeologic characteristic.

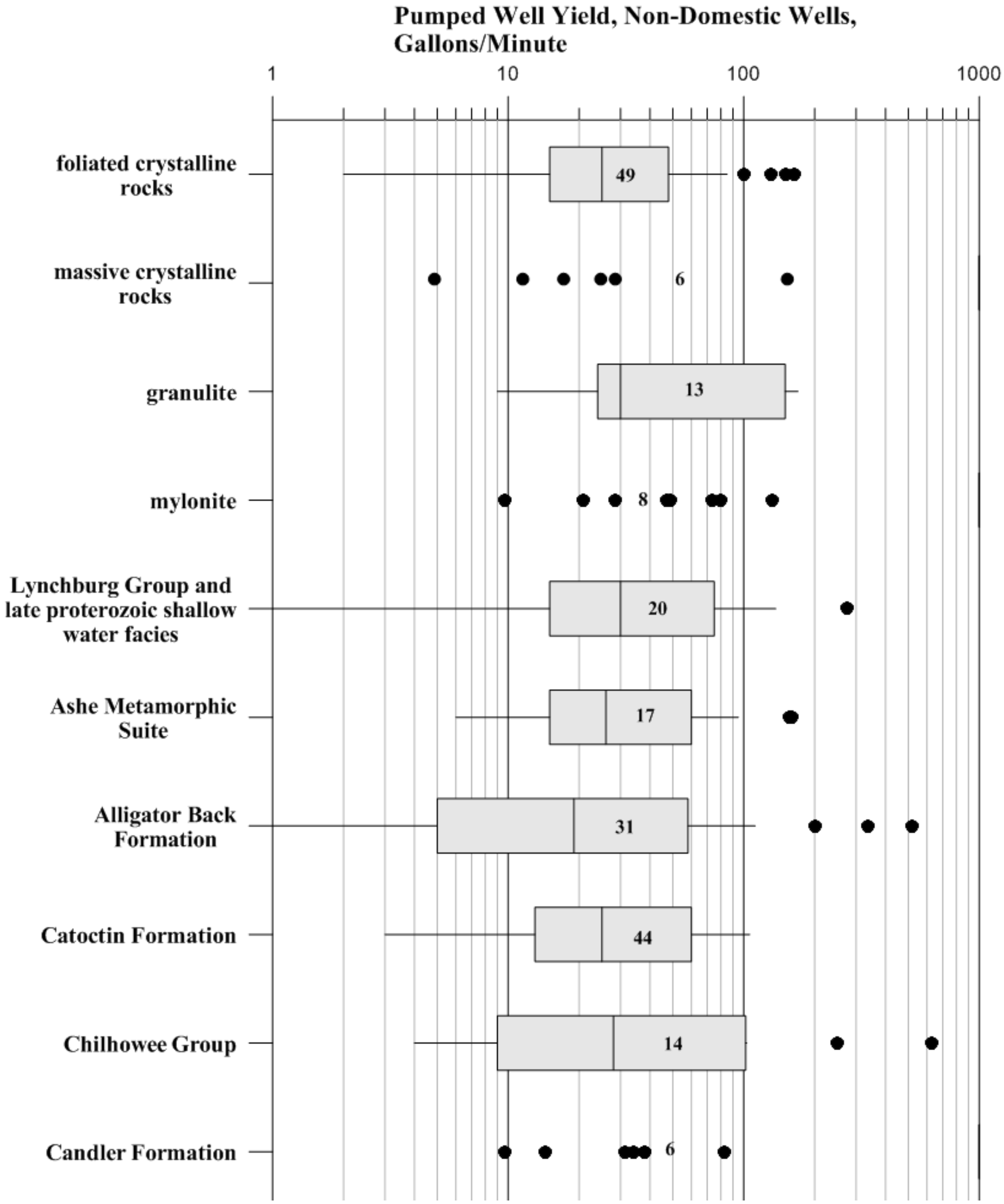


Figure 54. Distribution of pumped well yield by formation. Numbers denote number of observations occurring within each rock type.

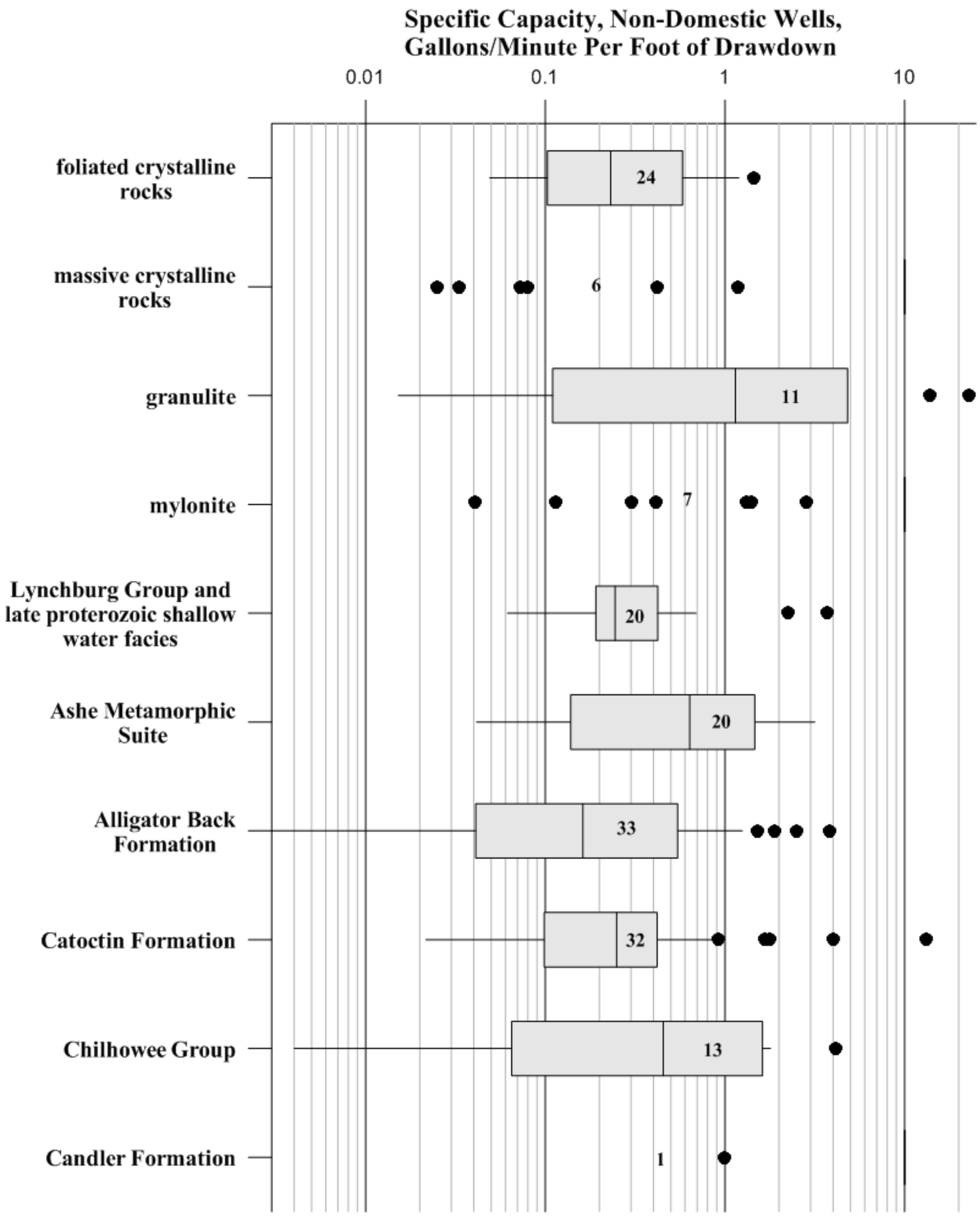


Figure 55. Distribution of specific capacity by rock type. Numbers denote number of observations occurring within each rock type.

Table 28. Hydrogeologic characteristics of wells completed in the Blue Ridge Geologic Province.

	Well Completion Depth				
Rock Type	**Mean**	**Median**	**Maximum**	**Minimum**	**Number of Observations**
foliated crystalline rocks	306	299	1320	5	6902
massive crystalline rocks	272	245	1300	16	1133
mylonitic crystalline rocks	269	265	900	60	606
layered granulites	271	265	705	10	794
Lynchburg Fm. & Proterozoic shallow water facies	259	245	1100	13	2075
Ashe Metamorphic Suite	293	300	1200	42	1282
Alligator Back Fm.	312	300	1200	35	1026
Catoctin Fm.	311	300	1125	6	2332
Chilhowee Group	348	300	1300	21	400
Candler Fm.	240	225	845	19	688

	Depth to Bedrock				
Rock Type	**Mean**	**Median**	**Maximum**	**Minimum**	**Number of Observations**
foliated crystalline rocks	28.6	23	140	1	2797
massive crystalline rocks	28.7	25	150	1	481
mylonitic crystalline rocks	41	36	110	5	63
layered granulites	41.7	38	157	2	147
Lynchburg Fm. & Proterozoic shallow water facies	36.1	30	215	1	782
Ashe Metamorphic Suite	60.4	57	145	1	91
Alligator Back Fm.	57.4	58	112	0	116
Catoctin Fm.	34	30	185	1	1299
Chilhowee Group	50.7	40	510	2	179
Candler Fm.	37.4	30	204	1	37

	Depth to Water				
Rock Type	**Mean**	**Median**	**Maximum**	**Minimum**	**Number of Observations**
foliated crystalline rocks	37.8	31.6	315	0.5	1980
massive crystalline rocks	39.4	31	192	7	205
mylonitic crystalline rocks	35.7	30	120	1	66
layered granulites	45.3	30	333	-3.34	94
Lynchburg Fm. & Proterozoic shallow water facies	39.9	30	390	-2	316
Ashe Metamorphic Suite	40	40	80	1	263
Alligator Back Fm.	47.8	46	155	3	171
Catoctin Fm.	41.9	34	379	0.91	790
Chilhowee Group	55.1	40	450	-9.2	162
Candler Fm.	29.48	28	80	1	37

Depth to First Water Bearing Fracture

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	210	165	1025	2	2428
massive crystalline rocks	164	140	895	14	410
mylonitic crystalline rocks	115	95	315	20	57
layered granulites	165	116	630	20	122
Lynchburg Fm. & Proterozoic shallow water facies	158	131	1040	19	587
Ashe Metamorphic Suite	132	111	335	10	70
Alligator Back Fm.	148	135	500	10	108
Catoctin Fm.	194	150	889	6	1093
Chilhowee Group	202	160	600	60	144
Candler Fm.	101	95	300	30	26

Depth to Lowest Water Bearing Fracture

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	289	260	1235	15	2427
massive crystalline rocks	234	200	941	18	413
mylonitic crystalline rocks	166	139	473	46	57
layered granulites	222	207	630	20	122
Lynchburg Fm. & Proterozoic shallow water facies	229	205	1070	20	587
Ashe Metamorphic Suite	167	162	335	35	70
Alligator Back Fm.	203	180	680	10	108
Catoctin Fm.	265	235	889	20	1094
Chilhowee Group	281	250	780	70	143
Candler Fm.	167	130	475	65	26

Reported Yield Non-Domestic Wells

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	33.6	18	800	1	284
massive crystalline rocks	28.7	16.5	180	1	80
mylonitic crystalline rocks	29.8	12	191	1	41
layered granulites	83.4	20	1000	1	89
Lynchburg Fm. & Proterozoic shallow water facies	32.4	15	275	1	165
Ashe Metamorphic Suite	37.3	20	425	1	113
Alligator Back Fm.	30.8	18	517	1	222
Catoctin Fm.	30.4	15	550	1	228
Chilhowee Group	34.3	15	632	1	81
Candler Fm.	21	15	88	1	28

Rock Type	Pumped Yield Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	37.2	25	164	2	49
massive crystalline rocks	42.6	22	165	5	6
mylonitic crystalline rocks	58.6	51	142	10	8
layered granulites	30	59.6	170	9	13
Lynchburg Fm. & Proterozoic shallow water facies	54.3	30	275	1	20
Ashe Metamorphic Suite	46	26	160	6	17
Alligator Back Fm.	58.6	19	517	1	31
Catoctin Fm.	35.7	25	106	3	44
Chilhowee Group	97.5	28	632	4	14
Candler Fm.	37.4	36	88	10	7

Rock Type	Specific Capacity Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	0.36	0.23	1.45	0.05	24
massive crystalline rocks	0.3	0.08	1.18	0.03	6
mylonitic crystalline rocks	0.92	0.41	2.85	0.04	7
layered granulites	4.31	1.14	22.7	0.01	11
Lynchburg Fm. & Proterozoic shallow water facies	0.56	0.24	3.7	0.06	20
Ashe Metamorphic Suite	1	0.63	3.16	0.04	20
Alligator Back Fm.	0.51	0.16	3.83	0.003	33
Catoctin Fm.	0.88	0.25	13.1	0.02	32
Chilhowee Group	0.86	0.45	4.13	0.004	13
Candler Fm.	1	1	1	1	1

GROUNDWATER GEOCHEMICAL PROPERTIES OF ROCK UNITS

Geochemical Evolution of Groundwater

Groundwater chemistry in fractured rock usually progress from more oxygen rich, slightly acidic water with low ion concentrations in recharge areas to more mature, oxygen depleted, increasingly alkaline and solute enriched groundwater in lower gradient and deeper portions of the groundwater flow system (Hem, 1992; Langmuir, 1997) . The magnitude of departure from the original meteoric chemistry (which varies by locality) is governed by the varying mineralogys, textures, and structures of the host rocks, the resident age (contact time) of the groundwater within the fractured host rock, and the levels of free energy available to drive reactions within the groundwater system. Departures from this down-gradient evolution are the result of the chemical mixing of groundwater from different flow paths, changes in the mineralogy and texture of the host rock, and chemical and thermodynamic alterations within the groundwater flow system (changes in groundwater chemistry due to contamination or other chemical input, and changes in temperature and pressure) (Hem, 1992; Langmuir, 1997).

The bulk of the chemical evolution of groundwater within the Blue Ridge Geologic Province usually occurs in the upper portions of the groundwater flow system where freshly infiltrated meteoric water reacts with vegetatively and bacteriologically respirated carbon dioxide in the soil to form carbonic acid. Carbonic acid is then available for reaction with the down gradient portions of the regolith and transmissive bedrock fractures. The extent of this zone of geochemical activity is largely coincident with the most notably weathered portions of the groundwater flow system – the regolith and upper portions of bedrock where hydrogen ions are actively transferred from solubilized acids and exchanged with freshly exposed minerals made available through persistent chemical and mechanical weathering. Aqueous reaction rates in deeper portions of the fractured bedrock flow system are usually slower as more minerals of the host rock come into chemical equilibrium with the groundwater, and the rock becomes harder to dissolve as available surface area is restricted to rock surfaces along fracture apertures (Hem, 1992; Langmuir, 1997). Ion concentrations in the Blue Ridge crystalline rock setting are low relative to ionic concentrations in groundwater stored in more soluble host rock such as the carbonate rocks of the Great Valley, but do show a trend of increasing solute concentration with depth (figure 56), which indicates an overall increase in residence time with depth of circulation in the groundwater flow system.

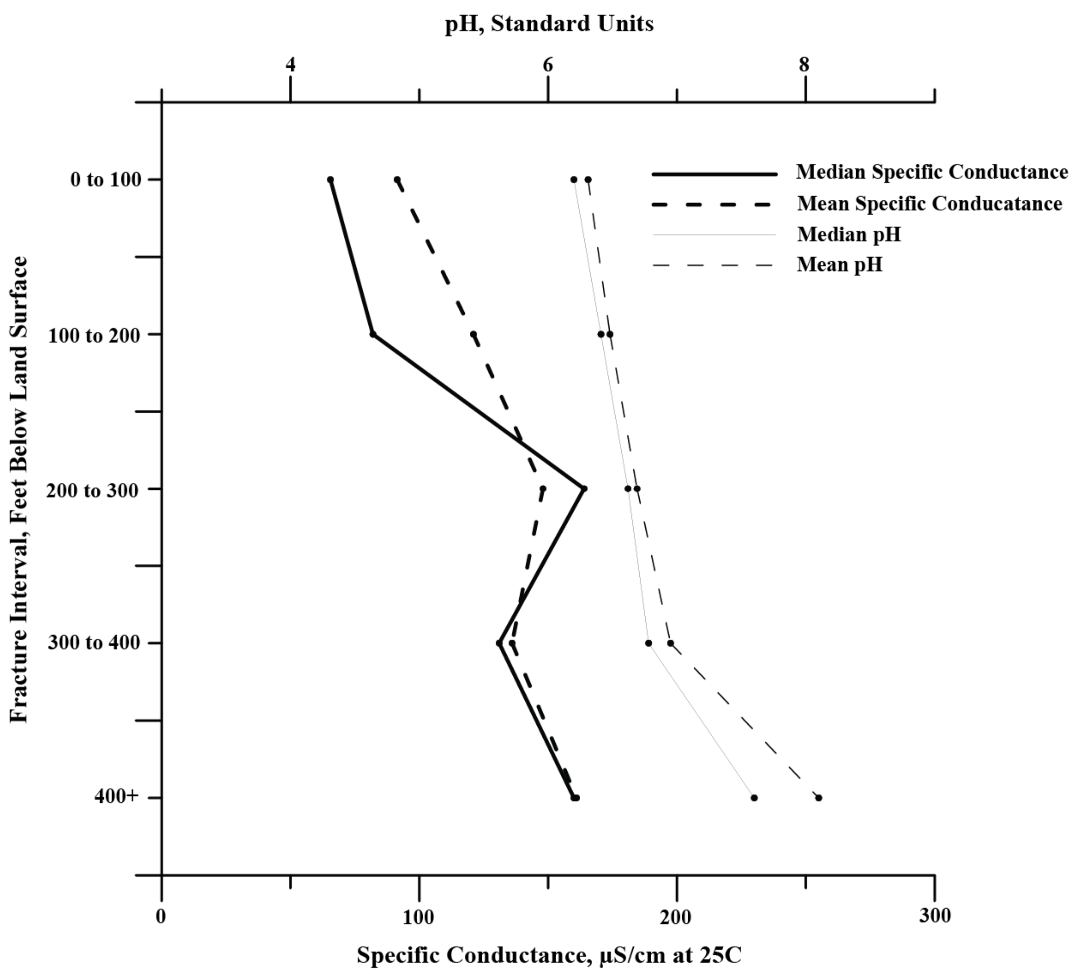


Figure 56. Mean and median values for pH and specific conductance at specified depth intervals for groundwater samples taken from the Blue Ridge Geologic Province. To investigate potential differences in pH and specific conductance with depth, only data from wells with fractures isolated to specified 100 foot intervals were used (ex: values in the 300 to 400 Ft. range were used from samples taken from wells with fractures open only between 300 and 400 Ft. BLS.)

Major Ions

The majority of dissolved species in groundwater are accounted for with 7 major ions: calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate. Dissolved oxygen and carbonic acid are also major constituents of the total dissolved content, but are commonly not reported in chemical analyses (Langmuir, 1997). Relative concentrations of the major ionic species are controlled by a complex interaction of geochemical factors including the solubility and mineralogy of the host rock, the chemical activity of the solutes, oxidization potentials present in the system, pH, and the relative abundance and type of biota present to force the transfer of electrons (Hem, 1992; Langmuir, 1997). Major ions in solution in the crystalline rock environments of the Blue Ridge are typically dominated by calcium, magnesium, and bicarbonate, with lesser concentrations of sodium, potassium, chloride, and fluoride. Brief descriptions of major ions and their sources are given in the following text; for detailed descriptions of the major ions as well as secondary constituents and physical properties used to describe groundwater geochemistry in later portions of this section, the reader is referred to Hem (Hem, 1992).

As with the hydrogeologic characteristics, a Kruskal-Wallis one-way ANOVA test was run to determine if there were any statistically significant differences at the 95% confidence level between major rock types for each groundwater geochemical property. For geochemical properties where Kruskal-Wallis ANOVA testing indicated a statistically significant difference for at least one rock type, a Dunn's multiple comparison test was run to test for statistically significant differences between all possible pairs of major rock types. Results from these tests are briefly summarized in the following paragraphs. Complete results from the non-parametric ANOVA and Dunn's multiple comparison testing are displayed in Appendix 2. Descriptive statistics of evaluated geochemical characteristics are displayed in Table 29.

Calcium

Calcium is common in many igneous, meta-igneous, and meta-sedimentary mineral assemblages throughout the Blue Ridge Geologic Province. Contributions of dissolved calcium originate from feldspar (plagioclase), amphibole, and pyroxene rich rocks, from meta-sedimentary rocks composed of these mineral grains, and from meta-sedimentary rocks containing calcium carbonate. Calcium is often found in concentrations of less than 20 mg/L throughout the study area (figure 57). Dissolution of pyroxene and plagioclase rich minerals of the fine grained Catoctin meta-basalts results in higher median concentrations of dissolved calcium when compared to other formations in the Blue Ridge Geologic Province, and this observation is supported by the occurrence of statistically significant differences in calcium concentrations between 6 of 9 rock type pairs with the Catoctin. Calcium concentrations for both groundwater samples taken in the Everona Limestone exceeded 50 mg/L.

Sodium

Sodium is a common constituent of plagioclase feldspars which are ubiquitous throughout the granitic and metamorphosed cover rocks of the Blue Ridge Geologic Province. Sodium is also a constituent of some amphibole and pyroxene mineral assemblages, but is not as widely distributed in these forms. Typical concentrations of sodium in groundwater are well under 10 mg/L (figure 58). Groundwater samples from the Chilhowee Group and Ashe Metamorphic Suite have the lowest median concentrations of sodium, with statistically significant differences occurring in 6 of 9 possible rock type pairs. Rocks of the Alligator Back Formation also have lower concentrations of sodium, with statistically significant differences occurring with 4 of 9 possible pairs.

Potassium

Sources of dissolved potassium in groundwater can originate from the potassium feldspar, muscovite, and biotite rich rocks (granitic rocks) of the Blue Ridge Geologic Province. Because more energy is required to free potassium from its host mineral assemblage than other major ions, potassium is usually found in lesser abundance than dissolved sodium or calcium (Hem, 1992). Concentrations of potassium in the Blue Ridge groundwater systems are usually less than 5 mg/L, and often less than 1 mg/L in the Catoctin Formation where potassium occurs with less frequency in the widespread metabasalts (figure 59). The median concentration of potassium for groundwater samples is lowest in the Catoctin Formation, and statistically significant differences in potassium concentrations occur between 6 of 9 possible rock type pairs with the Catoctin. Groundwater samples from the foliated crystalline rocks showed the highest median concentration, and 5 of 9 possible rock type pairs with the foliated crystalline rock type show statistically significant differences in potassium concentrations. Aside from differences with the Catoctin and foliated crystalline rocks, no statistically significant differences in potassium concentrations were observed between the other rock types.

Magnesium

Magnesium originates from the ferromagnesian minerals commonly found in igneous and metamorphic rocks (amphibole, pyroxene, biotite). Concentrations of dissolved magnesium in Blue Ridge groundwater systems are typically below 5 mg/L, with the exception of groundwater in the Catoctin Formation, where concentrations are slightly higher due to a more frequent abundance of magnesium in these basaltic rocks (figure 60). Statistically significant differences in magnesium concentrations occur between the Catoctin Formation and all other rock types, with the exception of the Candler Formation where concentrations of magnesium are slightly higher than in other rock types (with the exception of the Catoctin).

Sulfate

Sulfate occurs in a wide variety of mineral forms – soluble (hydrous) forms are typically bound with a metal (iron, zinc, lead, potassium, calcium) and are usually dissolved into solution within redox zones of groundwater flow systems. Sources of sulfate within the Blue Ridge occur in association with metallic ore deposits (such as the Great Gossan Lead deposit in Floyd, Grayson, and Carroll Counties), and are also widely disseminated in lesser quantities (typically as pyrite) throughout the entire Blue Ridge. Sulfate concentrations in the Blue Ridge groundwater systems are typically below 5 mg/L (figure 61). The highest median value for sulfate occurs in the Chilhowee Group, and groundwater samples taken from these rocks show statistically significant differences in sulfate concentrations with 2 of 9 possible rock type pairs (Chilhowee/massive crystalline rocks, and Chilhowee/granulite).

Chloride

Chloride does not commonly occur in mineral form within the crystalline rocks of the Blue Ridge – it is introduced to groundwater systems via infiltrated meteoric water (precipitation), which carries trace amounts of chloride commonly evaporated from ocean water. Because chloride behaves conservatively (is not reactive) in the groundwater flow system, higher concentrations of chloride in groundwater can indicate the presence of more mature groundwater or in rare cases, occur in extremely high concentrations (supersaturated brines), indicating the presence of connate water trapped within the rock. Figure 62 presents reported chloride concentrations within groundwater sampled from the various rock types described in this report. Concentrations of dissolved chloride in the Blue Ridge groundwater systems are usually below 5 mg/L. One statistically significant difference in chloride concentration occurs between the Catoctin/Chilhowee pair.

Bicarbonate

The main source of bicarbonate originates with the dissolution of atmospheric and biologically respirated carbon dioxide into infiltrated meteoric water within the unsaturated portion of the groundwater flow system. Hydrolysis of carbon dioxide by water produces carbonic acid, which is then converted to bicarbonate through the loss of a hydrogen ion during the chemical weathering of rock and organic materials. Bicarbonate is the predominate buffer in slightly acidic to slightly alkaline groundwaters (pH values for groundwater in the Blue Ride Province usually range between 5.5 and 7.5), and therefore plays a critical role in neutralizing acidity. Figure 63 presents reported bicarbonate concentrations within groundwater sampled from the various rock types described in this report. Dissolved concentrations of bicarbonate in Blue Ridge groundwater systems are usually less than 40 mg/L, with the exception of the Candler and Catoctin formations, which have median bicarbonate concentrations of approximately 40 mg/L and 60 mg/L, respectively. Statistically significant differences in bicarbonate concentrations from groundwater samples occur between the Catoctin Formation and all other rock type pairs. Comparatively higher concentrations of bicarbonate in groundwater from the Catoctin Formation are necessary to maintain a charge balance with elevated concentrations of calcium, magnesium, and sodium ions dissolved from these basaltic rocks.

Secondary Constituents

Secondary constituents in solution are usually found in low concentrations in natural groundwater flow systems of the Blue Ridge. Several of the most commonly sampled secondary constituents are described in the following paragraphs.

Iron

Iron is a common constituent of many minerals throughout the Blue Ridge (pyroxene, olivine, biotite, and amphibole) and once it is weathered from rock it tends to form into unstable complexes in the near surface environment. For this reason, iron can be found in a variety of soluble and insoluble forms dependent on the presence or absence of dissolved oxygen, pH, and presence of microbial biota that utilize iron for microbial respiration. Where dissolved oxygen is present in groundwater (such as upgradient portions of the groundwater flow system, zones of mixing in the groundwater flow system, and groundwater extraction or discharge points), reactions tend to favor the oxidization or precipitation into an insoluble form, ferric iron (FeIII). Depending on advective flow rates and the concentration of dissolved oxygen in the upgradient portions of the groundwater flow system, varying amounts of ferrous iron (FeII) will remain in solution and migrate with the flow of groundwater to deeper portions of the groundwater reservoir. In oxygen depleted zones of the groundwater flow system, the aqueous form of iron predominates, and can travel advectively with groundwater flow. Ferrous iron will usually remain in solution until oxygen is re-introduced and the solubilized iron is oxidized to its trivalent state, although in sulfate reducing conditions (which are often coincident with groundwater contamination) ferrous iron can be precipitated as iron sulfide (Chapelle et al., 1995).

Iron concentrations in excess of 300 micrograms per liter (μg/L), which is the USEPA Secondary Maximum Contaminant Level (SMCL) are not uncommon (figure 64), and precipitation of dissolved iron in oxygen rich environments can render wells and plumbing systems unusable over time (Houben and Treskatis, 2007). Properly sizing well pumps to reduce excessive drawdown will minimize aeration near the pump and (depending on the location of water bearing fractures in the well) insure that water bearing zones in the wellbore stay submerged during pumping. Minimizing the quantity of introduced oxygen at the well is necessary for managing groundwater with high dissolved iron (Houben and Treskatis, 2007) (in excess of 300 μg/L).

No statistically significant differences in iron concentrations were found between rock type pairs in the Blue Ridge Geologic Province.

Manganese

Manganese behaves similarly to iron in the aqueous geochemical environment but is less abundant. It is widespread throughout the Blue Ridge Geologic Province and is found in many of the same minerals that contain iron. It is mobilized by reduction reactions and can precipitate as a black oxide in sufficiently oxidizing portions of the groundwater flow system (Briel, 1997;

Hem, 1992). Figure 65 presents reported manganese concentrations within groundwater sampled from the various hydrogeologic groups described in this report. Distributions of manganese in groundwater samples from rock types throughout the Blue Ridge Geologic Province have median manganese concentrations below 30μg/L, with the exception of manganese concentrations in groundwater samples taken from the Candler Formation, which are closer to 40μg/L. One statistically significant difference in manganese concentration occurs between the Candler Formation/granulite pair.

Fluoride

A well documented occurrence of fluoride in the crystalline rocks of a lead and zinc deposit in southern Albemarle County was described by Thomas Leonard Watson (Virginia Division of Mineral Resources, 2003). This deposit is located in a vein within the Lynchburg Formation in a local swarm of diorite and diabase dikes likely associated with Grenvillian (?) rifting. Trace amounts of fluoride are commonly found in groundwater systems that occur in rocks containing alkali metals (feldspars) (Hem, 1992). Fluoride is also commonly associated with volcanic gasses and ash (Hem 1992) and can be a locally occurring element associated with volcanogenic formations such as occurs in pyroclastic sections of the Catoctin and Mount Rogers formations. Slightly higher median concentrations of fluoride occur in groundwater in the mylonites and granulites (figure 66), and statistically significant differences in the distribution of fluoride concentrations occur when groundwater samples taken from these rock types are compared with groundwater samples originating from rocks of the AMS, Alligator Back, and Catoctin formations.

Aluminum

Aluminum is abundant in minerals and clays throughout the Blue Ridge Geologic Province, but is usually found in low dissolved concentrations because it is not easily solubilized (Hem, 1992). Aluminum is one of the chief elements of many clays and its widespread presence there attests to the preference of this mineral to remain in solid form. Elevated concentrations of aluminum do occur in waters with low pH (acidic waters), and therefore may occur more frequently in groundwater associated with rocks having a poor buffering capacity. This is evident in the median concentration for aluminum in the Chilhowee Group rocks (figure 67). Median concentrations for aluminum in the Chilhowee are 45 μg/L, and 35μg/L or less for all other groups. Aqueous aluminum concentrations are the lowest in the Lynchburg Formation and late Proterozoic shallow water facies, the AMS, and the Alligator Back Formation. Statistically significant differences in the distribution of aqueous aluminum concentrations occur between these 3 rock types and remaining rock types, with the exception of the Candler Formation.

Silica

Silicate minerals within the rocks of the Blue Ridge Geologic Belt constitute the most abundant class of mineral within this region. Despite the abundance of silica, it is found in comparatively low concentrations in groundwater. The solubility of silica is controlled largely by the type of rock in contact with water, and the temperature of the water in the groundwater flow system (Hem, 1992). Significant contact time of groundwater with the host rock is required to elevate dissolved silica concentrations much above median values (typically 15-20 mg/L) under conditions approaching standard temperatures and pressures. Silica concentrations displayed in figure 68 indicate a trend toward higher dissolved silica concentrations within groundwater from the basement rock types (often more than 20 mg/L), and slightly lower concentrations in the cover rocks (usually between 10 and 20 mg/L). There were not enough data to analyze for statistically significant differences in the distribution of silica between groundwater sample populations.

Physical Properties

Physical properties of groundwater provide clues pertaining to the thermodynamic status, relative age, and relationships between groundwater sampling points. Physical properties are useful for assessing the "big picture" components of groundwater samples such as the acidity of the groundwater, the capability of the water to buffer acidity, the relative concentration of dissolved ions, and the level of hardness associated with the water sample. Many of these properties are useful for assessing groundwater systems on a temporal basis under both ambient and stressed conditions because they can be measured in the field through the use of field titrations and electrochemical meters. This report discusses the most common physical properties from the groundwater sample data available however there are many more physical properties that can be used for diagnosing and assessing the chemical conditions of groundwater flow systems. In depth descriptions of all these properties can be found in a number of texts including Hem (1992).

pH

The pH of a groundwater sample is the measurement of the total concentration (activity) of hydrogen ions and is expressed as negative (inverse) log units ranging from 1 to 14. Lower values of pH indicate more acid waters while higher values of pH indicate more basic (alkaline) waters. Knowing the acidity of a groundwater sample is necessary for estimating the overall aggressiveness of the groundwater system at the sampling point, and it is a required parameter for predicting the behavior of chemical constituents in solution. Figure 69 presents reported pH values within groundwater sampled from the various hydrogeologic groups described in this report. Median pH values ranged between 6 and 7 for all hydrogeologic groups described in this report, and are consistent with findings reported by Briel (1997). The highest median pH value among the distributions of pH displayed in figure 69 occurs in the Catoctin groundwater sample population. Statistically significant differences in the distribution of pH in groundwater occur between the Catoctin and 5 of 9 possible rock type pairs.

Temperature

The temperature of a groundwater sample can provide important information regarding the depth of the groundwater source, and for assessing the interconnectedness of groundwater flow systems in the field. Temperature data are especially useful for assessing the origin of spring water sources. Groundwater temperature data are diagnostic for assessing the presence of geothermal anomalies. Temperatures within the majority of observed groundwater flow systems in the Blue Ridge Geologic Province range between 55 to 60 degrees (Figure 70). There were not enough data to analyze for statistically significant differences in the distribution of temperature between groundwater sample populations.

Specific Conductance

Specific conductance is a measurement of the ability of a groundwater sample to conduct an electrical charge at a specified temperature (25 degrees C). Because the conductivity of a groundwater sample varies with solute concentration and temperature, specific conductance is an indirect measurement of ionic concentration. Groundwater samples with higher concentrations of dissolved ions will be more conductive than samples with lower ionic concentrations. Specific conductance values taken from groundwater samples within the Blue Ridge Geologic Province indicate that groundwater is usually of low ionic content (usually less than 100 µS/cm at 25C) (figure 71). Statistically significant differences in the distribution of specific conductance in groundwater occur between the Catoctin and 8 of 9 possible rock type pairs.

Under laboratory conditions, specific conductance and dissolved solids show a linear relation, making it possible to correlate the two parameters. Figure 72 displays the linear correlation between specific conductance and total filtered dried residue in mg/L for groundwater samples taken throughout the study area. This relation suggests that specific conductance values much more than 700 µS/cm indicate total dissolved solids content in excess of the US EPA SMCL of 500 mg/L, and that values of specific conductance (or total dissolved solids) in groundwater systems of the Blue Ridge Geologic Province at these levels are rare.

Filtered Residue

Measurements of filtered residue for groundwater samples are direct measurements of the total concentration of dissolved solids for a water sample. Filtered residue measurements are useful for determining the dissolved ionic content of a groundwater system at a sampling point, and correlate well with measurements of specific conductance. Figure 73 presents reported filtered residue concentrations within groundwater sampled from the hydrogeologic groups described in this report. The distribution for concentrations of filtered residue in the Catoctin and Candler formations are notably higher than concentrations for the other rock types in the study area, but concentrations are rarely above 200 mg/L regardless of rock type. Statistically significant differences in the distribution of filtered residue in groundwater occur between the Catoctin and 6 of 9 possible rock type pairs.

Hardness

The hardness of groundwater indicates the total activity of cations within a given volume of water. Although this parameter is expressed as a concentration of calcium carbonate, hardness is a composite value of commonly occurring cations, namely calcium, sodium, and potassium. Because the solubility of many ions are temperature dependant, hardness is a practical parameter for assessing the potential of cations to precipitate from solution when a sudden shift in water temperature occurs – such as the introduction of groundwater to atmospheric conditions and more specifically, when hard water is heated to temperatures well above typical atmospheric temperatures (like hot water heaters). Figure 74 presents reported hardness concentrations within groundwater sampled from the various rock types described in this report. Median values for hardness typically range between 30-40 mg/L for all basement hydrogeologic groups and the Ashe Metamorphic Suite, and between 40-65 mg/L for the remaining hydrogeologic groups in the Blue Ridge cover rocks. Statistically significant differences in the distribution of hardness in groundwater occur between the Catoctin and 6 of 9 possible rock type pairs.

Percent Distribution of Major Ions by Rock Type

Figures 75 and 76 plot major cations and anions as a percentage of total milliequivalent value (milliequivalents per liter value for a particular ion in a groundwater sample divided by the total milliequivalent per liter value for all summed cations or anions within that sample). These plots were generated from groundwater samples having major cation/anion milliequivlent values within 10% of each other, and are instructive for understanding the individual contributions of major ions to the overall ionic composition of groundwater in the Blue Ridge Geologic Province.

The percent composition of total milliequivalent value for major cations shown in figure 75 is dominated by calcium for all rock types (typically between 35 to 70% of the total milliequivalent value), followed by either magnesium or sodium (usually between 10 and 40% of the total milliequivalent value), with potassium comprising 2 to 8%. Magnesium occurs as the second highest distribution of the total cation milliequivalent in the Catoctin, Candler, and Chilhowee hydrogeologic groups, indicating that magnesium comprises a portion of the total cation milliequivalent in the groundwater of these rocks that is otherwise comprised of sodium and potassium in the basement, Lynchburg, Ashe, and Aligator Back hydrogeologic groups.

The percent composition distribution of total anion milliequivalent charge is similar among all Blue Ridge Province hydrogeologic groups (figure 76). The total cation milliequivalent is dominated by bicarbonate, typically comprising 70 to 90% of the total, followed by comparable distributions of chloride and sulfate, each constituting 5 to 10% of the total cation milliequivalent. Fluoride is often considerably less than 5% of the total cation milliequivalent for all groups. In comparison to the other hydrogeologic groups of the Blue Ridge Province, percent distribution of sulfate milliequivalent in the Chilhowee Group is higher.

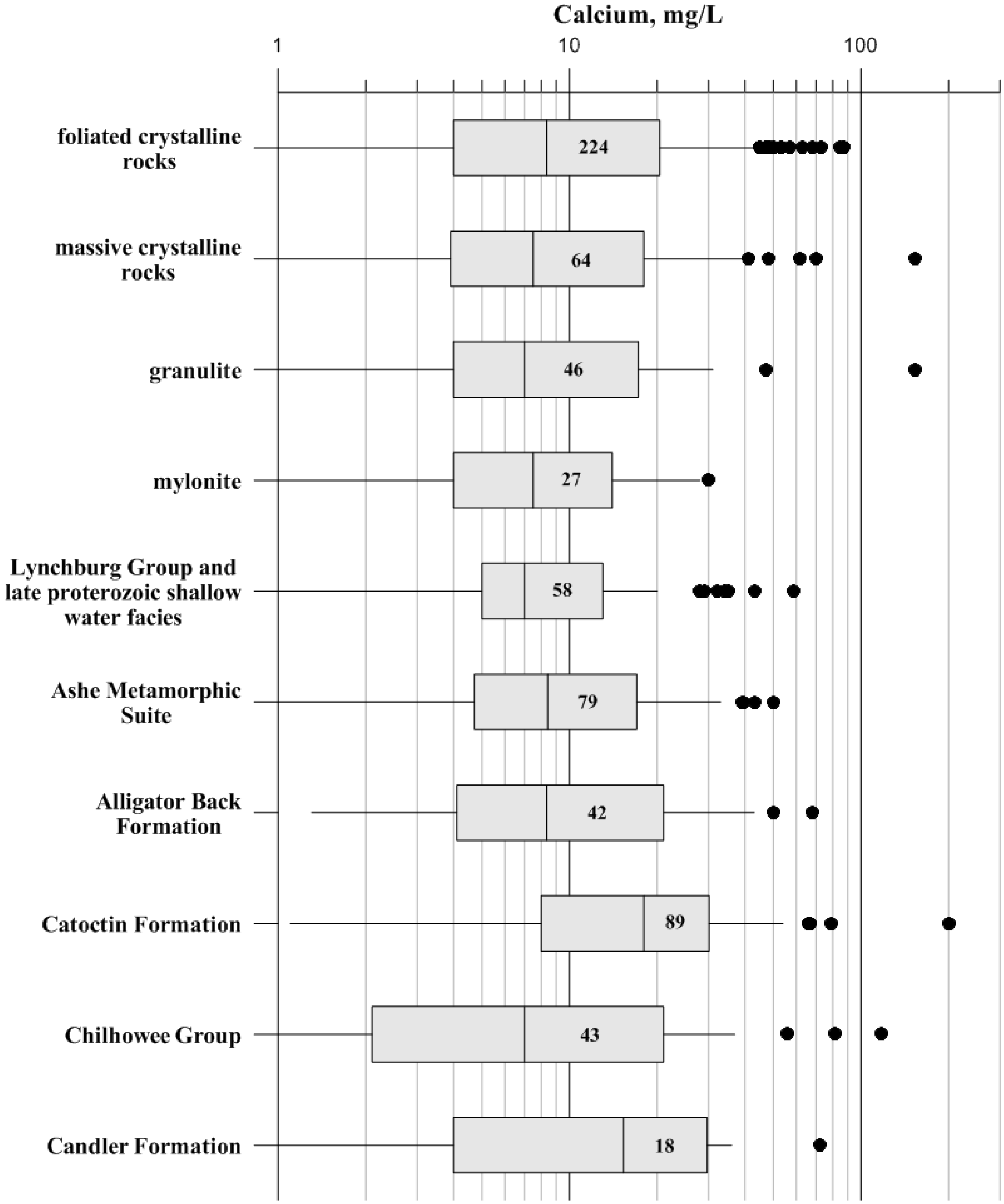


Figure 57. Distribution of calcium in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

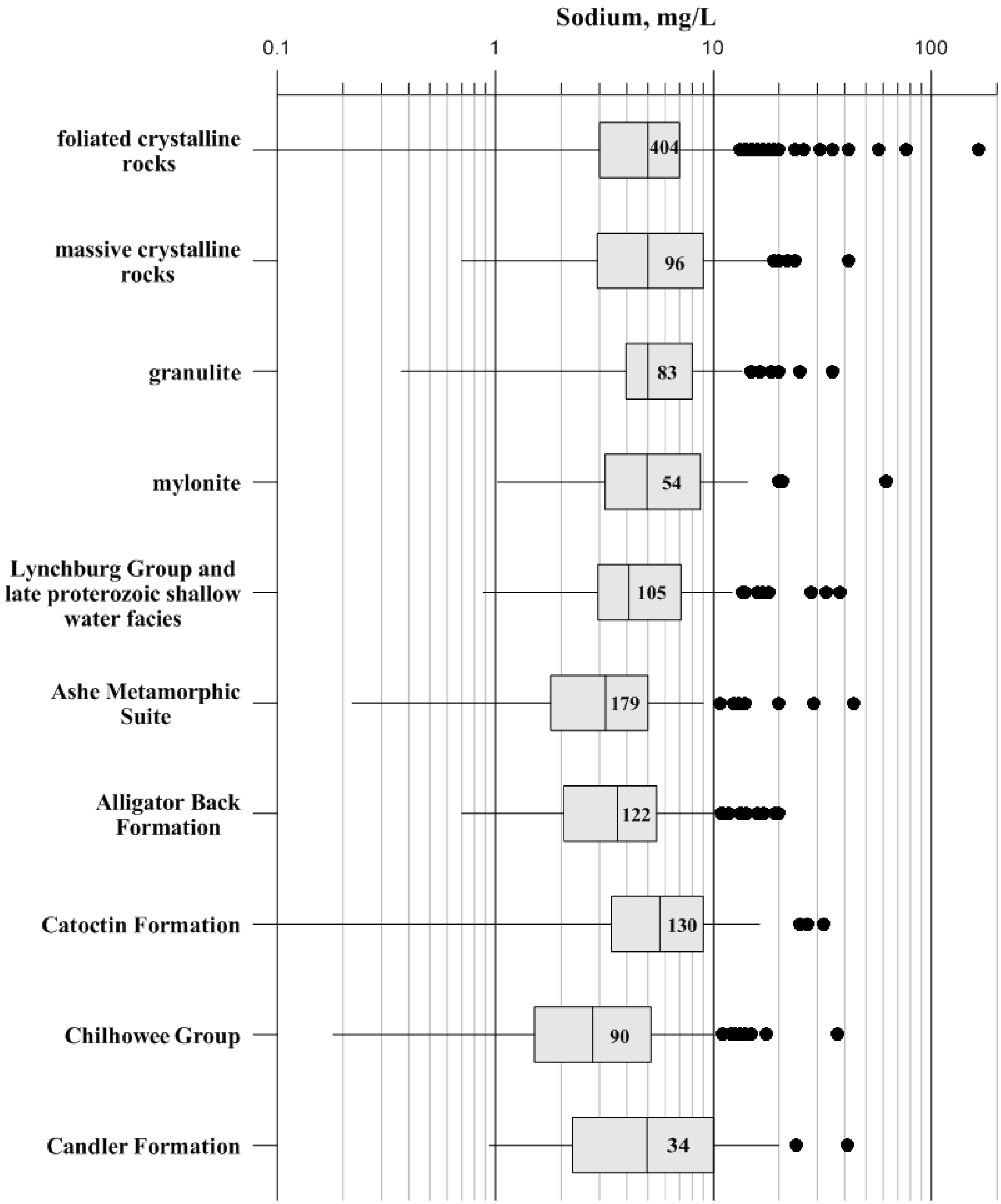


Figure 58. Distribution of sodium in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

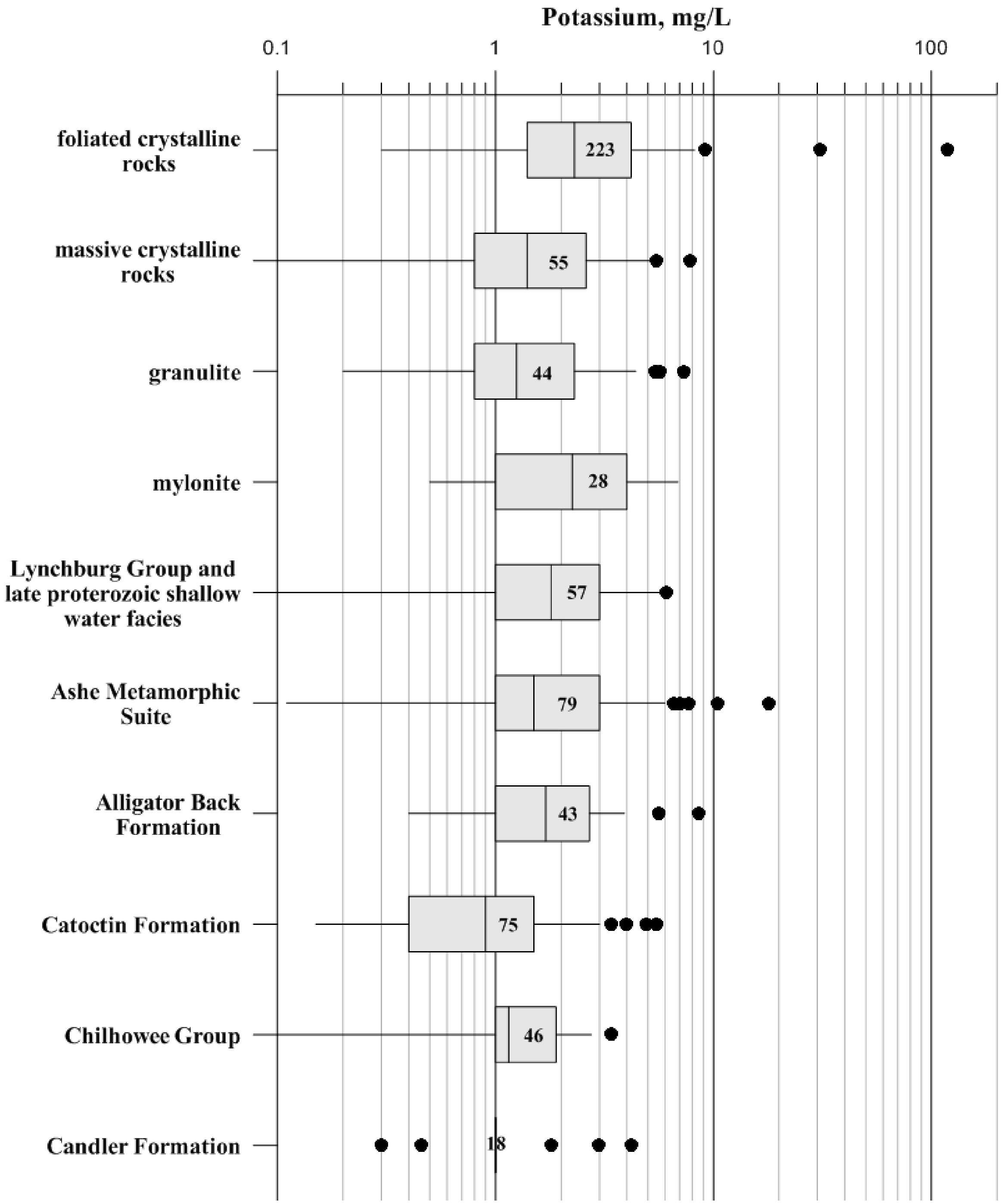


Figure 59. Distribution of potassium in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

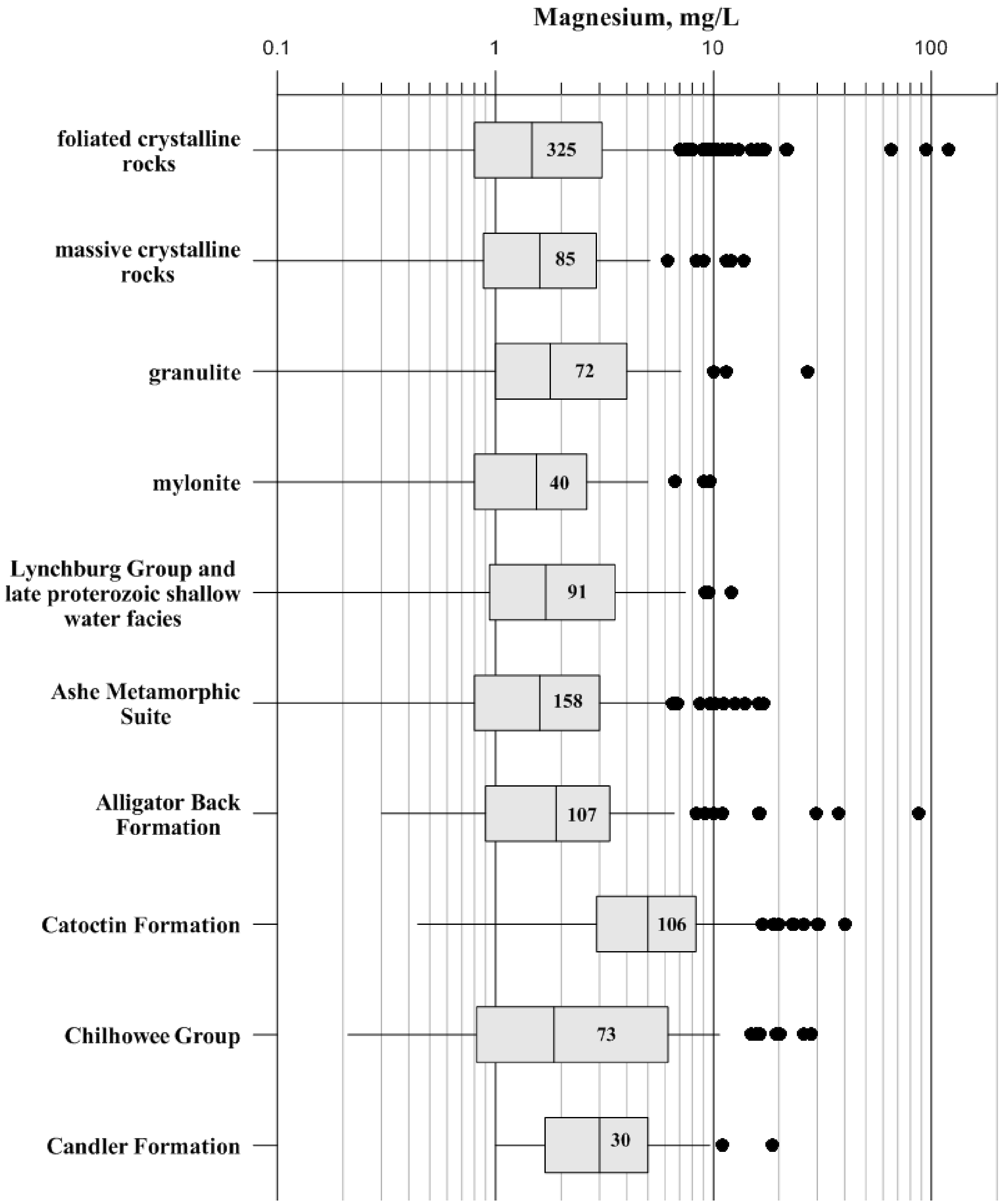


Figure 60. Distribution of magnesium in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

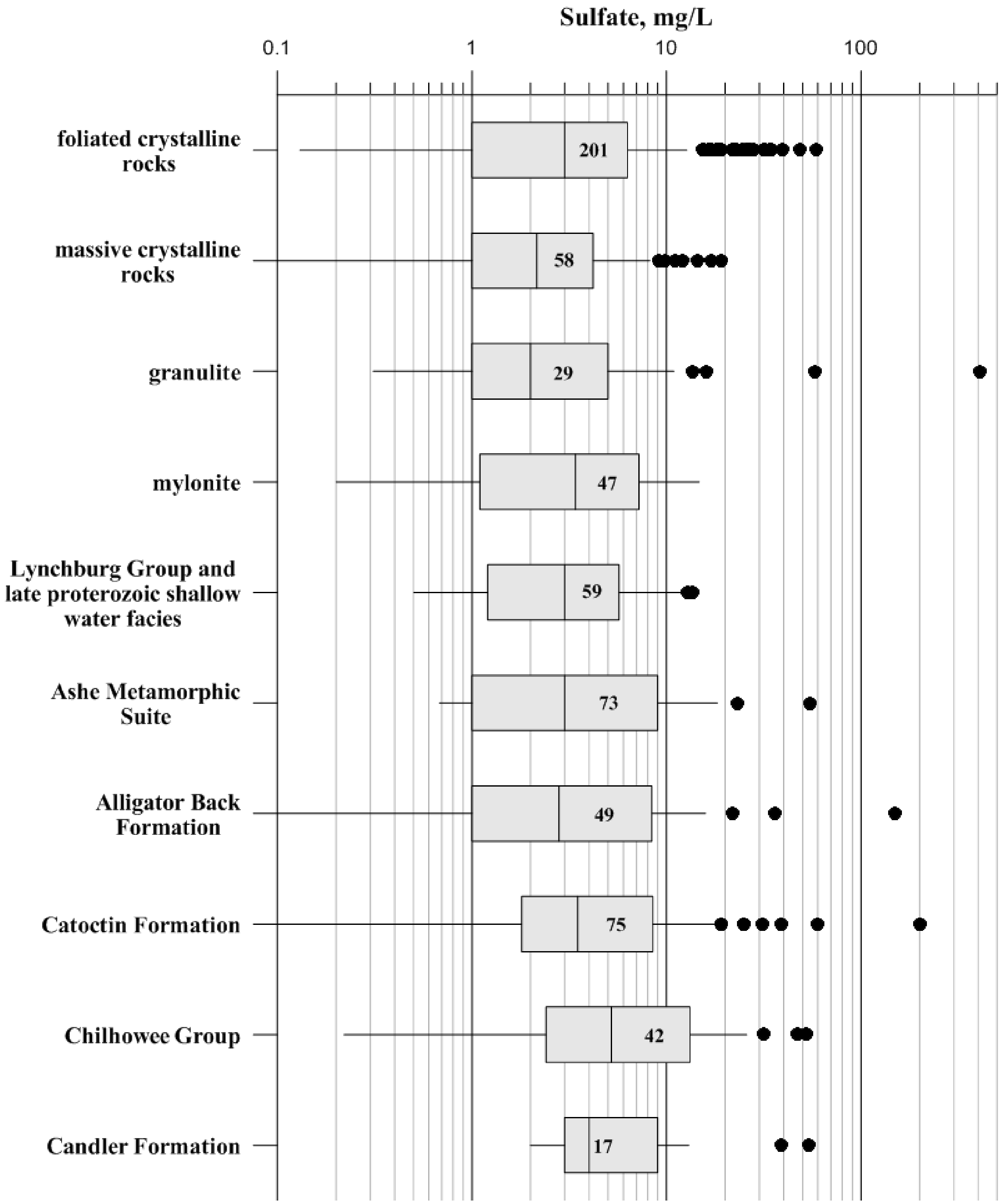


Figure 61. Distribution of sulfate in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

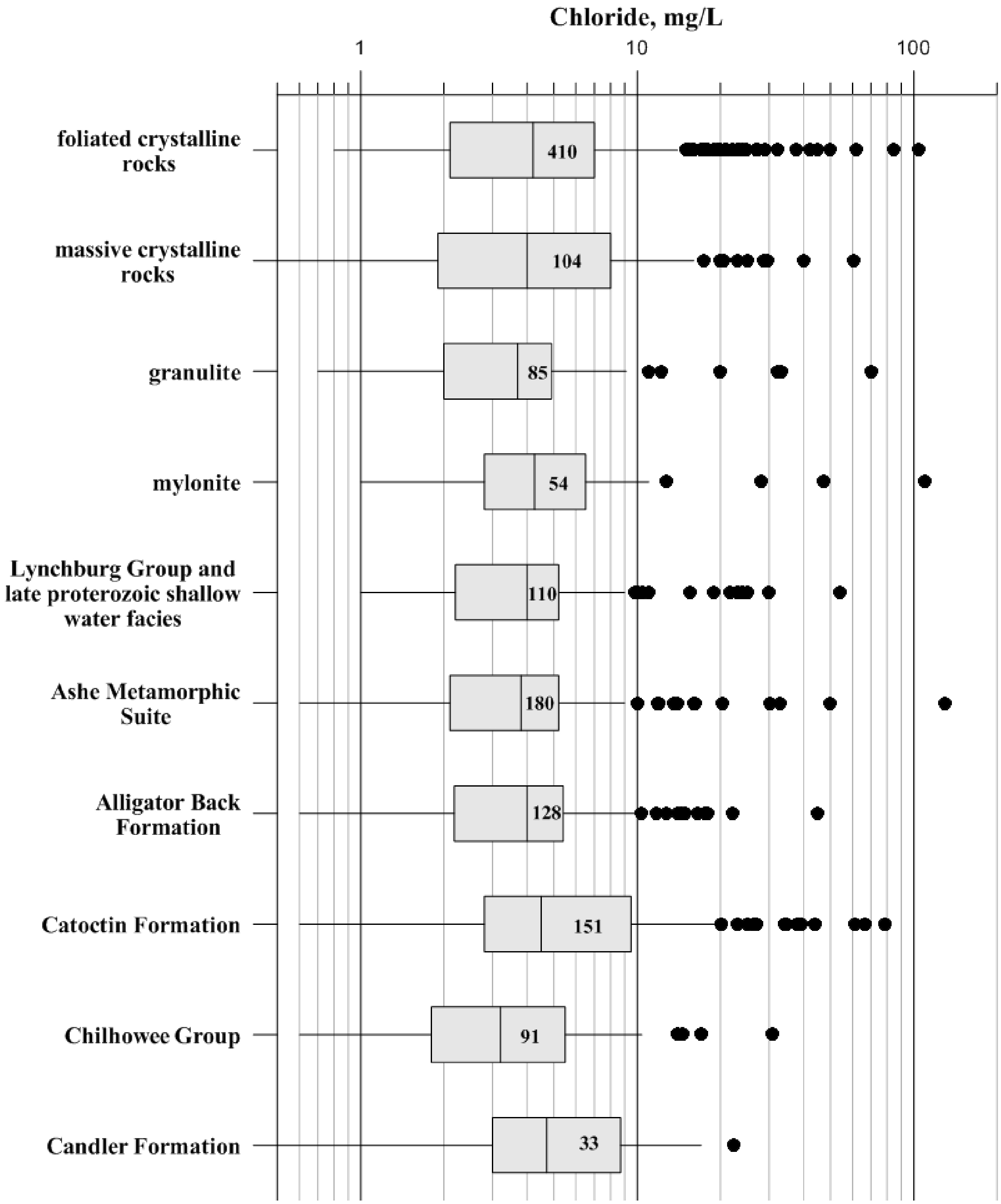


Figure 62. Distribution of chloride in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

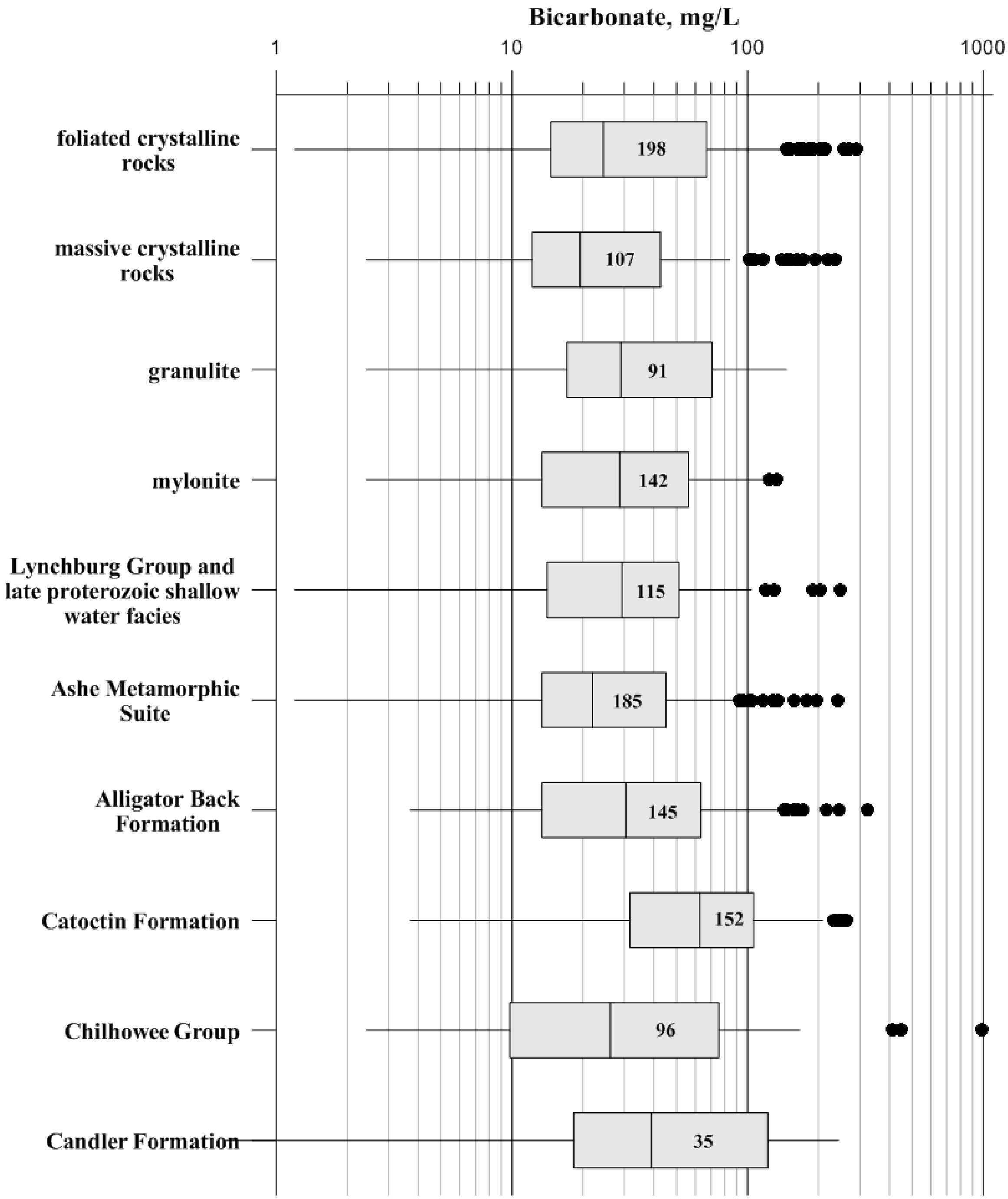


Figure 63. Distribution of bicarbonate in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

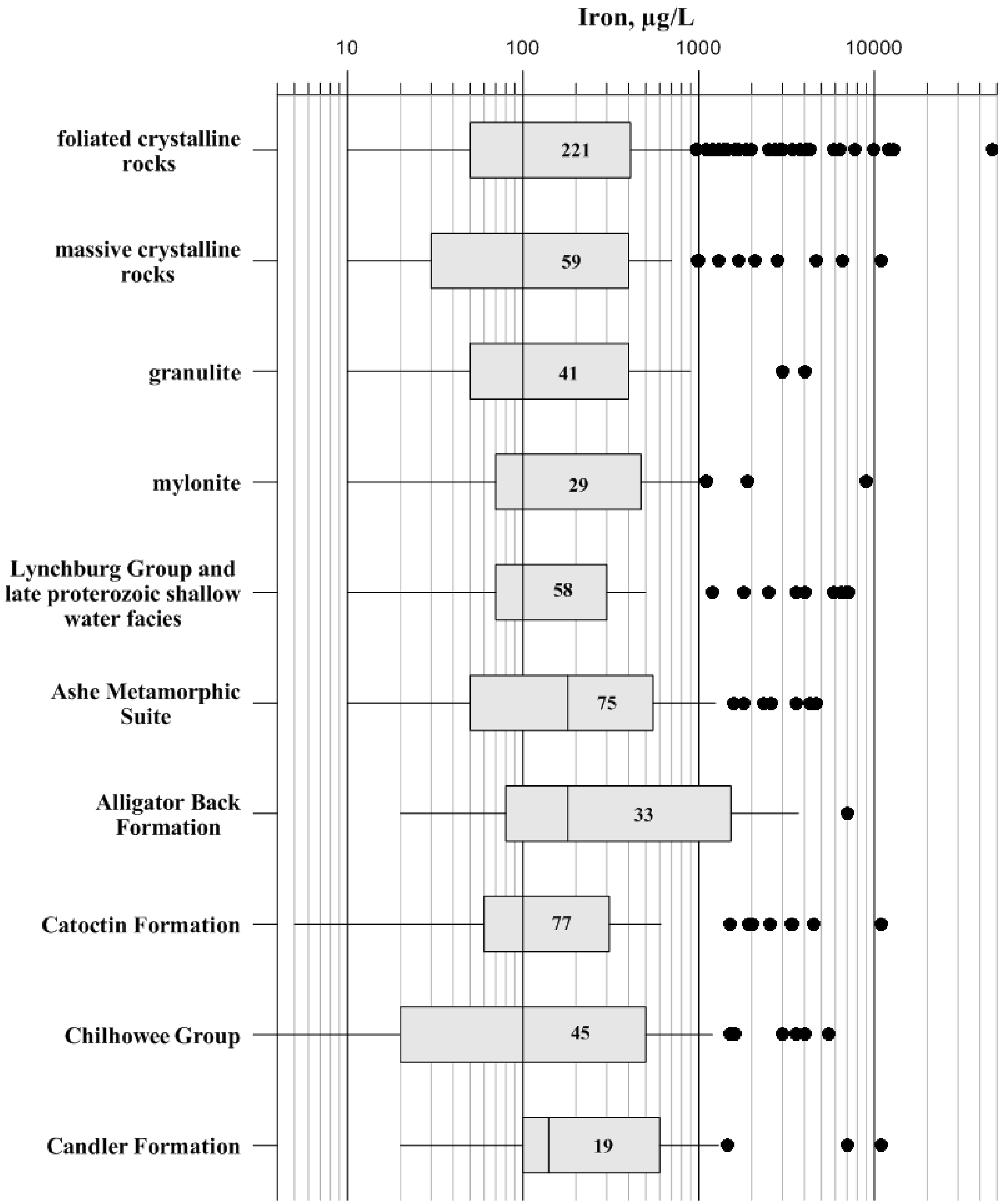


Figure 64. Distribution of iron in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

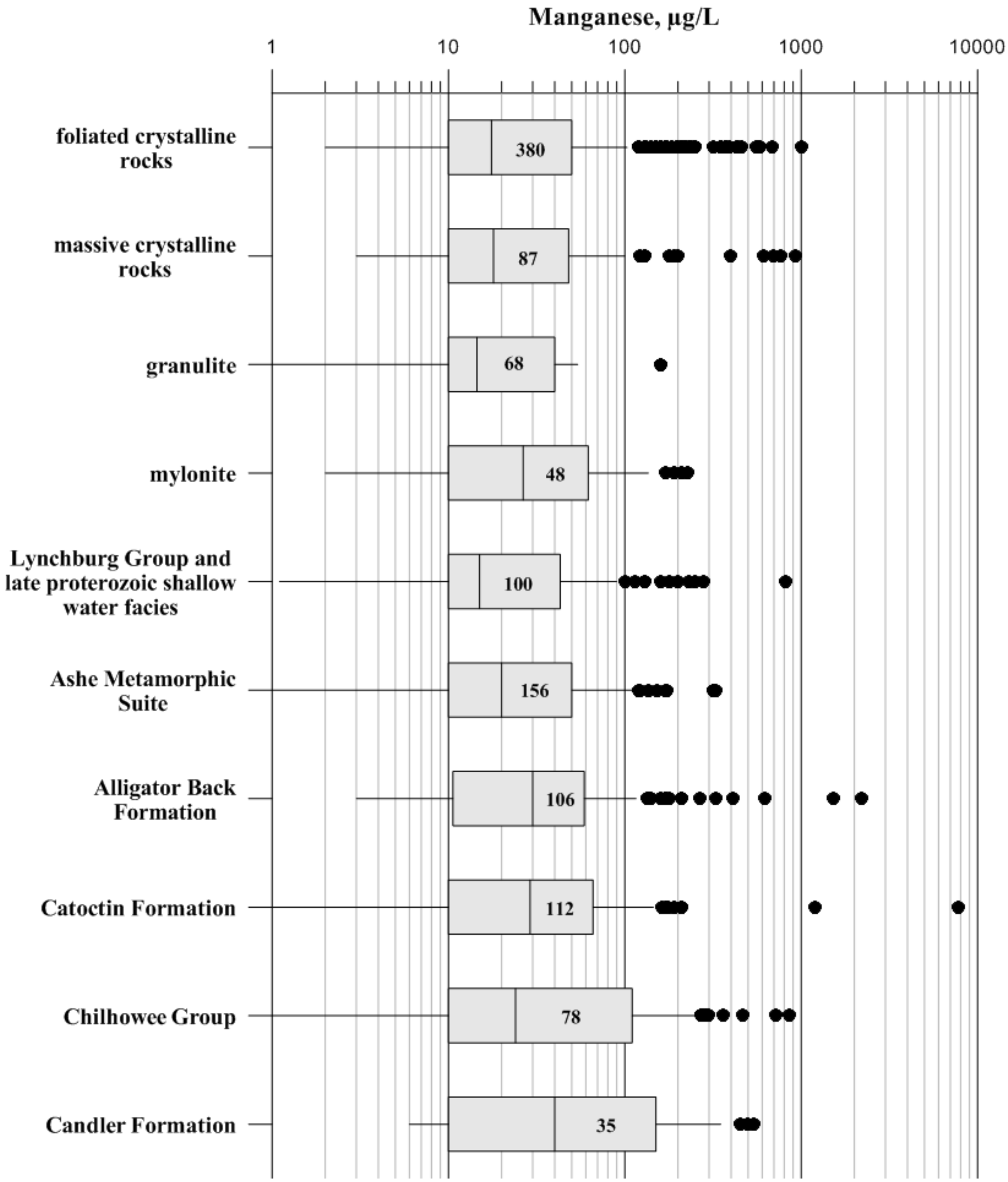


Figure 65. Distribution of manganese in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

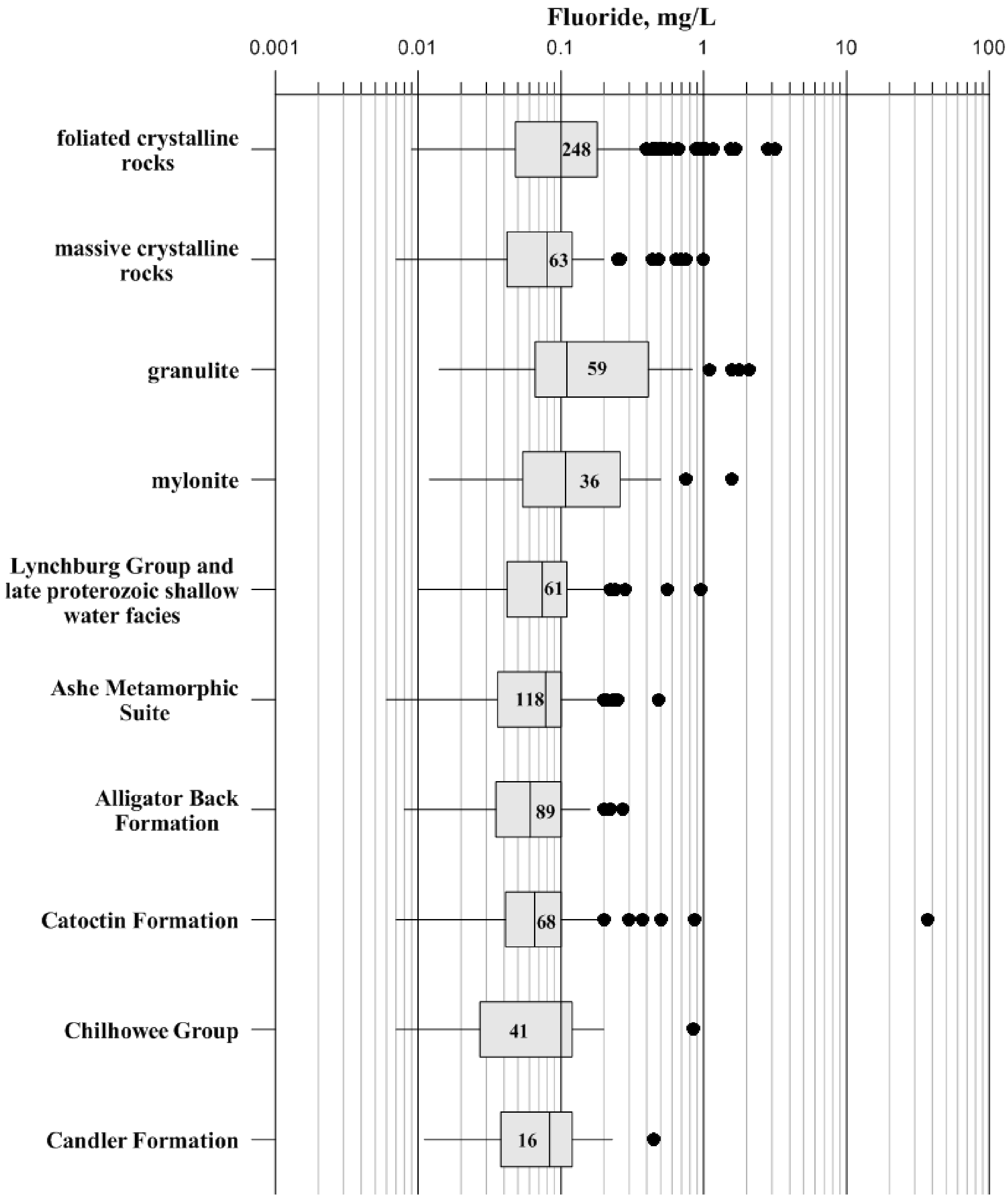


Figure 66. Distribution of fluoride in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

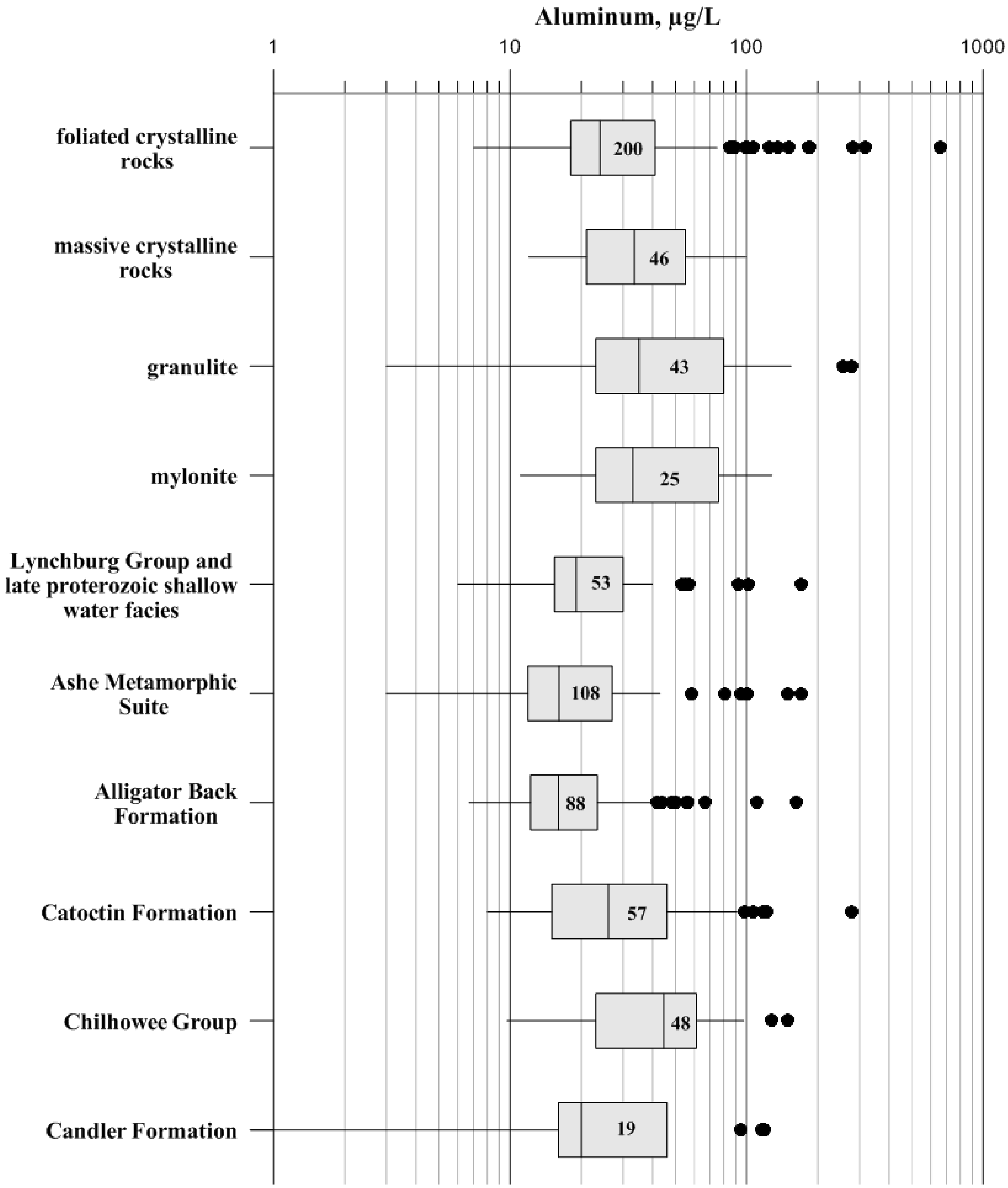


Figure 67. Distribution of aluminum in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

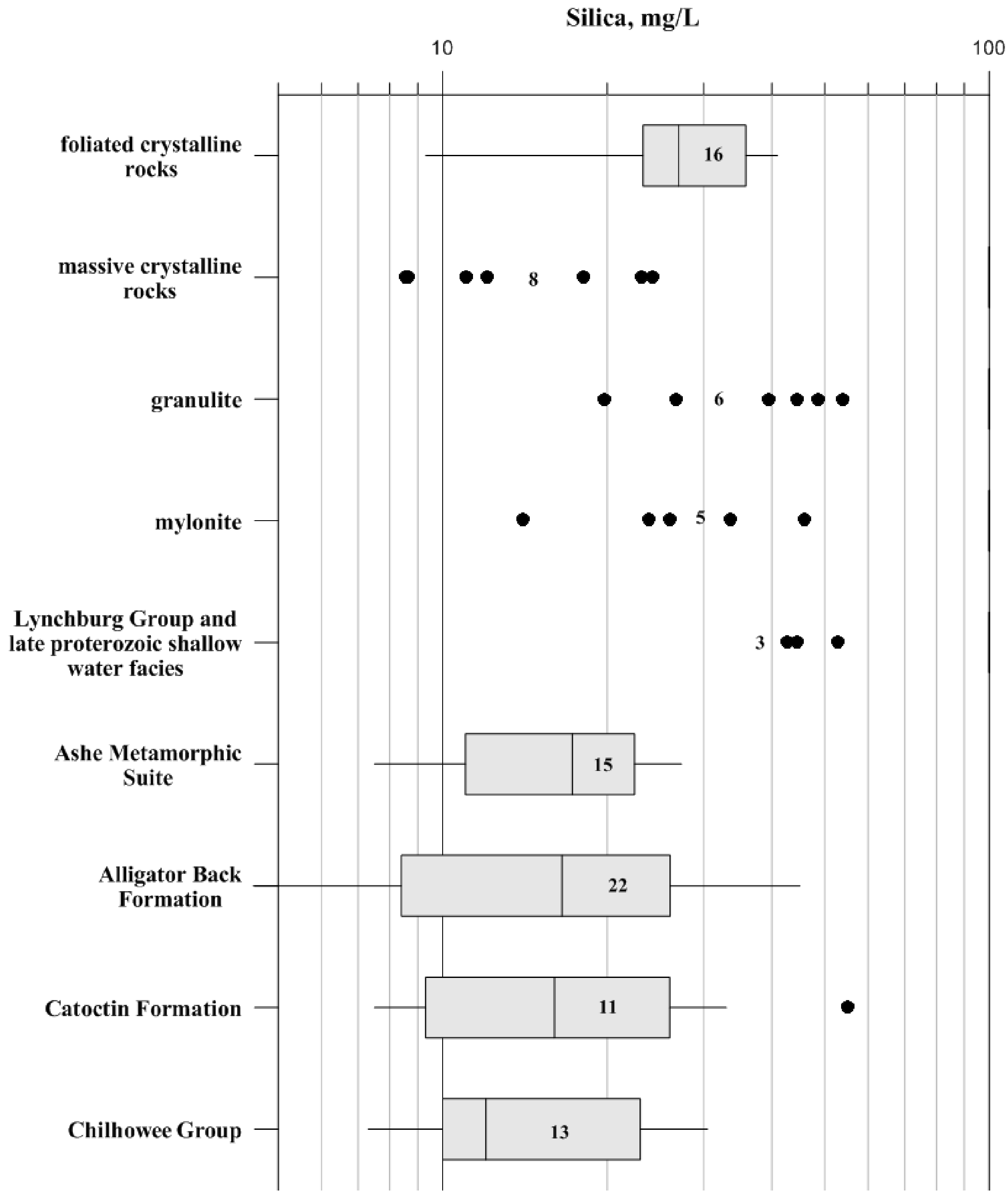


Figure 68. Distribution of silica in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

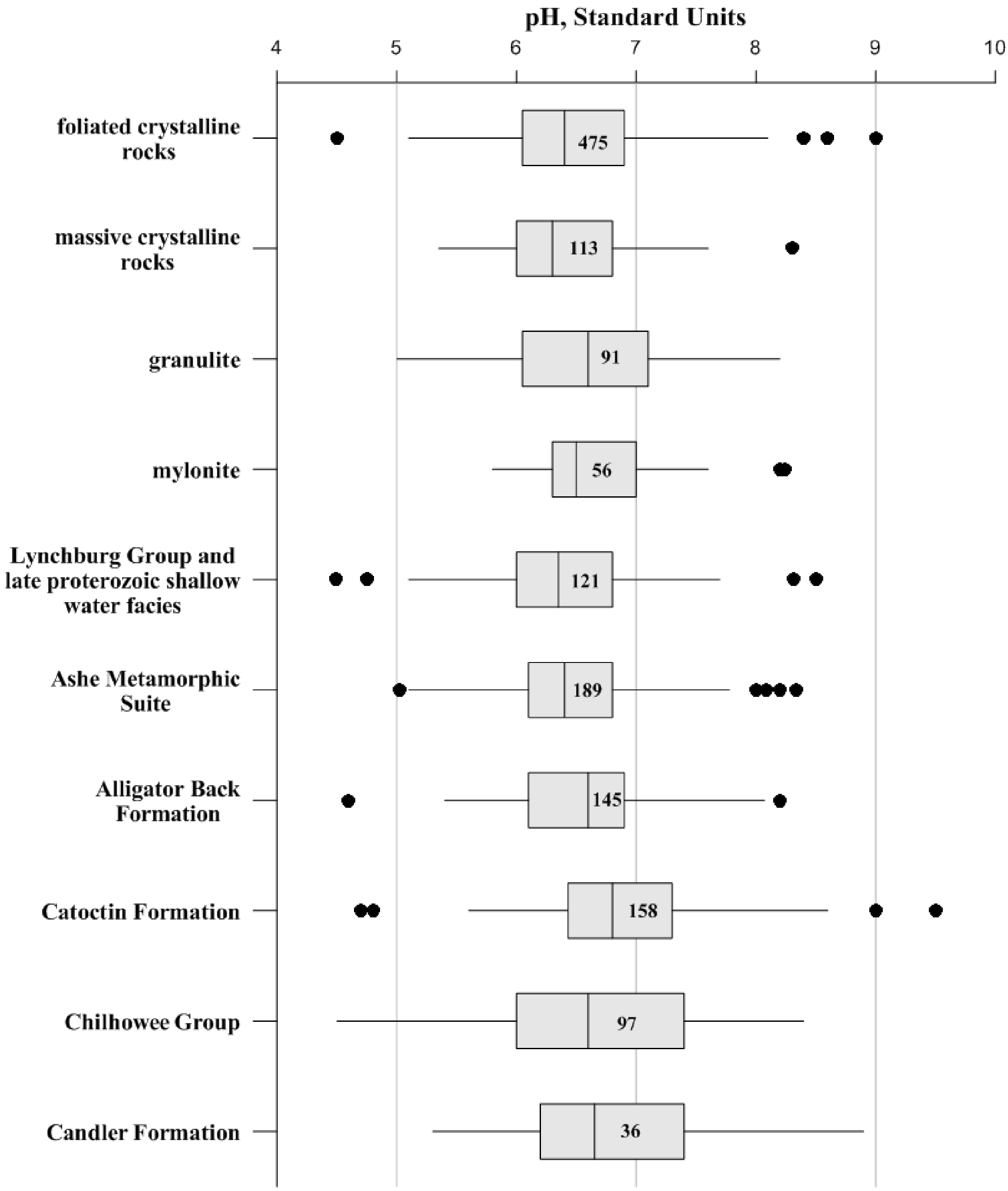


Figure 69. Distribution of pH in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

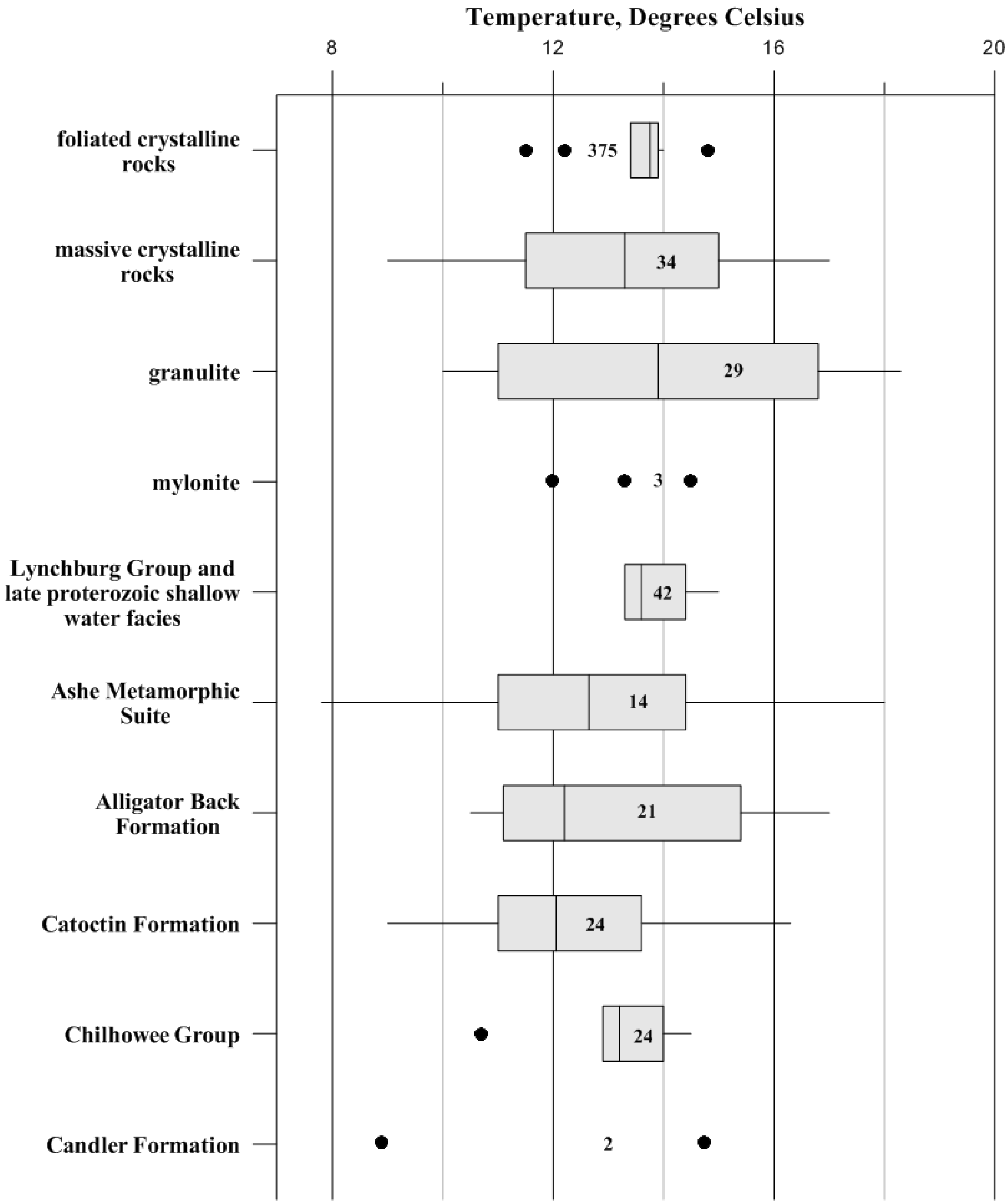


Figure 70. Distribution of temperature in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

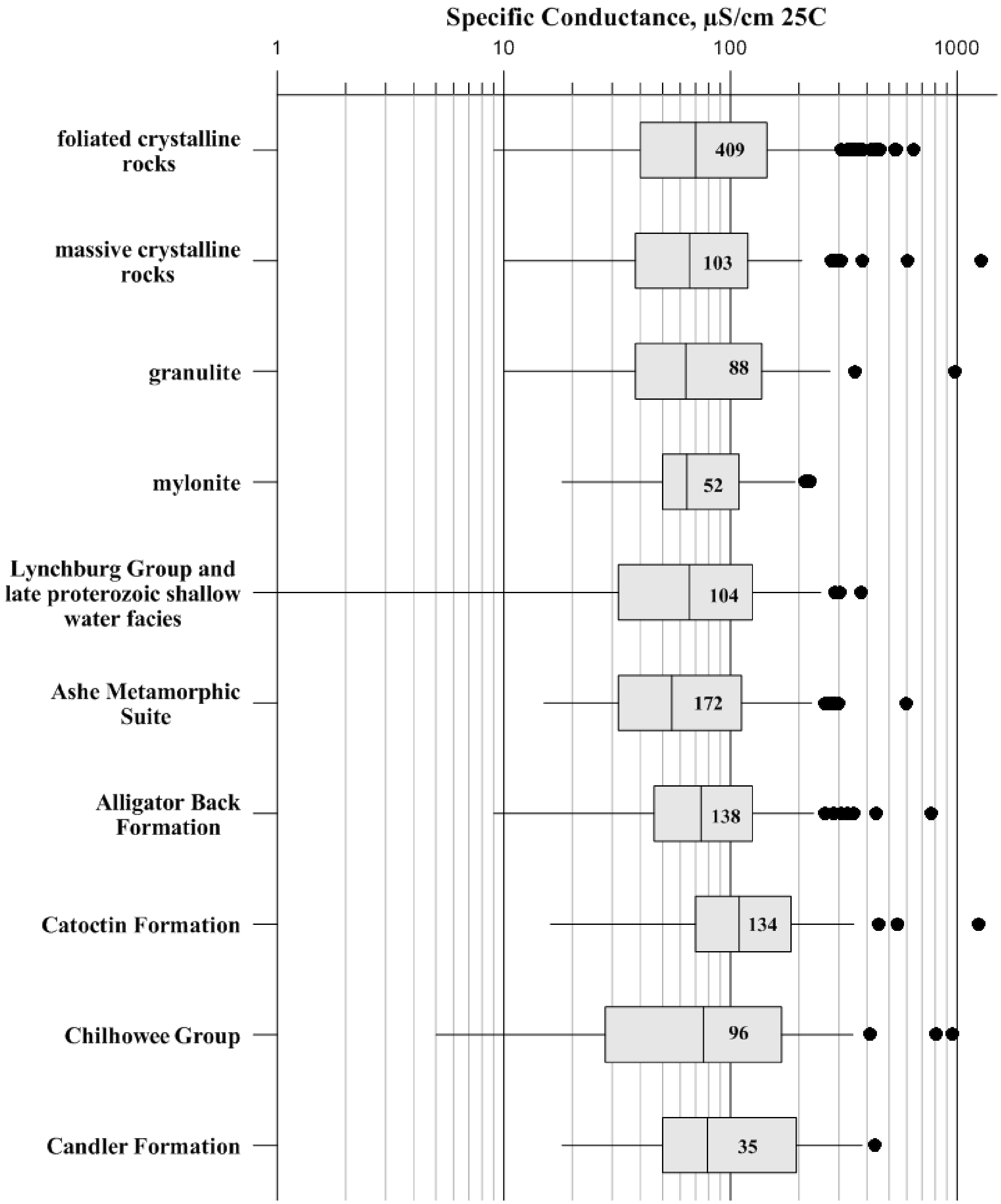


Figure 71. Distribution of specific conductance in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

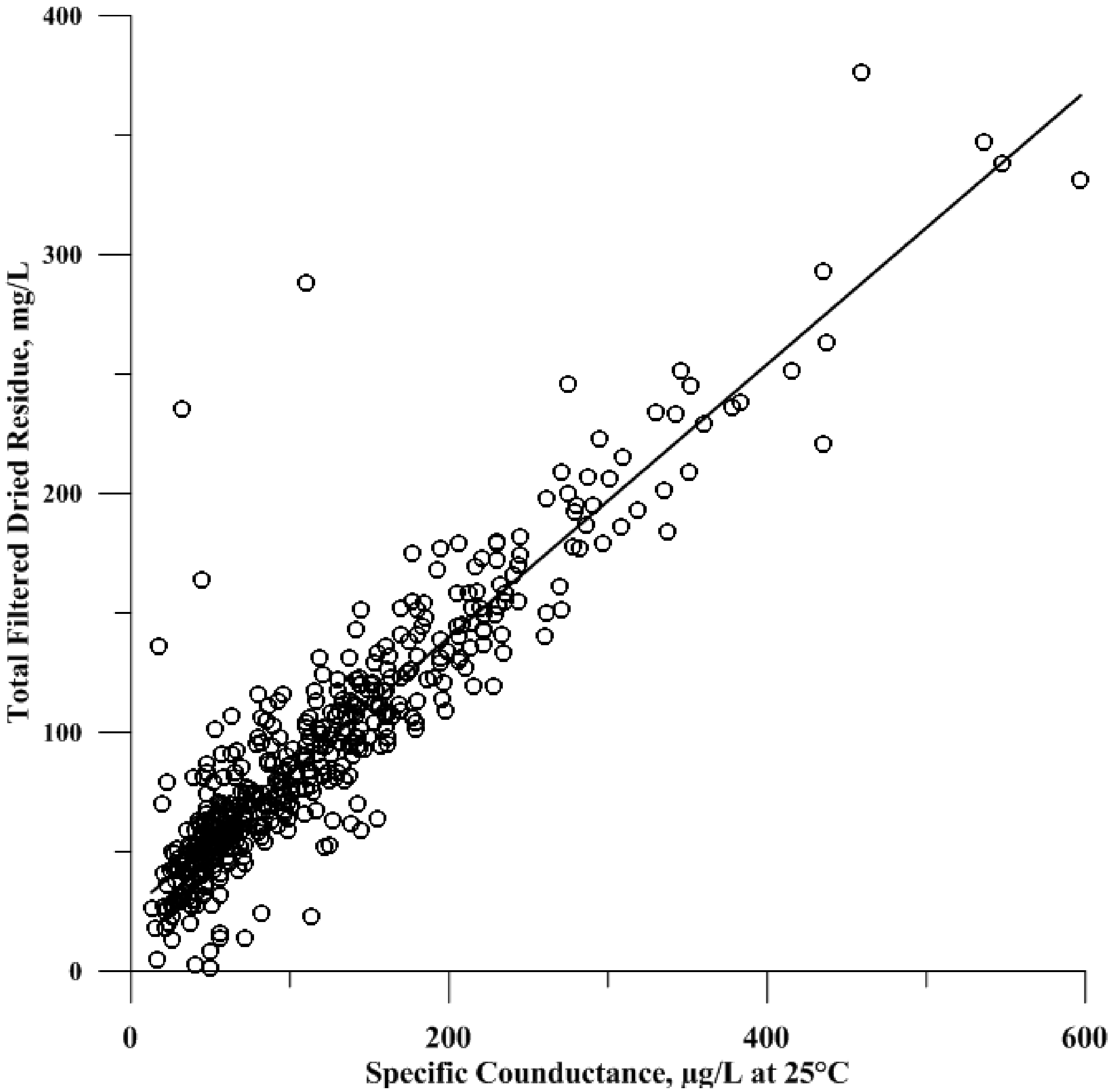


Figure 72. Relation of specific conductance to total filtered dried residue for groundwater samples taken throughout the Blue Ridge Geologic Province.

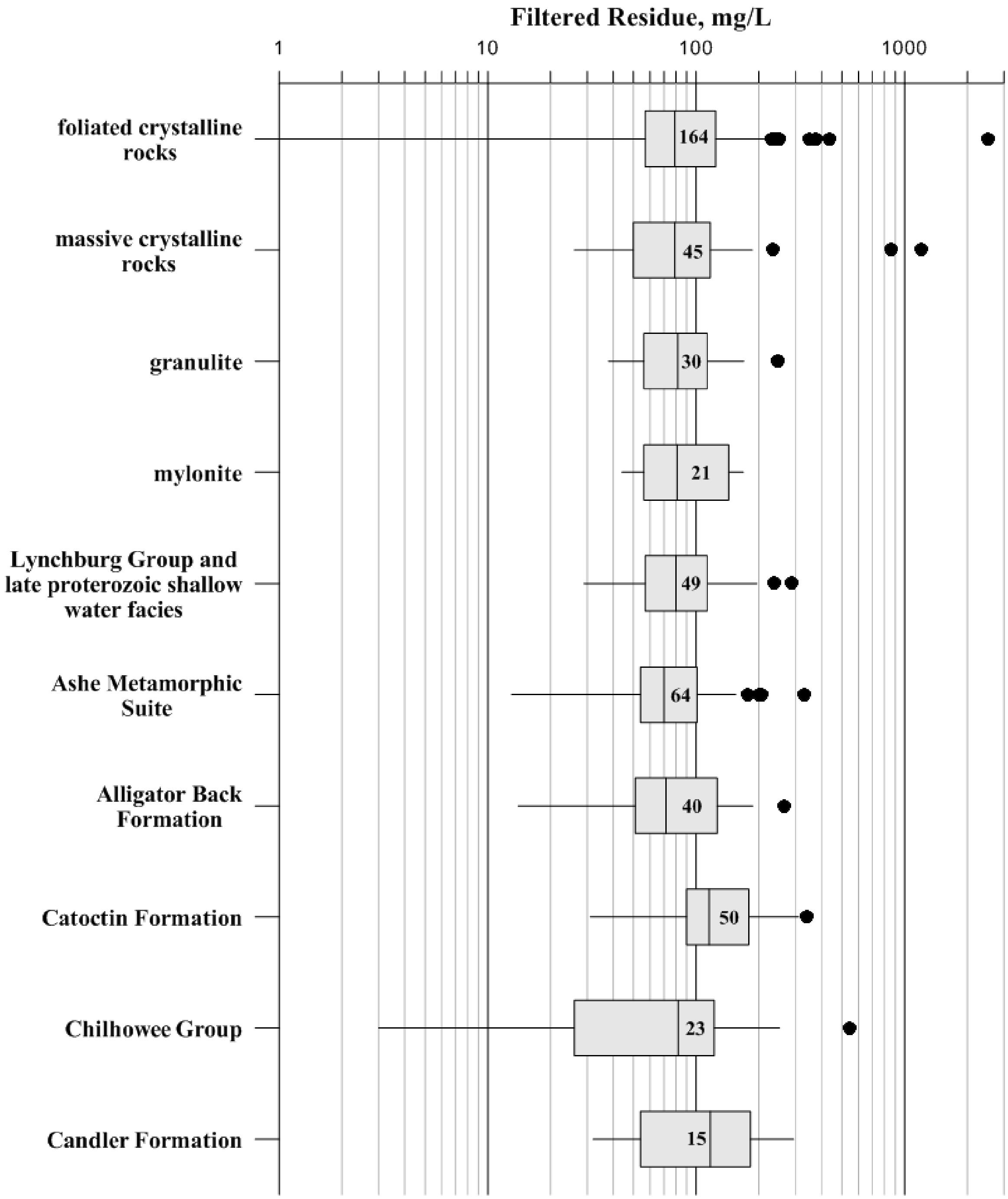


Figure 73. Distribution of filtered residue in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

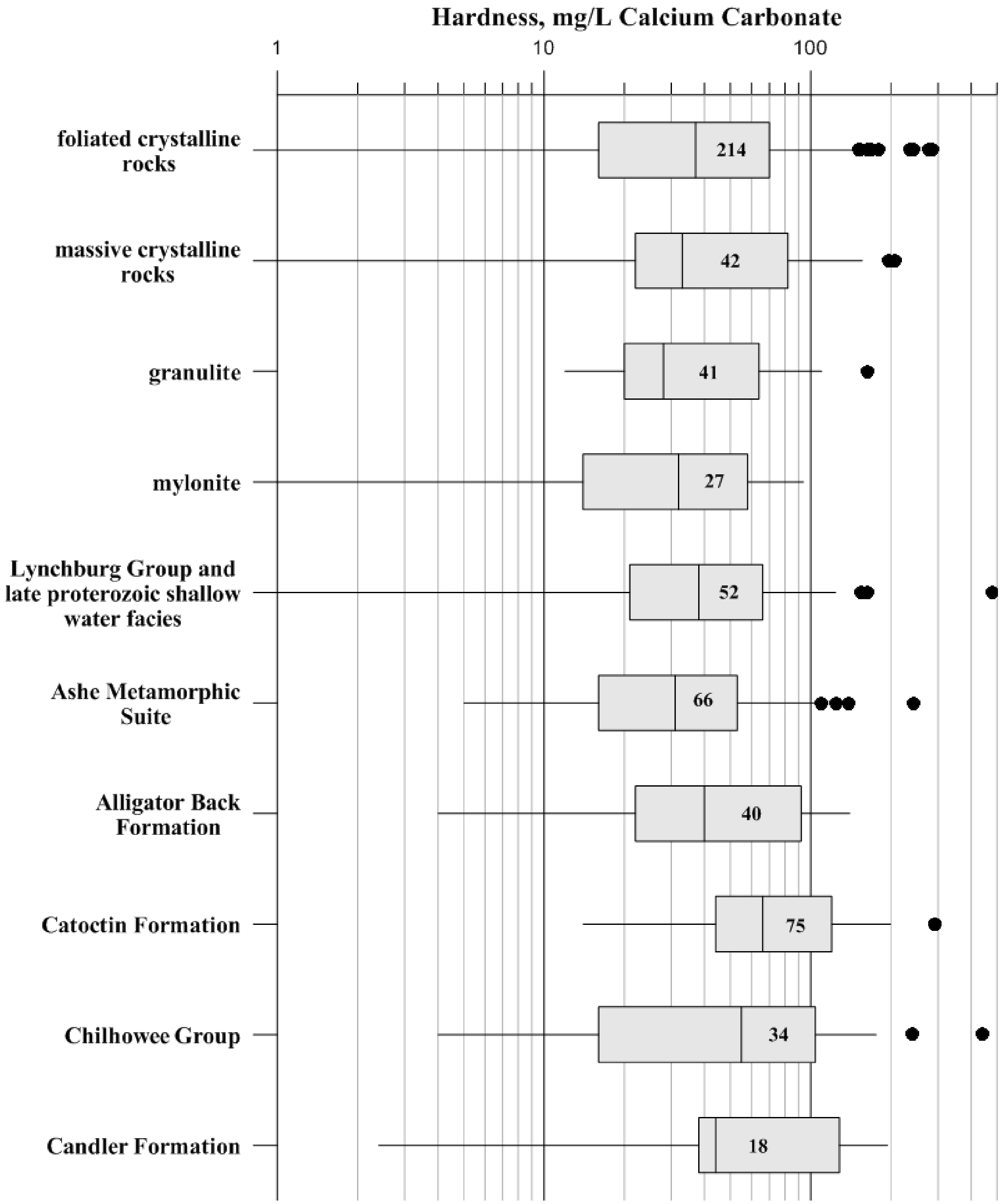


Figure 74. Distribution of hardness in groundwater samples taken from different rock types in the Blue Ridge Geologic Province. Numbers on box plots indicate the number of observations occurring within each population.

Table 29. Geochemical characteristics of groundwater samples taken from wells in the Blue Ridge Geologic Province.

Calcium mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	14.9	8.30	87.0	0.90	225
massive crystalline rocks	15.3	7.00	154	<0.01	65
mylonitic crystalline rocks	10.8	7.50	30.0	1.00	28
layered granulites	13.5	6.85	154	0.80	46
Lynchburg Fm. & Proterozoic shallow water facies	11.8	7.00	59.0	1.00	58
Ashe Metamorphic Suite	12.0	8.40	50.1	1.00	79
Alligator Back Fm.	13.7	8.00	68.0	0.60	43
Catoctin Fm.	24.1	18.0	200	1.10	89
Chilhowee Group	14.8	5.00	118	0.01	47
Candler Fm.	18.3	15.3	72.0	1.00	18

Sodium mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	6.48	5.00	164	0.10	404
massive crystalline rocks	6.89	5.00	42.0	<0.01	97
mylonitic crystalline rocks	7.34	4.96	62.0	1.02	54
layered granulites	6.79	5.00	35.0	0.37	83
Lynchburg Fm. & Proterozoic shallow water facies	6.04	4.10	38.0	0.88	105
Ashe Metamorphic Suite	4.07	3.20	43.9	0.22	179
Alligator Back Fm.	4.72	3.63	20.0	0.70	122
Catoctin Fm.	6.49	5.68	32.0	0.10	130
Chilhowee Group	4.39	2.77	37.0	0.02	91
Candler Fm.	7.47	4.96	41.0	0.94	34

Potassium mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	3.57	2.30	119	0.01	224
massive crystalline rocks	1.92	1.40	7.80	<0.01	56
mylonitic crystalline rocks	2.74	2.25	6.90	0.50	28
layered granulites	1.89	1.25	7.30	0.20	44
Lynchburg Fm. & Proterozoic shallow water facies	2.24	1.80	6.10	0.10	57
Ashe Metamorphic Suite	2.42	1.50	18.0	0.11	79
Alligator Back Fm.	2.08	1.70	8.60	0.40	43
Catoctin Fm.	1.22	0.90	5.50	0.15	75
Chilhowee Group	1.34	1.10	3.40	<0.01	47
Candler Fm.	1.26	1.00	4.20	0.30	18

Magnesium mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	3.48	1.47	120	0.10	325
massive crystalline rocks	2.33	1.60	13.7	<0.01	86
mylonitic crystalline rocks	2.1	1.54	9.70	0.10	40
layered granulites	2.98	1.78	27.1	0.10	72
Lynchburg Fm. & Proterozoic shallow water facies	2.41	1.70	12.0	0.06	92
Ashe Metamorphic Suite	2.57	1.60	17.0	0.10	158
Alligator Back Fm.	4.01	1.90	87.7	0.30	107
Catoctin Fm.	6.97	4.99	39.8	<0.01	108
Chilhowee Group	4.39	1.82	28.0	<0.01	74
Candler Fm.	4.06	3.00	18.7	1.00	30

Sulfate mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	6.07	3	59	0.13	201
massive crystalline rocks	3.66	2.15	19	0.1	58
mylonitic crystalline rocks	4.68	3.4	14.7	0.2	29
layered granulites	13.1	2	411	0.31	47
Lynchburg Fm. & Proterozoic shallow water facies	3.97	3	13.5	0.5	59
Ashe Metamorphic Suite	5.98	3	54.3	0.68	73
Alligator Back Fm.	8.1	2.8	149	0.1	49
Catoctin Fm.	9.47	3.5	201	0.1	75
Chilhowee Group	9.41	5.2	52.6	0.22	42
Candler Fm.	9.44	4.00	54.0	2.00	17

Chloride mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	6.79	4.20	104	0.80	410
massive crystalline rocks	6.61	4.00	60.8	0.50	104
mylonitic crystalline rocks	7.73	4.25	110	1.00	54
layered granulites	5.27	3.70	70.0	0.70	85
Lynchburg Fm. & Proterozoic shallow water facies	6.03	4.00	54.0	1.00	110
Ashe Metamorphic Suite	5.45	3.80	130	0.60	180
Alligator Back Fm.	5.02	4.00	45.0	0.60	128
Catoctin Fm.	9.61	4.50	78.2	0.60	151
Chilhowee Group	4.58	3.20	31.0	0.60	91
Candler Fm.	6.00	4.70	22.4	0.50	33

Bicarbonate mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	46.5	24.4	291	1.20	198
massive crystalline rocks	39.1	19.5	237	2.40	107
mylonitic crystalline rocks	38.8	23.2	174	1.60	142
layered granulites	43.6	29.0	146	2.40	91
Lynchburg Fm. & Proterozoic shallow water facies	40.6	29.3	247	1.20	115
Ashe Metamorphic Suite	35.8	22.0	241	1.20	185
Alligator Back Fm.	47.1	30.5	323	3.70	145
Catoctin Fm.	77.5	62.8	262	3.70	152
Chilhowee Group	64.1	26.2	991	2.40	96
Candler Fm.	68.3	39.0	244	0.60	35

Iron µg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	872	100	47,000	10.0	221
massive crystalline rocks	698	100	11,000	10.0	59
mylonitic crystalline rocks	606	100	9,060	10.0	29
layered granulites	367	100	4,000	10.0	41
Lynchburg Fm. & Proterozoic shallow water facies	796	100	7,200	10.0	58
Ashe Metamorphic Suite	577	180	4,710	10.0	75
Alligator Back Fm.	931	180	7,000	20.0	33
Catoctin Fm.	532	100	11,000	5.00	77
Chilhowee Group	598	100	5,500	4.00	45
Candler Fm.	1,260	140	11,000	20.0	19

Manganese µg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	54.9	17.5	1,000	2.00	380
massive crystalline rocks	70.7	18.0	920	3.00	87
mylonitic crystalline rocks	47.4	26.5	227	2.00	48
layered granulites	25.9	14.5	160	1.00	68
Lynchburg Fm. & Proterozoic shallow water facies	45.2	14.0	810	0.02	100
Ashe Metamorphic Suite	40.0	20.0	328	1.00	156
Alligator Back Fm.	92.4	30.0	2,200	3.00	106
Catoctin Fm.	127	29.0	7,840	1.00	112
Chilhowee Group	86.8	24.0	860	1.00	78
Candler Fm.	113	40.0	540	6.00	35

Fluoride mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	0.19	0.10	3.14	0.00	248
massive crystalline rocks	0.14	0.08	1.00	<0.01	63
mylonitic crystalline rocks	0.21	0.10	1.58	0.01	36
layered granulites	0.31	0.11	2.06	0.01	59
Lynchburg Fm. & Proterozoic shallow water facies	0.11	0.07	0.95	0.01	61
Ashe Metamorphic Suite	0.08	0.07	0.48	<0.01	118
Alligator Back Fm.	0.07	0.06	0.27	<0.01	89
Catoctin Fm.	0.64	0.06	37.0	<0.01	68
Chilhowee Group	0.10	0.10	0.85	<0.01	41
Candler Fm.	0.11	0.08	0.45	0.01	16

Aluminum µg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	38.9	24.0	660	7.00	200
massive crystalline rocks	42.4	33.5	99.0	12.0	46
mylonitic crystalline rocks	49.0	33.0	128	11.0	25
layered granulites	57.4	35.0	278	3.00	43
Lynchburg Fm. & Proterozoic shallow water facies	27.9	19.0	170	6.00	53
Ashe Metamorphic Suite	23.8	16.1	170	3.00	108
Alligator Back Fm.	22.6	16.0	162	6.70	88
Catoctin Fm.	38.8	26.0	277	8.00	57
Chilhowee Group	47.2	44.5	149	9.70	48
Candler Fm.	39.0	20.0	119	0.80	19

Silica mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	27.7	27.0	41.0	9.30	16
massive crystalline rocks	14.5	11.5	24.0	8.50	8
mylonitic crystalline rocks	28.7	26.0	46.0	14.0	5
layered granulites	19.2	20.8	32.3	5.50	6
Lynchburg Fm. & Proterozoic shallow water facies	25.4	23.3	31.5	21.6	3
Ashe Metamorphic Suite	17.2	17.2	27.3	7.50	15
Alligator Back Fm.	18.9	16.5	45.0	4.50	22
Catoctin Fm.	21.0	16.0	55.0	7.50	11
Chilhowee Group	14.4	12.0	30.5	7.30	13
Candler Fm.	na	na	na	na	0

pH

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	6.48	6.40	9.00	4.50	475
massive crystalline rocks	6.39	6.30	8.30	5.35	113
mylonitic crystalline rocks	6.63	6.50	8.24	5.80	56
layered granulites	6.62	6.60	8.20	5.00	91
Lynchburg Fm. & Proterozoic shallow water facies	6.33	6.35	8.50	4.49	121
Ashe Metamorphic Suite	6.46	6.40	8.34	5.02	189
Alligator Back Fm.	6.53	6.60	8.20	4.60	145
Catoctin Fm.	6.86	6.80	9.50	4.70	158
Chilhowee Group	6.62	6.60	8.40	4.50	97
Candler Fm.	6.79	6.65	8.90	5.30	36

Temperature Deg. C

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	14.2	14.4	15.0	11.5	375
massive crystalline rocks	13.7	14.4	17.0	9.00	34
mylonitic crystalline rocks	13.2	13.3	14.5	12.0	3
layered granulites	13.2	13.3	18.3	10.0	29
Lynchburg Fm. & Proterozoic shallow water facies	14.4	14.4	15.0	13.3	42
Ashe Metamorphic Suite	12.6	12.6	18.0	7.80	14
Alligator Back Fm.	13.0	12.2	17.0	10.5	21
Catoctin Fm.	12.2	12.0	16.3	9.00	24
Chilhowee Group	13.6	13.4	14.5	10.7	24
Candler Fm.	11.8	na	14.7	8.90	2

Specific Conductance µS/cm at 25˚C

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	108	70.0	643	9.00	409
massive crystalline rocks	105	66.0	1280	10.0	103
mylonitic crystalline rocks	82.0	64.0	225	18.0	52
layered granulites	97.0	63.0	972	10.0	88
Lynchburg Fm. & Proterozoic shallow water facies	86.0	65.0	378	1.00	104
Ashe Metamorphic Suite	80.0	55.0	597	15.0	172
Alligator Back Fm.	104	74.0	770	9.00	138
Catoctin Fm.	141	109	1250	16.0	134
Chilhowee Group	121	76.0	952	5.00	96
Candler Fm.	123	79.0	435	18.0	35

Filtered Residue mg/L

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	115	79.0	2490	1.00	165
massive crystalline rocks	128	79.0	1200	26.0	45
mylonitic crystalline rocks	90.4	81.0	168	44.0	21
layered granulites	95.7	81.5	246	38.0	30
Lynchburg Fm. & Proterozoic shallow water facies	90.9	80.0	288	29.0	49
Ashe Metamorphic Suite	83.7	70.0	331	13.0	64
Alligator Back Fm.	88.6	71.5	263	14.0	40
Catoctin Fm.	135	115	338	31.0	50
Chilhowee Group	97.1	82.0	544	3.00	25
Candler Fm.	119	117	293	32.0	15

Hardness mg/L $CaCO_3$

Rock Type	Mean	Median	Maximum	Minimum	Number of Observations
foliated crystalline rocks	56.0	37.0	999	1.00	215
massive crystalline rocks	78.0	34.0	999	1.00	43
mylonitic crystalline rocks	39.0	32.0	94.0	1.00	27
layered granulites	44.0	28.0	164	12.0	41
Lynchburg Fm. & Proterozoic shallow water facies	54.0	38.0	480	0.60	54
Ashe Metamorphic Suite	41.0	29.0	244	0.25	68
Alligator Back Fm.	50.0	40.0	140	0.68	41
Catoctin Fm.	83.0	66.0	292	14.0	75
Chilhowee Group	73.0	50.0	440	0.10	35
Candler Fm.	75.1	44.0	194	2.40	18

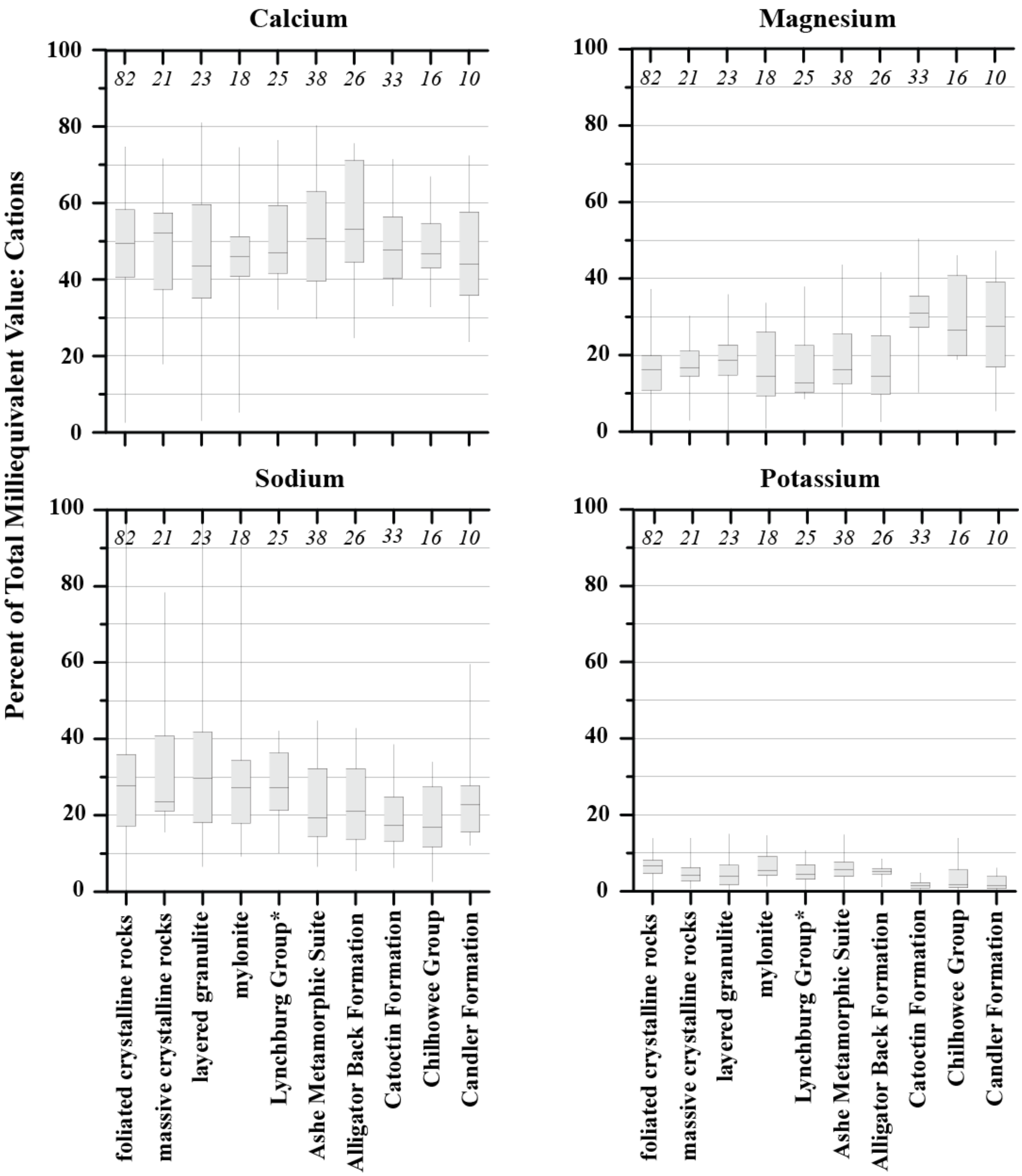


Figure 75. Percentage of total cation milliequivalent value for major cations by major ion and rock type. Box plots were constructed using data from groundwater samples with at least 90% charge balance between cations and anions (milliequivalents of total major cations were at least 90% of milliequivalents of total major anions). Numbers at the top of each plot represent the total number of samples evaluated for each population.

*Lynchburg Formation and late Proterozoic shallow water facies

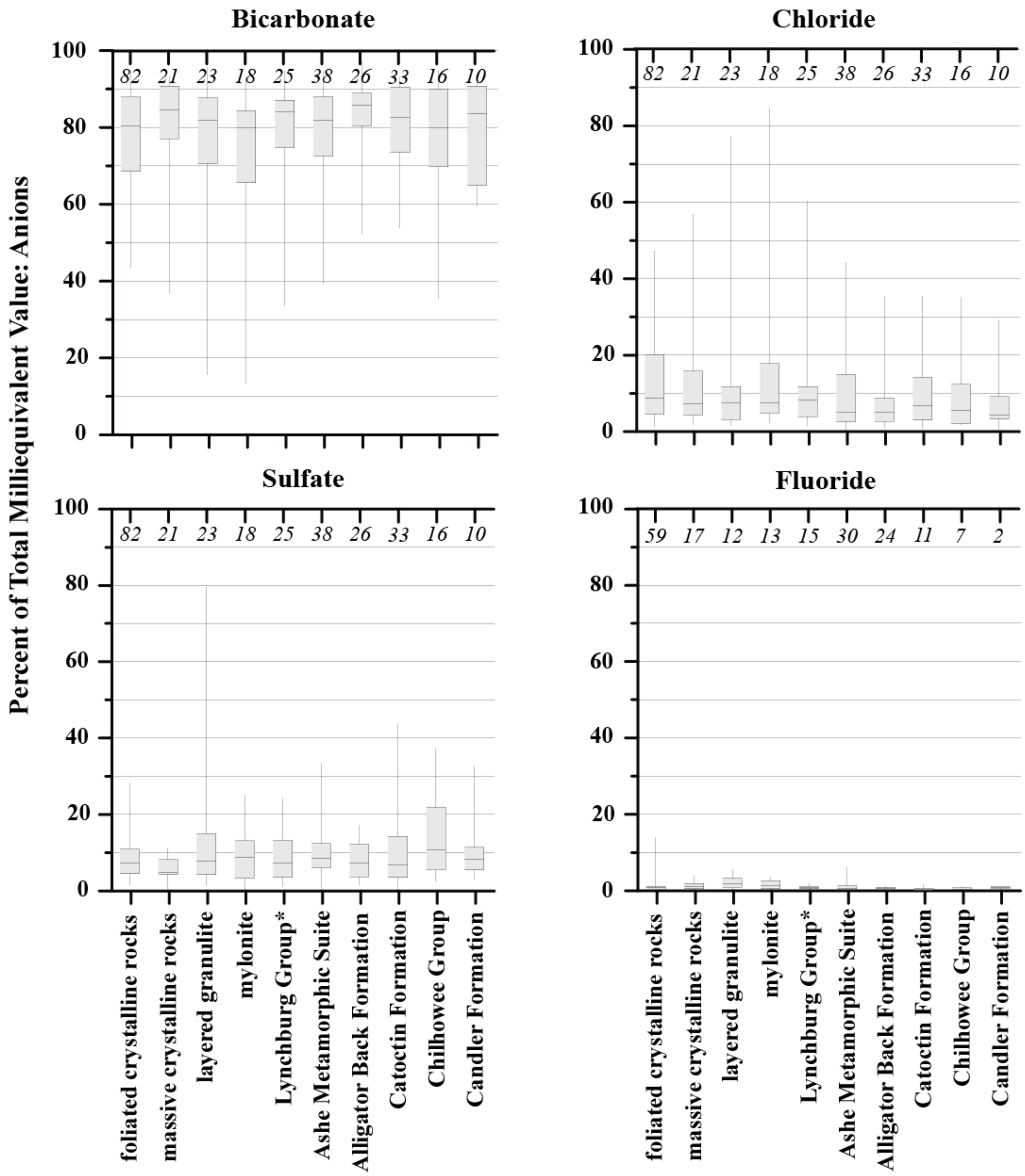


Figure 76. Percentage of total anion milliequivalent value for major anions by major ion and rock type. Box plots were constructed using data from groundwater samples with at least 90% charge balance between cations and anions (milliequivalents of total major cations were at least 90% of milliequivalents of total major anions). Numbers at the top of each plot represent the total number of samples evaluated for each population.

*Lynchburg Formation and late Proterozoic shallow water facies

HYDROGEOLOGY

Occurrence and Movement of Groundwater in the Regolith-Bedrock Aquifer System

Groundwater Recharge

Groundwater recharge to crystalline rock aquifers is controlled by a variety of limiting factors that can be separated into two categories: static and dynamic. Static controls on groundwater recharge include the topographic position, aerial extent of the recharge area, the permeability, thickness, and structure of the regolith, and the openness and orientation of fractures in the crystalline rock underlying the regolith. Dynamic factors related to the temporal and climatic variations in the timing and quantity of precipitation, the degree of saturation in the regolith prior to recharge events, and evapotranspiration rates within the recharge area are equally important controls on the groundwater recharge to fractured rock reservoirs. Structural features within the regolith such as clay lenses and differentially weathered saprolite can impart directional components to recharge pathways within the unsaturated zone to the water table or potentiometric surface (Harned, 1989; Rugh and Burbey, 2007; White and Burbey, 2007) although the overall hydraulic gradient within the unsaturated portion of the regolith is overwhelmingly vertical. Factors that promote recharge to the fractured rock reservoir include favorably oriented fractures associated with structural geologic features such as steeply inclined bedding and foliation, zones of concentrated fracturing associated with vertically oriented fractures (Williams et al., 2005) contrasting lithologies (quartz veins or granitic intrusives), fault related features and discrete zones of preferential weathering (Rugh and Burbey, 2007; Seaton and Burbey, 2000; Williams et al., 2005)– all of which must be in contact with the saturated near surface environment. Storage conditions within the fractured rock are additional important factors controlling the timing of recharge: if the hydraulic head within the bedrock fracture system is higher than the hydraulic head in the regolith, recharge to the underlying bedrock fractures will not occur. Under these conditions, water in the regolith will either remain in storage in the regolith, migrate laterally to a zone of lower head (like a stream, spring, or fracture set with a lower composite head, or will be taken up through evapotranspiration).

Figure 77 displays groundwater hydrographs for a number of rock wells completed in the Blue Ridge Province along with daily precipitation from nearby weather stations for Water Years 2009 and 2010. All hydrographs are displayed over 20 foot intervals to facilitate comparisons. Response time between precipitation inputs and the corresponding increase in pressure head registered within the water bearing fractures can be almost immediate, restricted to seasonal trends resulting from multiple periods of meteoric input during periods of low or little evapotranspiration, or not register at all during times of heavy evapotranspiration. The characteristics of the groundwater hydrographs displayed in figures 77a-f are notably different, and display annual water level records with overall amplitudes dominated by peaks associated with individual precipitation events (figures 77a-c), as well as records with overall amplitudes dominated by a subtle seasonal trend (figures 77e and 77f). The overall amplitude with 77d appears to be dominated more by a seasonal trend, but has a strong component relating to rapid response from individual precipitation events.

The "flashy" or "spiky" increases in hydraulic head associated with precipitation events for the well hydrographs displayed in 77a-c are probably not due to groundwater recharge, but rather caused by the propagation of pressure into the shallow fractured rock groundwater systems during precipitation events. Immediate and large water level rises in response to pressure loading by entrapped air have been explained by Todd (Todd, 1980) and Healey and Cook (Healy and Cook, 2002). Where fractures are in atmospheric communication with the regolith (as often occurs with fractures in close proximity to the regolith), pressure loading to the shallow fractured rock groundwater system can occur due to the entrapment of air between the nearly saturated pore spaces in the regolith near the water table, and the wetting front associated with recently infiltrated meteoric water. Where this occurs, pressure heads increase in the shallow groundwater system and are registered as rapidly increasing water levels in the well, followed by rapid declines in water level as air escapes from the unsaturated portion of the system. The absence of this phenomenon during periods of heavy evapotranspiration is theorized to be caused by a lack of saturated or nearly saturated conditions in the regolith, which are not conducive for the entrapment of air in the system (Healy and Cook, 2002). For wells exhibiting "spiky" or "flashy" hydrographs such as wells in figure 77a-c, the actual increase in head due to infiltrating water is probably a very small component of the increase in total head. Pressure loading on the aquifer by increasingly saturated vegetation and soil has also been shown to cause rapid rises in water levels in fractured rock aquifers overlain by regolith (Rodhe and Bockgard, 2006), and this phenomenon could also be contributing to rapid rises in groundwater level without much infiltration of water into the groundwater system.

Well USGS 48X 20 (figure 77a) and well USGS 49Y 1 SOW 022 (figure 77c) were both completed in the Weverton Formation of the Chilhowee Group, have at least one fracture within 100 feet of land surface, and are subject to rapid increases in hydraulic head after precipitation events during the wetter times of the year. During periods of active evapotranspiration (summer and early fall months) water level rise in response to precipitation is almost negligible. A "flashy" response to precipitation events for well USGS 49Y 1 SOW 022 (figure 77c) is followed by an asymptotic decline in water level that is probably associated with the rapid dissipation of pressure head in the upper fractures (at 64 and 76 feet in the wellbore), and to a lesser extent, gravity driven "thru flow" within the upper fracture set as horizontal hydraulic gradients carry the shallow groundwater across the wellbore to lower elevations, as well as to higher transmissivity fractures at a lower interval in the wellbore that "take" the water from the upper fractures. A 29 hour pump test conducted at well 49Y 1 SOW 022 indicates that the bulk of the storage within this well occurs within the fractures at 274 and 410 feet below land surface (the stabilized pumping level with a pumping discharge of 8.5 gallons/minute was well above the lower fracture set, and nearly 70 feet below the bottom fracture in the upper fracture set). As heads dissipate within the upper fractures of the wellbore, hydraulic head is governed by more stable hydraulic conditions and lower head values in the lower fracture set. Because well USGS 48X 20 is only 60 feet deep, its water is most likely derived from a shallow source, and displays the "flashy" characteristic in at least one fracture during periods of increasing head. As with well USGS 49Y 1 SOW 022, rapid responses in pressure head are either negligible or do not occur after precipitation events during times of heavy evapotranspiration. Wells 49Y 1 SOW 022 and 48X 20 are both situated on hilltops in steep terrain and groundwater gradients in these areas are likely high, contributing to the rapid dissipation of the groundwater component of total head observed in these well hydrographs.

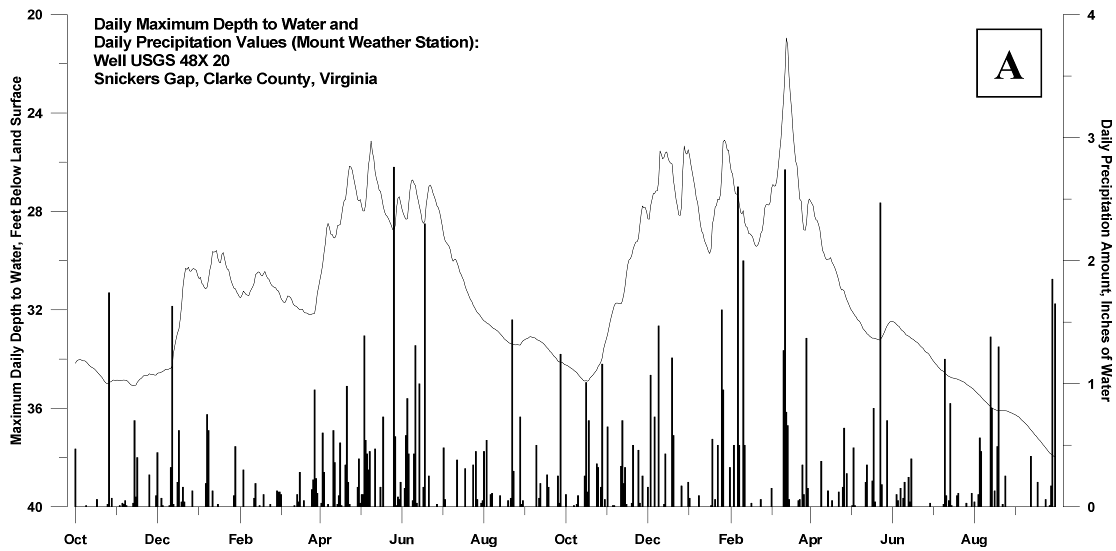
Well USGS 48U 26 SOW 215 (figure 77b) was drilled in massive metabasalt of the Catoctin Formation on the eastern flank of the Blue Ridge Anticlinorium. Most of the water in this well comes from fracture sets at 27 and 97 feet below land surface, with the majority of the yield issuing from the fracture at 97 feet. Upon completion, the well yielded approximately 3 gal/min, and during a 5 hour pump test the well yielded 2 gal/min with a drawdown of 48.5 feet (stabilized pumping level was at 69.9 feet bls). Large and rapid pressure head fluctuations in response to precipitation events are exhibited by the groundwater system in communication with this well, indicating that the well is in atmospheric communication with the regolith via a transmissive fracture intersecting the well bore. Shallow regolith (depth to bedrock was 1 foot), and a steeply dipping transmissive fracture intersecting the wellbore at 27 feet below land surface contribute to the rapid response of this well to precipitation events. During the hotter times of the year when evapotranspiration rates are high (late June – October), rapid pressure head responses to precipitation are not observable. Fractures noted on geophysical logs taken within the well are either longitudinal or perpendicular to the predominate schistosity of the rock, which dips fairly steeply to the southeast at about 60 degrees. The transmissive fracture at 27 feet is perpendicular to the predominately southeasterly dipping foliation in the vicinity of the well, dipping at about 65 degrees to the northwest.

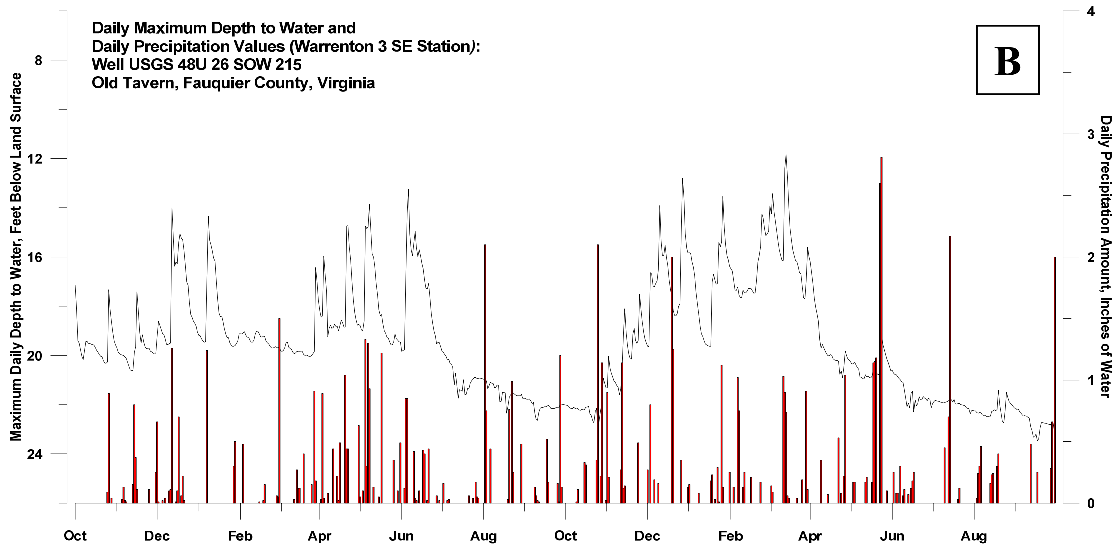
Well USGS 45P 1 SOW 030 (figure 77d) is drilled in arkosic and phyllitic rocks of the Candler Formation, and exhibits a different response to precipitation when compared with wells USGS 48X 20, 49Y 1 SOW022, and 48U 26 SOW 215. Transmissive fracture sets in this well were logged at 61-63 feet below land surface, and 76-80 feet below land surface, and are generally oriented perpendicular or longitudinal to foliation which strikes approximately 45 degrees and dips steeply between 60 and 80 degrees to the southeast. Depth to bedrock for this well was reported at 10 feet below land surface. Although this well is fairly shallow and water level rise in response to precipitation occurs quickly, the magnitude of response to individual precipitation events is less drastic in comparison to the groundwater hydrographs displayed in figure 77a-c. The reason for the dampened response to meteoric inputs associated with well 45P

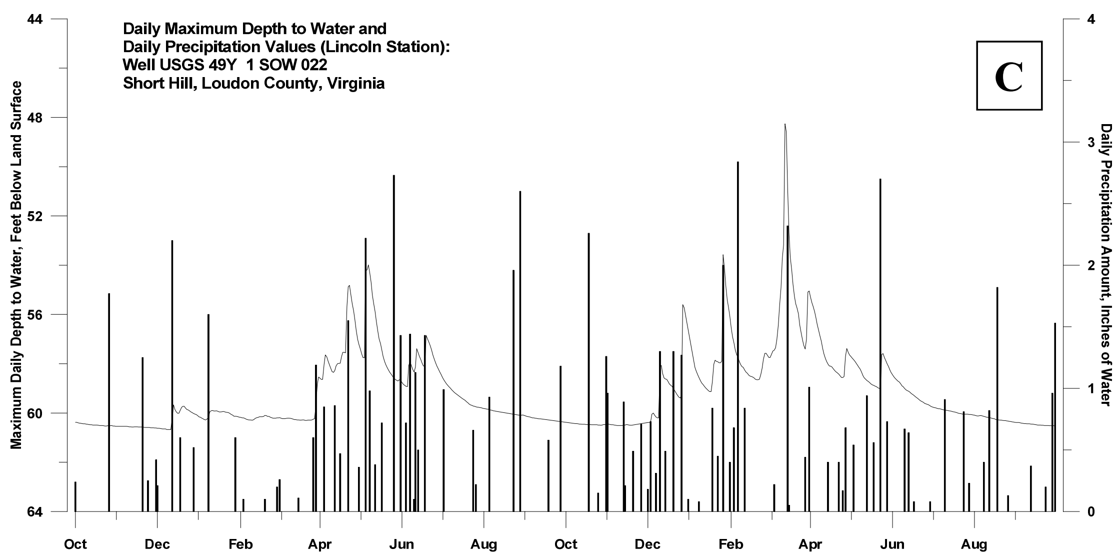
1 SOW 030 is related to the level of hydraulic connection between the precipitation input and the transmissivity and storage capacity of the fractures and regolith sourcing water to the well, but the degree to which each one of these mechanisms contributes to the response is currently not known.

Both well USGS 35H 1 SOW 226 (figure 77f) and well USGS 33G 2 SOW 225 (figure 77e) were completed in the Blue Ridge Basement Complex and display a different style of response to precipitation inputs when compared to the groundwater hydrographs displayed in figure 77a-77d. Well USGS 35H 1 SOW 226 was drilled in a mylonitic section of granitic gneiss to a depth of 181 feet below land surface. This well is sourced by a very low yielding fracture (about 0.1 gallon/minute) at 38 to 40 feet below land surface, and a much higher yielding fracture (about 60 gallons/minute) from 168 to 169 feet below land surface. Rocks within the borehole are strongly foliated, with foliations dipping about 60 degrees between 90 and 135 SE. The upper fracture is a nearly horizontal joint, and the lower fracture is orthogonal to foliation, dipping at about 20 degrees to 290 NE. Depth to bedrock at this well was ten feet below land surface. The hydrograph for this well (displayed in figure 77f) is dominated by a seasonal trend in water level fluctuation, indicating that the groundwater flow system in communication with this well is not in strong atmospheric communication with the regolith, and is sourced by recharged water over a slower time frame. Slower, more seasonal changes in groundwater levels may result from more distant and or greater aerial contributions to groundwater storage. At the scale used to display this hydrograph, immediate responses to recharge are barely discernible with the larger rainfall events, and may be related to recharge response in the upper low yield fracture. Rapid increases in pressure head after precipitation events are probably dampened in the lower, more transmissive fracture set due to its location in the system, and its higher transmissivity.

Well USGS 33G2 SOW 225 was drilled in layered granulite gneiss in the Blue Ridge Basement Complex to a depth of 201 feet below land surface. It is sourced by 3 water bearing zones : 95-96 feet below land surface (estimated at 1 gallon/minute), 165-166 feet below land surface (estimated at 1 gallon/minute), and 188-190 (estimated at 13 gallons/minute). It was subsequently pumped at a rate of 2 gallons/minute during geophysical logging for approximately 3.5 hours with a drawdown of 20 feet (pumping water level was 67.4 feet below land surface). Depth to competent bedrock was 82 feet. Fluid resistivity logs indicate an overall downward hydraulic gradient from the upper to lower fracture sets during ambient (non- pumping) conditions. The hydrograph associated with this well (figure 77e) is similar in nature to the hydrograph displayed in 77f.


Daily Maximum Depth to Water and
Daily Precipitation Values (Mount Weather Station):
Well USGS 48X 20
Snickers Gap, Clarke County, Virginia
A
Maximum Daily Depth to Water, Feet Below Land Surface
Daily Precipitation Amount, Inches of Water
20
24
28
32
36
40
4
3
2
1
0
Oct
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
Jun
Aug


Daily Maximum Depth to Water and
Daily Precipitation Values (Warrenton 3 SE Station):
Well USGS 48U 26 SOW 215
Old Tavern, Fauquier County, Virginia
B
Maximum Daily Depth to Water, Feet Below Land Surface
Daily Precipitation Amount, Inches of Water
8
12
16
20
24
4
3
2
1
0
Oct
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
Jun
Aug


Daily Maximum Depth to Water and
Daily Precipitation Values (Lincoln Station):
Well USGS 49Y 1 SOW 022
Short Hill, Loudon County, Virginia
C
Maximum Daily Depth to Water, Feet Below Land Surface
Daily Precipitation Amount, Inches of Water
44
48
52
56
60
64
4
3
2
1
0
Oct
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
Jun
Aug

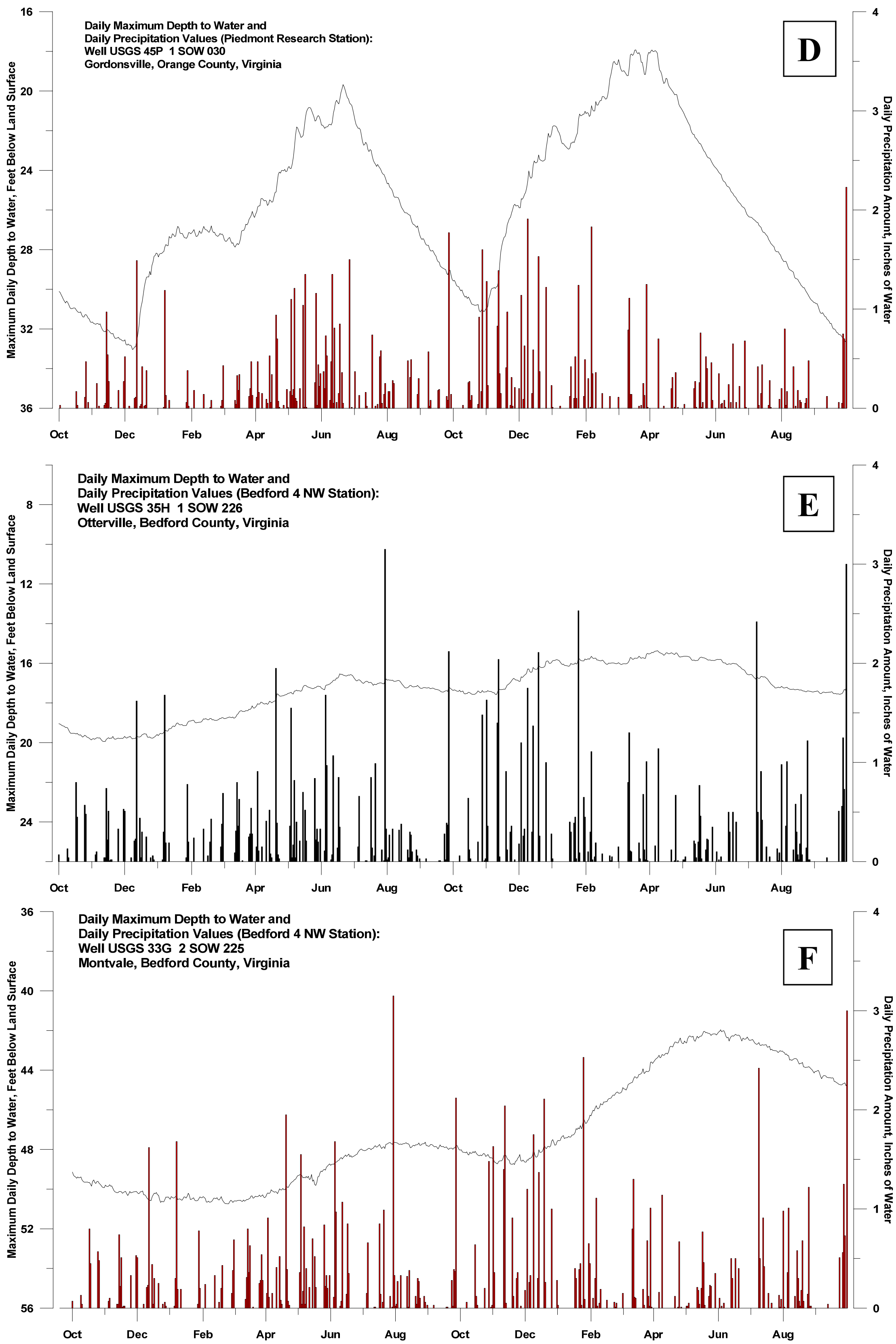


Figure 77. Groundwater hydrographs for selected observation wells in the Blue Ridge Geologic Province (2009 and 2010 Water Years).

Groundwater Discharge

The discharge of groundwater from crystalline rock aquifers is controlled by vertical and horizontal groundwater gradients and the transmissivity of the groundwater flow system. Groundwater stored within the regolith that does not migrate into fractured rock is either taken up through evapotranspiration or moves down gradient via topographically driven (gravity) flow within the regolith to the lowest elevation in the local groundwater flow system. In the highly dissected topography of the Blue Ridge Geologic Province, most of the down gradient outlets for local groundwater flow systems are the lowest points of elevation in the landscape-small streams and headwater springs that exhibit considerable seasonal variation in discharge, and are largely sustained by discharging groundwater during the drier times of the year. Groundwater within the crystalline bedrock portion of the local flow system is driven both by changes in elevation (gravity) and pressure head in the flow system and follows a more tortuous route to a point of discharge. Although deep groundwater is ultimately discharged back to surface water features, the most likely point of discharge from a bedrock groundwater system is back into the regolith via fractures in communication with the regolith where the total hydraulic head in the regolith is lower than the total hydraulic head within the fracture system discharging to the regolith. Water from the fractured bedrock system discharges to lower head portions of the groundwater flow system where the total head (usually dominated by elevation) in the saturated regolith is lower than the total pressure/elevation head of the fracture flow system. Where fractures in communication with the regolith are absent in the fracture flow system, it is possible for groundwater to bypass local topographic depressions in favor of the nearest point of discharge. Depending on the configuration of the flow system, the discharge point for the fracture flow system may be above the local topographic low, or some distance away from it. Figure 78 provides a visual conceptualization of local groundwater discharge points for both fracture flow and regolith groundwater systems in fractured crystalline rock.

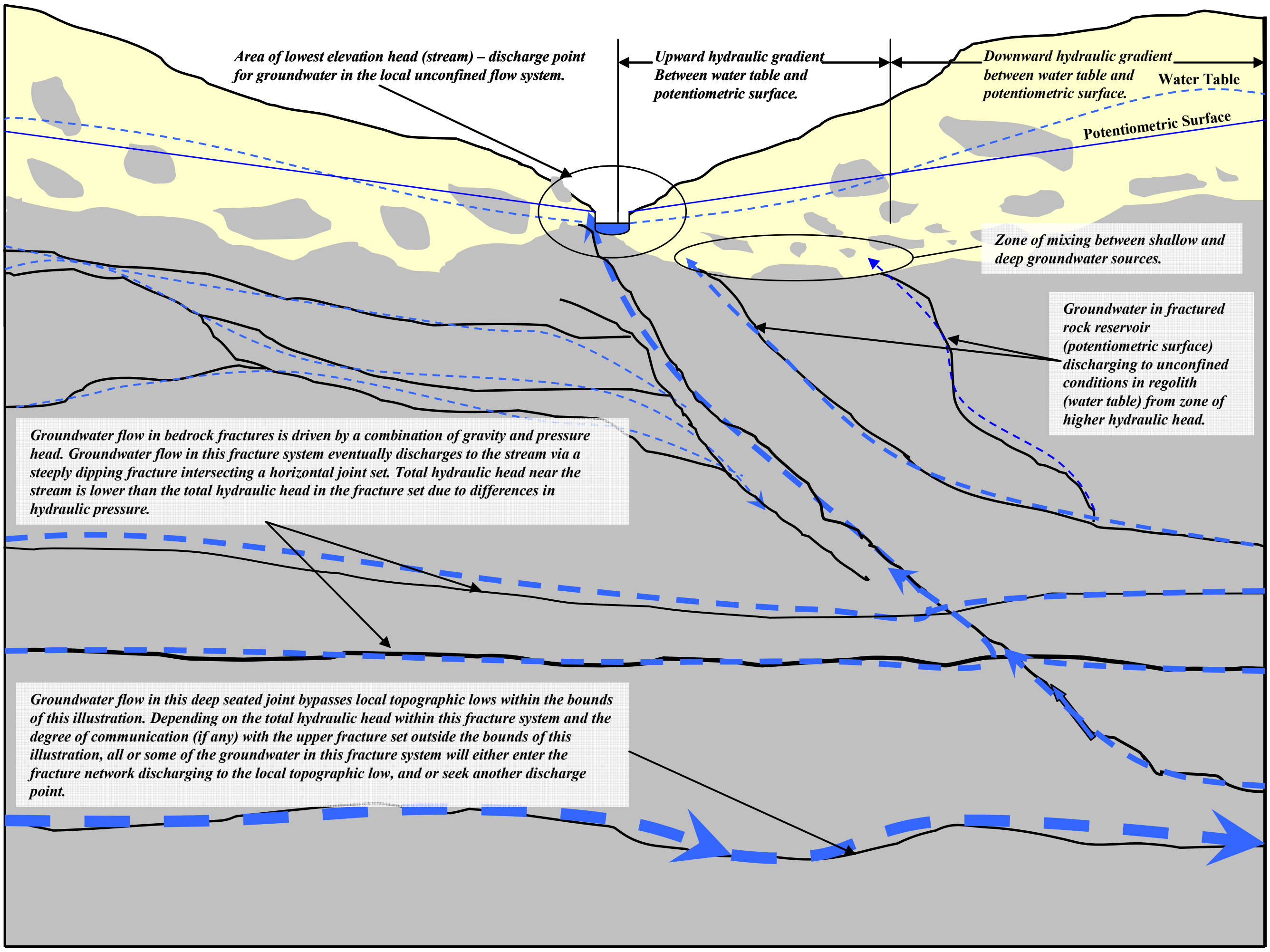


Figure 78. Conceptual diagram illustrating groundwater flow paths in a fractured crystalline rock setting.

Using Streamflow Records for Water Budgets and Estimating Groundwater Availability

Streamflow records provide a means for direct and indirect quantification of several major components of the hydrologic cycle. Stream flow data are particularly useful for developing watershed-scale water budgets for water supply planning or groundwater flow modeling needs, but water budgets do require adherence to a number of assumptions that may or may not hold true for the watershed.

At its simplest level, a water budget can be described in the following equation:

$$I\text{-}O=\Delta S$$

where *I* represents input rates to the watershed, *O* represents outflow rates from the watershed, and ΔS represents changes in storage within the system. Under natural conditions the only significant input is assumed to be precipitation, and major outputs from the system consist of stream flow and evapotranspiration (it is assumed that no groundwater is entering the system and that all groundwater in the system is eventually discharged into the stream at some point above the stream gage). If there are no major artificial additions of water to, or withdrawals of water from the system, inputs can be assumed to equal outputs and steady state conditions occur (there are no net changes in water storage within the system over the period of interest).

With a balanced water budget, variables that are harder to quantify through direct measurement can be attained indirectly: watershed wide evapotranspiration rates can be quantified by subtracting total stream discharge from precipitation. Estimates of basin-wide groundwater recharge can be attained through a technique called hydrograph separation. This method involves either computer or manual analysis of measured streamflow data over discrete time intervals (usually mean daily streamflow) to graphically calculate the groundwater component of stream discharge. Under steady state conditions, groundwater discharge can be assumed to equal recharge. When there are major withdrawals or returns to the water budget that are not naturally occurring (pumping wells, in stream withdrawals, artificial groundwater injections, inter-basin transfers of water) these factors should be quantified and incorporated into the water budget in order to attain the best possible estimates of water budget parameters.

Base-flow derived groundwater recharge estimates provide an empirically based estimate of total groundwater availability for a defined area (watershed). Groundwater recharge is not an estimate of total water available for groundwater withdrawal, but rather an estimate of total groundwater moving through the system – a portion of which can be sustainably used. Additional hydrologic factors such as base-flow variability (which can provide some indication of basin-wide groundwater storage characteristics), geologic structure and lithology, local well completion reports, aquifer tests, and precipitation amounts should be evaluated at the watershed scale for water supply planning and groundwater management purposes.

Figure 79 presents effective recharge rates calculated from base-flow estimates for a number of watersheds and sub-watersheds within the Blue Ridge Geologic Province. Effective recharge is defined as the amount of precipitation that infiltrates into the ground, is not removed from storage through evapotranspiration or groundwater withdrawal, and is ultimately discharged to streams as measurable stream flow.

Watersheds presented in figure 79 have effective recharge rates ranging from 0.29 in/yr to 33.07 in/yr. Effective recharge rates for most watersheds in the Blue Ridge Geologic Province fall somewhere between 5 in/yr and 15 in/yr, with extremely high and low values in effective recharge restricted to smaller sub-watersheds on the western side of the Blue Ridge Geologic Province. Effective recharge rates can vary significantly at the sub-watershed scale in the Blue Ridge due to marked differences in topography, precipitation, and geology, and do not necessarily reflect the storage characteristics of the groundwater system underlying the watershed under study (Nelms et al., 1997). In mountainous terrain where valley fill is abundant, hydrograph separation has been shown to overestimate groundwater recharge to the fractured rock system (Nelms and Moberg, 2010b).

Indicators that a productive watershed-scale groundwater system exists include favorable effective recharge estimates and low base-flow variability - a measurement of the rate at which the groundwater component of stream-flow diminishes during periods of no precipitation. Small decreases in base-flow discharge over a period of base-flow observation indicate discharge from a groundwater system within the basin that is capable of sustaining a fairly constant discharge rate. A relation between base-flow variability and basin wide arial diffusivity was illustrated by Nelms et. al. (1997): streams with low baseflow variability tend to have lower aerial diffusivity estimates (aerial diffusivity is the ratio of basin-wide estimates for transmissivty (T), and storage (S) (T/S)), and therefore presumably higher storage coefficients occur within these watersheds. Basin-wide storage coefficients and favorable groundwater storage conditions within fractured bedrock groundwater systems are related to a number of factors, including the thickness and permeability of the regolith, the topography of the basin, the degree of fracturing and weathering of the bedrock within the basin, and the degree of communication between the regolith and the bedrock (Giusti, 1962; Nelms et al., 1997). The occurrence of low base-flow variability indices do not guarantee success in finding high yield wells within the basins under study, nor do high base-flow variability indices mean that only low yielding wells will occur within a basin. Figure 80 presents ranges in base-flow variability indicies for selected watersheds in the Blue Ridge Geologic Province.

Data presented in figure 79, 80 and Table 30 were taken from the USGS Water Supply Paper 2457 (Nelms et al., 1997). Additional data pertaining to stream discharge characteristics of individual basins and regional surface and groundwater yield for the hard rock portions of Virginia can be found in USGS Water Supply Paper 2457.

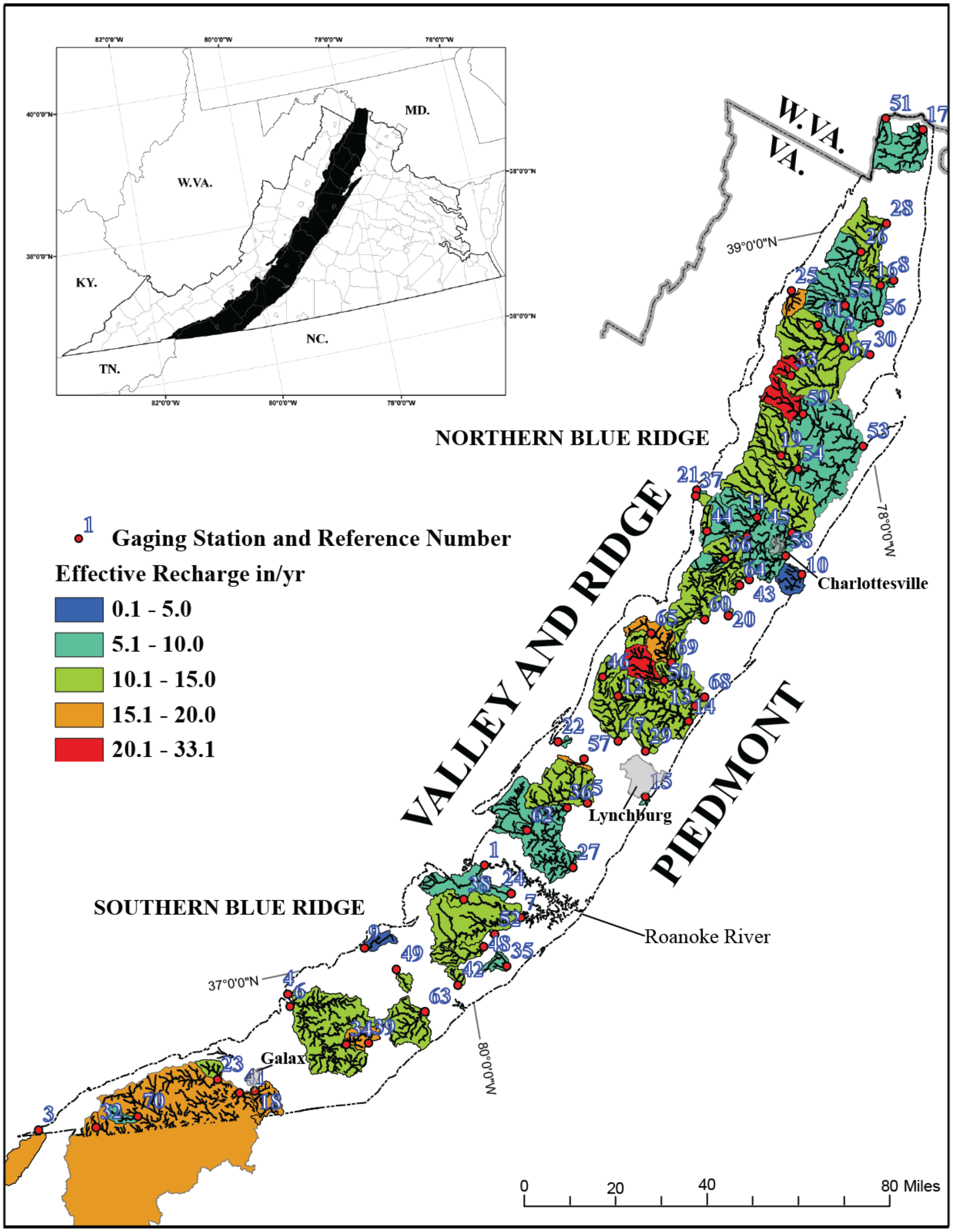


Figure 79. Effective recharge ranges calculated using streamflow recession methods for selected watersheds in the Blue Ridge Geologic Province. Information for referenced gaging stations presented in table 30.

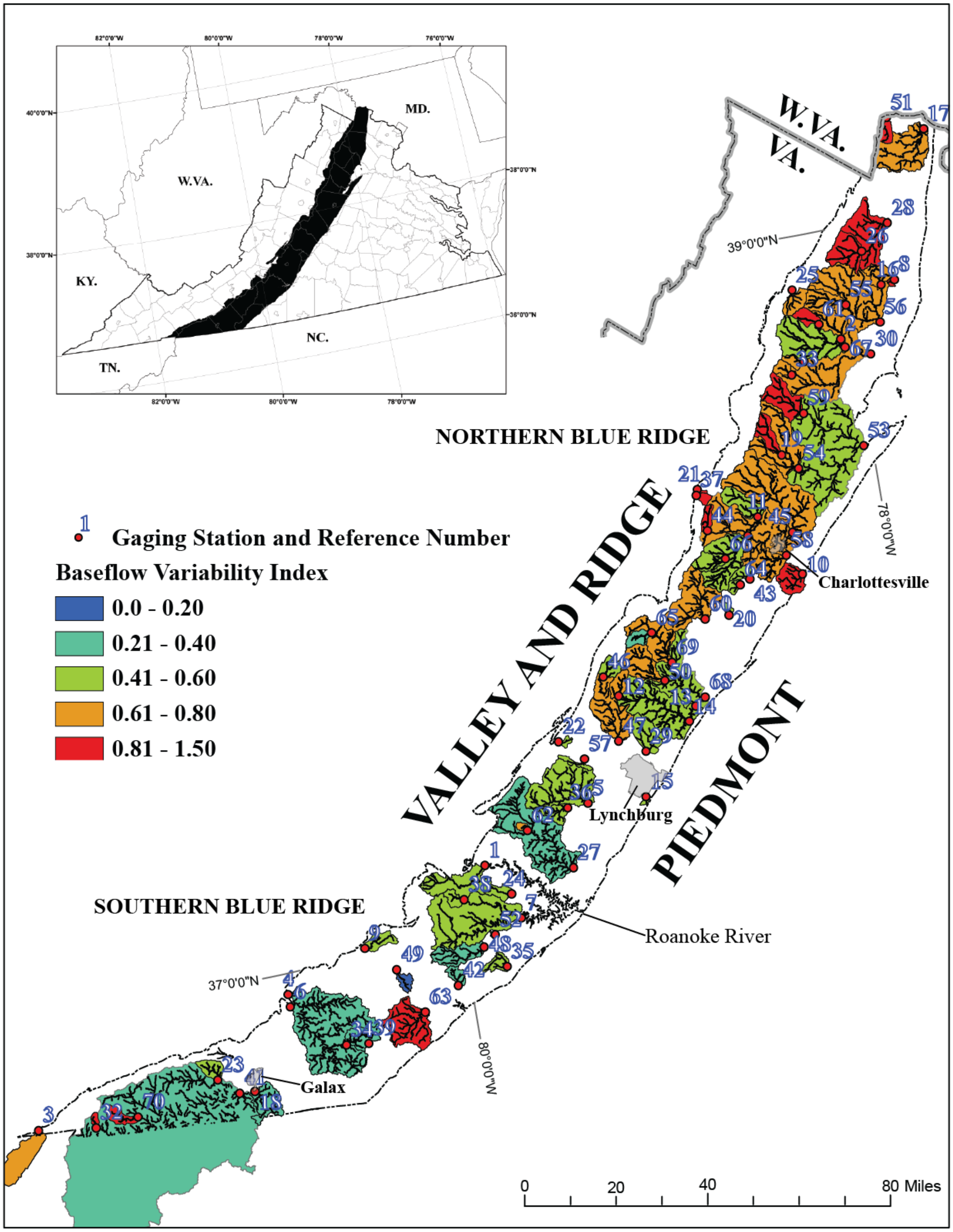


Figure 80. Ranges in baseflow variability indicies calculatd using streamflow recession methods for selected watersheds in the Blue Ridge Geologic Province. Information for referenced gaging station is presented in table 30.

Table 30. List of stream gaging stations and associated baseflow parameters used to generate maps shown in figures 79 and 80.

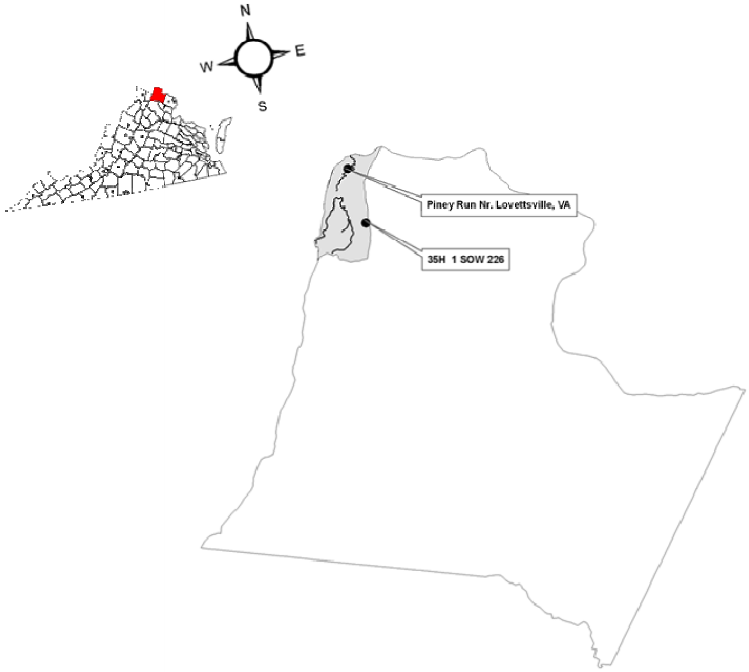
Station Name	Reference Number	Station Number	Drainage Area (square miles)	Baseflow Variability Index	Effective Recharge (inches/year)
Selected Stream Gages in the Virginia Blue Ridge Geologic Province					
Back Creek near Dundee, Va.	1	2056650	56.8	0.57	9.42
Battle Run near Laurel Mills, Va.	2	1662800	27.6	0.74	9.58
Beaverdam Creek at Damascus, Va.	3	3472500	56	0.61	15.86
Beaverdam Creek at Hillsville, Va.	4	3167695	4.19	0.19	13.44
Big Otter River near Bedford, Va.	5	2061000	116	0.52	11.48
Big Reed Island Creek near Allisonia, Va.	6	3167500	278	0.28	14.32
Blackwater River near Rocky Mount, Va.	7	2056900	115	0.44	11.4
Broad Run near Warrenton, Va.	8	1656200	2.94	0.87	7.25
Brush Creek at Route 616 near Riner, Va.	9	3169370	19.1	0.4	4.69
Buck Island Creek below Houchins Creek near Simeon, Va.	10	2033750	31	0.85	4.82
Buck Mountain Creek near Free Union, Va.	11	2032400	37	0.58	9.85
Buffalo River below Forks of Buffalo, Va.	12	2027600	15.9	0.71	13.66
Buffalo River near Tye River, Va.	13	2027800	147	0.54	11.48
Buffalo River Tributary near Amherst, Va.	14	2027700	0.46	0.92	11.8
Burton Creek Tributary at Lynchburg, Va.	15	2025800	2.36	0.53	6.84
Carter Run near Marshall, Va.	16	1661900	19.5	0.71	10.76
Catoctin Creek at Taylorstown, Va.	17	1638480	89.6	0.75	9.18
Chestnut Creek at Galax, Va.	18	3165000	39.4	0.27	18.13
Conway River near Stanardsville, Va.	19	1665400	25.8	0.95	13.68
Cove Creek near Covesville, Va.	20	2028700	4	0.51	12.55
Deep Run near Grottoes, Va.	21	1628150	1.17	0.85	6.75
East Fork Elk Creek at Belfast Trail near Natural Bridge, Va.	22	2020170	4.15	0.59	6.31
Elk Creek at Mount Carmel Church near Galax, Va.	23	3163500	63.5	0.56	10.69
Gills Creek at Route 122 near Burnt Chimney, Va.	24	2057050	21.8	0.45	8.09
Gooney Run near Glen Echo, Va.	25	1630700	20.6	0.64	16.47
Goose Creek at Delaplane, Va.	26	1643643	45.6	0.93	7.89
Goose Creek near Huddleston, Va.	27	2059500	188	0.38	8.4
Goose Creek near Middleburg, Va.	28	1643700	123	0.91	10.72
Harris Creek at Route 675 near Monroe, Va.	29	2025650	34.5	0.57	11.01
Hazel River at Rixeyville, Va.	30	1663500	287	0.66	10.94
Hazel River at Route 631 near Woodville, Va.	31	1662110	5.54	0.65	33.07
Helton Creek at US HWY 58 near Whitetop, Va.	32	3162415	5.28	0.81	19.92
Hughes River near Nethers, Va.	33	1662150	9.92	0.77	22.3
Laurel Fork at Route 638 near Laurel Fork, Va.	34	3167200	28.3	0.21	15.82
Little Chestnut Creek near Syndorsville, Va.	35	2057750	15.5	0.47	8.32
Little Otter River at Route 122 near Bedford, Va.	36	2061200	18.3	0.42	8.9
Madison Run near Grottoes, Va.	37	1628080	5.78	1.03	11.27
Maggodee Creek near Boones Mill, Va.	38	2056950	11	0.58	10.79
Maple Swamp Branch near Meadows of Dan, Va.	39	2067810	0.49	0.26	15.79
Mechums River near White Hall, Va.	40	2031000	95.4	0.5	10.78
New River near Galax, Va.	41	3164000	1131	0.34	16.41
Nicholas Creek near Ferrum, Va.	42	2071800	12.2	0.38	12.35
North Fork Hardware River at Red Hill, Va.	43	2029200	11	0.55	14.56

Station Name	Reference Number	Station Number	Drainage Area (square miles)	Baseflow Variability Index	Effective Recharge (inches/year)
Selected Stream Gages in the Virginia Blue Ridge Geologic Province					
North Fork Rivanna River near Proffit, Va.	45	2032680	176	0.64	11.71
Pedlar River below Davis Mill Creek near Buena Vista, Va.	46	2024900	18.2	0.41	10.07
Pedlar River near Pedlar Mills, Va.	47	2025000	91	0.64	10.1
Pigg River at Route 40 near Rocky Mount, Va.	48	2057600	40.5	0.35	13.57
Pine Creek at Route 682 near Floyd, Va.	49	3169150	10.7	0.16	11.41
Piney River at Piney River, Va.	50	2027500	47.6	0.74	20.92
Piney Run near Lovettsville, Va.	51	1636690	13.7	0.93	8.67
Powder Mill Creek at Rocky Mount, Va.	52	2057700	0.64	0.48	7.63
Rapidan River at Rapidan, Va.	53	1667000	446	0.56	8.11
Rapidan River near Ruckersville, Va.	54	1665500	114	0.67	13.33
Rappahannock River near Flint Hill, Va.	55	1661840	65.9	0.74	7
Rappahannock River near Warrenton, Va.	56	1662000	195	0.74	9.21
Reed Creek at Route 637 near Big Island, Va.	57	2024760	7.46	0.44	19.66
Rivanna River below Moores Creek near Charlottesville, Va.	58	2033500	507	0.75	7.18
Robinson River at Route 231 near Criglersville, Va.	59	1665850	47.8	1.09	24.13
Rockfish River near Greenfield, Va.	60	2028500	94.6	0.65	14.9
Rush River at Washington, Va.	61	1662500	14.7	1.12	11.55
Shockoe Creek at Route 755 near Irving, Va.	62	2059460	4.02	0.74	7.6
Smith River near Charity, Va.	63	2071600	79.7	1.29	13.62
South Branch North Fork Hardware River near North Garden, Va.	64	2029400	6.59	0.49	11.12
South Fork Tye River at Nash, Va.	65	2026400	14.2	0.39	14.81
Stockton Creek near Crozet, Va.	66	2030850	20.4	0.52	7.65
Thornton River near Laurel Mills, Va.	67	1663000	142	0.55	10.41
Tye (Buffalo) River near Norwood, Va.	68	2028000	360	0.49	13.17
Tye River at Roseland, Va.	69	2026500	68	0.69	19.07
Wilson Creek at Volney, Va.	70	3162650	17.7	0.9	6.33

Relation Between Precipitation, Baseflow Discharge, and Groundwater Levels

Figures 81-83 illustrate the temporal relationship between precipitation, variations in surface water discharge, and fluctuations in groundwater levels for several wells in 3 different watersheds in the Blue Ridge Geologic Province during the 2009 and 2010 water years. Daily median stream discharge values were obtained from USGS and VADEQ stream gaging station records, estimated values of groundwater discharge were obtained from the daily mean streamflow values by using the PART program developed by the United States Geological Survey (Rutledge, 1998), values of daily maximum depth to water for available real-time USGS and VADEQ observation wells were obtained from USGS groundwater level records, and daily precipitation values were obtained from the nearest available NOAA/NWS climatic station.

Wells 33G 1 SOW 224 in the Goose Creek Basin and 35H 1 SOW 226 in the Piney Run Basin are connected to fairly shallow groundwater flow systems (both wells have multiple water-bearing fractures within the first 100 feet of wellbore) and are well correlated with the variability in the daily groundwater discharge estimates. Fluctuations in groundwater levels (groundwater storage) within these wells mimic fluctuations in the baseflow estimates for their respective basins, and indicate a strong connection between the shallow groundwater flow system and stream baseflow. Measured daily hydraulic head values in wells 33G 2 SOW 225 and 35 H 1 SOW 226 are representative of hydraulic head measurements in the deeper portions of the groundwater flow system (main water bearing zone in 33G 2 SOW 225 at 188 feet, and 35 H 1 SOW 226 at 168 feet) and do not correlate as well with baseflow discharge estimates at their respective stream gage sites. Groundwater fluctuations in these wells follow a more seasonal trend, showing a more subdued or nonexistent response to precipitation inputs, and exhibiting lag times behind the period of peak baseflow discharge of up to 3 to 4 months. These observations indicate that there is substantial variability in the temporal patterns associated with natural changes in storage between shallow and more deeply seated groundwater systems in fractured rock which are influenced by a number of factors associated with topographic and geologic controls on groundwater recharge processes to deeper groundwater systems.



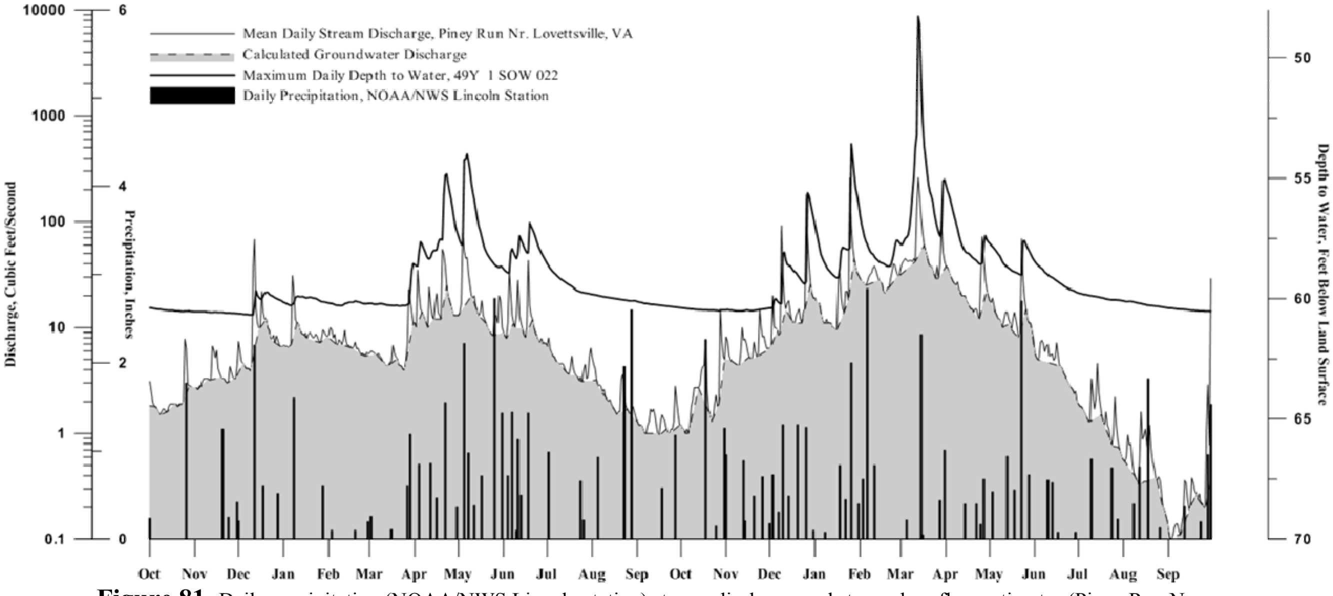


Figure 81. Daily precipitation (NOAA/NWS Lincoln station) stream discharge and stream baseflow estimates (Piney Run Nr. Lovettsville gage) and daily maximum depth to groundwater (well 49Y 1 SOW0220 in the Piney Run Drainage Basin.

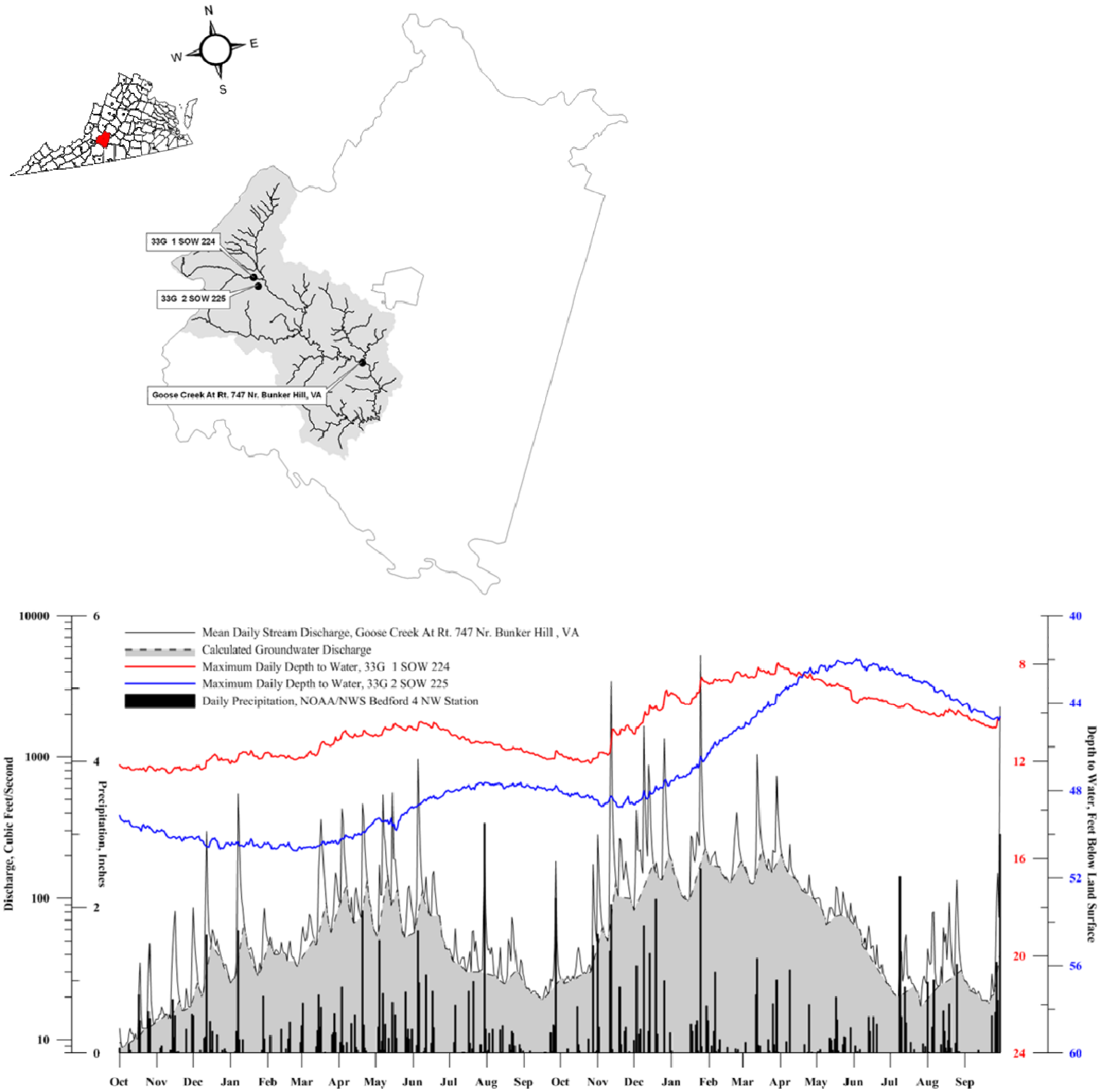
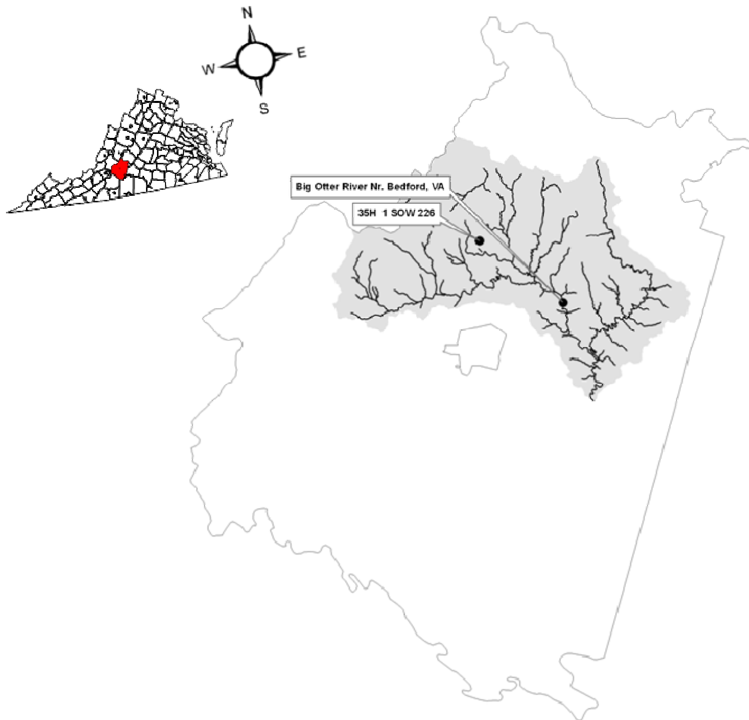


Figure 82. Daily precipitation (NOAA/NWS Bedford 4 NW station) stream discharge and stream baseflow estimates (Goose Creek at 747 Nr. Bunker Hill, VA gage) and daily maximum depth to groundwater (well 33G 1 SOW0224; 33G 2 SOW 225) in the Goose Creek Drainage Basin.



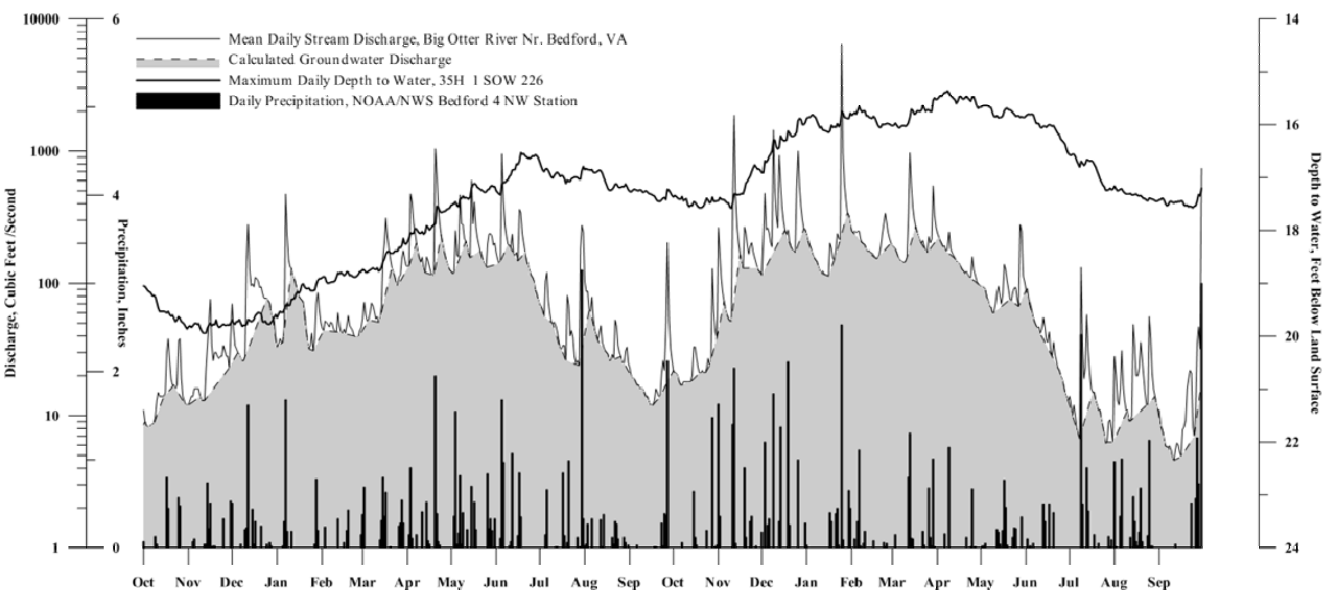


Figure 83. Daily precipitation (NOAA/NWS Bedford 4 NW station) stream discharge and stream baseflow estimates (Big Otter River Nr. Bedford, VA gage) and daily maximum depth to groundwater (well 35H 1 SOW0226) in the Big Otter River Drainage Basin.

Groundwater Storage

Groundwater storage within the Blue Ridge Geologic Province occurs within two separate media: the overlying regolith, and the fracture systems within the bedrock. The capacity of regolith to store infiltrated water is dependent on the porosity of the material, the thickness of the material, topographic position, and the orientation of relict structural features. Storage potential within regolith is usually higher in broad upland areas where it is thicker and hydraulic gradients are comparatively low. Storage within fractures is highly variable and controlled by the extent and interconnectedness of the fracture network providing water to the well. The extent of fracture networks is often local (on the scale of 10s of feet or less), but extensive fracture networks have been documented through the use of monitoring wells in fractured crystalline rock settings. Field observations of communication between wells in crystalline rock have been observed by the author at distances exceeding 2,000 feet. Observations of communication between wells completed in crystalline rock by others have been within the same order of magnitude with the largest reported distances exceeding a mile (Williams et al., 2005).

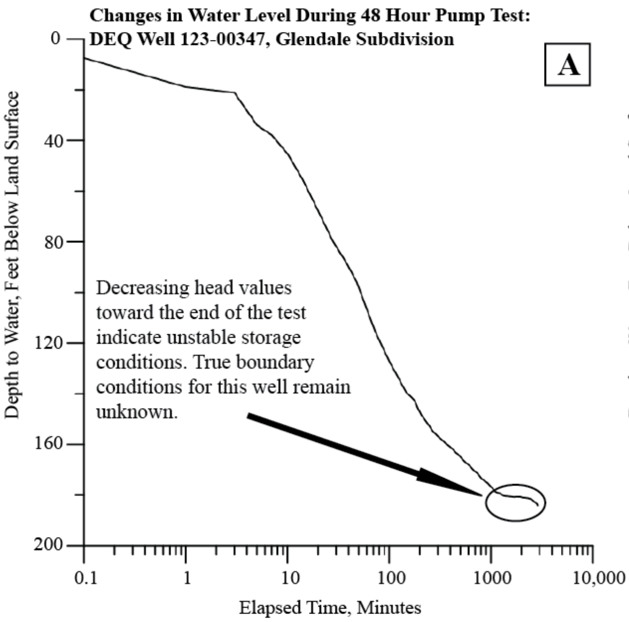
The ability of a fractured rock groundwater system to sustain an actively pumped well over long time periods is controlled by the degree of communication between the fracture network and the system of storage that is supplying water to the fracture network. Although some fracture networks have the capability to store significant quantities of groundwater, the fracture network is ultimately replenished by an external source which due to its overwhelming extent and higher porosity, is usually within the regolith. In some cases, wells completed in crystalline rock with high initial yields will yield substantially less water after they are pumped for a time due to the removal of readily attainable water from the fractured rock reservoir. Once the potentiometric surface of the fractured rock reservoir is sufficiently lowered, the productivity of the well is governed by the hydraulic properties of the recharge boundary. A good example of such a well is the Melissa Court well in Vinton, Virginia (DEQ Well 180-01079). This well yielded 600 to 800 gal/min during the initial pump test, but over time yield declined to about 50 gal/min and the well was taken off line for several months. During this interval, the fractured rock system was allowed to recharge and pumping well yields subsequently rebounded to allow more favorable and sustainable pumping rates and schedules.

The residence time of water in fractured bedrock is governed by the natural or induced distribution of hydraulic head within the fracture network, and the transmissivity of the fracture flow system. Areas with low vertical and horizontal hydraulic gradients that are supplied with sufficient recharge are more conducive to the formation of stable storage conditions in bedrock fractures. The ability of rocks to store and transmit groundwater over time can vary substantially, and may change over short time intervals (hours) or over the course of many years. These changes are attributed either to reductions in storage (S) over the time interval of interest as a result of pumping at rates that exceed the natural groundwater recharge, or losses in transmissivity (T) within the fracture system by mechanical or chemical changes to the fracture aperture (usually near the wellbore).

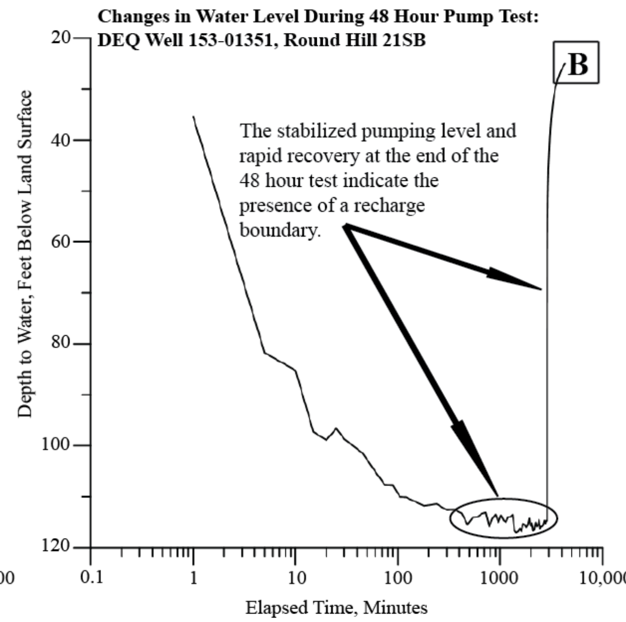
Occasional long term (48 hour or longer) constant discharge pump or aquifer testing is the most diagnostic way to assess either the initial sustainability of a new well completed within a fractured rock aquifer, or evaluate the current condition of an existing well (by comparing the current pump test results to the initial pump test). Water level changes over time in response to the constant discharge pumping rate allow for the evaluation of local storage conditions within the fractured rock intersecting the wellbore.

Figures 84a – 84d display four examples of different long-term pump tests selected from four different municipal wells in the Blue Ridge Geologic Province. When the pump is properly sized, most pump tests exhibit curves similar to either figure 84a or 84b where the late time pumping data indicate either a slow, continuous decline in water level with maximum drawdown still well above the pump intake at the end of the test, or late time stabilization of the water level through the end of the test. In some cases, pumps are oversized and do not match the natural production rate of the well (figure 84c), or over time the specific capacity of the well decreases, and rapid drawdown rates occur. In other cases, the sustainable pumping rate of the well will not be known until well into the pumping test due to finite storage conditions in contributing fractures that are exhausted only after pumping the system for some time (figure 84c, 84d).

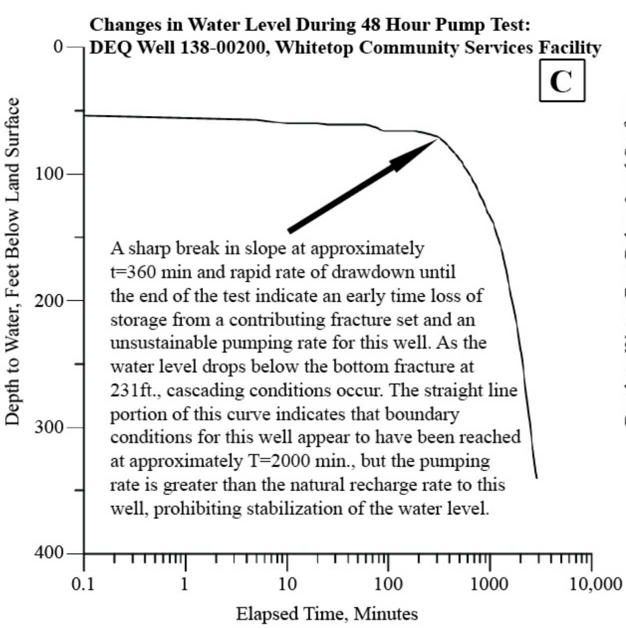
As indicated by figures 84a, 84c, and 84d, the true boundary conditions for a well completed in fractured rock may never be known at the end of a 2 day pump test because storage conditions within the fracture network(s) supplying water to the well are constantly adjusting during pumping. Even if a pumping test was continued for several days, the nature of fracture systems that store and transmit water may not allow the system to come to true steady state conditions. If a well is planned to be heavily relied upon, long term and periodic pump testing are important for assessing the amount of water potentially available to the well, and the storage characteristics of the fracture network. At a minimum, new municipal and industrial wells should be pump tested for 48 hours and ideally, until they come to a sustained drawdown rate that approaches steady state conditions.



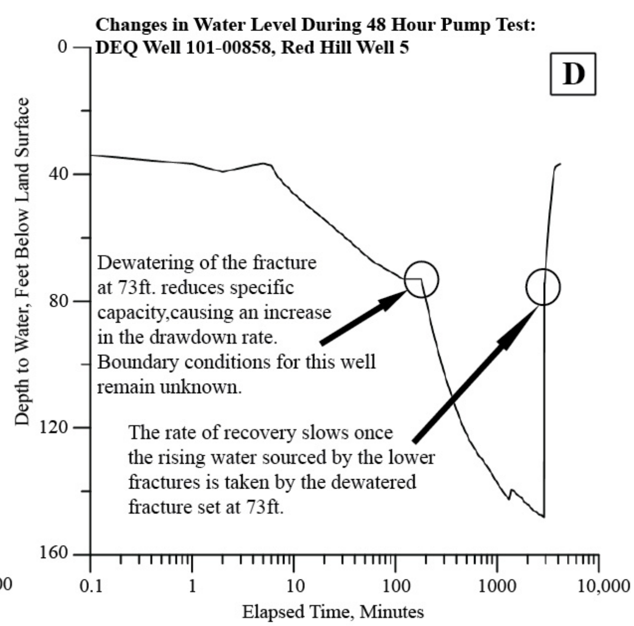
Semi-log plot of 48 hour pump test for DEQ Well 123-00347.
Pump Depth: 252ft.; water bearing zones: 67ft., 201ft.,241ft.
Initial pumping rate: 100 gal/min; final pumping rate: 93 gal/min.



Semi-log plot of 48 hour pump test for DEQ Well 153-01351.
Pump Depth: 210ft.; water bearing zones: 60-63ft., 113-116ft.,200-203ft.
337-338ft.,365-366ft.394-395ft.425-426ft.,460-461ft.
Initial pumping rate: 74 gal/min; final pumping rate: 74 gal/min.



Semi-log plot of 48 hour pump test for DEQ Well 138-00200.
Pump Depth: 380ft.; water bearing zones: 90-91ft., 230-231ft.
Initial pumping rate: 38 gal/min; final pumping rate: 32 gal/min.



Semi-log plot of 48 hour pump test for DEQ Well 101-00858.
Pump Depth: 400ft.; water bearing zones: 73-74ft., 380-385ft., 420-430ft.
Initial pumping rate: 32 gal/min; final pumping rate: 29 gal/min.

Figure 84. Progression of drawdown during 48 hour pump tests for selected wells in the Blue Ridge Geologic Province.

Fracturing of Rocks in the Blue Ridge Geologic Province

The metamorphic history of the rock, its mineralogy, and the orientation of local structural trends are important for understanding the distribution and orientation of groundwater systems in the crystalline rocks of the Blue Ridge. Groundwater storage and movement within crystalline rock is heavily dependent on fracture density and fracture orientation. Areas exhibiting dense fracture networks within the crystalline rocks of the Blue Ridge are often associated with the presence of high strain zones, brittle faulting, or localized zones of stress relief (jointing). Joint sets in the crystalline basement rocks often appear systematic at the outcrop scale but have a great deal of variation in orientation at the regional level. In the cover sequences, regional structural trends are often good indicators for predicting and understanding how rocks might fracture.

Rocks within the basement and cover sequences exhibit fracture styles that can be segregated into 3 basic families: jointing, cleavage, and faults.

Jointing

Joints are fractures in rock where there is no displacement between the masses separated by the fracture. Joints occur to accommodate changes in stress brought about by changes in morphology (erosion) and tectonic movement. As the pressure regime within a rigid body of rock changes, fractures form to accommodate the change.

Within the crystalline rock, joints serve as a major mechanism for groundwater storage and transmission, so a good conceptualization of joint orientation and occurrence on a local scale is helpful for understanding the setting of local groundwater systems. Joint orientations are variable and dependent upon the direction from which the change in stress occurs. A brief listing and description of the more prevalent joint types follows:

1. *Sheet joints* often occur in massive crystalline rock or horizontally bedded metasedimentary rock, and fracture parallel to the surface that has been unloaded (figure 85). In flat lying areas underlain by massive rock, sheet joints can be a major mechanism for groundwater storage and transmission if they are in contact with a significant source of groundwater recharge (Legrand, 1960; Lyford et al., 2003).

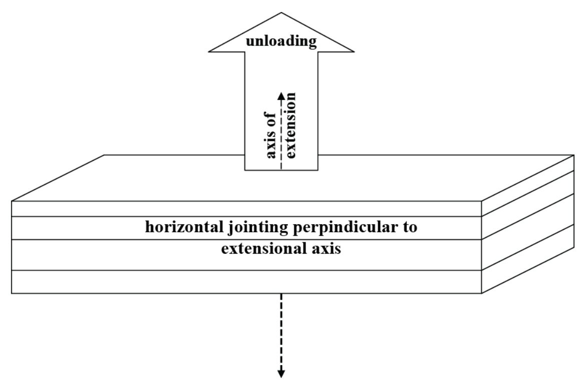


Figure 85. Formation of sheet joints in a massive rock body due to a vertical reduction in stress. Modifed from Billings(Billings, 1972).

2. *Extension joints* occur where rock masses are compressed, which causes horizontal expansion via the formation of joints parallel to compression (figure 86). Extension joints commonly occur in sedimentary and metasedimentary rocks and are evident in portions of the more massive sections of the Blue Ridge Cover Sequence. Extension joints can also

occur in rocks along the margins of igneous bodies where pressures have increased due to magmatism, and within the margins of igneous bodies themselves where cooling and pressure increases cause fracturing (Balk, 1937).

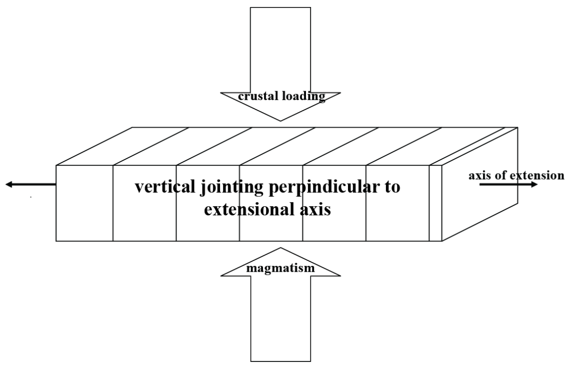


Figure 86. Formation of extension joints in a massive rock body due to a vertical increase in stress. Modified from Billings (Billings, 1972).

3. *Tension joints* are ubiquitous throughout the Blue Ridge. These fractures have been induced by the stresses associated with multiple periods of deformation and are oriented with respect to strain associated with distinct deformational periods. The local orientation of stress fields can be highly variable, and consequently there is much regional variation in the orientation and openness of tension-related fractures.

Figure 87 illustrates the relation between the orientation of strain along a hypothetical shear plane and the orientation of conjugate tension fractures that have occurred as the result of the strain. Note the presence of some fractures along the shear plane, but a more frequent occurrence of fracturing along the axis of minimum compression which has been rotated due to shearing. Rocks of the Blue Ridge Province are often scarred with fractures associated with multiple deformational events, although many of these fractures tend to be occluded or closed. Figure 88 displays a conjugate set of fractures at an outcrop of biotite gneiss in the Blue Ridge Basement Complex.

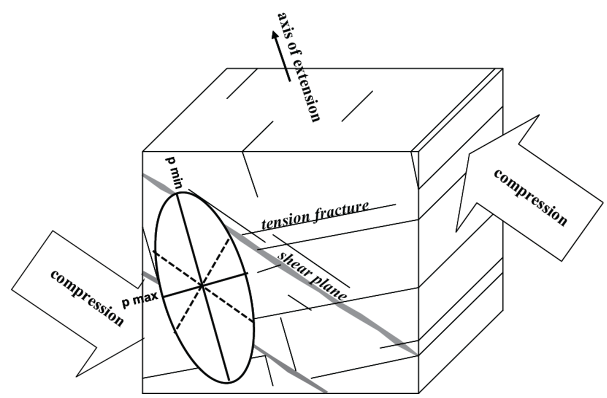


Figure 87. Formation of tension (tectonic) joints as a result of shear stresses from a single deformational event. Modified from Billings (Billings, 1972).

Figure 88. Conjugate joint set in porphyroblastic biotite-plagioclase augen gneiss (Ybg unit of 1993 VDMR Virginia State Geologic Map) near Ivy, Virginia. Predominate joint set approximately N15 E, 50S (aligned with hammer handle). Less prominent joint set roughly N30 W, 20S, perpendicular to end of hammer handle.

Digital structural measurements provided by the Virginia Division of Geology and Mineral Resources acquired from the recently mapped Amherst Quadrangle (Carter, 2008a), Arnold Valley Quadrangle (Carter, 2008b), Bent Mountain Quadrangle (Henika, 2007) Boones Mill Quadrangle (Henika, 2011a), Garden City Quadrangle (Henika, 2011b), Hardy Quadrangle (Henika, 2011c), Piney River Quadrangle (Carter, 2008c), and Redwood Quadrangle (Henika, 2011d), digital structural measurements within the Loudon County portion of the Washington DC Area Geologic Map Database (Davis et al., 2001) and digital structural measurements taken from oriented borehole geophysical logs collected by the Virginia Department of Environmental Quality were compiled and plotted in southern hemisphere polar plots for both the late Proterozoic metavolcanic and metasedimentary rocks (Blue Ridge Cover Sequence) and middle Proterozoic meta-igneous rocks (Blue Ridge Basement Complex) to investigate the relationship between jointing, foliation and schistosity (figures 89-92) at regional and local scales within the Blue Ridge Basement and Cover Sequences. Figures 89 and 90 show structural measurements collected from outcrop observations within the cover and basement sequences, respectively and figures 91 and 92 show structural measurements taken from borehole geophysical data within the cover (figure 91) and basement sequences (figure 92). The strike of foliations are overwhelmingly oriented NE/SW within the rocks of the Blue Ridge Basement but the aggregate orientation of joints do not appear to show discernible trends at the quadrangle scale. Documentation of jointing within the Basement rocks of the Madison Quadrangle (Bailey et al., 2003) describes the same lack of readily discernible joint orientation within the Basement Rock of the Blue Ridge within that area. The apparent lack of systematic joint orientation in the basement rock at the 1:24,000 scale does not mean that joints occur haphazardly, but rather there are multiple families of joint sets that have developed in response to prevalent local and regional stress fields that when plotted in aggregate, show no dominant trend. A systematic study of fracturing in the Swift Run Quadrangle revealed that there was no systematic orientation of fractures in the basement rock at the quadrangle scale, but did document systematic fracture orientations at outcrop locales (Hasty and Bailey, 2005). Additionally, Southworth and others (Southworth et al., 2009b) documented a preferential orientation of joints in granitic gneiss at an outcrop along the Blue Ridge Parkway that is predominately on strike with foliation and dips steeply to the southeast. Joint measurements obtained from borehole geophysical logs from a selection of wells completed in the Blue Ridge Basement Complex (figure 92) show a systematic orientation of joint sets within a borehole (usually a conjugate relationship) but no predominate joint orientation between borehole logs, agreeing with field observations of systematic jointing at the local, but not regional scale.

Within the cover sequences, discernible trends in joint orientations occur at the regional scale. As a general observation, jointing in the cover rocks tends to occur as steeply dipping features that are either parallel or sub-parallel to or nearly normal to schistosity, which commonly dips to the southeast or northwest. Toewe (1966) documented three prominent joint sets in the Catoctin and Weverton Formations at the regional scale within the Leesburg Quadrangle. Prominent joint sets in the Blue Ridge Cover Sequences were noted or compiled by a number of workers: Southworth and others (2009b) in the Shenandoah National Park, as well as in the Loudon portion of the Harpers Ferry Quadrangle (Southworth, 1991), the Swift Run Gap Quadrangle (Hasty and Bailey, 2005), and further to the south in the Amherst (Carter, 2008a) and Arnold Valley (Carter, 2008b) Quadrangles. Joint measurements taken from borehole geophysical data show a tendency for rocks to joint or fracture longitudinally or perpendicular to bedding and or schistosity, but the presence of joints perpendicular to the strike of bedding and schistosity are largely absent from the televiewer logs, due in part to the ineffectiveness of the device at resolving steeply dipping features that do not completely span the borehole.

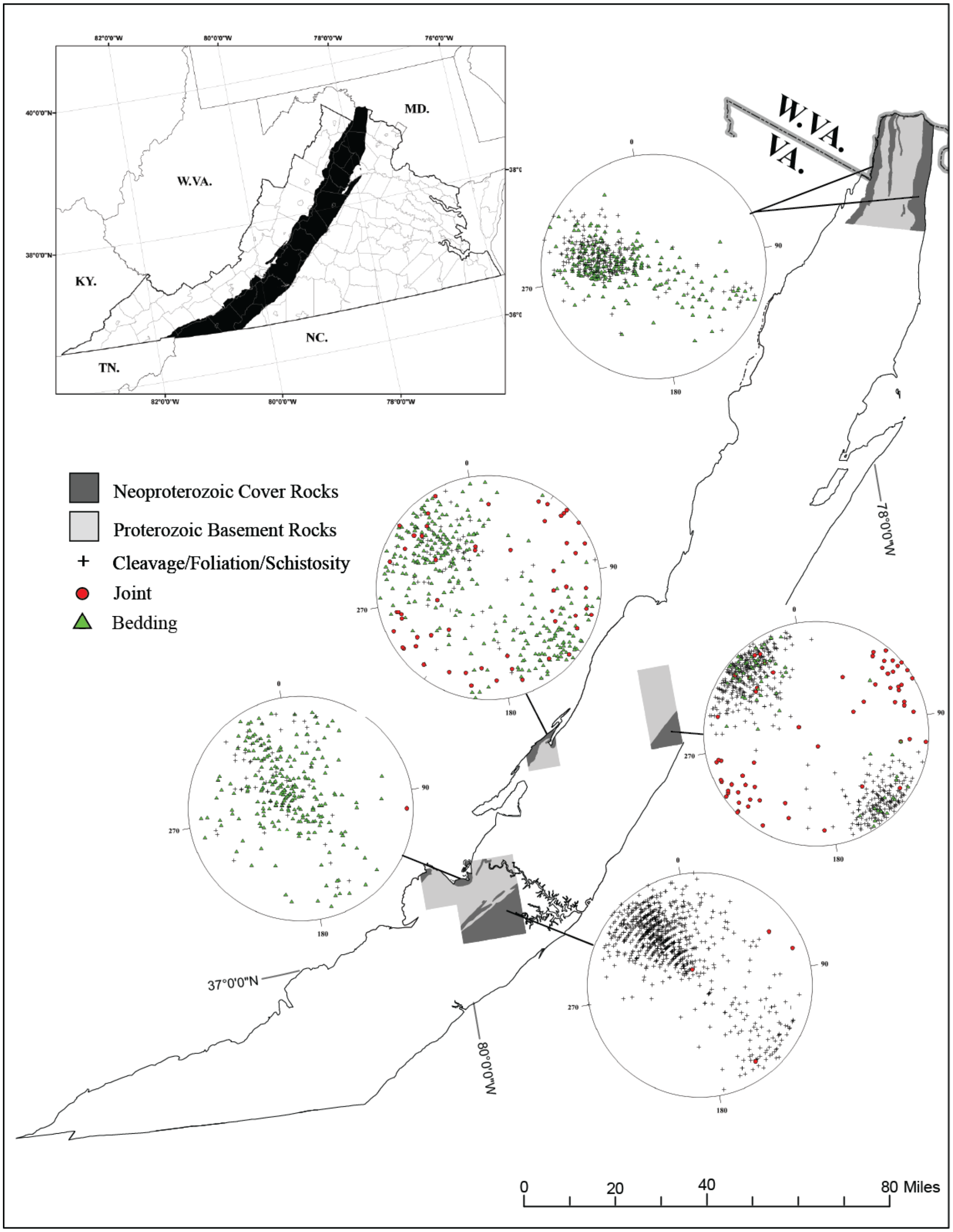


Figure 89. Southern hemisphere poles to planes plot of outcrop features in selected quadrangles spanning Blue Ridge cover rock sequences. Shaded portions of the map indicate the geographic extent over which structural measurements were made.

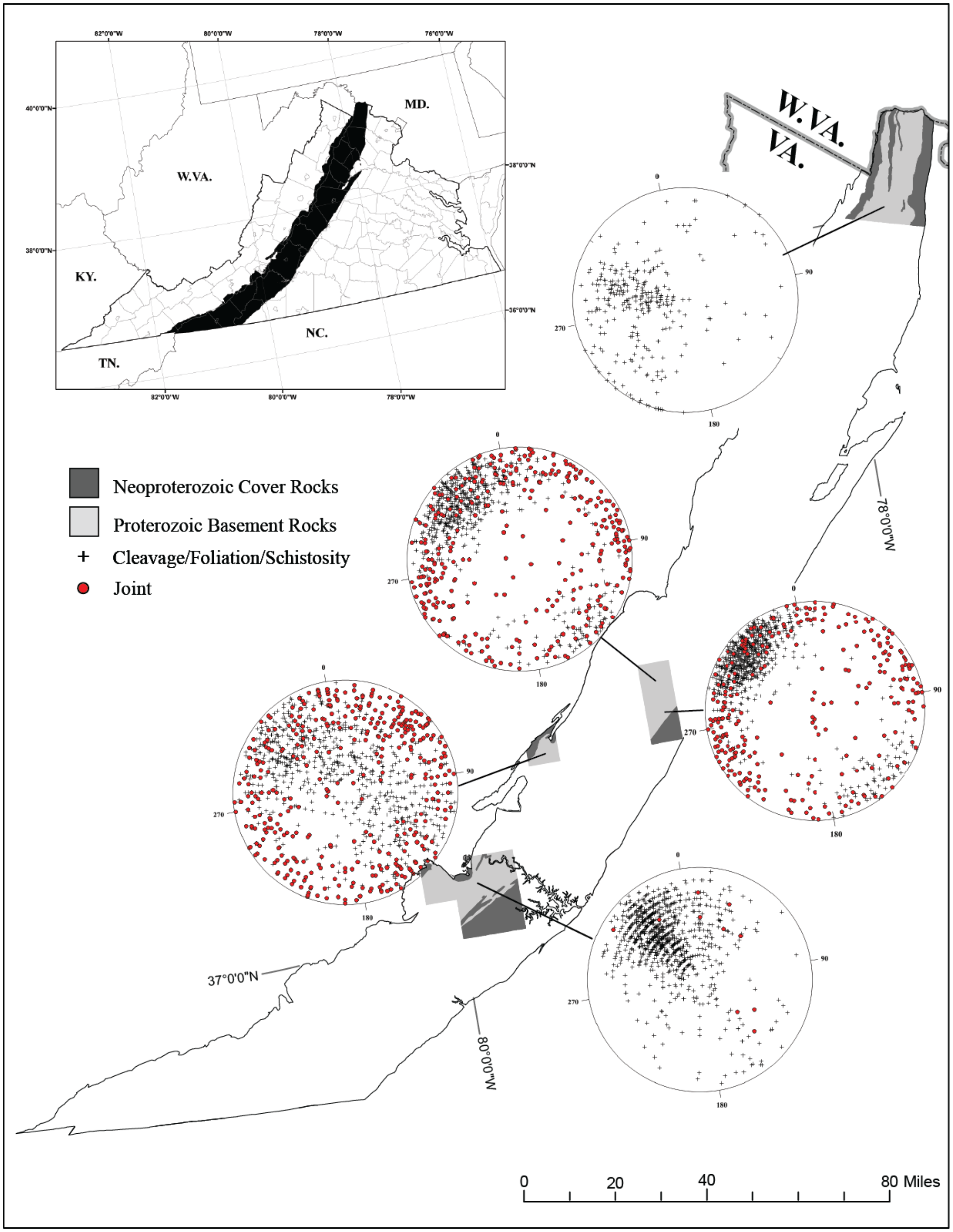


Figure 90. Southern hemisphere poles to planes plot of outcrop features in selected quadrangles spanning Blue Ridge basement rocks. Shaded portions of the map indicate the geographic extent over which structural measurements were made.

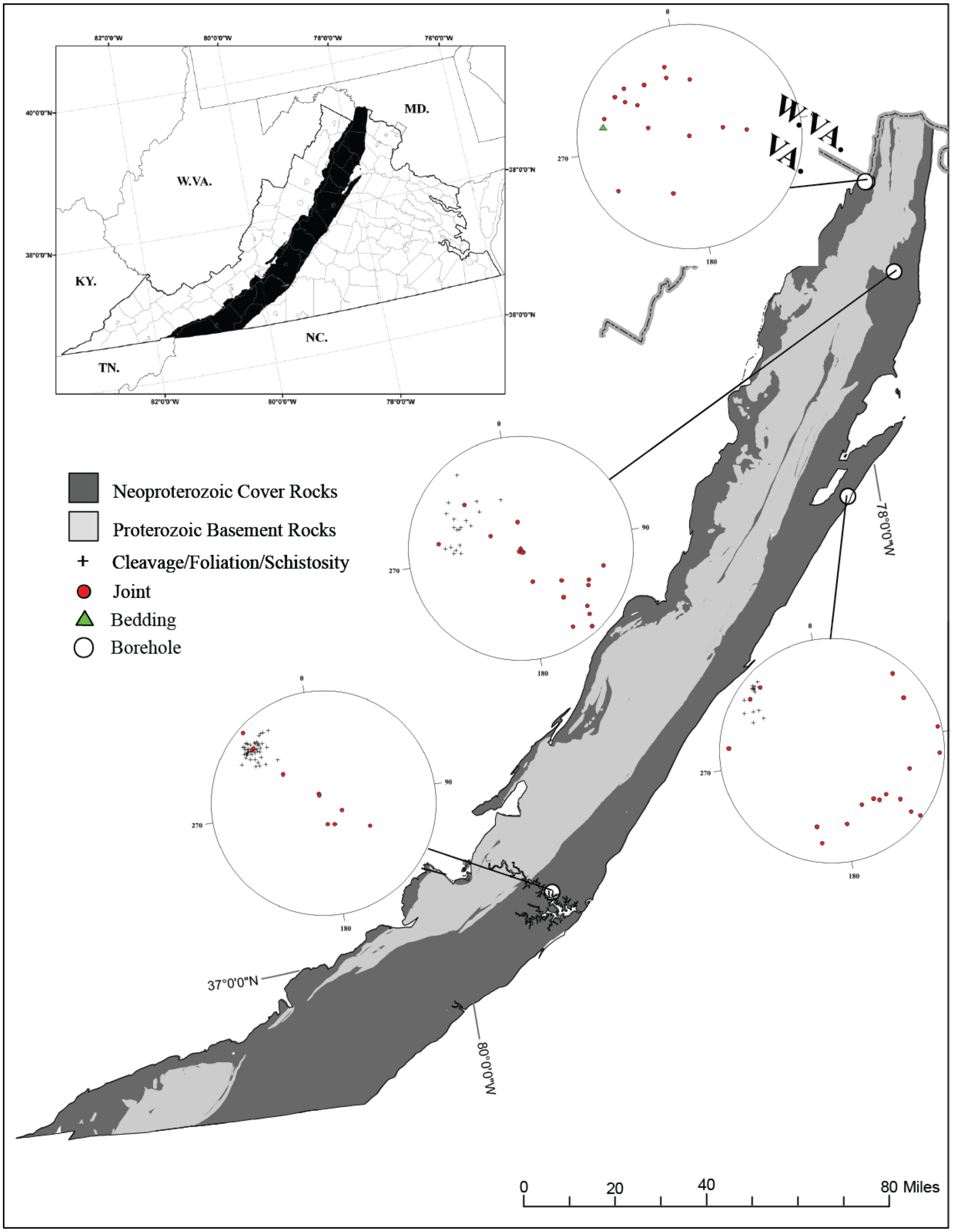


Figure 91. Southern hemisphere poles to planes plot of borehole geophysical measurements made in selected boreholes within the Blue Ridge cover rock sequences.

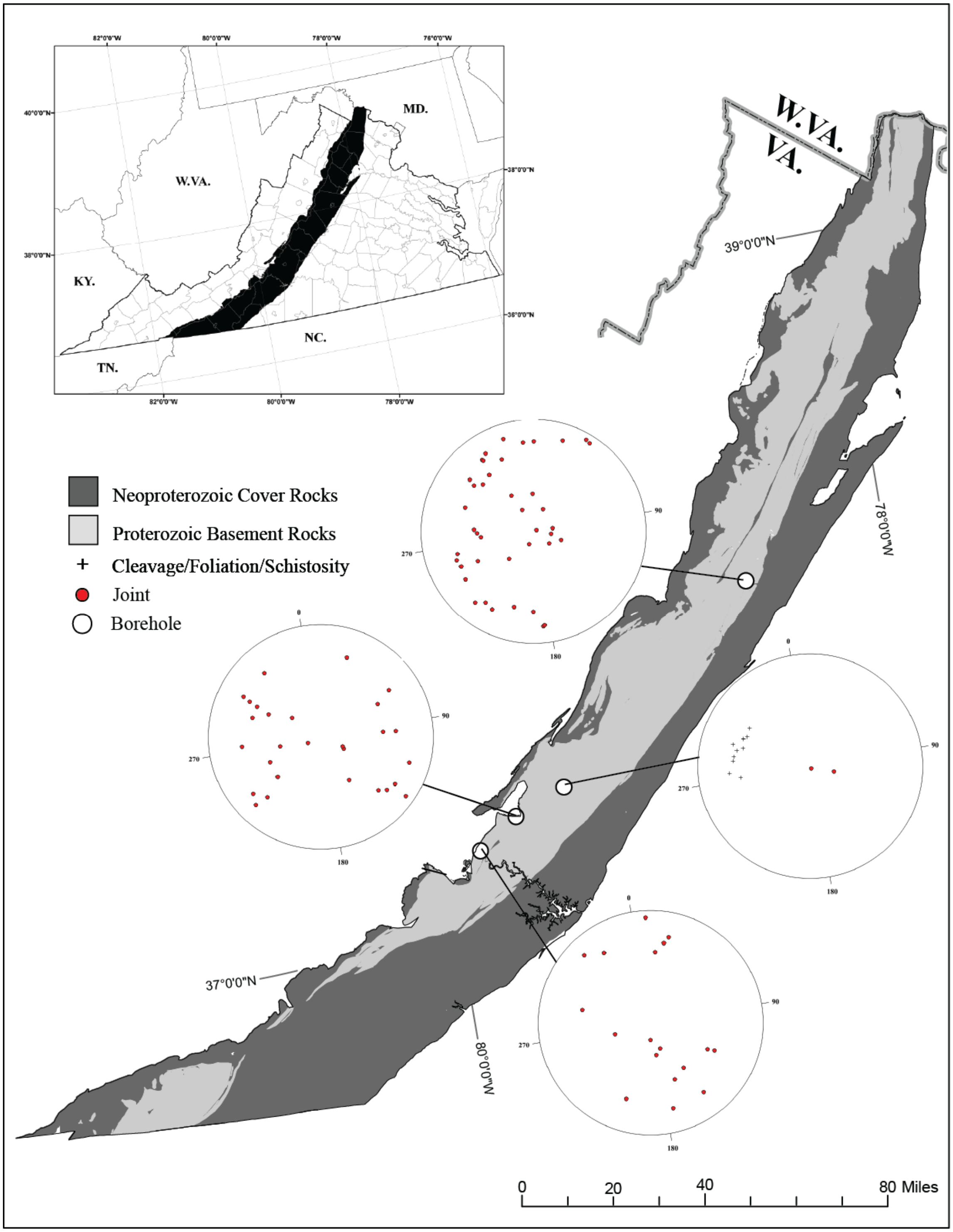


Figure 92. Southern hemisphere poles to planes plot of borehole geophysical measurements made in selected boreholes within the Blue Ridge basement rocks.

Cleavage/Schistosity/Foliation

Cleavage is the tendency of rock to split or part along planes of weakness imparted through deformation and the associated re-alignment of crystal structure. Schistosity and foliation are the planes of re-aligned minerals established during metamorphism that may or may not readily cleave or part, depending on the crystalline structure of the rock.

Much of the lineation evident in the Blue Ridge is thought to have been created during the periods of orogenesis in the Proterozoic (although in places, there is an older and pervasive foliation evident in the Basement lithology). During these distinct periods of crustal shortening, a regional series of northwest directed folds and thrust stacks were formed as the present day rocks of the Blue Ridge were detached and thrust westward. Folding and shearing of more ductile (clayey) metasedimentary rocks of the Blue Ridge group produced regional zones of penetrative axial planar cleavage and schistosity dipping predominately to the southeast and to a lesser extent to the northwest, and zones of fanning cleavage in the less ductile (silica rich) metasedimentary sequences (figure 94 and figure 95). Zones of schistosity and foliation have formed within and adjacent to deformation zones of the more competent crystalline rocks in the Catoctin Formation and the Blue Ridge Basement.

The structural orientation of cleavage, schistosity, and foliation in the Cover Rocks of the Virginia Blue Ridge has been documented by a number of authors (Carter, 2008a, b; Evans, 1994; Gathright and Nystrom, 1974; Reed, 1955; Southworth, 1991). Cleavage or schistosity has also been shown to occur within ductile deformation (mylonitic) zones of the Blue Ridge Basement (Bartholomew et al., 1981; Davis et al., 2001; Gathright et al., 1977; Griffin, 1971; Luckert and Nuckols, 1976; Mitra, 1979). Figures 89 and 90 illustrate the various orientations and attitudes of cleavage, schistosity, and foliation measured from cover and basement rocks by a number of workers in several locations along the Blue Ridge Anticlinorium. Schistosity measurements taken from borehole geophysical data indicate a common SE dipping orientation within the cover sequences, as well as in a borehole geophysical log taken from a mylonitic section of basement rock (figures 91 and 92). Although compositional banding and foliation were noted by downhole camera inspection in virtually all boreholes utilized for geophysical logging within the basement rock, oriented foliation measurements were not collected due to the inability of the acoustic televiewer to resolve foliation planes in the borehole.

In lineated crystalline rock where parting along foliation or schistosity is evident, a reduced incidence of horizontal or sheet jointing may occur because the reductions in stress are accommodated by the parting along lineation (figure 95). The aggregate effect of parting or cleavage along lineations is significant for the occurrence of groundwater recharge and the storage and transport of groundwater. *Foliation controlled parting* has been identified as an important mechanism for the storage and transport of groundwater in distinct crystalline rock lithologies (Johnston, 1962; Manda et al., 2008; Williams et al., 2005).

Figure 93. Folded beds of phyllite and quartzite of the Unicoi Formation. Long dashes highlight axial planar lineations in more compressible phyllitic beds and short dashes highlight fanning cleavage in more competent quartzite. Photo taken during field review of Arnold Valley quadrangle (Carter, 2008b).

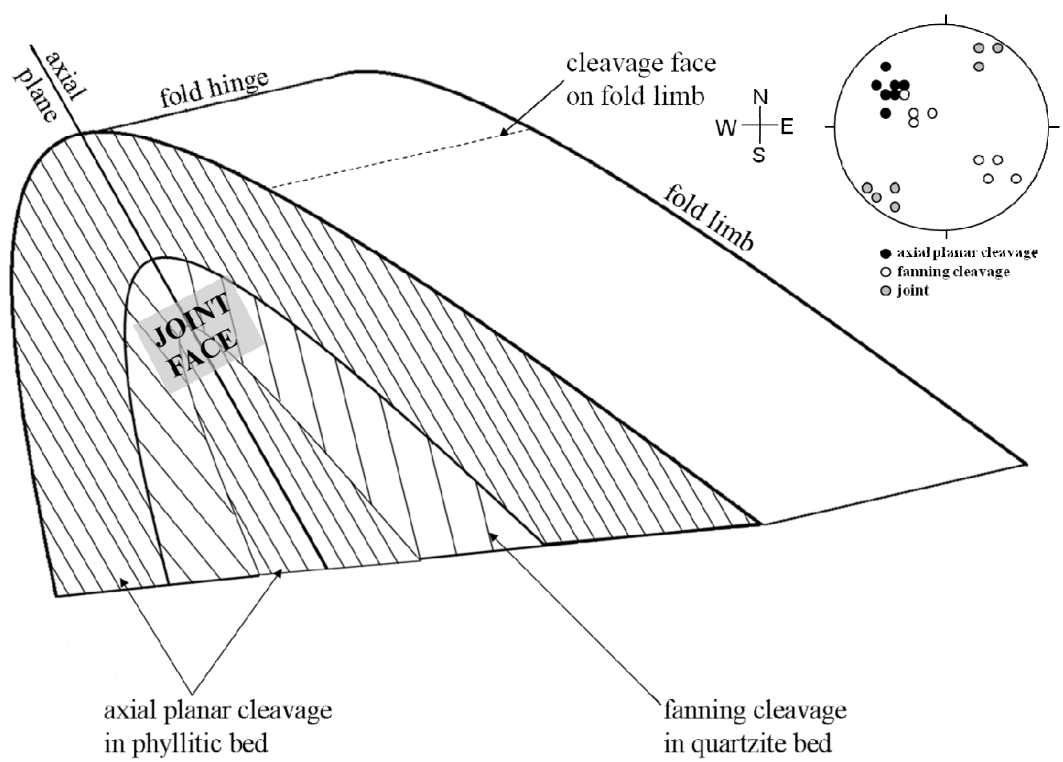


Figure 94. Axial planar cleavage in phyllite and fanning cleavage restricted to more competent rocks (quartzite, greywacke). Hypothetical southern hemisphere poles to cleavage planes (upper right hand corner) illustrates predominate azimuth and attitude for cleavage and joint families occurring in this setting. Modified from Maley (Maley, 2005).

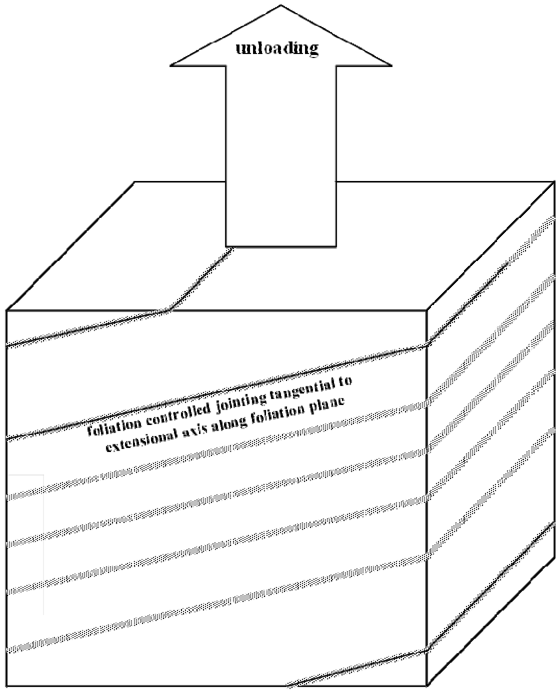


Figure 95. Parting along foliation due to unloading.

Faulting

Fault-related fracturing in zones adjacent to fault planes can serve as conduits and reservoirs for groundwater (Johnston, 1962; Meinzer, 1923; Seaton and Burbey, 2005). In some cases, the fault plane itself can serve as the zone of groundwater storage and movement, and in other instances the fault plane may act as a barrier to flow by bringing rocks of lower permeability in contact with an otherwise productive groundwater flow system, or because the fault plane itself is composed of lower permeability ‘gouge’ created through grain size reduction associated with faulting (Johnston, 1962). Figure 96 shows a lateral (side) view of a contact (dashed line) between crystalline granulite gneiss and fault gouge in a section of borehole at the Melissa Court Well in Vinton, Virginia. While a small portion of the total yield for this well issues from this zone, fault related fracturing above this fault plane accounts for the majority of well yield. This well was air lifted at approximately 600 gallons per minute for several hours after completion. Successfully targeting fault-related groundwater features often requires the analysis of aerial imagery, field mapping, and the use of shallow subsurface geophysical techniques to describe the orientation and nature of the fault-fracture system.

Figure 96. Lateral camera view of borehole wall in an 8" borehole. Contact between granulite gneiss (above dashed line) and fault gouge: Melissa Ct. Well, Vinton VA.

Depth of Water Bearing Fractures

Water-bearing zones in fractured crystalline rock have been reported to occur primarily within the upper 300 feet of borehole (Legrand, 1960; Powell and Abe, 1985; Sterrett and Hinkle, 1980). Although the frequency of jointing in crystalline rock is undoubtedly higher in the near surface environment, several phenomena have caused this observation to be somewhat misleading, and have given rise to the tenet that groundwater is not commonly found below depths of 300 feet: 1) When a well is drilled for domestic purposes, drilling is often terminated once an adequate supply of water has been obtained, which frequently occurs within the first 300 feet of drilling; 2) deeper wells are often drilled because water bearing fractures are not found within the upper 300 feet of rock - when an attempt is made to drill deeper in rock that is already poorly fractured, it is possible that the trend will continue at depth because the stress field within the rock at that particular location is not conducive to the formation of transmissive fractures; 3) the amount of georeferenced data available for a comprehensive analysis of fracture frequency at regularly spaced intervals below 300 feet is sparse, and has not yet been compiled and analyzed to yield sufficient statistically significant data.

Although available georeferenced data on fracture depths are insufficient for a comprehensive analysis of fracture frequency over regularly spaced intervals for the various rock types within the Blue Ridge

Geologic Province, an analysis was done with available data to evaluate the tendency of a rock type to fracture at depths exceeding 300 feet. Data used for the analysis were restricted to georeferenced wells drilled to or past 300 feet with reported water bearing zones, and results indicate that there is some variability among the different hydrogeologic groups with respect to the percentages of wells in each group with water bearing zones at 300 feet or greater, the percentage of fractures occurring at 300 feet or greater, and the frequency of fracturing, described by a fracture frequency index ((total number of fractures/total linear feet drilled)*100).

Within the basement complex, both the percentage of wells with fractures deeper than 300 feet and the percentage of fractures below 300 feet are fairly similar and tightly grouped among the layered granulites, massive crystalline rocks, and foliated crystalline rocks, indicating an abundance of fracturing below 300 feet depth (figure 97). The tendency for mylonitic rock to open up and accommodate groundwater volumes at shallower depths may be related to the weathering and subsequent opening along and jointing normal to pervasive cleavage planes within the mylonitic fabric (figure 17, photos A,B,D,E and figure 95). After mylonites, the frequency of fracturing is nearly identical among the layered granulites and massive crystalline rocks and lowest overall for foliated crystalline rocks. Data indicate that foliated crystalline rocks tend to fracture the most deeply but most infrequently relative to the other basement lithologies.

With the exception of rocks within the Ashe Metamorphic Suite (AMS), percentages of the total number of reported fractures occurring at or below 300 feet within the cover rocks ranged between 30 and 40 percent by group, and percentages of wells drilled to at least 300 feet with at least one fracture at or below 300 feet range between 45 to nearly 60 percent (figure 98). Percentages in these categories for rocks of the AMS were much lower: about 15 percent of all fractures in wells drilled to at least 300 feet were at or below 300 feet, and only 25 percent of all wells drilled to at least 300 feet had at least one fracture at or below 300 feet. A more notable spread in fracture frequency occurs among rocks in the cover sequences. Rocks in the Chilhowee Group and Catoctin Formation tend to host water bearing zones with the lowest frequency , but commonly have water in fractures at or below 300 feet. Rocks of the Alligator Back Formation, AMS, and Lynchburg Formation and late Proterozoic shallow water facies tend to fracture with nearly the same frequency, and rocks of the Candler Formation appear to have the highest frequency of fracturing. It should be noted that the dataset used to generate the Candler plot is not statistically significant and may not be representative of the true tendencies of this formation. Rocks of the AMS appear to have a tendency to fracture and weather higher in the borehole, whereas water bearing zones in the rest of the cover sequences tend to have a more significant contribution from fractures deeper than 300 feet.

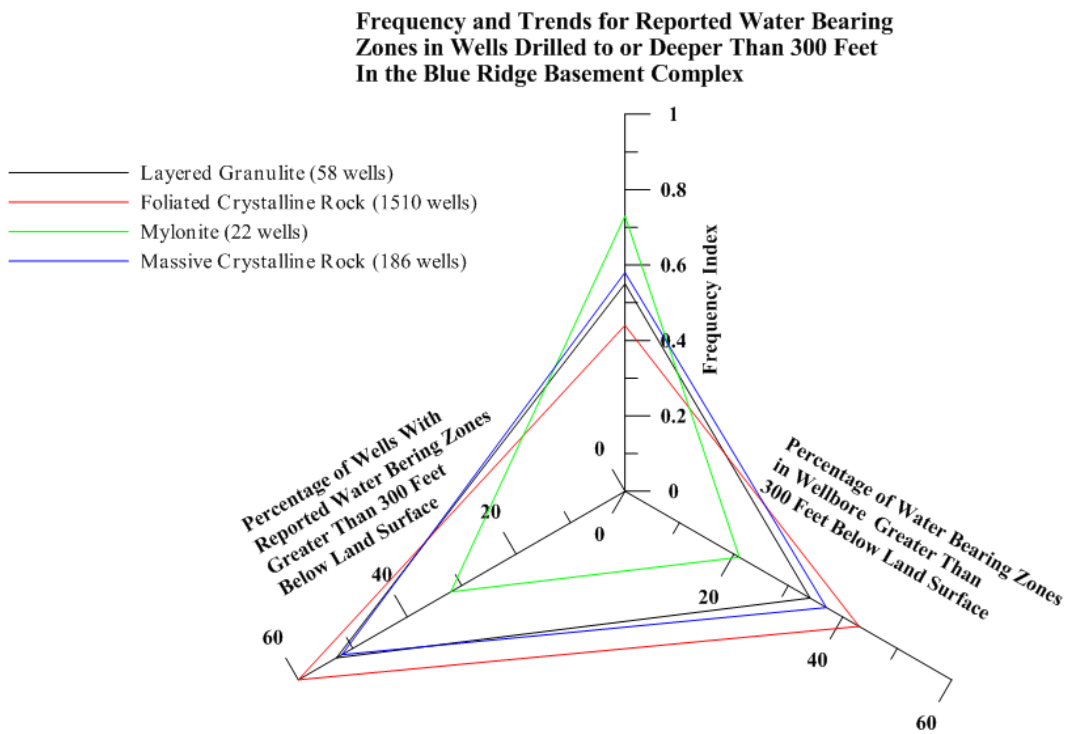


Figure 97. Fracture depth trends in the Blue Ridge basement rocks.

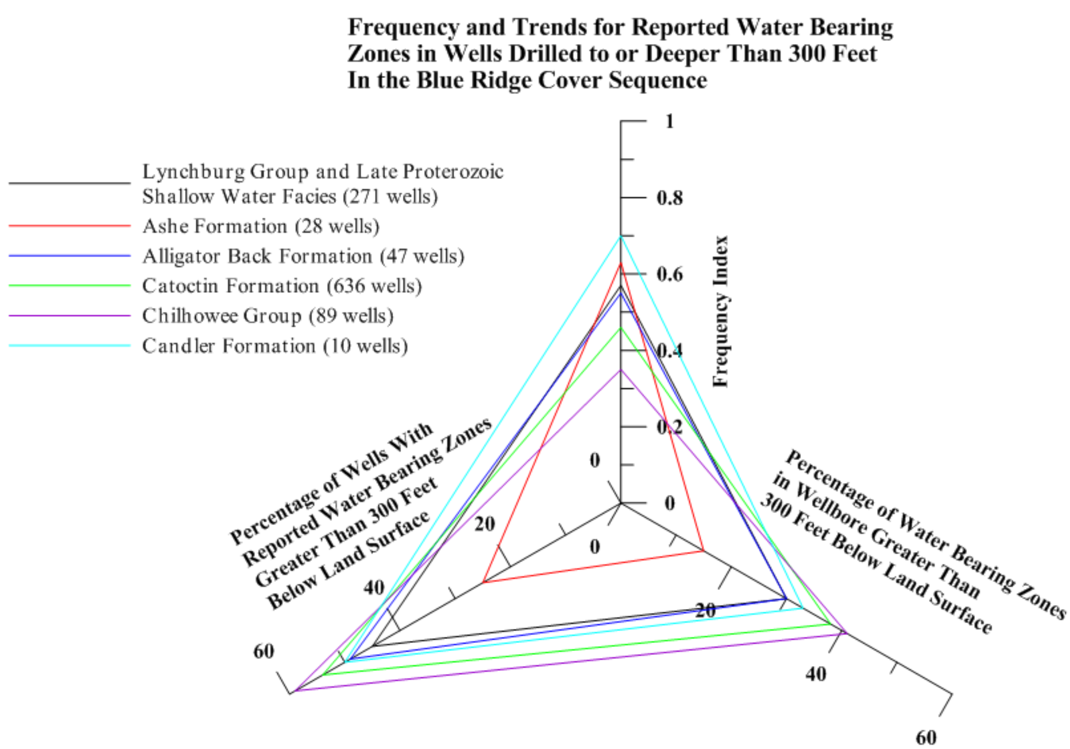
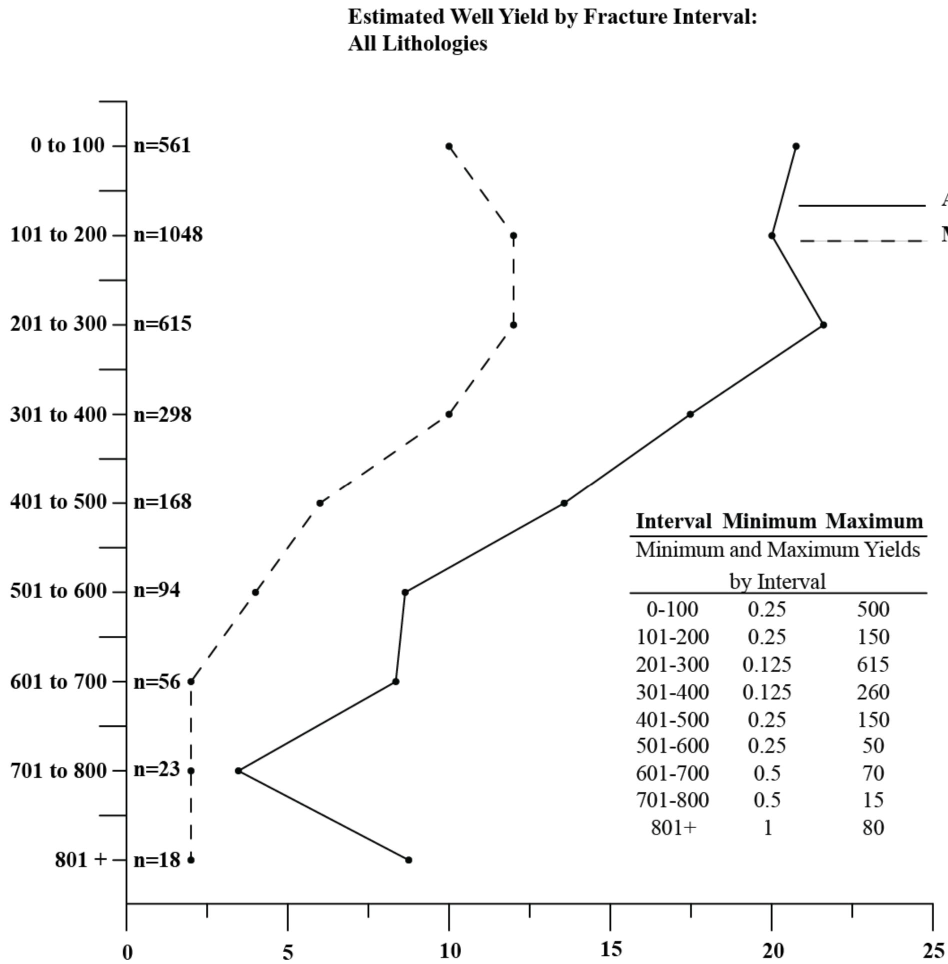


Figure 98. Fracture depth trends in the Blue Ridge cover rocks.

An analysis for trends in the water bearing capacity of individual fractures with regard to their depth of occurrence in the wellbore has not been conducted for wells within the Blue Ridge Geologic Province of Virginia. Data are limited regarding the estimated yields of individual fractures intersecting the borehole. An attempt was made to analyze for fracture yield with regard to depth by plotting well yield estimates for wells with reported fractures occurring exclusively within discrete 100 foot intervals (ie. yields for wells with fractures open exclusively between 0 feet and 100 feet, yields for wells with fractures open exclusively between 101 and 200 feet, and so on).

Figure 99 shows both average and median well yield for groups of wells with open fractures occurring in isolated 100 foot zones. Both median and average yield data indicate that there is a trend toward declining yield with depth. These data may be skewed due to the inherent nature of fracturing: the less fracturing there is in the upper portions of borehole, the less potential there may be for water to accumulate at depth. Trends in the data used to generate the plot in figure 99 indicate that more significant yields are commonly found within fractures occuring within the upper 500 feet of borehole, and that the bulk of the water in groundwater flow systems throughout the Blue Ridge appears to occur within the upper 500 feet of rock. Minimum and maximum well yield values for each interval are noted as part of the figure to more completely describe the trend and variations in the yield of water bearing fractures with depth.



Interval	Minimum	Maximum
Minimum and Maximum Yields by Interval		
0-100	0.25	500
101-200	0.25	150
201-300	0.125	615
301-400	0.125	260
401-500	0.25	150
501-600	0.25	50
601-700	0.5	70
701-800	0.5	15
801+	1	80

Figure 99. Reported well yield for wells with water bearing fractures restricted to single, discrete 100 foot intervals.

Influence of Fracturing on Groundwater Storage and Movement

The occurrence and orientation of lithologic and structural features in the Blue Ridge Geologic Province can be viewed as the aggregate record of a complex geologic history that documents Grenvillian through Mesozoic deformational events in varying degrees of clarity. Local changes in structural style, lithology, and fracturing are ubiquitous and do not always behave predictably. Uncovering the relationship between geologic structure and fracturing on groundwater movement and storage is further complicated by the paucity of outcrop or other data available for observing local geology.

Groundwater investigations for the development of groundwater resources often require identification and mapping of local geologic features (fractures, lineations, bedding, lithology) in order to better understand the influence of geology on groundwater availability. From a hydrogeologic standpoint, the nature and extent of local groundwater systems can only be understood if they are actively tested and analyzed – rarely are geologic controls simple enough to accurately predict the geometry of a local groundwater flow system. For this reason, it is important to evaluate groundwater systems in crystalline rocks through the site specific collection and analysis of geologic and hydrogeologic data. Data acquisition and analysis through controlled aquifer testing, and observation and analysis of geologic structure are the main requirements for describing the orientation and storage capacities of local groundwater flow systems, and for creating meaningful groundwater management and protection plans for private and municipal systems dependent on groundwater. By knowing the orientation, extent of drawdown, progression of drawdown, change in storage, and degree of communication between wells in communication with local groundwater systems, comprehensive and effective strategies with regard to the management of well pumping schedules, response to groundwater contamination, land use planning, and drought management can be prescribed.

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