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Bedrock Geologic Map of the Headwaters Region of the Cullasaja River, Macon and Jackson Counties, North Carolina

By William C. Burton

Explanatory text to accompany

Scientific Investigations Map 2887

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Conversion Factors

Inch/Pound to SI		
Multiply	**By**	**To obtain**
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound		
Multiply	**By**	**To obtain**
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

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

$$°F=(1.8\times°C)+32$$

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

$$°C=(°F-32)/1.8$$

Bedrock Geologic Map of the Headwaters Region of the Cullasaja River, Macon and Jackson Counties, North Carolina

By William C. Burton

Abstract

The headwaters region of the Cullasaja River is underlain by metasedimentary and meta-igneous rocks of the Neoproterozoic Ashe Metamorphic Suite, including gneiss, schist, and amphibolite, that were intruded during Ordovician time by elongate bodies of trondhjemite, a felsic plutonic rock. Deformation, metamorphism, and intrusion occurred roughly simultaneously during the Taconic orogeny, about 470 million years ago, under upper-amphibolite-facies metamorphic conditions. Two generations of foliation and three major phases of folds are recognized. The second- and third-generation folds trend northeast and exert the most control on regional foliation trends. Since the orogeny, the region has undergone uplift, fracturing, and erosion. Resistance to erosion by the plutonic rock may be the primary reason for the relatively gentle relief of the high-elevation basin, compared to surrounding areas. Amphibolite is the most highly fractured lithology, followed by trondhjemite; the latter may have the best ground-water potential of the mapped lithologies by virtue of its high fracture density and high proportion of subhorizontal fractures.

Discussion

Introduction

This bedrock geologic map was produced as part of a cooperative hydrogeologic project between the U.S. Geological Survey (USGS) and the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality, Groundwater Section, known as the Piedmont-Mountains Ground Water Project. The goal of the project is to better understand the hydrologic characteristics of major hydrogeologic settings in the North Carolina Piedmont and Blue Ridge geologic provinces, for the purpose of ground-water resource planning. The main focus of the project is an intensive study of small watersheds that are considered to be representative of larger areas within each geologic province.

One of the components of the Piedmont-Mountains Ground Water Project involves a comparison of two watersheds in the Blue Ridge, one in a developed area and one in an undeveloped area. The watershed in the undeveloped area is within the Bent Creek Experimental Forest, near Asheville, N.C., which is managed by the U.S. Forest Service. In the developed area, the watershed is the headwaters region of the Cullasaja River, near Highlands, N.C., which is the focus of this study. These areas were selected because hydrologic monitoring networks, including wells and stream gages, already exist in both watersheds, and because both areas are underlain by the same general suite of rocks, the Ashe Metamorphic Suite. The Ashe Metamorphic Suite is a large belt of greenschist-facies and amphibolite-facies metamorphic rocks, consisting mostly of mica schists, paragneisses, and lesser amounts of amphibolite, that extends the full length of the eastern Blue Ridge in North Carolina and that is considered to be Neoproterozoic to possibly earliest Paleozoic in age (Rankin, 1970; Abbott and Raymond, 1984). One of the goals of the Piedmont-Mountains Ground Water Project is to understand the similarities and differences in the geology of these two watersheds, and the extent to which the differences in geology affect the ground-water hydrology in each area.

The headwaters region of the Cullasaja River (also referred to in this report as the Highlands region, map area, and study area) is a high-altitude watershed, with elevations ranging from 3,400 feet (ft) to over 5,000 ft. It comprises the drainage area above a USGS stream gage (USGS 0350056050) just below Lake Sequoyah near the town of Highlands, and is entirely contained within the Highlands, N.C.-Ga., 7.5-min quadrangle (fig. 1). The watershed includes the town of Highlands (elevation 3,835 ft), a summer resort destination long favored by people from North Carolina, South Carolina, Georgia, and Florida. Many older summer homes as well as numerous relatively new gated developments with golf courses are contained in the area surrounding the town of Highlands. The resident population ranges from a

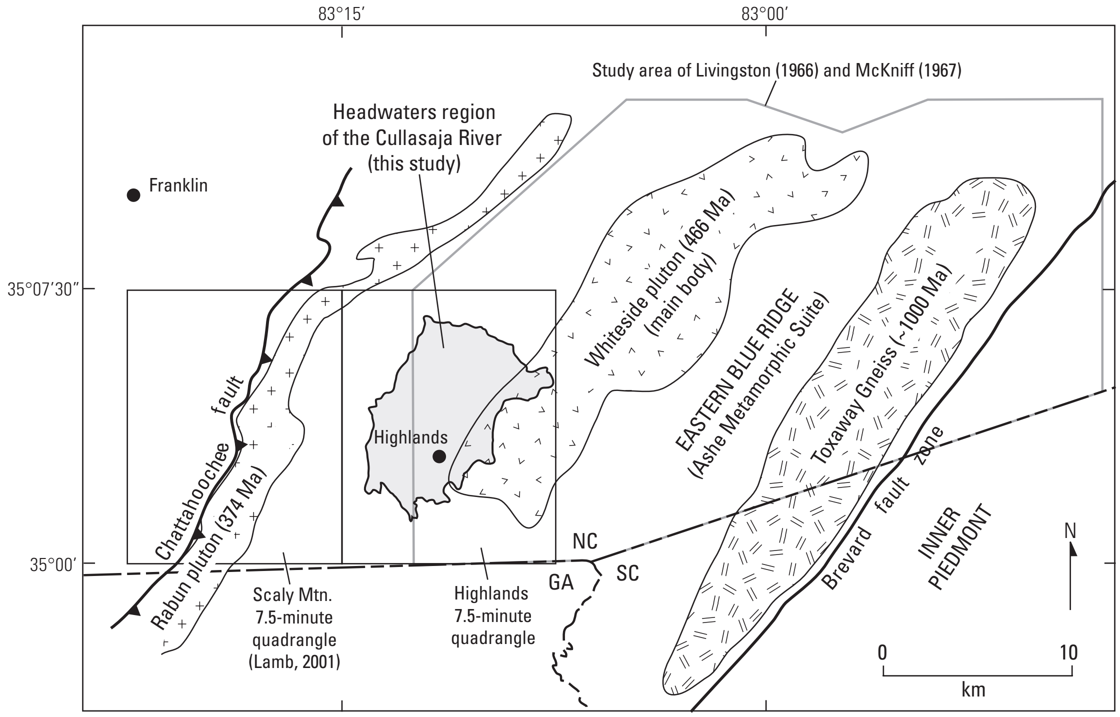


Figure 1. Location map showing mapped areas and generalized geology near the study area. Geology adapted from unpublished 2003 digital compilation of geologic maps of the eastern Blue Ridge and Inner Piedmont geologic provinces, by Robert D. Hatcher, Jr.

low of about 1,000 in the winter to as much as 10,000 in the summer, with an additional tourist peak during fall foliage season (Bob Wright, Upper Cullasaja Watershed Association, written commun., 2003). The topographic relief within the Highlands region is relatively low (fig. 2) compared to areas outside the region, which helps explain the area's popularity as a site for vacation homes. Because of the development, most of the Highlands region is extensively traversed by roads, and roadcuts were the source of most of the bedrock exposures observed during mapping.

Previous Work

The first detailed geologic mapping in the area was by John Livingston and Joseph McKniff, and accompanied doctoral thesis studies on structural geology and petrology at Rice University (Livingston, 1966; McKniff, 1967). Their combined map area stretched from the Cullasaja River headwaters in the west to the Inner Piedmont in the east, and included part of the Brevard fault zone and a granitic body now recognized as the ~1-Ga Toxaway Gneiss (fig. 1). McKniff's map, at a scale of 1:24,000, contained the western half of this area and included the eastern part of the headwaters of the Cullasaja River (fig. 1).

McKniff recognized three major bedrock lithologies in his map area: biotite-muscovite schist and gneiss, amphibolite, and a felsic rock he informally named the Cashiers gneiss. The Cashiers, a white, fine-grained, massive to well-foliated quartzofeldspathic rock, is the same rock as the Whiteside Granite of Keith (1907), who named it after the cliff exposures on Whiteside Mountain, at the eastern edge of the watershed. Olson (1952) reported the Whiteside Granite to be intrusive in origin and late Paleozoic in age. For a variety of reasons, including semi-conformable field relations with the other stratified units, and the roundedness of zircons in the rock, McKniff concluded that the felsic gneiss was originally a stratified felsic volcanic rock, and Precambrian in age. He came to this conclusion despite noting that the contacts of the Cashiers gneiss were migmatitic and featured "injection gneiss" (McKniff, 1967, p. 9) and that the Cashiers formed "sill-like bodies" (p. 21). He correctly noted that the Cashiers locally formed discordant, intrusive contacts, which he ascribed to local remobilization during regional Paleozoic metamorphism. The concept of the Cashiers gneiss as stratified in origin has been discounted by more recent work, discussed below, and the rock is again considered to be intrusive and Paleozoic in age.

In his structural analysis of the region, McKniff postulated the existence of early, minor recumbent folding as part of an initial nappe-stage deformation, followed by later, upright folding that produced the dominant map patterns and present distribution of units. The axes of both early and late folds were approximately colinear and trended

Figure 2. View of the study area looking southwest from Shortoff Gap.

north-northeast. Of greatest significance is the fact that McKniff portrayed his felsic map unit, the Cashiers gneiss, as the oldest unit in a conformable sequence, underlying all other rocks and appearing only in the cores of antiformal folds on both his map and cross section.

A bedrock map of the Scaly Mountain, N.C., 7.5-min quadrangle, adjoining the Highlands quadrangle to the west (fig. 1), was recently produced by Lamb (2001). In the eastern part of his quadrangle he mapped biotite gneiss and metagraywacke that generally agree lithologically with rocks mapped in the western part of this study area. To the west of these rocks he mapped a northeast-trending body of granodiorite (the Rabun granite of Hatcher and others, 1995), which is a pluton with an age of 335.1±2.8 Ma (Miller and others, 2006), and the northeast-trending Chattahoochee fault of Paleozoic age (Hurst, 1973). The mapping by Lamb (2001) shows that the Chattahoochee fault truncates the Rabun pluton and has imparted a tectonic foliation to it, and that the fault is itself folded (fig. 1). On the basis of this evidence, Robert Hatcher (oral commun., 2005) considers the Chattahoochee to be an Alleghanian fault, and the intrusion of the Rabun to be synkinematic with respect to Alleghanian deformation. According to the cross sections of Lamb (2001), the Chattahoochee fault is a gently east-dipping to subhorizontal thrust fault that extends under the Highlands region at a below-land-surface depth of about 4,000 to 4,500 ft.

Recently, Miller and others (1997, 1998, 2000) conducted a regional study of intrusive rocks in the eastern Blue Ridge, including the felsic rock near Highlands, which they referred to as the Whiteside pluton (fig. 1). Miller and others (1997) cited the presence of igneous foliation, aplite and pegmatite dikes, country-rock enclaves, and migmatitic contacts between felsic gneiss and other rocks as proof for an intrusive origin. They noted considerable variability in grain size and fabric development in the rock as evidence that the intrusion occurred during regional deformation. Geochemical analyses of the Whiteside pluton by Miller and others (1997) showed it to be mostly trondhjemite, with minor amounts of granodiorite. Uranium/lead (U/Pb) dating of zircon rims, using the sensitive high-resolution ion microprobe (SHRIMP) technique, yielded a crystallization age of 466±10 Ma (Ordovician) for the Whiteside pluton (Miller and others, 1998, 2000). Cores from the same zircons yielded Mesoproterozoic and Archean ages, suggesting ancient crust at depth. The dated sample came from an abandoned quarry in the Cashiers 7.5-min quadrangle, which adjoins the Highlands quadrangle to the east. Miller and others (1997) proposed that the Whiteside and other plutons formed by melting of underplated mafic crust during tectonic convergence and crustal loading, but noted that these plutons do not represent subduction-zone arc magmas. Miller and others (2000) speculated that the plutons could represent tectonically displaced remnants of an arc rooted in the Inner Piedmont, to the southeast. Thomas (2001) stated that if an arc did exist in the region, its remnants are buried or were eroded away.

McKniff (1967) determined that there was a single, regional prograde metamorphic event in the Highlands region that reached kyanite grade, with a minor, greenschist-facies metamorphic overprint in places where younger shearing occurred. In a regional study of Blue Ridge metamorphism, Carpenter (1970) placed the sillimanite-kyanite isograd a few kilometers west and northwest of the town of Highlands, and Butler (1991) placed it just south and west of Highlands. Eckert and others (1989), in a metamorphic and structural study that focused on an area of granulite-facies metamorphism within lithologically similar rocks of the Tallulah Falls Formation, about 25 km northwest of the Highlands region, determined that the metamorphic peak was synchronous with development of a dominant, second-generation foliation (S_2) in that area.

Merschat and Carter (2002) published a 1:12,000-scale geologic map of the Bent Creek watershed, about 80 km northeast of the Highlands region, an area also underlain by rocks of the Ashe Metamorphic Suite. In their interpretation, the Bent Creek rocks have a simple stratigraphy consisting mainly of sillimanite-garnet-bearing schist that is overlain by metagraywacke, which itself is overlain by garnet-sillimanite-bearing metasiltstone. Smaller lenses of amphibolite, metaconglomerate, and metagraywacke occur throughout the lower two units. This sequence was deformed during regional metamorphism, according to Merschat and Carter (2002), by northeast-trending, upright to moderately overturned folds, with the watershed roughly centered on a northeast-trending, upright to slightly northwest-verging anticlinorium.

Lithologies

The rocks underlying the headwaters region of the Cullasaja River comprise six rock units that belong to three major groups: metasedimentary and metavolcanic rocks of the Ashe Metamorphic Suite, Ordovician felsic plutonic rocks that intrude the Ashe Metamorphic Suite rocks, and migmatitic rocks formed as a result of this intrusion.

Neoproterozoic Ashe Metamorphic Suite

The Ashe Metamorphic Suite was renamed by Abbott and Raymond (1984) after the Ashe Formation of Rankin (1970), a large body of metasedimentary and meta-igneous rocks in the eastern Blue Ridge of North Carolina. The suite is considered to be Neoproterozoic in age on the basis of stratigraphic correlation with other formations to the north (Rankin, 1975), and rocks of this suite in the map area are also considered to be correlative with rocks of the Neoproterozoic (?) Tallulah Falls Formation to the south (Hatcher, 1971, 1978). The protoliths for rocks of the Ashe Metamorphic Suite perhaps originated as deepwater sediments and mafic volcanic rocks deposited on oceanic or transitional oceanic-continental crust at a passive continental margin (Abbott and Raymond, 1984). The presence of prograde epidote in the amphibolite of the map area suggests that some of the amphibolites may have had an origin as calcareous sediment; however, no obvious quartzose calc-silicate rocks were identified in the map area. The rocks of the Ashe Metamorphic Suite mapped in this area include three lithologies: biotite-muscovite schist, muscovite-biotite gneiss, and amphibolite. (Minerals in hyphenated sequence are listed in increasing order of abundance.) Along with their map-scale distributions, the schist, gneiss, and amphibolite are finely interlayered in some outcrops, on a scale of centimeters to decimeters, within map units shown as schist or gneiss. The differences between the gneiss and schist are locally subtle and their contacts gradational, reflecting a probable origin for the rocks as a thick, interbedded, deepwater sedimentary sequence of mud and poorly sorted sand (graywacke). Preserved bedding was not found in either the schist or the gneiss.

Biotite-muscovite schist (Zbms; see map) is gray to tan weathering, fine-grained to mostly medium-grained (1–5 mm in diameter) and well foliated (fig. 3). The schist typically has thin metamorphic layers and lenses of white, fine-grained intergrown quartz and plagioclase that alternate with muscovite-biotite-rich zones, locally producing a flaser texture. Garnet is commonly intergrown with the mica but is less abundant. Accessory minerals include kyanite, sillimanite, and (or) apatite. A large ledge of biotite-muscovite schist can be seen at Bridal Veil Falls, on U.S. Route 64 at the western edge of the map area.

Muscovite-biotite gneiss (Zmbg; see map) is distinguished from schist by being darker gray and finer grained, more quartzofeldspathic and less micaceous, but with more biotite, and with finer, more planar compositional layering (fig. 4). Garnet is less abundant in the gneiss than in the schist. Apatite is a common accessory mineral. Thin quartzofeldspathic layers are concordant to layering in the gneiss and suggest a sandy component to the protolith, whereas pinch-and-swell textures are less common. Representative exposures of muscovite-biotite gneiss can be seen in small roadcuts between downtown Highlands and the Highlands cemetery to the north.

Amphibolite (Zam; see map) is gray to ruddy weathering, dark green to black, and consists of fine-grained, intergrown plagioclase and hornblende, with lesser quartz (fig. 5). Epidote is locally present as idioblastic grains in textural equilibrium with hornblende. Sphene and ilmenite locally are common accessories. Amphibolite is well foliated but has much less pronounced compositional layering than the schist or gneiss. Small roadcuts of amphibolite can be seen in the housing development northwest of Mirror Lake.

Figure 3. Biotite-muscovite schist (Zbms). Pen for scale is 13.5 cm long.

Ordovician Plutonic Rocks

What distinguishes the map area from much of the rest of the eastern Blue Ridge underlain by the Ashe Metamorphic Suite is the large volume of intrusive rock, called here the Whiteside trondhjemite (Owt; see map), which is equivalent to the 466-Ma Whiteside pluton of Miller and others (2000) and the Whiteside Granite of Keith (1907). In his map of the Pisgah quadrangle, which contains the present map area, Keith (1907) named the rock after the cliffs of Whiteside Mountain, but also included under this label bodies of intrusive rocks to the north and east now known to be Devonian and Mesoproterozoic in age. The main body of intrusive rock lies to the northeast of the map area (fig. 1). Over its range, the Whiteside pluton varies from trondhjemitic to granodioritic in composition, with trondhjemite being the most abundant (Miller and others, 1997); hence the use of the term trondhjemite. The trondhjemite is white to light gray, medium-grained, and has a variable texture that can range within a single exposure from massive to well foliated or gneissic (fig. 6). The mineralogy of the trondhjemite, in ascending order of abundance, is microcline, muscovite, biotite, quartz, and plagioclase, with potassium feldspar (microcline) ranging in abundance from 0 to 10 percent of volume, and muscovite and biotite generally up to 10 percent of volume. Accessory minerals are apatite and garnet. The variability in texture is due to the fact that the pluton intruded during regional deformation, as noted by Miller and others (1997), and parts of the magma experienced more deformation and became more strongly foliated than other parts. A systematic map

Figure 4. Muscovite-biotite gneiss (Zmbg), cut by pegmatite dike (on right). Hammer for scale is 33 cm long.

Figure 5. Ruddy weathering, fine-grained amphibolite (Zam), which typically is more fractured than other lithologies. Pen for scale (just to left of center) is 13.5 cm long.

pattern of the degree of foliation in the trondhjemite could not be determined. Crosscutting planar aplite and pegmatite dikes from 5 centimeters (cm) to 3 meters (m) thick are represented on the map by structure symbols only; they may represent late-stage phases of the Whiteside intrusion. Quartz veins possibly related to metamorphic activity are less than 1 m in thickness and are represented only by structure symbols on the map.

Migmatitic Rocks

Migmatitic rocks mapped in the study area are hybrid, interlayered mixtures of metamorphosed sedimentary and volcanic country rock and felsic intrusive rock. The source of the felsic rock is the Whiteside trondhjemite, of Ordovician age; therefore the migmatites are labeled here as Ordovician and Neoproterozoic. The migmatites commonly have strong centimeter-scale gneissic compositional layering, consisting of alternating light-colored felsic layers (leucosomes) composed of quartz, plagioclase, and minor potassium feldspar, and dark, more mafic layers (melanosomes) consisting of quartz, plagioclase, muscovite, biotite, and minor hornblende (fig. 7). Map-scale bodies of migmatite are found along the intrusive contact between the Whiteside trondhjemite (Owt) and metasedimentary rock (Zbms and Zmbg), or as isolated bodies within the intrusive trondhjemite (see map). They appear to have formed mainly by thin fingers of intrusive rock penetrating along layers in the metasedimentary country rock. This contrasts with the migmatites found in the high-grade metamorphic zone studied by Eckert and others (1989) in the Wayah Bald area northwest of the map area, which formed in the absence of plutonism via metamorphic reactions that produced localized partial melting. Some contacts between metasedimentary and plutonic rocks in the map area lack migmatite, perhaps reflecting locally more rapid, crosscutting intrusive activity that did not allow sufficient time for fine-scale intrusive injection to form migmatites.

Two types of migmatite were mapped, in an effort to distinguish the protolith (country rock) from which each was

Figure 6. Whiteside trondhjemite (Owt) has texture that varies from massive to locally gneissic. Hammer for scale is 33 cm long.

Figure 7. Well-layered muscovite-biotite migmatitic gneiss (OZmg). Light-colored injected aplite layers locally terminate at noses of F_2 folds (arrow) as a result of synkinematic folding and intrusion. Pen for scale is 13.5 cm long.

derived, although differences in the field are subtle. Migmatite that has lighter, more schistose (mica-rich) melanosomes, possibly derived from biotite-muscovite schist, is called biotite-muscovite migmatitic schist (OZms; see map); and migmatite that has darker, more gneissic melanosomes, possibly derived from muscovite-biotite gneiss or amphibolite, is called muscovite-biotite migmatitic gneiss (OZmg; see map and fig. 7). Both types of migmatite are commonly strongly deformed, and may have very complex fold patterns and crosscutting relations between intrusive layers and metasedimentary layers (fig. 8).

Figure 8. Complex pattern in muscovite-biotite migmatitic gneiss (OZmg) reflects interplay of deformation and intrusion, followed by upright F_3 folding. Hammer for scale is 33 cm long; handle is parallel to axial surface of F_3 folds.

Ductile Structures, Metamorphism, and Deformational History

The rocks of the headwaters region of the Cullasaja River show evidence of several phases of folding and a single dominant, prograde metamorphic event that was possibly overprinted by a second, less pervasive prograde event. This suggests that most of the deformation and recrystallization occurred during a single orogeny. If the 466-Ma age for the Whiteside pluton is accurate, and the pluton intruded synchronously with deformation of the country rocks, then deformation and metamorphism occurred during the Taconic orogeny (about 470 to 440 Ma). This is commensurate with conclusions reached elsewhere in this part of the southern Appalachian Blue Ridge about age of metamorphism and deformation (for example, Eckert and others, 1989). However, less than 10 km to the west of the map area lies the eastward-dipping, low-angle Chattahoochee thrust fault which, for reasons stated above, probably formed during the Alleghanian orogeny (about 335 Ma). If this is correct, then some effects of the Alleghanian orogeny are to be expected in the study area as well.

Figure 9. Folded contact (arrow) between Whiteside trondhjemite (Owt, on right) and muscovite-biotite migmatitic gneiss (OZmg). Hammer for scale (near bottom of photograph) is 33 cm long.

Syntectonic Intrusion

During the Taconic orogeny, the southern Appalachian Blue Ridge in general experienced southeast-northwest compression, with a component of up-from-the-southeast shear that produced northwest-verging folds and southeast-dipping thrust faults (Hatcher and Goldberg, 1991). In the Highlands region, another major factor in the development of the structural framework was the intrusion of the Whiteside trondhjemite. Mapping indicates that the pluton intruded into country rock during regional deformation as a series of foliation-parallel concordant sheets that presently dip southeast (cross sections; see map). Evidence for the synkinematic timing of the intrusion can be seen in outcrop, as illustrated in figures 7–10. Synkinematic features include injected aplite layers terminating at noses of F_2 folds (fig. 7), complexly intermixed and folded aplite and country rock (fig. 8), F_2-folded contact between Whiteside trondhjemite and migmatitic gneiss (fig. 9), and development of S_2 foliation synchronous with aplite injection (fig. 10). The migmatites

Figure 10. Coarser grained, more schistose S_2 foliation, accompanied by aplite segregations (upper arrow), is developed coplanar with S_1 gneissic layering (lower arrow) in muscovite-biotite migmatitic gneiss (OZmg). Pen for scale is 13.5 cm long.

appear in outcrop to have undergone the most folding of all the lithologies, perhaps because their higher melt-phase component rendered them more susceptible to deformation.

Foliation

The foliation pattern in the headwaters region of the Cullasaja River is complex, showing a wide range of strikes and, in many places, reversals of dip. Two generations of foliation were mapped: a first-generation metamorphic foliation (S_1; open foliation symbols on map) that is planar and generally parallel to gneissic compositional layering, and a second-generation foliation (S_2; closed foliation symbols on map) that is more schistose in texture and has a wispier, flaser-like habit. Nowhere in bedrock exposures were the two generations of foliation observed at an angle to each other. In a number of places, distinct, schistose S_2 foliation is developed concordant to S_1 compositional layering in metasedimentary rock and migmatite, typically in zones that also contain thin sills and lenses of intrusive material (fig. 10). The association of S_2 development with intrusion of sills, combined with outcrop-scale evidence that intrusion was syn-F_2 (figs. 7, 9) and map-scale evidence that the Whiteside trondhjemite (Owt) crosscuts S_1-parallel lithologic contacts in the metasedimentary/metavolcanic country rock (see map and cross sections), indicates that the intrusion of the Whiteside was roughly synchronous with the development of the S_2 foliation. The variably developed foliation in the trondhjemite is therefore also considered to be S_2.

Minor (Outcrop-Scale) Folds

Upright to overturned, open to isoclinal folds having a wide range of orientations are common in exposures throughout the study area (see map). Because of the structural complexity of the area, this interpretation of folding history and recognition of distinct generations of folds is speculative. Most folds have hinges that plunge gently to moderately to the northeast or southwest, as reflected in the stereonet plot of poles to all foliation, which shows a well-developed fold girdle (fig. 11); girdles are also seen in plots of poles to foliation in most of the map units (fig. 11). The subhorizontal maximum seen in these girdles could either be a product of earlier, recumbent folding or later, gentle folding that has produced broad hinge zones with gently dipping foliation (fig. 11). In several of the plots, especially those for all stations and for muscovite-biotite migmatitic gneiss (OZmg), pairs of maxima indicate two dominant northeasterly strikes for steeply dipping foliation, which could be explained by two generations of foliation. However, plots of all S_1 foliation and of all S_2 foliation (not shown) show the same maxima pairs, so the two generations of foliation recognized in the study area are not the explanation for the double trend.

Only one fold in outcrop was recognized as first-generation (F_1), in which the folded surface is primary compositional layering (see map, unit Zbms, about 1 km southeast of Highlands Reservoir); all other observed folds are considered to be second-generation (F_2) or younger. Tight to isoclinal F_2 folds commonly have well-developed, schistose axial planar S_2 foliation (fig. 7). Fold axial surfaces mapped as F_2 generation are generally northeast-striking, but with a range of strikes as well as a wide range of dips, probably in part due to later folding (fig. 12). Mineral lineations consisting of aligned grains of biotite or hornblende were locally observed in outcrop oriented (with one exception) parallel to fold axes considered F_2 in age (fig. 12).

The most obvious folds in outcrop (figs. 8, 13) consist of north- to northeast-trending folds that are typically upright to strongly overturned to the northwest, with gently southwest- or northeast-plunging hinges (fig. 12); these are considered to be F_3 in age because they deform S_2 foliation. Smaller-amplitude F_3 crenulations are seen in outcrop that are presumed to be parasitic to larger folds. The variation in strike in both F_3 axial surfaces and fold axes (fig. 12) may reflect the effect of superposition of F_3 folds on older, folded surfaces. The large range in dip of F_3 axial surfaces (fig. 12) may simply reflect the nature of the folding event, from upright to overturned. Rare, northwest-trending, upright to overturned late-stage crenulate folds are seen in outcrop in a few places but are not recognized at the map scale; they are shown on the map with the same symbol as northeast-trending F_3 folds, but are interpreted to be F_4 folds (see map).

Major (Map-Scale) Folds

The polydeformed rocks of the study area reflect a folding history at small and large scales that is difficult to decipher. Interpreted axial traces of map-scale folds of generations F_1 to F_3, shown on the map, all trend northeast. Confidence in the placement of the younger-generation fold axial traces is greater than for the older ones. Dip reversals occur on the limbs of the younger folds that indicate minor parasitic folds or overprinted older-generation folds. The most obvious map-scale fold is the doubly plunging Whiteside Mountain synform, which folds a roof pendant of country rock within a large mass of Whiteside trondhjemite (see map). Although the plutonic rock itself is named after the cliffs on Whiteside Mountain, the top of this high ridge is mostly underlain by biotite-muscovite schist of the synform, as originally noted by McKniff (1967). The synform is considered to be F_3 in age because it folds trondhjemite/migmatite and migmatite/schist contacts and S_2 foliation. It is shown on cross section *A–A´* as overturned to the southeast—a contrast in orientation with most F_3 folds measured in outcrop (fig. 12) and the other map-scale F_3 folds, which are upright (see map); the unusual orientation of the F_3 fold at Whiteside Mountain may be explained by superposition on an older, southeast-verging F_2 fold. Another prominent, upright, gently south-plunging F_3 fold underlies the ridge known as Brushy Face, along the southwest boundary of the watershed, producing an elongate, north-trending inlier of

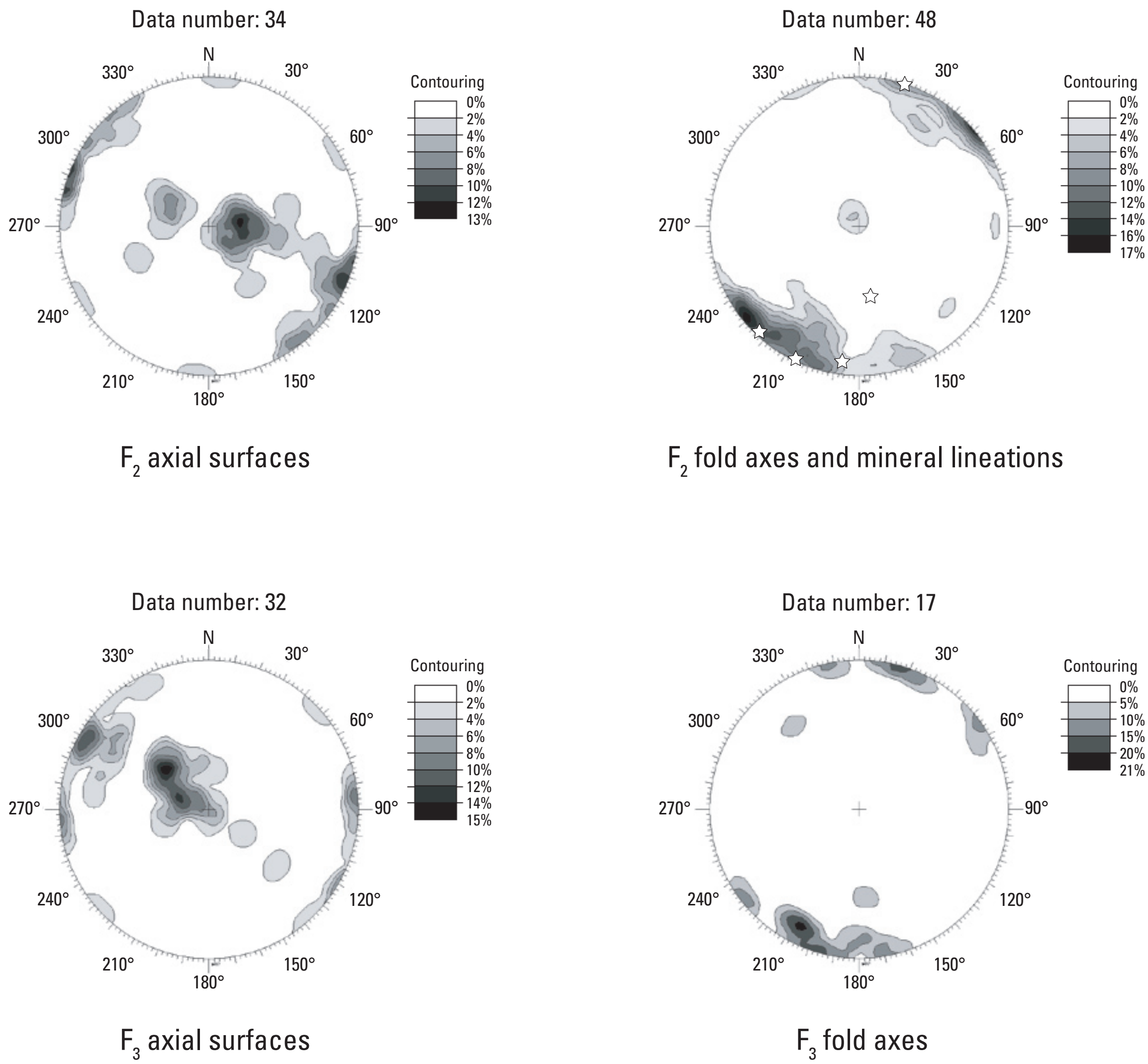


Figure 12. Summary of plots of F_2 and F_3 fold structures. Lower-hemisphere, equal-area projections of poles to F_2 and F_3 axial surfaces (left column), F_2 and F_3 fold axes (right column), and F_2 mineral lineations (stars on F_2 fold axes plot); contour intervals are given in accompanying keys. Data are plotted using the Structural Data Integrated System Analyzer software (DAISY, version 3.28b; Salvini, 2002).

country-rock migmatite within trondhjemite (see map and cross section *C–C´*). These and the other folds mapped as F_3 reflect the latest major phase(s) of regional southeast-northwest compression, which occurred after the intrusion of the Whiteside trondhjemite. They could have formed during the Alleghanian orogeny, considering the proximity of the Rabun pluton to the west (fig. 1), synkinematic with respect to the Alleghanian orogeny (Lamb, 2001), or they could be Acadian in age.

Axial traces of folds older than F_3 are more speculative, and their presence on the map attempts to emphasize the complex folding history. In the west-central part of the watershed, a body of muscovite-biotite gneiss (Zmbg) is mapped mantling a body of amphibolite (Zam), both containing predominantly S_1 foliation that is interpreted to be axial planar to the hinge of an F_1 fold (see map). To the southeast, an isolated, thick body of amphibolite containing only S_1 foliation is thought to mark the trace of the same F_1 fold, which was refolded by an intervening F_2 fold (see map and cross section *B–B´*). Both sets of fold traces are truncated in map view by the intrusive contact of the Whiteside trondhjemite, whereas in cross section the F_2 axial surface is roughly parallel to the intrusive contact. It is possible that regional F_1 folds in this area, restored to their pre-intrusive and pre-F_2/F_3-folding state, might trend more east-northeast to east, similar to the Taconian formlines mapped southeast of the Hayesville fault by Eckert and others (1989), and similar to the strike of first-generation Taconian folds mapped in the Bent Creek watershed by Merschat and Carter (2002).

Metamorphism

The metamorphic grade of the rocks in the headwaters region of the Cullasaja River is best reflected in the mineral assemblages in the metasedimentary rocks. Biotite, muscovite, and garnet are common in the schists and gneisses and are in textural equilibrium, whereas the aluminosilicate minerals most indicative of metamorphic grade are uncommon. These include kyanite and sillimanite, both of which were seen in thin section in a few of the samples of biotite-muscovite schist (Zbms) (fig. 14). Kyanite occurs as scattered porphyroblasts intergrown with muscovite and biotite. In a number of samples, sillimanite in fibrous or needle form appears to have been derived from the breakdown of muscovite, although a few prismatic sillimanite crystals were also observed. Slightly corroded kyanite crystals can be found in several thin sections coexisting with secondary fibrolitic sillimanite and intergrown muscovite. In one thin section, small kyanite grains are mantled by fibrolitic sillimanite, as observed under high power; more commonly, the two minerals coexist in the same thin section but are not in contact (fig. 14). This lack of grain contact was also observed by Eckert and others (1989) in their study of Taconian metamorphic rocks, and ascribed to rocks transitional in metamorphic grade between the kyanite and sillimanite zones.

Based on these fabric relations, kyanite appears to have crystallized first during metamorphic recrystallization, perhaps during formation of the S_1 foliation. The breakdown of kyanite and growth of sillimanite suggests an increase in temperature at relatively constant pressure, which could be produced either by heating during intrusion or by a separate regional metamorphic event. The sample evidence suggests that the distribution of sillimanite in the Highlands region is not simply a function of proximity to intrusive contacts, but is probably controlled primarily by bulk composition. Neither kyanite nor sillimanite is reported from the schists and gneisses in the eastern part of the Scaly Mountain quadrangle, to the west of the study area (Lamb, 2001), and they appear to be rare here. In the headwaters region of the Cullasaja River the kyanite+sillimanite transition zone appears to be quite broad (at least several kilometers wide), in contrast to the narrow transition zone (<1 km wide) mapped by Eckert and others (1989) in their study area, which lacks large plutonic bodies. Although minor amounts of retrograde chlorite and epidote were observed in thin sections from the Highlands region, there is no evidence of a widespread retrograde metamorphic event or associated tectonic fabric.

Figure 13. Upright F_3 folds in well-layered biotite-muscovite migmatitic schist (OZms). View approximately 2.5 m across.

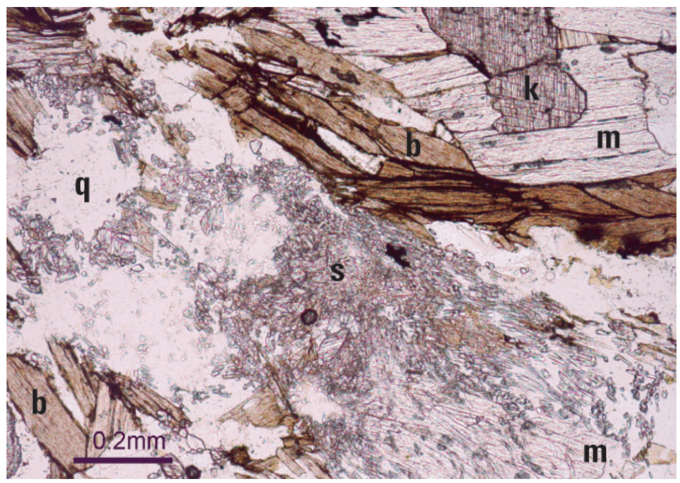


Figure 14. Photomicrograph (plane-polarized light) of biotite-muscovite schist (Zbms) with coexisting, but not texturally equilibrated, kyanite and sillimanite. Abbreviations used: m, muscovite; b, biotite; s, prismatic and needle sillimanite; k, kyanite; q, quartz.

$^{40}Ar/^{39}Ar$ Age Analysis of Metamorphic Minerals

Five localities in the map area were sampled by Michael J. Kunk (USGS) for $^{40}Ar/^{39}Ar$ isotopic-age analysis of the minerals hornblende, muscovite, biotite, and potassium feldspar (see map). Results indicate that the minerals cooled below their respective closure temperatures for argon in the interval 310–320 Ma (Burton and Kunk, 2006). These Alleghanian cooling ages suggest two distinct possibilities for the thermal history of the region: (1) the rocks stayed at elevated temperatures (>500°C) for about 100 to 150 m.y. following the Taconian and Acadian orogenies; or (2) a later, regional metamorphism in Alleghanian time elevated temperatures sufficiently (>500°C) to reset the cooling ages for the minerals. The cooling ages indicate rapid Alleghanian uplift, perhaps as a result of movement along the underlying Chattahoochee thrust fault (Burton and Kunk, 2006); therefore the preferred explanation is slow cooling from elevated temperatures in the early Paleozoic, followed by rapid uplift during the Alleghanian orogeny and closure of the argon systems. If this is true, then some of the later structures observed in the study area, such as the F_3 folds, may be Alleghanian in age.

Fractures

Fractures in the study area were mapped by examining outcrops and measuring the orientation of fractures having trace lengths of a meter or longer. Fractures observed are of two main types: joints that cut across foliation and variations in lithology; and partings, or joints that formed parallel to foliation and (or) compositional layering. Four observed fractures exhibited evidence of movement in the form of slickensided surfaces, and each is shown on the map as a minor fault with slickensided surface. Unless otherwise indicated, they are all collectively referred to here as joints. Joint sets containing multiple co-planar surfaces were accounted for by measuring the orientation of one member of the set and multiplying this measurement by the number of joints in the set. Scan-line analyses of outcrops, which involve measuring all joints that intersect a (typically) chest-high horizontal line, were not conducted.

The rocks in this part of the Blue Ridge may be relatively unfractured compared to crystalline rocks of similar grade elsewhere. Only 356 joints having trace lengths greater than 1 m were recorded in the study area, including all joints within joint sets. Although their fracture-mapping methods are not given, Merschat and Carter (2002) recorded only 223 joints in the Bent Creek watershed, of similar size to the study area and about 80 km to the northeast in the Blue Ridge. In contrast, while using the same method as this study in the similar-size Hubbard Brook watershed of central New Hampshire, Burton and others (2001) recorded 1,239 joints in schist and granite, not including multiples in joint sets (although minimum trace length was not specified in that study). Walsh and others (2006) mapped 1,357 joints in a 7.5-min quadrangle underlain by gneiss in western Connecticut, using similar methods and a minimum trace length of 20 cm. This total includes neither multiples in joint sets, nor foliation-parallel (parting) fractures.

Fracture data for the map units of the study area are summarized in figure 11. The data are broken down by lithology, with the idea that lithologic fracturing characteristics might be applicable to other areas in the North Carolina Blue Ridge having similar bedrock. Of the 356 joints observed in the map area, 170, or 48 percent, have dips less than 45°, and the plot of all joints shows a subhorizontal maximum, suggesting that exfoliation is an important fracture-forming process in this area (figs. 11, 15). Forty-seven joints, or 13 percent, were noted along foliation planes (foliation-parallel parting, fig. 11); of these, 27 joints (57 percent) have dips less than 45°, suggesting that gently dipping foliation is more likely to produce parting. The subhorizontal maxima for both foliations and joints suggest that foliation-parallel parting may have been even more prevalent than observations indicate. Of the four observed minor faults with slickensided surfaces, two strike north-northeast and dip steeply northwest, with southwest-plunging slickenlines; the third and fourth strike almost east and dip steeply north, with downdip-plunging or steeply north-plunging slickenlines.

Figure 15. Exposure of Whiteside trondhjemite (Owt) showing well-developed subhorizontal sheeting joints. Arrow shows hammer (33 cm long) for scale.

Considering the individual map units, amphibolite (Zam) is the most fractured, having an average of 2.33 joints recorded per station, followed by Whiteside trondhjemite (Owt) with 1.23 joints per station and biotite-muscovite migmatitic schist (OZms) with 1.13 (table 1). Obviously, exposure size can affect this number, although amphibolite exposures are generally smaller than others. Muscovite-biotite gneiss (Zmbg) is apparently the least-fractured lithology, with 0.22 fractures recorded per station (table 1). The lithology having the highest proportion of foliation-parallel partings relative to total fractures is Zbms (29 percent; table 1). Biotite-muscovite migmatitic schist (OZms) has the highest percentage of gently dipping fractures (56 percent), followed closely by Whiteside trondhjemite (Owt; 54 percent) and muscovite-biotite migmatitic gneiss (OZmg; 53 percent) (table 1).

The rose diagrams for the more steeply dipping fractures (≥45°) show different dominant strike orientations for different rock types, suggesting that there is not a single dominant joint set over the whole map area (fig. 11). Whiteside trondhjemite (Owt) shows a preferred direction of northeast-southwest for moderate- to high-angle joints, while biotite-muscovite schist (Zbms), biotite-muscovite migmatitic schist (OZms), and muscovite-biotite migmatitic gneiss (OZmg) have north-northwest to south-southeast peaks; and muscovite-biotite gneiss (Zmbg) and amphibolite (Zam) have west-northwest to east-southeast peaks (fig. 11). Another way to examine joint distribution is to subdivide the study area into domains, based on the approximately northeast-trending belts of rock (fig. 16). The westernmost domain (I) shows north and northwesterly preferred trends for steeply dipping fractures, whereas the easternmost domains (IV and V) show easterly trends, and the two domains in the middle (II and III) have northeasterly and northwesterly dominant trends, respectively (fig. 16). A trend between 270° and 290° appears to be the most persistent in all of the domains, showing up in 10 percent or more of the data for each domain, and producing normalized peak heights

Table 1. Summary of fracture data for bedrock map units in the study area.

Map unit	Number of stations	Total fractures	Fractures per station	Foliation-parallel partings	Foliation-parallel partings as percent of total fractures	Gently dipping fractures (<45 °)	Gently dipping fractures (<45 °) as percent of total
Zam	21	49	2.33	9	18	11	22
Owt	82	102	1.23	2	2	55	54
OZms	38	43	1.13	7	16	24	56
OZmg	57	58	1.04	1	2	31	53
Zbms	102	90	0.92	26	29	43	48
Zmbg	65	14	0.22	2	14	6	43
Total for all units	365	356	0.98	47	13	170	48

greater than 50 percent of the highest peak (fig. 16). Such peak heights are considered by Hardcastle (1995) to signify principal fracture trends. This trend is roughly orthogonal to the lithologic belts and suggests a weak regional cross-jointing. Orthogonal cross-jointing does not appear to be well developed in the well-defined map-scale F_3 fold on Whiteside Mountain (fig. 16, domain V).

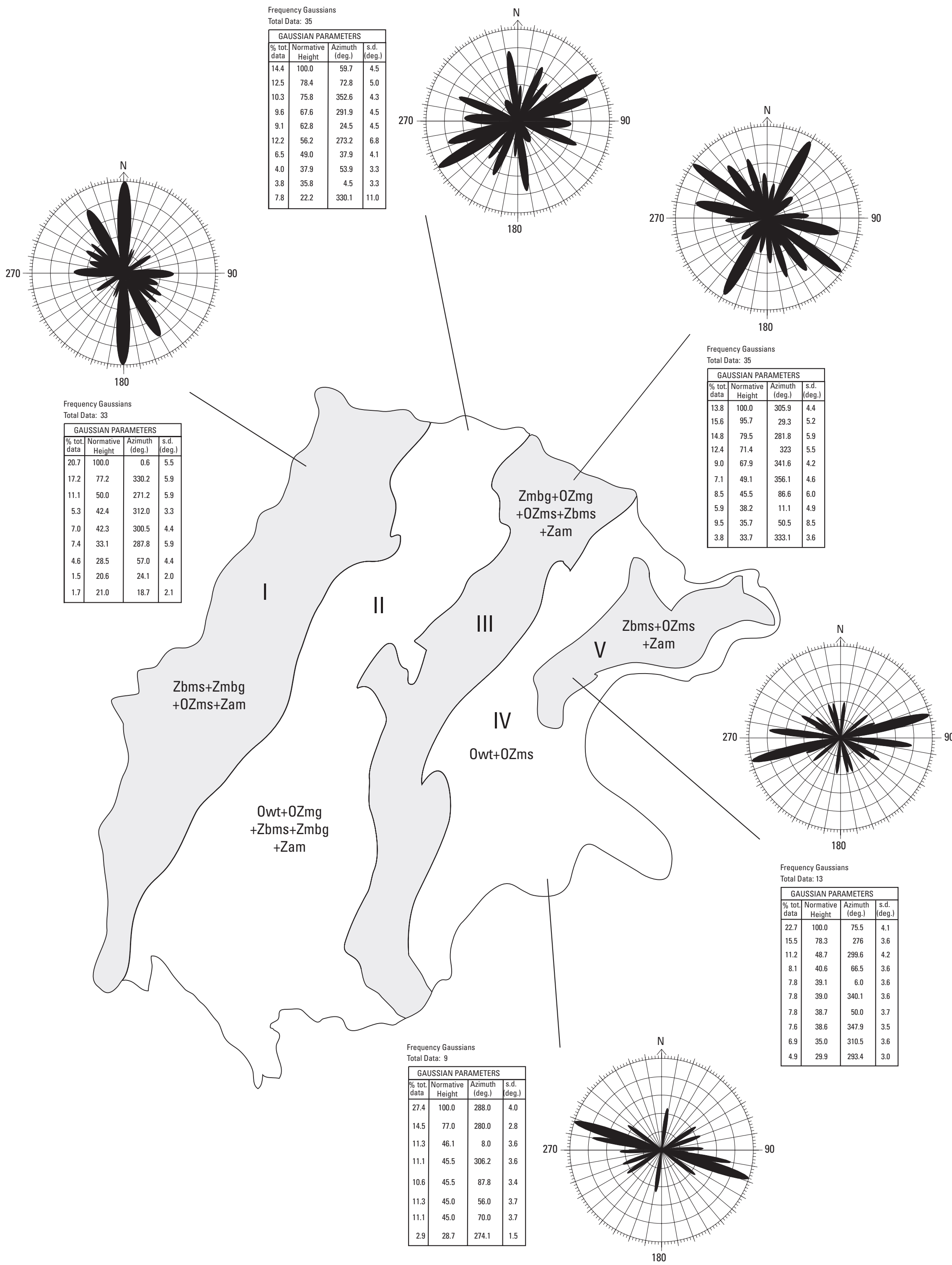
Summary

The headwaters region of the Cullasaja River is underlain by metasedimentary and meta-igneous rocks of the Neoproterozoic Ashe Metamorphic Suite, including gneiss, schist, and amphibolite. These rocks began their history as deep marine sediments and volcanic rocks that were deposited at the margin of continental and oceanic crust. They were then deeply buried and recrystallized into muscovite-, biotite-, garnet-, and hornblende-bearing schists and gneisses during the Taconic orogeny, about 470 Ma (Rankin and others, 1973; Rankin, 1975). The initial metamorphic recrystallization reached the upper amphibolite facies, producing kyanite, and was accompanied by at least one phase of isoclinal folding (F_1) and formation of the first generation of foliation (S_1). The overthickened crust generated melting near its base, which produced trondhjemitic magma about 466 Ma (Miller and others, 2000). This magma intruded the schist and gneiss in sheet-like bodies during deformation, and produced migmatite along contacts with country rock. This intrusion was accompanied by a second phase of folding (F_2), formation of S_2 foliation, heating, and growth of sillimanite in the schists and gneisses. The intrusion and mineralogical changes were followed by a third, weaker phase of upright folding (F_3), which may have occurred during the subsequent Acadian or Alleghanian orogenies. The second- and third-generation folds trend northeast and exert the most control on regional foliation trends, as shown in stereographic projections. They were followed by weak, crenulate, northwest- to west-trending cross-folds (F_4) of undetermined age (probably late Paleozoic). Alleghanian $^{40}Ar/^{39}Ar$ cooling ages on metamorphic minerals suggest slow cooling from peak temperatures in the early Paleozoic followed by rapid uplift in the late Paleozoic, perhaps along the underlying Chattahoochee thrust fault. Resistance to erosion by the plutonic rock following uplift may be the primary reason for the relatively gentle relief of the high-elevation basin, compared to surrounding areas.

About half of all joints measured in the study area have dips that are less than 45°, and subhorizontal exfoliation joints dominate fracture orientations. The exfoliation process may have been facilitated by the common presence of subhorizontal foliations. No single high-angle joint set is prevalent over the area. Amphibolite is the most highly fractured lithology, but is not a good prospect for ground-water exploration because it occurs in thin, discontinuous bodies. If the most accessible ground water in this area occurs in shallow, subhorizontal fractures, then the widespread Whiteside trondhjemite, with its relatively high fracture density and high percentage of gently dipping fractures, might have the best ground-water potential of the mapped lithologies, followed by the two types of migmatite.

Comparison of the Cullasaja Headwaters and Bent Creek Watersheds, and Recommendations for Future Study

One of the motives for mapping the Highlands region is to make a hydrogeologic comparison of the headwaters region of the Cullasaja River with the previously mapped Bent Creek watershed (Merschat and Carter, 2002). The Bent Creek area is part of an ongoing study by the USGS and the NCDENR. Geologically, the main similarity of the two areas is that they are both underlain by rocks of the Ashe Metamorphic Suite that have been metamorphosed under upper amphibolite facies conditions. As mapped by Merschat and Carter (2002), the



Frequency Gaussians
Total Data: 35

GAUSSIAN PARAMETERS			
% tot. data	Normative Height	Azimuth (deg.)	s.d. (deg.)
14.4	100.0	59.7	4.5
12.5	78.4	72.8	5.0
10.3	75.8	352.6	4.3
9.6	67.6	291.9	4.5
9.1	62.8	24.5	4.5
12.2	56.2	273.2	6.8
6.5	49.0	37.9	4.1
4.0	37.9	53.9	3.3
3.8	35.8	4.5	3.3
7.8	22.2	330.1	11.0

Frequency Gaussians
Total Data: 33

GAUSSIAN PARAMETERS			
% tot. data	Normative Height	Azimuth (deg.)	s.d. (deg.)
20.7	100.0	0.6	5.5
17.2	77.2	330.2	5.9
11.1	50.0	271.2	5.9
5.3	42.4	312.0	3.3
7.0	42.3	300.5	4.4
7.4	33.1	287.8	5.9
4.6	28.5	57.0	4.4
1.5	20.6	24.1	2.0
1.7	21.0	18.7	2.1

Frequency Gaussians
Total Data: 35

GAUSSIAN PARAMETERS			
% tot. data	Normative Height	Azimuth (deg.)	s.d. (deg.)
13.8	100.0	305.9	4.4
15.6	95.7	29.3	5.2
14.8	79.5	281.8	5.9
12.4	71.4	323	5.5
9.0	67.9	341.6	4.2
7.1	49.1	356.1	4.6
8.5	45.5	86.6	6.0
5.9	38.2	11.1	4.9
9.5	35.7	50.5	8.5
3.8	33.7	333.1	3.6

Frequency Gaussians
Total Data: 13

GAUSSIAN PARAMETERS			
% tot. data	Normative Height	Azimuth (deg.)	s.d. (deg.)
22.7	100.0	75.5	4.1
15.5	78.3	276	3.6
11.2	48.7	299.6	4.2
8.1	40.6	66.5	3.6
7.8	39.1	6.0	3.6
7.8	39.0	340.1	3.6
7.8	38.7	50.0	3.7
7.6	38.6	347.9	3.5
6.9	35.0	310.5	3.6
4.9	29.9	293.4	3.0

Frequency Gaussians
Total Data: 9

GAUSSIAN PARAMETERS			
% tot. data	Normative Height	Azimuth (deg.)	s.d. (deg.)
27.4	100.0	288.0	4.0
14.5	77.0	280.0	2.8
11.3	46.1	8.0	3.6
11.1	45.5	306.2	3.6
10.6	45.5	87.8	3.4
11.3	45.0	56.0	3.7
11.1	45.0	70.0	3.7
2.9	28.7	274.1	1.5

Figure 16. Steeply-dipping (≥45 °)-joint data from the headwaters region of the Cullasaja River, organized by domain (areas I through V). Data are plotted using the Structural Data Integrated System Analyzer software (DAISY, version 3.28b; Salvini, 2002). Azimuth-frequency (rose) diagrams for these joints were generated using a Gaussian curve-fitting routine. Table accompanying each rose diagram shows data for each peak, arranged in order of percent of total data represented per peak (% tot. data), followed by peak height as percentage of height of tallest peak (normative height), azimuth of each peak in degrees, and the standard deviation (s.d.) for each azimuth, in degrees. In each table, percentages of total data may not add up to 100 percent because of rounding errors or because not all azimuth peaks are included in the table.

dominant lithologies at Bent Creek are garnet-sillimanite-bearing metasiltstone, garnet-bearing metagraywacke, and sillimanite-garnet-bearing schist. These rocks are generally finer grained than the metasediments in the Cullasaja headwaters study area, and appear to have been recrystallized at a slightly lower metamorphic grade. Amphibolite is relatively sparse, as in the Cullasaja headwaters area, and rare beds of metaconglomerate also occur. The large felsic intrusive bodies mapped in this study area are lacking in the Bent Creek watershed.

Only one generation of folding was recognized at Bent Creek by Merschat and Carter (2002), in contrast to the polyphase history recorded in the headwaters region of the Cullasaja River. Preliminary observations by the authors at Bent Creek indicate that two distinct generations of foliation are present there: a generally steeply-dipping S_1 that is parallel to bedding and primary compositional layering, and a gently to moderately southeast-dipping S_2 that is axial planar to northwest-verging, locally recumbent map-scale folds that dominate the structural framework. Joints measured in the Bent Creek watershed by Merschat and Carter (2002) are steeply dipping and have a strong northwesterly trend, roughly orthogonal to the trend of their map-scale folds.

The NCDENR and the USGS have installed a series of piezometers at Bent Creek along a transect that spans from ridgetop to creek bottom, in order to investigate the near-surface flow of ground water in the predominantly schistose bedrock. A comparable transect in the Cullasaja headwaters region would logically be installed within the large area underlain by biotite-muscovite schist (Zbms) in the western part of the watershed. However, it also would be important to construct a second transect within an area underlain by the plutonic rock (Owt), in order to understand how these contrasting lithologies—schistose and granitic—affect ground-water flow. Such a comparison would have transferability to other areas of the Blue Ridge and Piedmont where plutonic bodies are found.

Acknowledgments

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